Synchronized Measurement Technology Supported Operational Tripping Schemes

A thesis submitted to the University of Manchester for the degree of

Doctor of Philosophy

in the Faculty of Engineering and Physical Sciences

2015

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School of Electrical and Electronic Engineering
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<td>CB</td>
<td>Circuit Breaker</td>
</tr>
<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
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<tr>
<td>DC</td>
<td>Data Concentrator</td>
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<td>DSA</td>
<td>Dynamic Security Assessment</td>
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<td>DTLR</td>
<td>Dynamic Thermal Line Rating</td>
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<td>DTM</td>
<td>Dynamic Thermal Management</td>
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<td>E-OTS</td>
<td>Existing transmission line OTS</td>
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<td>EN-OTS</td>
<td>Economic optimized N-OTS</td>
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<td>GB</td>
<td>Great Britain</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>IED</td>
<td>Intelligent Electronic Devices</td>
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<td>NG</td>
<td>National Grid</td>
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<td>N-OTS</td>
<td>Novel transmission line OTS</td>
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<td>OTS</td>
<td>Operational Tripping Scheme</td>
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<td>PLC</td>
<td>Programmable Logic Controllers</td>
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<td>PMU</td>
<td>Phasor Measurement Unit</td>
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<td>RTU</td>
<td>Remote Terminal Units</td>
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<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
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<td>SMT</td>
<td>Synchronized Measurement Technology</td>
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<td>SSA</td>
<td>Static Security Assessment</td>
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<tr>
<td>WAM</td>
<td>Wide Area Monitoring</td>
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<td>WAMPAC</td>
<td>Wide Area Monitoring Protection And Control</td>
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Abstract

The University of Manchester
Faculty of Engineering and Physical Sciences
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Doctor of Philosophy

Synchronized Measurement Technology Supported Operational Tripping Schemes
20/12/2015

The increasing volume of renewable and intermittent generation that is being connected to power systems means that system operators need more advanced dynamic control tools to manage the increase in congestion and the resulting pressure on system constraints. The introduction of synchronised measurement technology provides the wide area real-time measurements that are essential to develop and implement adaptive online solutions for current network issues.

The objective of the research presented in this thesis is to design intelligent system integrity protection schemes (SIPS) that protect transmission lines and power transformers from thermal overloading. An intelligent protection scheme should be able to identify the fault severity, predict the post disturbance trend of system states, continue monitoring specific vulnerable system variables and propose an accurate solution that is tailored to the actual system conditions and the specific contingencies that have occurred. The intent of this research is to contribute to the development of adaptive protective schemes that are enabled by modern synchronized measurement technologies for future power systems.

The research presented in this thesis focuses on the creation of novel Operational Tripping Schemes (OTSs) that explicitly satisfy both the functionality and economical requirements by integrating an improved assessment of thermal behaviour of the monitored assets. Novel OTSs are proposed for both transmission lines and transformers and they can be considered to be intelligent, adaptive and efficient SIPS for the thermal protection of system assets. A novel functional block is proposed that be included within the OTS and that uses optimization theory to determine the lowest cost solution to overheating in the time available. Furthermore, case studies have been conducted to verify the performance of each novel OTS using simulations of a full GB system model.
Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
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Acknowledgements

I would like to take this opportunity to thank National Grid for funding my PhD project. They have provided me the chance to explore one of the most exciting parts of network operation. A special thanks to Dr Wen An, who help us have a smooth start of the project and Dr Mark Osborne, who continue delivering useful suggestions and technical feedbacks across the project progress.

I would like to express my sincere gratitude to my supervisor Professor Vladimir Terzija, who secured the project and provided unlimited support in my PhD study and related research. Without his constant supervision, guidance, feedback, technical and moral support, this PhD could not have been accomplished.

My sincere thanks also goes to all of my colleagues and friends who have helped me during my time at the University of Manchester. They have made this PhD journey a rich and pleasurable memory for me. I will never forget the fun time we used to enjoy. I would especially like to thank Peter. He has been very kind and helpful in providing advices through my research in technical and English aspects.

Last but not the least, I would extend my most sincere thanks to my parents for supporting me spiritually and financially throughout the whole education of me from bachelor to PhD and making my dream coming true. I love them and promise here that I would keep on working hard in my coming career and make myself a good son they are very proud of. I would also like to thank to my wife Yiqi. She has accompanied me for my whole PhD period and inspired me with love, patience and understanding.
1. **Introduction**

This chapter introduces the objectives, background and motivation of this Ph.D. research as well as its specific goals and main contributions. Section 1.1 describes the primary objectives, followed by a general description of the background and motivation for the research in Section 1.2. The goals of this research are listed in section 1.3 and a brief introduction of the research methodology is given in Section 1.4. A summary of the contributions made by this research is provided in Section 1.5 and a list of publication is displayed in Section 1.6. Finally, the content of the other thesis chapters is briefly summarised in Section 1.7.

### 1.1 Research Objectives

The objective of the research presented in this thesis is to design intelligent system integrity protection schemes (SIPS) that protect transmission lines and transformers from thermal overloading. After a disturbance occurs within the network, such as an unexpected loss of several transmission lines or tripping of transformers, there will be significant changes to the power flow across the network. An intelligent protection scheme should be able to identify the fault severity, predict the post disturbance trend of system states, continue monitoring specific vulnerable system variables and propose an accurate solution that is tailored to the specific contingencies that have occurred. The intent of this research is to contribute to the development of these real-time based adaptive protective schemes that are enabled by modern synchronized measurement technologies for future power systems. A specific focus was placed on the prediction and monitoring of the post-disturbance thermal behaviour of assets, as this would be a valuable resource for improving thermal protection schemes and situational awareness before, during and after a disturbance.

The focus of this work is on predicting and accessing the trend of temperature change on the monitored assets. Its ultimate objective is to protect assets from excessive temperature. The overheating of electrical elements would cause damage in the insulation system within a device and dramatically decrease the lifespan of it.
In the past, the real-time temperature of a network asset is not achievable due to the lack of effective measurements. The transmission line current or transformer loading were used to represent temperature traditionally and are widely used as the determinant factor of the existing thermal protection schemes.

The developments of new system measurements like Wide Area Monitoring (WAM) and Synchronized Measurement Technology (SMT) system affords system operator highly accurate reliable real-time data across the entire network, which enables the better understanding of the thermal behaviour within a monitored asset than before. Due to the existence of thermal time constants, the temperature rise might be much slower compared to its current or frequency change since a disturbance appears. An intelligent thermal protection scheme should use real-time temperature as threshold of initiating protective actions and be able to assess the time duration between contingency occurs and temperature violation. Current radical and conservative protective actions could be delayed, avoided or optimized with mild operation strategy based on this information. Enormous cost could be saved by tailoring unnecessary operation actions for each contingency rather than monotonous operation mode.

An example of an existing thermal protection scheme is presented Figure 1-1.

This is the general block diagram of an existing thermal protection scheme. If a disturbance occurs in the power system, the post-fault current will be sent to a judgement block where the post-fault current will be compared to its rated value. It is worth noting that the presence of a thermal overload is judged based on the violation of the current limit. If the current limit is not violated, the selected element is believed to be thermally safe. If the current limit is violated then this is considered to be an overloading condition and the element is under threat of overheating. However, in reality, the violation of electrical current limit could only indicate a thermal violation will happen rather than it has. This fact proved the existing schemes to be too conservative.
Some of the work presented in this thesis will show how SMT can be used to enable the protection scheme to assess the real-time temperature of the asset when determining suitable protection actions. Protective actions will be approved by the novel protection schemes only if there occurs temperature violation within certain asset. The novel scheme have ‘waited’ enough time before necessarily operates. This new algorithm has been described fully in Chapter 4. The system operator will be able to elaborate more suitable actions which might save enormous cost than pre-defined actions within the available time period. As a result of the execution of these protective actions, the loading of the monitored elements would be reduced back to an acceptable level and the scheme has accomplished its task.

The existing examples of thermal protection scheme are generally event based algorithms that perform fixed protection actions for all cases of overloading and use real-time current measurements to judge if a temperature violation will occur. The weakness of these conventional schemes will be verified in Chapter 3 and 5.
Therefore, the primary advantages expected from the design of the novel thermal protection scheme is that it should allow the real-time assessment of the thermal behaviour of the monitored element based on the use of wide area measurements. This information enables:

- Reliable information about the system topology and state (situational awareness)
- The ability to classify different severities of contingencies and respond with adaptive unique protective actions.
  This unique can be reflected in several aspects, e.g. a) if an action is needed for the same faults but with different pre-fault loading or b) when exactly the protective action needs to be executed.
- The decisions and actions are expected to be taken based on the real-time system state rather than that anticipated at the planning stage which is common for the existing protection schemes.

1.2 Background

The growing volume of renewable and intermittent generation that is being connected to power systems, the increasing demand for electricity, and the urgent need for CO₂ reduction have all created new challenges in modern power systems. These challenges include more load congestion, which forces the network to operate closer to capacity limits than ever before; more faults on the network, due to its increased complexity; and the increasing importance of economic requirements in operation. These new challenges have made power systems increasingly vulnerable to cascading failures and blackouts.

Given these new challenges and the increasing levels of uncertainty, there is a high demand for contingency plans that can be optimally adapted to combat this increasing uncertainty and minimize the cost of operation, without compromising system security. The following subsections describe the theory and techniques that will be used in the design of the novel protection schemes.
1.2.1 WAMPAC and Synchronized Measurement Technology

A valuable tool for overcoming the aforementioned new threats in a cost effective way is Wide Area Monitoring, Protection and Control (WAMPAC) [1], which collects, distributes and processes wide area measurements from synchronized sensors (usually Phasor Measurement Units (PMUs) [2]) to provide operators and power system applications with real-time data from the power system. This real-time data is made available by the development of synchronised measurement technology (SMT) and, as such, SMT is one of the key enablers of WAMPAC applications.

SMT provides each power system measurement made with an accurate time stamp, usually with the support of the Global Positioning System (GPS). It combines measurements from different locations but with the same time stamp into an individual set of measurements that represent the whole network. It also provides higher reporting rates than conventional measurements. It is not difficult to understand that a higher reporting rate of system measurements (e.g. 50 frames per second) will enable a more detailed understanding of system behaviour in real-time. However, for the data generated by SMT to have value to the power system, applications must be developed that convert the data into information that can be used to take improved and more intelligent actions and create new solutions.

Like any form of WAMPAC, the novel thermal protection schemes proposed in this thesis are only feasible if accurate time stamped measurements of conductor current and transformer loading are made available by SMT. Therefore, throughout this work it is assumed that sufficient PMUs are installed across the network to ensure redundant monitoring of the protected assets. It is justifiable as lots of research have been conducted into the optimal PMU placements to provide full observability of the network and the redundant monitoring of critical assets [3]-[6]. A judicious choice of PMU sites could meet the constraint of costs and functional requirement of the intended applications [6].

However, WAMS and SMT applications are only good at supporting protection that is slower, e.g. thermal protection and backup protection. But less definite for primary protection, e.g. frequency protection and voltage protection, which requires fast
response. There exist concerns about communication delays, which are currently intolerable for those primary protection schemes.

### 1.2.2 System Integrity Protection Schemes and Operational Tripping Schemes

System Integrity Protection Schemes (SIPS) are well established in power systems and are a valuable tool for improving system security [1], [7]. Unlike conventional protection devices, which are designed to selectively isolate faulted elements, the actions of a SIPS are designed to go beyond the protection of equipment and extend to maintaining the integrity of the entire power system or a portion of the power system during stressed operating conditions. SIPS do not respond to a single contingency. A SIPS will be armed by one condition (e.g. the loss of a line in a corridor) and then triggered by a second condition (e.g. the loss of a second line in a corridor). An essential aspect of a SIPS is that it monitors elements of the system that it does not control, e.g. monitoring the power flow on several transmission lines to determine whether it is necessary to trip generation to relieve an overload on those lines. SIPS can have a wide variety of functions that can enhance system security under specific conditions, e.g. overload mitigation measures or generator rejection. A comprehensive review of SIPS, led by the IEEE Power System Relaying Committee, is presented in [8].

In general, there are four levels of SIPS, classified by the scope of area protection from local (distribution network), local (transmission network), sub system and system wide [9]. If classified by the decision making process, SIPS can be event-based, parameter based, response based, and any combination of the previous three types [8]. Four architectures are commonly adopted when designing SIPS, including: the flat architecture, hierarchical architecture, centralized architecture and distributed architecture [8].

A typical SIPS is the Operational Tripping Scheme (OTS) installed in the Humber SmartZone in the GB National Grid [10]-[14]. The scheme is armed when abnormal conditions like thermal overheating appear in the network, and acts to prevent the propagation of disturbed conditions after the loss of transmission lines in the
SmartZone by tripping pre-selected generation assets. For example, the OTS can be used to prevent the cascading outage of several transmission lines due to the sequential overloading of these lines. This is possible since the disconnection of the pre-defined generators would reduce the loading of the overloaded transmission lines and return the system to a secure state of operation. Two types of OTS for thermal protection are employed now within GB network: one is to protect transmission lines from sequential overloading and the other is to protect transformers from overheating. Therefore, both of the existing OTSs employed within the GB network protect electrical assets from thermal overloading. They are the schemes that are analysed and enhanced in this thesis and further details are provided in Chapters 3 to 6.

1.2.3 Thermal Constraints in Power Systems

As overheating will cause damage in insulation system which leads to element failure, thermal issue is a problem that cannot be neglected within the power system. System could fail if certain elements temperature limit is violated [15] [16]. Especially in modern networks, with the dramatic increase in the power consumptions, thermal management issues become more prominent.

Dynamic thermal management (DTM) has become an active topic with the development of multi-core computation processors. It was originally designed to enable thermal-aware high performance microprocessor [17]. The term dynamic thermal management is defined as a combination of possible hardware and software strategies work dynamically on real-time basis, to control a chip’s operating temperature. The core idea of DTM can be referenced in the power network with the increased availability of synchronized measurement within the system. The SMT provides the essential information to assess temperature of system assets which allows DTM now be applied to power system. A DTM methodology allows an adaptive thermal constraint calculated and implemented on real-time basis in the network. These adaptive limits will increase asset utilization and allow development of more intelligent operating/protection practices [16].

One example of an application of DTM in power systems is Dynamic Thermal Line Ratings (DTLRs). A DTLR is defined as the rated current capacity of a transmission
line that is calculated based on the properties of the line and the prevailing weather conditions [18]-[20]. Details of DTLR calculation is presented in Section 4.1. The conventional static thermal rating is calculated offline for the worst case scenario. This means that a DTLR will provide an improved understanding of the true capacity of a transmission lines maximum loading in real-time. It would be reasonable to expect an additional 10%-40% rating from a circuit using dynamic thermal ratings which could in turn improve boundary constraints 2-3 times. This information will allow operators or SIPS to make a more informed decision about whether a conductor is overloaded.

Furthermore, the calculation of DTLRs, combined with real-time monitoring of the line current, allows the time it will take for the conductor to reach an unacceptable temperature after an increase in loading to be estimated. This delay exists because the thermal time constants of the line delay the temperature increase caused by the increased ohmic losses.

The transmission line current or transformer loading which result in device thermal overheating is the post-disturbance steady value of that rather than the transient fault current or instantaneous loading of transformer. For this reason, a thermal protection scheme may not be considered as a fast, highly selective as a primary fault protection scheme.

Due to this nature of thermal progress, thermal protection schemes can be very different from those schemes monitoring voltage or frequency. In frequency and voltage protection, or emergency control, actions must respond very quickly, which limits the degree of adaptation that can be achieved in a robust fashion. For example, Under Frequency Load Shedding (UFLS) in GB is based on local frequency measurements and a definite time response to these measurements indicating a violation of a fixed frequency threshold. However, this need not be the case for thermal protection schemes, as the relative duration of the thermal time constants means that in many cases time will be available to take robust, adaptive actions (e.g. generator ramping). An example of the thermal progress of a transmission line after a step change in current is given in Figure 1-2.
Figure 1-2: Delayed response of temperature compared to step change current

Figure 1-2 presents an example of the delayed response of the conductor temperature to a step change in line current. This figure will be furtherly analysed in Section 4.1.2 (page 87). The nature of the thermal progress enables the possibility of designing a delayed thermal protection scheme. However, any such scheme could only be realized in a network with sufficient synchronized measurements.

1.2.4 Optimization Theory

Optimization theory is widely used in many subjects and research areas. It can be defined as the way to find out solutions which are the best or optimal for a problem with respect to a specific goal and many types of constraints [21].

Applications in power systems include ‘optimal transmission line routing’ and ‘optimal power flow’. Often, these complex problems will not be solved in a single step and instead, the solution process will be divided into a series of steps that will be executed one by one. The general procedure would include [21] [22]:

- Recognizing and defining optimization purpose
- Setting up the models
- Input the constraints
- Solving the model
- Evaluating each of the solutions
• Identifying the best or optimal solution
• Implementing the selected solution and output

The role of optimisation theory in the work presented in this thesis is the optimal cost calculation for the OTS actions, with respect to different types of system requirements. Including an optimisation module in the OTS allows it to implement flexible, cost effective operation plans that adapt to the prevailing system conditions.

1.3 Motivation

The motivation for conducting this research can be summarized as follows:

• In the past, the conventional thermal protection schemes were kept simple, robust and inflexible due to the lack of modern techniques on system measurements and estimation methods. The presence of a thermal overload is judged based on the violation of the current limit. This assumption is not ideal as it ignores the nature of thermal procedure and leads to unnecessary operations. (Chapter 3)

• WAM and SMT are the key enablers of the design of novel thermal protection schemes as they provide unprecedented data on real-time transmission line current, transformer loading and weather conditions. By conducting calculation procedure like DTLR, these data could be transformed into information which contains real-time temperature of monitored assets and reflects the true state of power system. There is no longer need to make assumption about thermal limits. All types of slower protection can benefit from this information today when communications delay and other issues requires guaranteed speed of response are less pressing.

• Actions from a thermal protection are not required as fast as voltage/frequency protection due to the existence of thermal time constant. The ability of continuous monitoring the temperature within the asset and utilization of temperature as threshold of operation enables the design of an intelligent
thermal protection which can adaptively delay or avoid the protective actions. Moreover, unnecessary actions could be avoided through the enhanced understanding/awareness of system status. (Chapter 4, Chapter 5)

- By integrating DTLR calculation, the intelligent thermal protection scheme can also predict a time to temperature violation since the disturbance occurs. The assessment of this time would benefit systems by enabling design of adaptive optimal actions replacing simple over-conservative operation strategies. For example, in this thesis, economic optimization functions have been introduced into the OTS as one option in enriching the operations of it. A combination of tripping and rescheduling actions on generators commanded by the novel OTS would achieve the same effect on thermal protection with much less cost than the scheme used to be. (Chapter 6)

- The thermal protection operation cost could be significantly reduced by integrating DTLR and economic optimization functions. This might be realized through two aspects: reducing the numbers of operation and replacing expensive schemes with cheaper actions. It is worthy to explore functions that realize these expectations. (Chapter 6)

- Apart from benefits in accurate performing and delaying thermal protective actions, applying dynamic thermal line rating would achieve additional benefits. It doesn’t necessary have to be highly technical but could potentially achieve the conventional spring/autumn ratings in the summer on days with wind. If real-time ratings could be applied through the whole network, huge capacities will be enhanced without building any additional new assets.

In this thesis, how the motivations have been realized will be demonstrated using the NG OTSs as examples.

1.4 Goals

The main goal of this research is to develop enhanced OTSs that, by exploiting the potential of SMT, can accurately monitor the thermal behaviour of assets within the
power system and respond with adaptive protective actions to prevent thermal constraints from being violated at both the minimum cost to the customer and disruption to the system. The research will use two OTSs that are in use within National Grid as a basis for the creation of these enhanced OTSs. One of these OTSs protects transmission lines and the other protects transformers.

Achieving this main goal can be broken down into the following sub-goals:

- **Literature Reviews**
  - Review literature relevant to SIPS
  - Review to WAMPAC and SMT
  - Review literature on conventional thermal protection schemes and understand the thermal behaviour of system elements including transmission lines and transformers
  - Review literature relevant to dynamic thermal line ratings and their application
  - Review literature relevant to the thermal behaviour within a transformer and understand how the temperature could be estimated through calculations
  - Review the literatures on optimization function application in non-electrical and electrical areas

- **Understand the functional structure of the existing OTS in National Grid that protects transmission lines and develop simulations that are suitable for testing their performance for different contingencies and system conditions**

- **Create a novel transmission line OTS that is capable to assess the conductor temperature of the transmission line and afford adaptive protective actions to system operator if the temperature limit is violated**
  - Implement approval signal to prevent unnecessary operation
  - Create an alarm scheme to improve system operator awareness of danger situations
  - Develop a new function within alarm scheme which could estimate the time to temperature violation
  - Explore possibilities and necessaries of integrating economic optimization function into the operations of OTS
Create a new economic optimization function within OTS, using estimated time to temperature violation to support performing adaptive, optimal actions

Demonstrate the benefits of the novel OTS with support of economic optimization function

- **Understand the functional structure of the existing OTS in National Grid that protects transformers and develop simulations that are suitable for testing their performance for different contingencies and system conditions**

- **Create a novel transformer OTS which is able to assess the top oil and hot spot temperature within a transformer and afford adaptive protective actions to system operator if the temperature limit is violated**
  - Implement approval signal to prevent unnecessary operation
  - Create an alarm scheme to improve system operator awareness of danger situations

- **Validate both novel OTSs using simulations of a full GB power system in PowerFactory®**
  - Functionality of OTS
  - Security/dependability of OTS operation
  - Cost minimization

1.5 **Methodology**

All research work in this Ph.D. project has been carried out using MATLAB software run on an Intel Core 2 Duo E7500, 2.93 GHz processor within a 8.00 GB RAM, 64 bit Windows 7 system.

DlgsILENT Power factory is computer aided engineering tool for the analysis of performance of many aspects of power system, such as transmission and distribution network or individual electrical element like transformer. The Power Factory is believed to be one of the most powerful software that helps its customer to achieve the main objectives of planning and operation optimization in power system. The network
A model used to conductor simulations and validating novel protection schemes are provided by National Grid in Power Factory software.

MATLAB is the most commonly used programming language/interface in the field of electrical engineering due to the large number of integrated calculation functions and its speed in processing and computation. In this research, the MATLAB program is used to support functions in novel protection schemes by providing independently fast assessment of thermal trend in conductors or transformers or solving optimization problems.

1.6 Thesis Contributions

The research presented in this thesis focuses on the creation of novel operational tripping schemes (OTSs) that explicitly satisfy both the functional and economic requirements. They are considered as smart, adaptive and efficient SIPS application in thermal protection of system elements. As such, they can be considered as a typical Smart Grid solution, using emerging synchronized measurement technology (SMT).

The main contributions of this research can be separated into four parts:

1. Critical assessment of performance of the two existing National Grid OTSs under contingency conditions.
2. Creation of a novel transmission line OTS that provides enhanced protection against the cascading outage of a group of transmission lines due to the sequential overloading of these lines.
3. Creation of a novel transformer OTS that conducts on-line assessment of the temperature within a transformer and provides the system operator with adaptive actions that will prevent the assets from overheating.
4. Creation of a new functional block within the OTS structure that uses optimization theory to determine the lowest cost solution to overheating in the time available (temperature violation time as estimated by the OTS). This new function enriches the solutions for relieving thermal overloading generated by OTS.
1.7 **Outline of the Thesis**

The Thesis consists of seven chapters. The first chapter is an introduction and the rest of chapters are briefly described below.

**Chapter 2 - A summary of System Integrity Protection Scheme**

This chapter describes the theoretical background of system integrity protection schemes including their definition, functional structure, classification, typical architecture, design process and existing applications. Understanding the past experience with SIPS was critical to developing a novel protection system. Moreover, development and functional description of WAMPAC and SMT system are also introduced in this chapter. They are the key enabler of the proposed novel OTS schemes within the thesis. SMT provides real-time synchronized data which is essential for realizing the novel OTSs.

**Chapter 3 – National Grid Operational Tripping Scheme**

An example of a SIPS is the Operational Tripping Scheme (OTS) installed in the GB National Grid to protect the system from abnormal conditions after the loss of transmission lines in the SmartZone by tripping pre-selected generation assets. The functional structure, working algorithm and test network (GB model in DlgsILENT power factory) are all described in this chapter. Several case studies were carried out to test the performance of the transmission line OTS. The merits and weakness of this existing transmission line OTS are summarized and potential improvements that can be made are stated.

**Chapter 4 – Using Dynamic Thermal Line Ratings for Improving Operational Tripping Schemes**

The advent of WAMPAC and SMT enables the practical implementation of online tools such as dynamic thermal line rating and real-time conductor temperature estimation. This chapter describes the integration of a DTLR based approval function, i.e. approval signal, into the tripping logic of the existing OTS. The novel OTS is
expected to monitor the real-time status of the transmission lines, response to the system contingency with adaptive protection actions and send alarm signals to system operator indicating the presence of potential or happening overheating. Case studies were performed for the novel OTS and results of these are given at the end of the chapter.

Chapter 5 – Using Real Time Temperature Estimation for Improving an Operational Tripping Scheme for Transformers

This chapter focus on a SIPS that protects a transformer from overheating. It contains a detailed description of the transformer thermal progress and methods for estimating top-oil and hot-spot temperatures within the transformer. An existing transformer OTS is presented here; however, as with the existing OTS for a transmission line, the actions of the current scheme a bit too conservative. A novel transformer OTS is then proposed, which integrates the real-time temperature assessment function into the decision scheme. This improvement will significantly enhance the situational awareness of system operator and make the performance of the OTS more effective by avoiding unnecessary tripping.

Chapter 6 – Economic Optimisation of the actions of the novel transmission line OTS

Apart from functional requirement, cost optimization has been an increasingly important aspect of modern power system design and operation. This chapter details the creation of a function within the novel transmission line that allows the OTS to perform more cost-effective actions based on the solution to an optimization problem. This novel supplementary function in the OTS enables generation tripping to be replaced with less invasive and cheaper generation re-dispatch. The time available before a thermal overload can be estimated using an extension of the alarm signal presented in Chapter 4 and used as the basis for the economic optimization. The design, validation and testing of a the economic optimisation enhancement for the OTS is presented and the benefits of these optimised action are demonstrated using cases studies for the full GB model in DlgsILENT PowerFactory.

Chapter 7 – Thesis Summary
This chapter summarises the research presented in this thesis and the major achievements during the Ph.D. project. In addition, some possible opportunities for the further development of this research are addressed.
2. **System Integrity Protection Schemes – an Overview**

This chapter provides a detailed description of the design of system integrity protection schemes (SIPS) and potential techniques for their improvement. Section 2.2 discusses the general definition, objective and requirements for power system protection. The motivation of a SIPS as well as its objective, applications, inputs, classifications, architecture, and design process is presented in Section 2.3. Section 2.4 presents the development and structure of three modern techniques: Synchronized Measurement Technology (SMT), Supervisory Control and Data Acquisition System (SCADA) and Dynamic Security Assessment (DSA) that have been considered as key enablers of a revolution in the performance and functionality of SIPS. Finally, Section 2.5 summarizes contents in this chapter and how it informed this research.

### 2.1 Chapter Introduction

Understanding the existing power system protection and schemes was necessary before creating a novel protection system integrity protection system. Based on this understanding the weak points of existing SIPS could be identified and corresponding solutions created. These solutions will be based on the use of emerging technologies (e.g. SMT, DSA) that are also described in this section.

### 2.2 Power System Protection

Power system protection detects and deals with faults or abnormal conditions in the power system through isolation of the faulty parts from the rest of the electrical power system. Its objective is to keep the rest portion of network function satisfactorily without any severe damage caused by the fault current [23].

There are five types of components commonly involved in a protection system:

- Measuring units, including voltage and current instrument transformers;
- Protection relay;
- Operation units, including circuit breakers and switches;
- Energy storage to maintain power supply to protection hardware after loss of external power supply; and
- Communication channels between all protective devices.

Protection systems can be separated into two types based on their objective:

1. Device (unit, single element) protection such as transmission line protection, generator protection, and transformer protection; and
2. System (multiple-elements) protection like system integrity protection schemes (SIPS).

Based on its function, a protection system can be categorized into two styles: Predictive protections e.g. disconnecting elements from the system before potential faulty conditions propagate and Remedial protection e.g. tripping of a transmission line when a physical three phase fault occurs.

To design an effective protection system, three requirements must be fulfilled [23]:

- **Reliability** – The protection system must operate under appearance of a fault and avoid any unnecessary operation in the absence of a fault or under a fault outside of its designed protection zone. The reliability consists two aspects:
  - *Security* – The security of a protection system is used as an indicator of the ability of the system to operate correctly. It is referred as the ability of a system or device to refrain from unnecessary operations.
  - *Dependability* – The dependability of a protection system is used as an indicator of the ability of the system to operate correctly when required.
- **Selectivity** – The protection system comprises different levels of operation threshold, timing or operation conditions. Selectivity makes sure only the protection devices designed to clear the fault, operate to isolate the faulty element.
- **Sensitivity** – The ability of a protection system to detect a fault or faulty conditions on elements inside their protection zone. A protection system is normally required to response to the faulty situation immediately.

In early stage of development of power system protection, the design of protection focuses on protecting the area of the system that is ‘local’ to the fault. The local protection schemes prevent the spread of serious contingencies through pre-set
automatic actions. They are mainly designed to avoid serious equipment damage during major events [9]. However, modern power systems suffer increasingly from complex, system-wide disturbances [24]. The local protection schemes are unable to address these system-wide disturbances and ensure that system integrity is preserved during stressed conditions. Therefore, more advanced and system-wide protection systems have been developed. These system integrity protection schemes (SIPS) have played a major role in ensuring the secure and efficient operation of power systems and are now evolving to counter the new threats faced by power systems by exploiting emerging technologies.

2.3 System Integrity Protection Scheme

With the growing demand for electricity, CO₂ reduction and high penetration of renewable energy sources, modern power systems are facing an increasing number of new challenges. These new challenges include: more faults on the transmission network, due to its increased complexity; operating the system closer to its security limits; and the increasing importance of economic and environmental factors when managing system operation. Furthermore, these new challenges must be faced at a time when power systems will be increasingly vulnerable. This increasing vulnerability is driven by the rise in the level of uncertainty in the system that will occur with high penetrations of intermittent renewable energy resources, the increased numbers of HVDC transmission corridors, series compensated transmission lines and an increase in the number of active participants in the power system (e.g. energy storage, PV, distributed generators and electrical vehicles).

Given these new challenges and increasing levels of uncertainty, there is a high demand for contingency plans that can be optimally adapted to combat this increasing uncertainty and minimize the cost of operation, without compromising system security. SIPS are a valuable tool for improving system security [7]-[9]. A SIPS can be defined as an automatic protection system designed to identify abnormal or predetermined system conditions or disturbances and perform predictive or remedial actions other than and/or in addition to the isolation of faulted components to maintain system integrity [25]. In the past, conventional protection devices were designed to protect individual elements of equipment from being damaged during faults by quickly
detecting overcurrent conditions, or other dangerous operating conditions, and then selectively and quickly isolating the faulty equipment from the system. In contrast, SIPS are designed to maintain the integrity of the entire power system by simultaneously monitoring and controlling multiple elements of the system [24]. It integrates and analyses both local and system level information against wide area contingencies. This approach allows SIPS to improve the efficiency and security of system operation under specific conditions.

According to [8], the SIPS encompass few different levels or schemes: Special Protection Schemes (SPS), Remedial Action Schemes (RAS), as well as additional schemes such as, under frequency (UF), under voltage (UV), out-of-step (OOS), etc. It is commonly believed that the modern SIPS are derived from the coordination of different levels of local protection schemes.

Technically, comprehensive contingency analysis is a precondition for the design of a SIPS [26]. Therefore, a typical SIPS can be summarized as a set of pre-determined actions for responding to a set of abnormal system conditions that have been detected and pre-studied in the system. A disturbance in a power system can be observed in many ways, including measurements of voltages and currents, status flags or the operation of individual relays. These signals will be used as the input of the SIPS and are processed by a decision making element. Pre-defined actions will be implemented if certain decision making criteria are met. A block diagram of this process is shown in Figure 2-1 [27].

![Figure 2-1: Block diagram of a typical SIPS](image-url)
The following subsections describes the objective of a SIPS as well as its applications, inputs, classifications, architecture, and design process.

### 2.3.1 SIPS Objective and Control Methodology

SIPS is part of protection system of power network. Therefore, its objective is defined as protecting power system against different issues including [8], [28]:

- Power flow congestion;
- System Instabilities:
  - small-disturbance angle instability;
  - transient instability;
  - frequency instability;
  - voltage instability;
- Thermal overloading

These objectives are realized by execution of specific corrective actions commanded by SIPS. A SIPS can have various applications, the following are those described in the open literature [9], [28], [30]-[34]:

- generator rejection/re-dispatching;
- load rejection;
- under frequency/under voltage load shedding;
- adaptive load mitigation;
- voltage/angular instability advance warning scheme;
- overload / congestion mitigation;
- system separation / islanding;
- load and generation balancing;
- shunt capacitor switching;
- tap-changer control;
- generator runback;
- bypassing series capacitor;
- busbar splitting;
- HVDC controls;
- discrete excitation.
A SIPS may involve one or more methods listed based on its applications and purpose.

Like the mitigation methods, a SIPS could achieve more than one function at the same time. For example, in the later chapters of this thesis, a new SIPS is presented that prevents potential thermal overloading on transmission lines and transformers and keep these assets in operation without comprising any security requirements under stressed conditions. According to [8] [25], the ideas and technique of SIPS are now widely accepted in power systems across the globe and most schemes are highly reliable.

2.3.2 SIPS Inputs

To realize the aforementioned corrective actions, there are several types of inputs of intelligent SIPS, including [28]:

- Power system voltages/currents: These measurements can now be time synchronized, which not only allows the measurement of the magnitude of voltage/current magnitude but also the phase angles.
- Power system frequency
- Control signals: Such as automatic voltage regulator (AVR) settings of generator or synchronous machine, field current of generators, protective relay settings, FACTs, etc.
- System status: Including the circuit breaker status, transformer tap changer positions, etc.
- Last valid state: system state estimation results and telemetry data in the case of losing a communication channel during fault
- Arming status: Status of SIPS activation, system elements selected to be involved in the corrective actions, etc.

A more detailed explanation and the complementary parameters used in implementation of SIPS has been defined and presented by CIGRE [28].

2.3.3 Classification of SIPS
Based on the scope of protection, SIPS can be classified into four levels, given in Figure 2-2 [9]:

![Figure 2-2: SIPS Classification [9]](image)

A comparison of these four levels is presented in the following Table 2-1 [8] [9],

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Local (Distribution system)</th>
<th>Local (Transmission system)</th>
<th>Subsystem</th>
<th>System Wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>One distribution substation</td>
<td>One transmission substation</td>
<td>Regional control centre</td>
<td>National control centre</td>
</tr>
<tr>
<td>Users</td>
<td>Distribution network</td>
<td>Small power company or Portion of large utility</td>
<td>Large utility or regional system operators</td>
<td>National System Operators</td>
</tr>
<tr>
<td>Impact of operation of SIPS</td>
<td>Limited portion of distribution network</td>
<td>On neighbouring interconnected system and generators</td>
<td>On large geographic area consisting multiple power utilities</td>
<td>Significant impact on entire interconnected system</td>
</tr>
</tbody>
</table>

Another classification for SIPS design is according to its input and decision making process [8]:

- Event based
- Parameter based
- Responses based
• Any combination of the above.

*Event based SIPS* – This type of SIPS is activated by detecting a pre-defined combination of events, e.g. the loss of a group of transmission lines. The decision making and output is highly pertinent to the event. The event based SIPS respond more quickly than other types of SIPS as they do not need input from any system states, measurements or data analysis before a decision is generated. However, the lack of measurement input may lead the event-based SIPS to mal-operate or perform costly, unnecessary operations. An example of an event based SIPS is the Operational Tripping Scheme (OTS) commissioned by National Grid in the Humber Zone in the GB transmission network.

*Parameter based SIPS* – This type of SIPS is armed by detecting significant change or disturbance in measured system variables. In practice, these schemes are usually designed to be initiated by a combination of events and parameter changes [28]. The decision making of this type of SIPS is based on the pre-study of system contingencies. Pre-decided, automatic and remedial actions are executed after a certain disturbance occurs in the system. Due to the time required for data communication and analysis, this type of SIPS have a slower response to a fault but can provide more accurate solutions compared to an event-based SIPS.

*Response based SIPS* – This type of SIPS has the same input as a parameter based SIPS, which is the detection of system events and measurements of selected system variables. However, unlike the pre-determined actions of a parameter based SIPS, a closed-loop decision making process allows response based SIPS to perform adaptive actions. For example, response based SIPS will respond with different solutions to a fault on a heavily loaded transmission line and a fault on the same transmission line when it is lightly loaded. These adaptive solutions are beneficial as they allow system protection to adapt to the true impact of a fault, which will vary with the pre-fault conditions, rather than responding to the conditions assumed during offline simulations. Response based SIPS are designed to be more adaptive and effective to all system disturbances but incur increased delays due to the need to process system measurements when adapting their response. Furthermore, this type of SIPS is far more complex than a simple event based SIPS, which creates a higher possibility of the scheme failing.
Any combination of the above – In modern power systems, an individual type of SIPS may not meet the system owner or operator’s requirements for system protection. A coordination of multiple SIPS, either groups of the same types of SIPS or different types of SIPS, becomes one of the solutions. Moreover, due to the possible failure of more advanced and complex schemes, a simple event or parameter based SIPS could be used as a backup to these schemes. An example of this new combination is a dynamic thermal line rating controlled OTS that will be presented in later chapters.

2.3.4 Architecture of SIPS

Four common SIPS architectures have been described [8], [28] [29]:

- Flat architecture
  In this SIPS architecture, the measurement, decision making and operation elements are all located in one location. A communication link is needed between initiating corrective actions and collecting remote system information. A typical example of a flat architecture SIPS is underfrequency load shedding [8].

- Hierarchical architecture
  In this architecture, several steps and different levels of elements are involved in the SIPS decision making and initialisation of corrective actions. Instead of single layer decisions and actions in a flat architecture, a hierarchical scheme always consists of multiple layers and communications between multiple control locations. A more complex logic, design and actions will be performed under this architecture [8] [28].

Figure 2-3 provides a comparison between the flat and hierarchical architectures
• Centralized Architecture
  As the name implies, all of the information from monitored substations and elements are collected and transmitted into one central location. The decision making is all performed in this central location as all data processing and arming is performed in a single location [8] [29]. In this architecture, only input/output (I/O) interface devices will be installed at remote sites. Their task is to transfer all collected data to the centralised processor then receive and execute the commands from this processor [29]. A communication link is required between all remote sites and the central site.

• Distributed Architecture
  In contrast to the centralized architecture, in a distributed SIPS decision making is performed by different controllers installed in various stations across the system. The processor at each location generates individual output and initiates local protective actions. Once a contingency occurs, the system level integrity protection function can be realized through coordinated operation and control of distributed local controllers. In this structure, communication links are implemented between each local station instead of communicating with one central site [8] [29].

Figure 2-4 compares the centralized and distributed architectures:

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Figure 2-3: Example of flat and hierarchical architectures [28]
There are a few key elements involved in designing a SIPS, including power system studies, contingency analysis, identifying the main type of instability the SIPS should address and how this instability should be addressed by the SIPS [28]. These factors are presented in the following Figure 2-5:

**Figure 2-4: Example of centralized and distributed architectures**

**Figure 2-5: Elements involved in the design of a SIPS [28]**
2.3.5 SIPS Design Process

The design process for a SIPS can be described by following steps [8], [28]-[29]:

1) **System Study**

   Comprehensive and accurate system must be carried out prior to deploying a SIPS. These studies help clarify the motivation for a SIPS and the information collected includes:

   - **Identification of system limitations and restrictions.** Different systems, subsystems or portion of a large network have various critical limits such as voltage or thermal limits. The objective of SIPS has significant influence on the design of more advanced SIPS.

   - **System requirements.** Except for the critical limits of the system, the SIPS is always required to coordinate with existing protection schemes or installed SIPS. This requirement must be considered before an effective SIPS is designed.

2) **Hardware description and outage detection scheme.**

   - The hardware description contains the hardware that has been employed in the system. The information will include the protective relay types, response speed, the availability of communication channels, etc. For example, the implementation of SIPS must follow the protocols of existing communication devices or output corrective actions that can be executed by existing assets.

   - Outage detection is the process that allows a SIPS to detect the outage of one or more of its monitored elements and may have different forms. The simplest way of detecting an outage is to record the breaker status of the monitored element. A more secure way of detecting outage is to monitor a combination of adjacent system elements and process the collected information through a logic calculation. For example, to detect a line outage, the simple way is to record circuit breaker open and the complex way is to not only identify the circuit breaker change but also to measure that the current on the line is zero. Only when both conditions are met will the complex logic confirm the loss of the monitored transmission line.

   - The speed and accuracy of outage detection are critical factors in determining the performance of a SIPS that must be balanced against one another. Factors
to consider will include the reliability of any communication links and signal transmission, and the efficiency of central programmable logic controllers.

3) **Scheme Architecture**

The architecture of a SIPS must consider two main aspects:

- **Functionality.** The objective of the proposed SIPS is defined during the first stage of SIPS design. To realize this functionality, a proper architecture needs to be decided. As described before, there are four main types architecture available including flat, hierarchical, centralized and distributed type. Each of these architectures have their own advantages and disadvantages that make some architectures preferable for certain applications.

- **Redundancy.** Failure of a SIPS to operate when required or other mal-operation of the scheme will have an adverse impact on the power system. Therefore, the design of a SIPS requires redundancy for the main scheme and this redundancy will be reflected in the architecture. Most SIPS are equipped with a redundant scheme, which may be a complete duplicate of the main scheme with redundant measurements and logic processors or may be a simplified version of the main scheme.

4) **Data acquisition, communication, networking and related tools**

- **Data acquisition.** The traditional measurements that have been used in SIPS are bus voltages, line/transformer currents and the power output of generators. In recent years, synchronized measurement technology (SMT) based on time synchronization have developed rapidly and are now commonly adopted in power systems. With support from modern EMS/SCADA systems more advanced and intelligent SIPS can now be created.

- **Communication and networking.** Creating an intelligent SIPS will usually require that remote parts of the power system are observable by the SIPS. The communications required by the SIPS should all obey a unique protocol and redundancy should exist in case of main communication failure.

5) **Core logic function**
The requirements for the SIPS core functions have been defined in the previous stages. The programmable core logic will be designed to fulfil these functional responsibilities.

6) **Arming methodology**

The corrective actions will be generated by the armed SIPS if certain contingency occurs in the power system. The command will be sent to local SIPS or protective devices to be executed. The operating methodology of a SIPS will always be set in advance and it is strongly associated with the specific system contingency.

7) **Cost considerations**

The operation of a SIPS involves different type of corrective actions, such as pre-determined generator tripping, generation re-dispatch or load shedding. These actions can be costly, so the design of a modern SIPS must consider economic optimization. A new block that estimates the cost of the different corrective actions has been introduced into some SIPS. This allows the SIPS to select the most cost-effective corrective actions without compromising system security.

8) **Testing Procedure**

The final step of designing a new SIPS will be compulsory simulation based testing. These tests will include an assessment of the accuracy of operation, sensitivity analysis, and contingencies for the SIPS (e.g. losing communications during a fault or resources for corrective actions being unavailable). Only if a SIPS meets the functional, economical and reliability requirements will it be armed in the real power system.

After completing all of the above steps, the design of a SIPS is believed to be finished and could be armed in the real power system.

### 2.4 Technology for Modern SIPS
Integrating new technologies into many aspects of modern SIPS including the inputs, decision making and selection of remedial actions allows improved performance to be achieved. This improved performance may be in the form of delivering existing functionality more efficiently or delivering entirely new functionality.

2.4.1 Synchronized Measurement Technology

Synchronized measurement technology (SMT) has been commonly employed as an input of modern SIPS. It has developed significantly in recent years due to the improvement of time synchronized devices, communication facilities and data handling capabilities [24]. Supported by the global positioning system (GPS), SMT allows the power system measurements to be marked with accurate time stamps, which allows the measurement of relative phase angles across the power system. Furthermore, Phasor Measurement Units (PMUs) stream measurements at a significantly higher reporting rate than existing measurement systems. It is not difficult to understand that a higher reporting rate of system measurements will enable a better prediction of its behaviour after any operation actions or disturbances.

An important control theory developed based on SMT is the Wide Area Monitoring, Protection, and Control (WAMPAC). WAMPAC prevents the propagation of large system disturbances by using time synchronised system wide data and communications between local sites and remote locations. It is a powerful tool to collect, transmit, analyse, and process the enormous amount of data made available by SMT. It is employed as an online platform with various applications integrated.

There are four components in a WAMPAC system [1], [35]-[37]:

- Phasor measurement units (PMUs)

A phasor measurement unit (PMU) is a device that samples voltage and current waveforms and with the support of GPS for synchronization measures time stamped voltage phasors, currents, and frequency. PMUs are believed to be the most advanced and accurate time synchronized technology available in the power network. PMUs perform the role of data acquisition in a WAMPAC system.
• Data Concentrator (DC)
  The measurement signals from PMUs are streamed to a DC where they are
time aligned before any analysis or further processing. A data concentrator is
defined as hardware /software connecting different data channels with one
destination. The installation of DCs has hierarchy. DCs that are lower in the
hierarchy have information from a smaller area, but with less delay, whilst
higher DCs can have information from a wider area, but with more delay. The
level of hierarchy is decided by the needs of an application. Some critical
applications may have their own DC, to help ensure dependable delays and
availability.

• Application Software (AS)
  The application software of a WAMPAC system could be installed in the main
control centre or in certain DCs. Application software uses the time aligned
wide area data to deliver new functionality to the power system. The examples
of applications will be presented later in this section.

• Communication Networks (CN)
  WAMPAC generates huge quantities of data that is expected to be transmitted
in real time. This calls for strong supporting communication networks.
Moreover, redundant communication channels should be available when the
main channel is lost due to unexpected situations. The widely used
communication media applied in modern system includes fibre optic, power
lines, microwave, Wi-Fi.

An example of a WAMPAC system is given in the Figure 2-6, which is taken from [1].
Figure 2-6: Example of WAMPAC system structure [1]

The applications and benefits of a WAMPAC system has been summarized as [1] [38]:

- Improvement in real-time system visualization
- Real-time monitoring and control of power system
- Ability of designing an advanced early warning system
- Enhancement in system state estimation (SE)
- Real-time congestion management
- Overload monitoring and dynamic rating
- Planned power system separation/islanding, and restoration
- Protection against wide-area disturbances
- Validation of generator models
- Load model parameters estimation
- Development of distribution automation system [39]

The critical applications discussed here are:

- **Real-time congestion management**
  There are two types of congestion management: one is performed by power schedulers in the advance market and the second is performed by the system
operator in real time. In some contingency case, the pre-calculated and pre-determined corrective actions would be unnecessarily conducted due to conservative estimation of system contingency conditions. The congestion management involves many actions such as generation dispatch, re-dispatch under system faulty conditions, or load shedding. With support of SMT inputs, the system operator would have improved awareness of system situation, accurate estimation of real-time available capacity of assets and produce varied operation solutions under same type of contingency.

- **Overload monitoring and dynamic rating**
  An example of this technology is the application of real-time transfer capability in the power network. The static thermal rating of a transmission line is commonly adopted as the limit of capacity of existing assets. It is defined as the current loading of the transmission line that will result in it reaching its maximum operational temperature for a worst scenario of weather conditions. The capability or dynamic thermal rating is calculated based on real-time system data, such as pre-fault loading and weather conditions. Dynamic ratings will usually increase the capability limit of an asset, compared to conservative static ratings that are estimated offline. This will release more transmission line capacity during normal and fault conditions without compromising system security.

- **Protection against wide-area disturbances**
  A disturbance and disruptive event is normally developed gradually from local to system wide. The time scale of its impact propagation can be varied from milliseconds to several minutes. With the support from SMT system, a better understanding of the system status under fault conditions will enable more abundant selections of corrective actions with considerations including the economic aspects, further system oscillations after fault clearance or actions impact on customer.

With the rapid development of SMT/WAMPAC, increasing number of intelligent algorithms and schemes are being involved into the modern system operation and protection. These techniques would afford system owner and operator better awareness
system status, more effective operations in normal operation and cost-effective corrective actions under fault conditions.

### 2.4.2 Supervisory Control and Data Acquisition System

Supervisory Control and Data Acquisition (SCADA) system is an existing and developed type of wide area monitoring and control system. It has been widely implemented in many modern power systems. A SCADA system is designed to collect field information from remote local sites, transfer it to a central computer facility, in where, the integrated information is presented graphically or textually to the system operator. This system enables the system owner or operator to monitor and control the whole network from one central location on a real-time basis [40]. The general layout of a SCADA system is given in the Figure 2-7, taken from [40]:

![General Layout of a SCADA system](image)

**Figure 2-7: General Layout of a SCADA system [40]**

A SCADA system has a similar architecture as a WAMPAC system and uses both hardware and software to deliver these elements:

- Field sites
  The programmable logic controllers (PLC), intelligent electronic devices (IED), and remote terminal units (RTU) are all installed at the local site. Various applications could be conducted through these devices, e.g. IEDs can
collect/output required data, communicate to other local devices or perform local logic control functions.

- **Wide area network**
  Within the communication network, the data will be transferred bidirectionally between control centre and remote sites. Multiple Devices such as modem and WAN card, communication media (e.g. satellite, radio microware and power lanes) are involved in this step.

- **Control Centre**
  Most of the data collected from local sites will be analysed here. There are two main tasks done in the control centre: real-time operation and data storage. A human-machine interface (HMI) is introduced here to allow system operators to monitor the state of system, modify control settings of system devices or select/conduct corrective actions under system contingency.

Based on this general architecture, modern advanced control theory and devices could be introduced into any stage of the SCADA system, which will form a new ‘Smart’ power system monitoring and control system. The data collected as part of the SCADA system has been used as a key input of many SIPS.

### 2.4.3 Dynamic Security Assessment

In operation, the power system is considered as secure, if all elements maintain a normal steady state or establish a new nominal steady state after a credible contingency has occurred. In contrast, if a system fails to reach a new steady state after a fault, the operating constraints are being violated, or emergency issues arise, the system is insecure [43] [44].

There are 5 system operation states, presented in Figure 2-8:

- **Normal State**
  It is the ideal state of system operation. All the system constraints including load, operational, security requirements are met under this circumstances. The system operates in a secure manner and is able to survive contingencies without violating constraints [43].
- **Alert State**
  A small disturbance or light contingency will increase certain system constraints of a normal state system closer but not beyond their limits. This state of system operation is considered as alert. Though the system is still under an acceptable operation conditions, it becomes more vulnerable to any further disturbances. A further disturbance will push the system violate its operation constraints and enter the system to emergency status. However, if proper preventive control actions are conducted, the alert will be released and system will be back to normal and secure state.

- **Emergency State**
  It is the second worst state a power system could suffer. One or more types of system constraints have been violated due to larger disturbances happening in the network. In this stage, voltages of many buses can be low and equipment loadings exceed short-term emergency ratings [43]. If not handled properly, the emergency state will turn into an extreme system operation. Emergency control actions will be activated to prevent abnormal status further propagation under this crucial issue. These includes cutting off faulty elements from network, load shedding and even islanding. At this stage, after stopping the disturbance propagations, this system transfers to restoration stage.

- **Extreme Emergency State**
The extreme emergency state is a result of the occurrence of an extreme disturbance or action of incorrect of ineffective emergency control actions. The power system is in a state where cascading outages and shut down of a major part of power system might happen. The system is highly unstable. The control actions needed in this state must be powerful.

- **Restoration state**
  This is a transition state between the emergency and normal system operation. The system in this stage is considered as insecure. More corrective measures need to be conducted. For example, picking up loads in order when its operation requirements are met and no voltage or frequency limits are violated by these switching actions, or synchronization of two subsystems under certain pre-conditions have been met [45]. Inside this state, the topology of network, elements connected, or communication network may have been changed sometimes significantly due to emergency actions in previous stage. This means, after the restoration stage, the system could hardly recover to its status before the disturbance. A new nominal state will be established with the remaining network.

Power system security is referred to the ability for a network to maintain nominal technical performance and quality of service when exposed to a contingency that is one of a predefined list of credible contingencies (e.g. N-1 secure means that the system is secure against the loss of any single element in the system) [41] [42]. Theoretically, a small change or switch on/off in load can be treated like a small disturbance as it changes the system steady state. However, only ‘larger’ disturbances such as a transmission line loss are considered when assessing the security of a system and the need for protection/control actions.

When a large disturbance occurs in the system, the pre-disturbance steady state is broken and all the system components respond to the change. A new acceptable equilibrium condition is expected to be reached by these elements after a disturbance [43]. If an acceptable equilibrium is not achievable, then the system is under threat if suitable actions are not taken and/or any further contingencies occur. The mathematical analysis of the procedure of building up new equilibrium by electrical elements is referred as security analysis.
According to [43], there are two types of security analysis:

- **Static Security Assessment (SSA)**
  SSA is the analysis which focuses on the evaluation of the predicted post fault steady state or new equilibrium. Mathematically, the steady state equations known as the power flow equations will be solved in this type of security analysis.

- **Dynamic Security Assessment (DSA)**
  This type of analysis is more concerned with the transient procedure before the system reaches the next steady state. It evaluates the system performance during disturbances and estimates the ability of the system to survive the current disturbance and move to a new acceptable steady state. Dynamic or transient state equations of the power system will be used in these calculations.

In the past, the capacity of the network which enabled by off-line studies has not been heavily utilized and the behaviour of elements connected to the network can be accurately predicted. The new steady state after losing individual or multiple elements could be estimated and predicted and thus could be controlled. The SSA is commonly applied in this stage.

However, due to the expansion of DG integration and increased complexity of connections, the operation of modern power systems has been pushed closer to the limits. Therefore, the actual conditions of system under fault could strongly differ from a reference which is generated in SSA. The SSA may provide misleading results under certain contingencies. Under this stage, the DSA has been introduced as an essential tool of network operation.

In DSA, the system stability before a disturbance is evaluated based on a snapshot of real-time power system. This analysis of a real-time power system significantly improves system operator awareness rather than using a forecasted condition from offline studies. When the fault occurs, the DSA could either enable a quick automated control action due to a severe contingency, or provide alert information to the operator if the DSA detects that the system may now be insecure [41]. This function is practical as not all contingencies may immediately cause insecure operation, but the threat of these cases may gradually emerge and cause huge negative impact on system operation if no suitable actions taken. A typical example of this type of threat is the
transmission line temperature. If a line becomes overloaded, its conductor temperature may take several minutes, or longer, to violate its limit. Therefore, with sufficient situational awareness, this delay can be of benefit to the system and DSA may be used to determine an optimal response to these conditions based on the true system conditions rather than immediately initiating conservative tripping actions. Moreover, as the input of DSA is the real-time data captured from the power system, it would provide clear understanding of system behaviour under faulty conditions. The effectiveness of automatic protective actions and further system response like losing another element after the main fault would be reflected in DSA. The DSA will record all the actions inside the power system and update its operation strategy in real time.

An online DSA consists 6 main blocks given in Figure 2-9 [41],

![Diagram of DSA system](image-url)

**Figure 2-9: Components of an Online DSA system [41]**

- **Measurements**
  This block can be treated as the input of a DSA system. Data that contains information about the system status will be collected here. The source of data would include a SCADA system, SMT system (such as PMUs) or disturbance recorders. The data will be transmitted to and shared by the modelling block and computation block.
• Modelling
In this block, a detailed, high quality system model is expected to be integrated. This model should contain the network topology, interconnections, load models and other key components like generators and transformers. However, an oversized model may reduce the speed and efficiency of calculations, the solution is to include mainly components which have significant contribution or key characteristics on the application of DSA. For example, if the DSA aims to protect a transmission line from thermal overloading, detailed modelling of the transmission line is needed, but a detailed AVR model for a generator may not be necessary.

Inputs from the state estimator, auxiliary devices (e.g. weather measurement), real-time system measurements, and models for neighbouring systems will be used to support and improve the main system model. For instance, the traditional state estimators are normally the source for the power flow models.

• Computation
It is the core part of an online DSA system. All applications of DSA are integrated into this block. There are a few requirements that need to be met in designing this computation block including:

*Comprehensive and Accurate Computation Capabilities:* the DSA must be able to perform a full assessment of its desired functionality. For example, it should conclude eigenvalue analysis when conducting assessment of small signal stability.

*High speed of calculation:* to achieve a real-time security assessment, the DSA must be able to conduct high speed calculations, although there is always a challenge due to the huge system model and quantity of data. One common solution to speed up calculation is to divide the tasks simultaneously into several distributed DSAs where more servers and supercomputers could be involved.

*Automation:* under any circumstances of system operation (nominal and faulty), the DSA must be able to run automatically based on time cycle and complete
its task. It must always be ready to figure out the weakest point/link in the current network and provide suggested operations if any contingency occurs.

**Reliability**: the reliability is a crucial requirement for all online system analysis software or complex intelligent system. The inaction of DSA would provide the system operator a wrong estimation of the system state and lead to incorrect operations. One possible solution for the enhancement of reliability is to introduce redundancy into the DSA [41] [42]. For instance, if the desired corrective operation that has been determined by the DSA is not available for any reasons, e.g. loss of communication, the computation should provide an alternative solution for this case.

The calculation block will process the data collected from modelling and measurements and output control suggestions and system visualization to the system operator.

- **Reporting and Visualization**
  The DSA system would have a comprehensive visualization tool to present key information based on calculated results. There information includes [42]:
  - *Overall status of the system*, if it is secure or insecure;
  - *Critical points/links* which is vulnerable from disturbance;
  - *Security indices* for all assessed contingency analysis, which figure out the most severe contingency could happen in the system and make the operator aware of its possibility;
  - *Security violation details* such as potential over heating transmission lines and transformers;
  - *Status of protection control* including if it is armed, activated or under maintenance;
  - *More information would be displayed as required.*

- **Control**
  The DSA system can directly conduct control actions or notify the operator that control actions are required. If the DSA detects an insecure situation or a contingency may lead the system to insecure case, remedial measure will be promoted. These remedial actions could be either preventive or corrective.
Available actions may include, capacitor switching, line disconnection, transformer tap changing, and in some severe cases, generation rejection and load shedding will be performed [41].

- **Other functions**
  - *Study mode*: An off line study mode becomes available with access to the detailed system model and an archived online data. It is an important supplement to the on line DSA, as the offline study could be used to verify the effectiveness of online control actions and to conduct offline load prediction and system planning cases.
  - *Archive*: This is storage of historic system operation and analysis data. It could be conducted on offline studies and learn from experience from both successful actions and system failure.
  - *Failover*: This is a backup function of a DSA system. If the DSA system fails due to any reason, no system visualization or operation suggestion will be provided to the system operator. Under this extreme case, other protection schemes like SIPS would be automatically armed into the system no matter it is under normal or faulty conditions, to avoid potential or existing disturbance propagation. In some advanced DSA, the failover function has been integrated into calculation or control block.

High quality and reliable communications channels are required between these blocks. Hence, a data transmission failure will result in DSA losing functionality and accuracy. The DSA has been included in a wide variety of academic papers as well as the latest technological achievements and services offered by well-known companies, such as Siemens, EUROSTAG, DSATools, etc.

### 2.5 Chapter Summary

The core objective of power system protection is to isolate the faulty elements from the rest of network without causing losing stability to the power system. To efficiently realize its function, four requirements including reliability, security, selectivity, and sensitivity must be met in designing of a protection scheme/system.
In the early stage of the development of power system protection, local protection devices are installed to simply cut off faulty elements from the network directly without communication with adjacent protection system or schemes. In some cases, this simple action did its task and stopped the potential disturbance propagation. However, for some other cases, especially in modern networks which operate closer to their limits, the local protective actions may result in cascading failures and further disturbance to the network. For example, cutting off a faulted transmission line may lead the adjacent elements to overloading. However, dealing with these complex system failures is beyond the scope of this local protection and attempting to incorporate would compromise the fast, selective and reliable operation of this protection. Therefore, modern protection includes system protection functions that coordinate local schemes and provide a comprehensive system wide view of protection.

SIPS provide a key aspect of this system protection. They will not only protect the local electrical elements from severe damage, but also maintain the system integrity after protection actions. They are designed to provide system level protection by simultaneously monitoring and controlling multiple elements of the entire system. This approach affords an improved efficiency and security of system operation under certain contingencies. The OTS discussed in this thesis is examples of SIPS.

SIPS are complex and require rigorous design, the stages of which are presented here including its layers, architectures, and design procedures. In a modern SIPS, more advanced and newly developed techniques have been involved and integrated. SMT, SCADA will contribute to the data collection or signal input and DSA will have significant influence on the decision making procedure.

Due to the improvement of time synchronized devices, SMT has been widely applied in modern power system operation. Synchronized data enables a more accurate and comprehensive system state estimation. Also, the SMT is believed to be the key enabler of a WAMPAC system and advanced SIPS. Four main blocks are employed by a SMT system such as PMUs, Data concentrator, application software and communication network. Except for providing synchronized measurement to SIPS, the SMT/WAMPAC would have more functions like load congestion management and dynamic rating estimation.
DSA is a valuable tool introduced into modern SIPS to improve its decision making process. It affords the system operator with real-time system stability analysis tool which enables a real-time state estimation of system during a fault disturbance. A DSA system contains six parts: measurement, modelling, computation, reporting and visualization, control and complement functions. The main application and function of a DSA tool is to generate more targeted operation solutions of disturbance for different contingencies or different severity of same contingency.

The main focus of this PhD is to design a SMT and DSA supported SIPS. This chapter reviews the development of these two types of new techniques and explains the definition of a SIPS. In the following chapter, an example of SIPS commissioned in real network and analysis of its performance will be presented. It will help explain why modern techniques need to be integrated into modern design of SIPS.
3. National Grid Operational Tripping Scheme

This chapter provides an existing example for a system integrity protection scheme. Section 3.1 presents a brief introduction of National Grid Company and an overview of the GB transmission network. Section 3.2 presents the specific part of the GB transmission network named the Humber SmartZone that will be studied during this research. The area has been modelled in DlgSILENT PowerFactory and details of this model are given in Section 3.4. The existing OTS (E-OTS) is designed to prevent transmission line from overheating by reducing its load through generation intertrip and will be described in Section 3.5. Four case studies were carried out to test the performance of the E-OTS for different faults and the results are presented in Section 3.5. Section 3.6 gives a summary of the E-OTS and proposes a number of improvements.

3.1 National Grid

National Grid is an international electricity and gas company based in the UK and north-eastern U.S. It is the largest electricity transmission owner (TO) and System Operator (SO) in Britain. It delivers energy to millions of British customers, businesses and communities [46].

The NG Company own and maintain the high-voltage transmission network in England and Wales. It is responsible for balancing supply with demand on a minute-by-minute basis, managing generation outputs and maintaining the voltage and frequency within an acceptable level through control actions. The national electricity transmission system (NETS) consists mainly of 400 kV, 275 kV and 132 kV assets including overhead lines, underground cables and substations. Moreover, the NETS has connections with the transmission system in France, the Netherlands and Northern Ireland through interconnectors. This enables the exchange of electricity between GB and these other networks, which allows cheaper power from these networks to serve the demand in the GB network and vice versa [46] [47].

According to [48] [49], the demand of the GB transmission network has been falling since 2005/2006. The average cold spell (ACS) peak demand, which reflects peak
demand for average weather conditions, was up to around 60.5GW in 2005/2006. In 2014/2015, this figure was approximately 54 GW. In the future, the ACS peak demand is expected to be lower, approximately 52 GW, by the year 2017/2018. The forecasted ACS demand depends on how the system develops in the future and the range becomes larger between future energy scenarios (FES) [46]. There are also many other factors that influence the demand such as the warmer winter, the slower growth of the economy, reduced industrial development. In 2014, on a typical summer day the average demand in Britain varies from 21GW to 37GW and on a winter day from 25GW to 51GW [46].

The total installed generation capacity decreased in the last few years as well. This is due to the shutdown of high emission power plants and generators that had reached the end of their operational life. Unlike the demand, the generation capacity in the GB network will increase in the near future due to the extensive deployment of distributed generation and sustainable generation. This growth in capacity is being driven by the strong support for clean, sustainable generation, including: wind, solar and tide, due to strong support for these technologies from NG and the UK government. However, whilst the installed capacity is increasing, the contrasting operational nature of these renewable generation technologies and the conventional generation they are replacing means that the network is facing more challenges than before.

For example, the output of wind generation is inherently uncertain due to the uncertainty of wind speed. The wind farm will only generate power within a specific range of wind speeds, which means that there will be no output during periods of high wind and low wind. This will result in increased variations in power flows through a boundary due to more intermittent and geographically varied generation sources. For example, the prediction of power flow into Humber zone receiving from wind generation in Scotland becomes harder and less accurate. These issues, and others, mean that there will be an increasing number of challenges faced during the operation and protection of the GB power system in the future and these will call for more advanced, adaptive protection and control measures.

The GB transmission system is one of the largest modern super grid networks in the world. The full dynamic model of the GB system, which has been used in this research, has more than 1850 transmission lines, 2850 busbars and 330 large generators and
power stations in the GB system. More transmission assets are being constructed to integrate the massive increase in the connection of renewable energy and to extend power exchange between Great Britain and the European continent.

A full geographic GB transmission network is shown in Figure 3-1, taken from [47].

![Figure 3-1: Existing GB Transmission System [47] (Green circle: Humber Zone)](image)

The blue line stands for the 400 kV level transmission lines and the red and black lines represent 275 kV and 132 kV, respectively. As can be seen from the above figure, the main voltage level for transmission network in England and Wales is 400 kV and 275 kV. The voltage level in Scotland is lower and is primarily 275 kV and 132 kV.
Generally, the loads are mainly located in the south of Great Britain while the generation assets are mostly concentrated in Scotland. Therefore, the power flow within the GB network is from the generation centres in the north (Scotland) to the demand centres in England. In recent years, Scotland has experienced a massive growth in the connection of renewable generation capacity, which has caused the power transfer from the north to the south to become closer to the network capacity limits. This may lead the system to be more vulnerable to disturbances.

### 3.2 National Grid Humber SmartZone

Due to the extreme complexity of conducting research on the whole NG network, the Humber Estuary was chosen to test new smart grid applications. Most of the research performed and novel techniques developed in this thesis will be based on this part of the full GB network model. This region has been selected because it will encounter many of the challenges that the GB system will face in the long term and provides a good microcosm of the issues facing NGT.

Humber Estuary group is a group of several 400 kV substations on the east coast of England (Green circle in Figure 3-1). This area is also called the Humber SmartZone as it has been selected by NG to test new smart techniques. Intelligent system (IS) infrastructure has been installed within this zone to support smart grid applications. For example, PMUs have been employed here to produce real-time synchronised measurements and data concentrators (DC) are in operation for collecting real-time measurement.

Moreover, the available transmission capacity in the Humber SmartZone has been in heavy use as it is a crucial connection between the northern generation centres and the southern demand centres. The Humber estuary is also going to be a key import region for offshore generation and as such will be a major beneficiary of developments in dynamic rating and congestion management.

Figure 3-2 presents the geographic connections of the Humber Estuary group, while Figure 3-3 demonstrates detailed transmission line connections between each substation inside the group. For further convenience in presenting power flow within
the group, a single line connection given in Figure 3-4 within the Humber SmartZone is extracted from these two figures.

Figure 3-2: Geographic representation of Humber SmartZone [47]

Figure 3-3: Single Line representation of Humber SmartZone
This simplified single line diagram of the Humber SmartZone network will be commonly used in this thesis to demonstrate fault locations, power flows, and relative position and connection of transmission lines. ‘CB’ stands for the circuit breaker and ‘L’ means the transmission line. The six substations are Creyke Beck (CREB), Humber Refinery (HUMR), Killing Holme (KILL), South Humber Bank (SHBA), Grimsby West (GRIW) and Keadby (KEAD). The number ‘4’ after each substation name stands for its voltage level, which is 400 kV. This number will be omitted in later sections. In total, there are 11 transmission lines (2 three-terminal lines and 5 two-terminal lines), 16 circuit breakers (circuit breakers are only modelled at each terminal of the transmission lines) and 6 substations in this area. There will be some wind farms connected to GRIW station through HVDC-VSC links in the future. The capacity of these wind farms may vary between 2 GW and 4 GW depending on the final investment decision made by the developer.

### 3.3 DlgSILENT PowerFactory and the National Grid Model

During this PhD research, the DlgSILENT PowerFactory software was used as the main tool for conducting power system analysis, simulations, and testing of the novel SIPS proposed here.
DlgsILENT stands for “DIGital SImuLation and Electrical NeTwork calculation program”, it is developed by the German company DlgsILENT GmbH [50] [51]. It is a computer aided engineering tool for the analysis of the performance of many aspects of a power system, such as transmission and distribution networks or individual electrical elements, like transformers.

The functions available in PowerFactory include [50]:

- **Load flow analysis within a AC, DC or a combined type of networks (performed using Newton Raphson method)**
- **RMS (time-domain simulation for stability analysis )/EMT (time-domain simulation for electromagnetic transients) simulations**
- **Contingency Analysis**
- **Eigenvalue Analysis**
- **Reliability Analysis**
- **Optimal Power Flow**
- **Network reduction**
- **State estimation**

The functions in bold type in this list are those that are primarily used in this research.

The sponsor and data provider of this PhD project, National Grid has been using DlgsILENT PowerFactory since 2006. For example, the software is used for operations planning purposes (including load forecasting, contingency analysis and fault handling) on a timescale down to the hourly basis, and transmission planning (such as increased DG integration and new transmission line construction) up to seven years ahead [52].

The model of the National Grid system that was used during this research is implemented in PowerFactory and is named the NG 2015_V 5.0 model (National Grid Full GB network work model for year 2015, version 5.0, built in 2010).

Figure 3-5 shows the overview of the Humber Zone model in PowerFactory.

For the purpose of investigating the existing or novel Operational Tripping Scheme (OTS) within this zone, the rest of the GB network has been considered an external
network. The boundaries have been defined at the 400kV lines leaving the area, which are depicted in Figure 3-5. The system beyond these boundaries is treated as an external network and is assumed not to vary but the dynamics of this external network are fully modelled. The full GB network model was used with no reduction or equivalenting.

![Figure 3-5: Overview of DlgsILENT Model of Humber SmartZone](image)

The base case for the power flow on these boundaries is given in Table 3-1. (The ‘-’ in reactive power stands for the direction of inductive reactive power)

<table>
<thead>
<tr>
<th>Interface</th>
<th>Busbar</th>
<th>Active Power (MW)</th>
<th>Reactive Power (Mvar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>CREB4B</td>
<td>80.91</td>
<td>-14.16</td>
</tr>
<tr>
<td>B</td>
<td>CREB4A</td>
<td>80.91</td>
<td>-14.16</td>
</tr>
<tr>
<td>C</td>
<td>CREB40</td>
<td>412.65</td>
<td>-169.36</td>
</tr>
<tr>
<td>D</td>
<td>CREB40</td>
<td>671.17</td>
<td>-164.04</td>
</tr>
<tr>
<td>E</td>
<td>KEAD42</td>
<td>459.90</td>
<td>220.99</td>
</tr>
<tr>
<td>F</td>
<td>KEAD43</td>
<td>44.75</td>
<td>55.39</td>
</tr>
</tbody>
</table>
The eleven monitored transmission lines data are given in Table 3-2 and Figure 3-6 shows the powerflow within the Humber SmartZone in steady state for the base case.

### Table 3-2: Initial Circuit Data

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Rating (kA)</th>
<th>Resistance (ohms)</th>
<th>Active Power (MW)</th>
<th>Reactive Power (Mvar)</th>
<th>Loading (%)</th>
<th>Active Power Out</th>
<th>Active Power In</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Ine_HUMR40_KEAD4A_1</td>
<td>4.05589</td>
<td>0.688</td>
<td>1016.82</td>
<td>-29.79</td>
<td>35.77</td>
<td>HUMR40</td>
<td>KEAD4A</td>
</tr>
<tr>
<td>L2</td>
<td>Ine_CREB40_KEAD4A_1</td>
<td>3.99815</td>
<td>0.416</td>
<td>552.76</td>
<td>-23.12</td>
<td>19.76</td>
<td>KEAD4A</td>
<td>CREB40</td>
</tr>
<tr>
<td>L3</td>
<td>Ine_KEAD41_KEAD4A_1</td>
<td>4.58993</td>
<td>0.128</td>
<td>459.83</td>
<td>-48.25</td>
<td>14.38</td>
<td>KEAD4A</td>
<td>KEAD41</td>
</tr>
<tr>
<td>L4</td>
<td>Ine_KEAD4B_KILL40_1</td>
<td>3.63731</td>
<td>0.64</td>
<td>1051.75</td>
<td>1.03</td>
<td>41.26</td>
<td>KILL40</td>
<td>KEAD4B</td>
</tr>
<tr>
<td>L5</td>
<td>Ine_CREB40_KEAD4B_1</td>
<td>4.43116</td>
<td>0.416</td>
<td>584.97</td>
<td>-68.85</td>
<td>19.02</td>
<td>KEAD4B</td>
<td>CREB40</td>
</tr>
<tr>
<td>L6</td>
<td>Ine_KEAD42_KEAD4B_1</td>
<td>3.99815</td>
<td>0.128</td>
<td>462.64</td>
<td>26.35</td>
<td>16.59</td>
<td>KEAD4B</td>
<td>KEAD42</td>
</tr>
<tr>
<td>L7</td>
<td>Ine_HUMR40_KILL40_1</td>
<td>3.99815</td>
<td>0.048</td>
<td>238.82</td>
<td>45.18</td>
<td>8.68</td>
<td>HUMR40</td>
<td>KILL40</td>
</tr>
<tr>
<td>L8</td>
<td>Ine_KEAD41_KILL40_1</td>
<td>3.63731</td>
<td>0.624</td>
<td>1056.66</td>
<td>-29.74</td>
<td>41.47</td>
<td>KILL40</td>
<td>KEAD41</td>
</tr>
<tr>
<td>L9</td>
<td>Ine_KILL40_SHBA40_1</td>
<td>3.56514</td>
<td>0.272</td>
<td>996.70</td>
<td>-128.67</td>
<td>40.31</td>
<td>SHBA40</td>
<td>KILL40</td>
</tr>
<tr>
<td>L10</td>
<td>Ine_GRIW40_SHBA40_1</td>
<td>4.12805</td>
<td>0.192</td>
<td>475.94</td>
<td>-180.71</td>
<td>17.69</td>
<td>SHBA40</td>
<td>GRIW40</td>
</tr>
<tr>
<td>L11</td>
<td>Ine_GRIW40_KEAD42_2</td>
<td>4.12805</td>
<td>0.848</td>
<td>1316.65</td>
<td>-49.96</td>
<td>45.78</td>
<td>GRIW40</td>
<td>KEAD42</td>
</tr>
</tbody>
</table>
The substation named SHBA4 is particularly relevant to this research. This is because the generation that is contracted to be disconnected by the NG E-OTS is located here. Therefore, an enlarged structure of this substation is extracted from Figure 3-5 and given in Figure 3-7:

![Figure 3-7: SHBA Station Single Line Diagram](image)

As seen from the single line diagram of SHBA, there are seven generators connected to its main Busbar through two-winding transformers. Only three of them, SHBA8T, SHBA8E and SHBA8D are in operation. Their nominal output of active power is 501.2 MW.
3.4 National Grid Operational Tripping Scheme

An operational Tripping Scheme (OTS) is installed in the GB system to protect the system from abnormal conditions after the loss of transmission lines in the SmartZone by tripping pre-selected generation assets [10]-[13]. In general, it is an example of a SIPS.

It is formally defined as “a balancing service, which involves the initial states of a power system without fault and a pre-determined set of corrective actions for system under fault occasions. Inside this OTS, automatic tripping of the user’s(customer) circuit breaker(s) will result in the tripping of balancing mechanism (BM) unit(s), or (where relevant) generating unit(s) comprised in a BM Unit to prevent abnormal system conditions occurring, such as overvoltage, overload, system instability, after the tripping of other circuit-breakers following power system fault(s)” [12].

To put it simply, the role of this OTS is to trip generators after the outages of transmission lines to prevent abnormal system conditions like thermal overheating or frequency fluctuations from occurring. For example, the OTS can be used to prevent the cascading outage of a group of transmission lines due to the sequential overloading of these lines. This is possible as the disconnection of pre-defined generators would reduce the loading of the overloaded transmission lines and return the system to a secure state of operation.

The input to this OTS is the status of the monitored circuit breakers. When the OTS detects that a certain combination of circuit breakers are in the open position it responds by disconnecting certain pre-defined generators. This should prevent abnormal system conditions such as overvoltage, overload or system insecurity from occurring. This form of OTS is a typical example of an event-based SIPS.

3.4.1 Implementation of Operational Tripping Scheme in GB network Model

The full description of the existing OTS is contained in National Grid document BP1818 [14]. This document includes all the necessary details to model the scheme in
any simulation software package. The main principle of the OTS is very simple: certain circuits (lines) in the zone are monitored and a loss of a circuit selected to the scheme result in generation tripping in SHBA station. These circuits are depicted in Figure 3-8.

Monitoring of the selected circuits is realized through monitoring of the status of particular Circuit Breakers (CBs). If a selected combination of CBs are open, then the selected generation will trip after a predefined delay. The conditions that must be satisfied for the 2-terminal circuits are:

- Any of two ends (CBs) of the transmission line is open

In the case of the 3-terminal circuits L1-L2-L3 (CREB-KEAD-HUMR) and L4-L5-L6 (CREB-KEAD-KILL), more complex logic is used. The following conditions need to be fulfilled in order to trip the generation:

- only the HUMR end (CB4) or the KILL end (CB1) is open or
- both the CREB and KEAD (CB5 &CB6 or CB2&CB3) ends are open or
- all three ends are open

Assuming that the status of a circuit breaker is 1 when closed and 0 when open, the above conditions for the three terminals line CREB-KEAD-KILL can be depicted by the logical operations given, as a block diagram (using IEC symbols), in Figure 3-9.
The same logic can be expressed in the equation:

\[ \text{DETECT} = \overline{CB_1} \lor (\overline{CB_2} \land \overline{CB_3}) \]  \hspace{1cm} (3-1)

Each circuit added to the scheme will produce a separate DETECT signal that indicates a detection for that circuit. All these signals are then collected into one multi-input OR gate to produce the trip signal. This logic can be simply expressed as:

\[ TRIP = \text{DETECT}_1 \lor \text{DETECT}_2 \lor \cdots \lor \text{DETECT}_n \]  \hspace{1cm} (3-2)

where \( n \) is the number of circuits selected to the scheme.

It should also be mentioned that the generation disconnected by the scheme is connected at the South Humber Bank substation (SHBA) and currently produces approximately 502 MW.

This OTS has been implemented in DIgSILENT using DIgSILENT Simulation Language (DSL) [50]. The frame of the OTS model created using DSL slots is depicted in Figure 3-10. The status of the selected CBs is used as an input by the respective logic circuits, the outputs of which are then connected to the ‘Crc’ logic. The ‘Crc’ signals are set to present the operational status of the monitored transmission line. If ‘Crc\(n\)’ is equal to 1, the \( n \)-th transmission line is out of service. Otherwise, ‘Crc\(n\)’ is equal to 0 and the monitored line is in service.

The current configuration of the OTS allows monitoring of up to 7 circuits (two of which are 3-terminal) but this can easily be extended if the need should arise. Such a structure allows for easy modifications/extensions. The graphical representation ensures clarity and ease of control over the scheme. In order to disable any element of
the scheme it can be taken out of service. The tripping logic consists of a signal stacking processor, a Boolean ‘greater than’ gate and a simple delay. The trip signal directly opens selected CBs at South Humber Bank substation in order to disconnect the generation.

Figure 3-10: Frame for the OTS built in DIgSILENT

It is worth mentioning that, the OTS is normally armed only when there are severe disturbances happening across the system; for example, when the network has lost three transmission lines in a short period of time. The National Grid network is believed to be ‘N-2’ secure for most contingencies. Therefore, there is an additional logical operation used inside the tripping logic block (shown in Figure 3-11) to prevent OTS operation under ‘N-1’ or ‘N-2’ cases.

The ‘signal sum’ block will stack the transmission line status signals collected (‘Crc’ signals) from the six detection logic blocks. The output ‘yi’ indicates the number of outage transmission lines. For instance, if ‘yi’ is equal or larger than 3, this means that more than 3 monitored transmission lines have been lost.
The value of \( C \) in the ‘logic > \( C \)’ block is 3. This means that the OTS would be armed and activated when three or more transmission lines are out of service. Only if this tripping precondition has been met will a trip command be sent to open the CBs of the pre-determined generators connected to SHBA station. The power flow within the Humber SmartZone will be reduced with the goal of reducing the loading of the transmission lines that are still in service in the SmartZone.

### 3.4.2 Performance of the Existing Operational Tripping Scheme

In this section, to demonstrate the performance of the E-OTS four case studies are considered. These cases study the system for two different sets of line outages and when the E-OTS is disabled and also when the E-OTS is enabled. These tests will present the impact on extreme contingencies on the power system and the effectiveness of the E-OTS in dealing with them.
3.4.2.1 Case 1: Outage of L10, L8, L1 with E-OTS disabled

In this case, the lines L10, L8, L1 were tripped at t=10 s, t=15 s and t=20 s, respectively. These lines are marked in Figure 3-12. The OTS is disabled, which means there will be no generation tripping after the line outages.

As shown in Figure 3-13, after the outages of the three transmission lines the percentage loading of L4 exceeded 100 % of its static rating. Only L4, L5, and L11 are presented here as they are the most heavy loaded of the eight lines inside the group for this case. The system is vulnerable to a cascade of overloads, so corrective remedial actions are crucial to ensure secure and stable grid operation.

The above results indicate that the NG SmartZone is vulnerable to a cascading failure in the event of the outages of these three transmission lines if no further layers of protection and/or control exist. Ensuring system security after more severe contingencies, like the outages of three lines, due to failures or in combination with planned maintenance is the role played by this OTS and, in general, by other SIPS.
3.4.2.2 Case 2: Outage of L10, L8, and L1 with the E-OTS armed

Case 2 is the same as Case 1, but with the E-OTS enabled. The available capacity of generator tripping is 501.2 MW. The faulted lines are marked in Figure 3-12.

![Figure 3-14: Loading of transmission lines in % of static limit for Case 2](image)

The percentage loading of the selected transmission lines in Case 2 are shown in Figure 3-14. The E-OTS operates at t=20.1 s and this reduces the percentage loading of all three monitored lines (L4, L5 and L11) to values below 100% of their static ratings.

![Figure 3-15: Fault detection and tripping signals of Case 2](image)

As shown in Figure 3-14, the action of the OTS causes a clear reduction in the loading on all three transmission lines, due to the tripping of the generation at the SHBA station. Figure 3-15 shows that the disconnection of the three transmission lines was detected by the OTS and a trip signal, shown as a light blue dashed line, was generated to trip the pre-determined group of generation. As mentioned in Section 3.5, only if the
outage of 3 transmission lines is detected will the E-OTS scheme generate this trip signal.

The tripping of the generation successfully prevented the lines from exceeding their static thermal limit and eliminated the potential threat of a system collapse due to cascade overloading of the lines.

Figure 3-16 presents a comparison of the power flow on the monitored transmission lines before the first line outage, after the third line outage and after the E-OTS operates. It reflects the impact of the E-OTS on system operation.

3.4.2.3 Case 3: Outage of L7, L8, L10 with E-OTS disabled

In this case a different group of transmission lines, L7, L8, L10 are tripped at t=10 s, t=15 s and t=20 s, respectively. These lines are marked in Figure 3-17. The OTS is disabled, which means there will be no generation tripping after the line outages.
As shown in Figure 3-17, after the outages of the three transmission lines the percentage loading of three monitored transmission lines L1, L4, L11 did not exceed 100% of its static rating. A before, the lines shown here were selected because they carry the heaviest loading inside the group for this case.

After losing this combination of three transmission lines the system will not experience a cascade of thermal overloads; therefore, corrective remedial actions are not needed for this case.

These results indicate that the NG SmartZone can survive certain N-3 contingencies without further actions. An effective SIPS should identify these cases and not operate for them.

### 3.4.2.4 Case 4: Outage of L7, L8, L10 with E-OTS enabled

Case 4 is the same as Case 3, but with the E-OTS enabled. The faulty lines are marked in Figure 3-17.
The percentage loading of the selected transmission lines in Case 4 are shown in Figure 3-19. The E-OTS operates at $t=20.1$ s and this reduces the percentage loading of all three monitored lines (L1, L4 and L11). However, the loading of the most heavily loaded transmission lines had not exceed the static limit at any time, which means that the E-OTS operation was unnecessary. Unnecessary tripping would waste huge amount of money for no benefit and expose stressed system to any further major disturbances. Though the system may be thermally secure, it could be still vulnerable in some other way.

Figure 3-20 helps to explain why the E-OTS operated in this case. The E-OTS detected the outages of three transmission lines after 20 s which means that the pre-condition for tripping generation has been met. Though the tripping was ‘unnecessary’, the E-OTS executed its function and this cannot be treated as mal-operation.
Figure 3-21 presents a comparison of the power flow on the monitored transmission lines before the first line outage, after the third line outage and after the E-OTS operates. It reflects the impact of the E-OTS on system operation.

![Diagram of transmission line loading comparison for Case 3 and Case 4](image)

3.4.2.5 Summary of Case Studies

Case 2 shows that the action of the E-OTS does eliminate the threat of cascade overloading; however, Case 4 shows that its design can allow it to operate unnecessarily.

The existing scheme has certain advantages, including: simple operation, quick response and high reliability. However, the simplicity of the scheme may allow unnecessary tripping to occur. These unnecessary actions could incur high financial costs or even initiate other disturbances in the system. The only input to the E-OTS is the circuit breakers’ status; therefore, its ability to assess the system conditions is limited.

It is possible to significantly reduce the likelihood of unnecessary actions and improve the E-OTS by using wide area measurements to assess the loading of the lines in real-time and compare this to the dynamic thermal line ratings.

3.5 Chapter Summary

This chapter presented the National Grid model that is used during this PhD research and described some of the challenges faced in GB that are motivating this research.
The Humber SmartZone that is the study area within GB that is the focus of this research is described in detail.

The Humber SmartZone locates in the east coast of England, consists six 400 kV substations and eleven main transmission connections between them. It is a dedicated area within the GB system that is used to trial new ‘smart’ solutions and the area is selected to participate this research is because a SMT system is being installed within the area which enables the possibility of developing applications based on WAM. Therefore, the Humber SmartZone seemed a logical candidate for the study of the performance of the novel enhancements to OTSs proposed in this research.

The OTS that is in service in the Humber SmartZone is also described in this chapter, and is defined as the E-OTS. It is an event-based SIPS, designed to prevent transmission line from overheating by reducing its loading through generation intertrip. The E-OTS working process is logical and straightforward. The OTS will detect the outage of certain combination of transmission lines and output a tripping command based on these detection signals. If a pre-determined condition is met, the OTS would send out commands to trip pre-selected generation assets from the network and relieve the existing or potential overloading within the network. Case studies are presented here shows the OTS does eliminate the threat of cascade overloading but also highlights the potential for the E-OTS to operate unnecessarily, which increases the cost of operation and may initiate further contingencies.

This unnecessary operation is found to be due to the simplicity of the schemes design and inputs. This simplicity is beneficial in terms of ensuring the availability of the scheme, but limits its ability to deliver the adaptive and intelligent response that will be required in the future GB system.

A possible solution in improving the OTS and to significantly reduce the likelihood of unnecessary actions is to equip the OTS by using wide area measurements to assess the loading of the lines in real-time by using dynamic thermal line ratings. The new technique is going to be presented in the following chapter.

This chapter will introduce the theory of dynamic thermal line rating and its application in improving the performance of a OTS. Section 4.1 discusses the general definition, methods of calculation and application of dynamic thermal line ratings. The methodology of integrating DTLRs into the existing transmission line OTS is given in Section 4.2. Section 4.3 summarizes the inputs required to realize the functionality of the novel transmission line OTS and case studies conducted to verify the performance of the novel OTS are presented in Section 4.4. Finally, Section 4.5 summarizes the contents in this chapter.

4.1 Dynamic Thermal Line Rating

Dynamic thermal line ratings (DTLR) are an extension of traditional static ratings and exploit the availability of wide area monitoring to provide a real-time thermal rating of a transmission asset. Since the first developments of real-time thermal rating systems for overhead transmission lines, dynamic thermal line ratings have been seen as an important opportunity for improving the planning and operation of power systems [53]. Using the DTLR of a line will not only provide higher power transfer capability, but also afford the system more security margin. Now, the DTLR has been developed to be an essential tool of modern smart-grid applications.

4.1.1 Static Thermal Rating Theory

For a bare stranded conductor, if the conductor temperature and the steady-state weather parameters (Wind speed, ambient temperature, etc.) are known, then the heat losses due to convection and radiation, the solar heat gain, and the conductor resistance $R$ for the conductor temperature can be calculated by solving a set of heat balance equations (given below). The conductor current ($I$) that corresponds to this conductor temperature under these weather conditions can then be found from the steady-state heat balance [18].
The static thermal rating of a transmission line can be defined as the current loading of the transmission line that will result in it reaching its maximum operational temperature for a pre-defined set of weather conditions [19][20]. The most common method to obtain the static thermal rating is to solve the heat balance equation defined in IEEE STD 738-2006 [18]. While these heat balance equations can be solved for any combination of conductor temperature and weather conditions, a maximum allowable conductor temperature (e.g., 75 °C to 150 °C) and “conservative” weather conditions (e.g., 0.6 m/s to 1.2 m/s wind speed, 30 °C to 45 °C summer ambient) are often used to calculate a steady-state thermal rating for the conductor[18]. This “conservative” rating always leads to a waste of conductor capacity.

The steady-state heat balance equations are presented as follows [18]:

\[
q_c + q_r = q_s + I^2 R(T_c) \\
I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}}
\]

(4-1) (4-2)

where \(q_c\) is the heat loss from convection; \(q_r\) is the radiated heat loss; \(q_s\) is the heating effect of the sun; \(R(T_c)\) is the AC resistance of the conductor at temperature \(T_c\) and \(I\) is the conductor current.

\(q_c – Convection\) [18]-[20]

Convection is the process of heat transfer between a surface and a fluid flowing in contact with it. If the flow is caused by an external device like a pump or blower, it is termed as forced convection (this is calculated as \(q_{c1}\) for high speed wind and \(q_{c2}\) for low speed wind). If there is no wind, convection will be caused by the buoyant forces generated by the heating or cooling of the fluid in a process referred to as natural or free convection (calculated as \(q_{cn}\)). At any wind speed, the largest of these three calculated convection heat loss rates is used. The equations used to calculate \(q_c\) are given in (4-3)-(4-6):
\[
q_{c1} = \left[1.01 + 0.0372 \left( \frac{D \rho_f V_w}{\mu_f} \right)^{0.52} \right] k_f K_{angle}(T_c - T_a) \quad (4-3)
\]

\[
q_{c2} = 0.0119 \left( \frac{D \rho_f V_w}{\mu_f} \right)^{0.6} k_f K_{angle}(T_c - T_a) \quad (4-4)
\]

\[
q_{cn} = 0.0205 \rho_f^{0.5} D^{0.75} (T_c - T_a)^{1.25} \quad (4-5)
\]

\[
q_c = \max \{q_{c1}, q_{c2}, q_{cn}\} \quad (4-6)
\]

where \(D\) is the conductor diameter; \(\rho_f\) is the density of the air; \(V_w\) is the wind speed striking the conductor; \(\mu_f\) is the dynamic viscosity of the air; \(k_f\) is the thermal conductivity of the air, \(K_{angle}\) is the wind direction factor and \(T_a\) is the ambient temperature.

**\(q_r\) – Radiation [18]-[20]**

Radiation is the process by which heat is transferred from a body by virtue of its temperature, without the aid of any intervening medium. The higher the temperature of the body, the more heat it radiates. The equation used to calculate \(q_r\) is equation (4-7).

\[
q_r = 0.0178 D \varepsilon \left[ \left( \frac{T_c + 273}{100} \right)^4 - \left( \frac{T_s + 273}{100} \right)^4 \right] \quad (4-7)
\]

where \(D\) is the conductor diameter and \(\varepsilon\) is the emissivity.

**\(q_s\) – Solar Heat Gain [18]-[20]**

This is the process of temperature increase of the conductor due to solar radiation. The equations that describe this type of heat transfer are given in (4-8) and (4-9):

\[
q_s = \alpha Q_{se} \sin(\theta) A' \quad (4-8)
\]

\[
\theta = \arccos[\cos(H_c) \cos(Z_c - Z_i)] \quad (4-9)
\]

where \(\alpha\) is the temperature coefficient of resistance, \(Q_{se}\) is the total solar and sky radiated heat flux, \(\theta\) is the effective angle of incidence of the sun’s rays, \(A'\) is the projected area of the conductor per unit length, \(H_c\) is the altitude of the sun and \(Z_c\) and \(Z_i\) are the azimuth of the sun and line respectively.
The calculation of these heating effects is dependent on 14 inputs and this process is described in detail in [18]-[20]. Five of these parameters can change in real-time: wind direction, wind speed, ambient temperature, the time of day and the date. The rest of the parameters are fixed when the conductor is manufactured and installed: conductor diameter, maximum conductor temperature, emissivity, solar absorptivity, line orientation, resistance at high temperature (assumed to be 75 °C), resistance at low temperature (always set as 25 °C), and the elevation above sea level.

Traditionally, the static thermal rating is used to define the thermal rating of the transmission line and is calculated based on the worst case scenario. This is because a static rating must be suitable for all circumstances that it may encounter, which inevitably leads to a conservative limit that wastes capacity. In recent years, a new type of rating, the dynamic thermal rating, has been developed. It considers the real-time conductor ambient environment and better reflects the true capacity of the conductor for the actual system condition.

4.1.2 Dynamic Thermal Rating Theory

Dynamic Thermal Line Rating (DTLR) is the rated current capacity of a transmission line that is calculated based on the properties of the line and the prevailing weather conditions. They are calculated using the same methodology as static thermal ratings but are based on the real-time measurements of the five parameters that change in real-time, rather than conservative estimates or historical values.

Adopting DTLR as capacity limit would afford system operation two aspects of benefits:

- Increasing the thermal limit of a line. (The static thermal rating is calculated based on worst scenario weather conditions, while the DTLR are estimated based on real-time weather. For most cases, the weather will not be the worst scenario)
- Estimating the time for temperature increase to violation may provide flexibility in system operation. (It is done by solving transient heat balance equations which will be presented later)
Furthermore, the real-time measurements used to calculate the dynamic ratings can also be combined with real-time measurements of current and transient heat balance equations to describe the delayed variation in conductor temperature in response to a change in the current loading on the transmission line. An example of the delayed response of the conductor temperature to a change in line current is depicted in Figure 4-1.

![Figure 4-1: Delayed response of temperature compared to step change current](image)

At time $t$, the current on this conductor experienced a step increase from $I_i$ to $I_f$. This increase in current produces increased joule heating of the conductor and breaks the previous steady state heat balance. This imbalance will cause the temperature of the conductor to increase until it reaches a new equilibrium point. The conductor temperature at this equilibrium point is denoted as $T_f$.

The rate of this temperature increase is influenced by several factors, including: the initial conductor temperature, the magnitude of the change in the conductor current, the new steady state temperature and the weather conditions.

Any transmission line will have a maximum allowable temperature, which will not vary. However, the conductor current that causes the line to reach this temperature will vary with the weather conditions and dynamic thermal line ratings allow this variation to be exploited.
As shown in Figure 4-1, if $T_f$ is assumed to be the maximum allowable temperature of this conductor, the current $I_f$ will be the lowest value of current that will cause the conductor temperature to reach $T_f$ for these weather conditions. This means that $I_f$ the current on this conductor is lower than $I_f$ the conductor will never reach its maximum allowable temperature for these weather conditions. When the conductor carries a load current lower than $I_f$, it will be considered as “normal” and not overloaded with respect to the dynamic thermal line rating.

On the other hand, if the conductor is carrying a current higher than $I_f$ it will reach its maximum allowable temperature more quickly. For this situation, the line will be considered as “overloaded” with respect to its dynamic thermal line rating. However, the time it will take for this overload to cause the conductor to overheat will depend upon the real-time current and dynamic thermal line rating.

Transient thermal rating equations describing the transmission line thermal progress (shown in Figure 4-1) are given as follows:

\[
q_c + q_r + mC_p \frac{dT_c}{dt} = q_s + I^2 R(T_c) \tag{4-10}
\]

\[
\frac{dT_c}{dt} = \frac{1}{mC_p} [R(T_c)I^2 + q_s - q_c - q_r] \tag{4-11}
\]

where $q_c$, $q_r$, $q_s$ and $R(T_c)$ all have the same meaning as in (4-10) and (4-11), $T_c$ is the conductor temperature and $mC_p$ is the total heat capacity of the conductor.

The value of $T_c$ in equation (4-11) can be solved using numerical integration methods. The formula for the integrand is known, but finding a suitable antiderivative that is an elementary function is challenging. It may be possible to find an antiderivative symbolically, but it is simpler to compute a numerical approximation than to compute the antiderivative. This is the case if the evaluation of the antiderivative requires a special function that is not available. $T_c$ reflects the real-time transmission line thermal status, which means knowing it will enhance the situational awareness of system operator. Moreover, if the trend of $T_c$ can be estimated, the time for temperature increase to violation will allow more flexibility in actions for disturbance handling.
The DTLR theory increases the thermal limit of a transmission line and allows the introduction of real-time conductor temperature estimation as part of modern transmission network management. Instead of judging if a conductor is overloaded by whether it is violating its static thermal rating, the DTLR provides the network designer and operator a deeper understanding of how the conductor temperature will vary based on weather conditions and loading. For instance, from the thermal point of view, if the conductor is not exceeding its temperature limits, it is not actually overloaded even though the current may be higher than its static rating. The technique affords network operators more freedom when facing ongoing or potential load congestion.

4.1.3 Applications of Dynamic Thermal Line Ratings

For most cases, the dynamic thermal line ratings are believed to be higher or even much higher than the conservative ‘worst case’ static ratings. This fact enables many applications of DTLRs in modern network operation and system design. Some typical functions are:

- **Transmission constraints relief**
  
  If the real-time dynamic thermal rating can be accurately estimated, it can replace the static thermal rating as the new loading limit. This enables the network to relieve congestion on corridors that are constrained by the existing static thermal limits without compromising thermal security [56] [57].

- **Load congestion management**
  
  Short-term emergency ratings could be achieved by adopting DTLRs into network monitoring. The DTLR technique would collect and process measurements from transmission assets during stressed system conditions to calculate a maximum short term rating according to the operators’ requirement. This affords the system operator more flexibility in disturbance handling [58]. Moreover, the improved load congestion management would support existing traditional load congestion relief actions. For instance, the new scheme helps to reduce the congestion cost and risk of load shedding by proposing a flexible load shedding strategy [59].

- **Improved Distribution Network Utilisation**
Enhanced distribution network load management has been realized with the help of prototype relays that collect local electrical and environmental data from transmission lines. The trials made by SPEN (Scottish Power Energy Networks) have proved the effectiveness of DTLR for network monitoring [60]. Protective relays can collect local electrical and environmental data and continuously update its setting using estimated DTLR of transmission assets. It evaluates the extra thermal capacity available in the critical network.

- **Improved Methodology for DG Integration**
  There is a strong relationship between weather-dependent renewable energy generation and weather-related DTLR techniques. They use the same weather variables such as wind speed, ambient temperature and shortwave radiation to predict generation output and DTLR ratings. This link can be optimized and utilized to propose new methods for designing wind farms [61] [62].

- **Reducing Power Generation Emissions**
  By reducing constraints on the transmission network DTLR may help to incorporate more renewable generation. This benefit from DTLR indirectly helps to reduce the power generation emissions from the conventional generators [63].

- **Support Optimal Routing of Power Transmission Lines**
  Building new transmission assets is hugely costly and time consuming. Widespread adoption of DTLR based techniques would provide insight into how climatological conditions and availability of meteorological data can influence the performance of a transmission line in terms of ratings and ageing processes. Therefore, these factors could be considered when routing new transmission lines in order to maximise the benefit of any investment [64].

These are all examples of how DTLR can enable new application that will benefit the power system. In the following part of this chapter the integration of DTLR techniques into the existing SIPS in the GB network will be presented.

### 4.2 Integration of DTLR into the Existing NG OTS

As presented in Chapter 3, an existing OTS has been commissioned in the Humber SmartZone of GB transmission network. The existing scheme has certain advantages,
including: simple operation, quick response and high reliability. However, the simplicity of the scheme may allow unnecessary tripping to occur. There is a demand for using wide area measurements to assess the loading of the lines in real-time which may significantly reduce the likelihood of unnecessary actions and improve the effectiveness of the OTS.

SMT supported DTLR techniques provide the possibility to realize the above expectation. The novel integration of dynamic thermal line ratings (DTLRs) into the E-OTS, as an additional input, will allow the creation of an improved OTS, referred to as a novel transmission line OTS (N-OTS). This is possible due to the unprecedented access to system measurements that is afforded by WAMPAC systems.

The N-OTS consist three main parts:

- **E-OTS.** The E-OTS is kept as it is now in the N-OTS and used as source for generating tripping command.
- **DTLR comparison scheme.** It is the major innovation of the N-OTS and used as the source for approval signal of tripping command.
- **Alarm scheme.** This the addition function enabled by DTLR comparison scheme which issue alarm signals when system is under danger.

### 4.2.1 Design of the DTLR Comparison Scheme

The DTLR comparison scheme is used to analyze the necessity and determine if the generator tripping command activated by the E-OTS will be approved.

Figure 4-2 depicts the logic implemented by the DTLR comparison scheme that is to be integrated into the E-OTS. This block detects if the calculated temperature of a line is violating its maximum operating temperature $T_{\text{limit}}$. The real-time line current and weather data blocks collect the real-time data from the monitored transmission line and a local weather station, respectively. This information is used to solve (4-11) in the temperature calculation block. The output of this block is the real-time conductor temperature $T$. This signal is then passed in to the temperature violation logic and compared to a pre-set value, e.g. 80 °C. If this limit on the conductor temperature is
exceeded then the tripping signal $b$ will be set to 1. Otherwise, $b$ continues to hold its initial value 0.

![Diagram of DTLR comparison scheme](image)

**Figure 4-2: Design of DTLR comparison scheme**

### 4.2.2 Design of the Alarm Scheme

The alarm scheme is designed to provide system operators with an alarm signal that will indicate if one of the monitored lines will violate its thermal limit in the near future. The real-time current data, $I_1$, is collected from the monitored transmission line. The weather data is collected from the weather stations and is used to calculate the dynamic thermal line rating $I_2$. This rating is calculated by solving equation (4-2).

![Diagram of DTLR alarm scheme](image)

**Figure 4-3: Design of DTLR alarm scheme**

A key input of this block is the maximum allowable temperature ($T_c$ in equation (4-2)). The calculation result $I_2$ represents the minimum current level necessary to heat the transmission line to the maximum allowable temperature $T_c$ for the given weather conditions. In other words, if the load current is higher than $I_2$ then the heating of the transmission line will eventually cause its temperature $T$ to exceed $T_c$.

It is important to recognise that the line’s dynamic thermal line rating will always be greater than or equal to its static thermal rating. After the conductor has been manufactured, its static thermal rating is fixed. To guarantee the healthy operation of
the line this static rating will be calculated based on the worst case of weather conditions, e.g. high ambient temperature, low wind speed and strong solar absorption. This static rating is very conservative when compared to the dynamic thermal line rating that uses the real-time weather conditions, which will rarely be the worst case. Therefore, by using the dynamic thermal line rating the maximum loading of the conductor can be increased under stressed system conditions and will help avoid unnecessary actions.

The current comparison block collects both the signal $I_1$ and $I_2$. If $I_1$ is lower than 90% of the limit $I_2$ the alarm signal will remain at its initial value of 0. If $I_1$ is greater than 90% of $I_2$ the alarm signal will be set to 1 for the relevant line. This margin of 10% is included here because if the transmission line loading is close to the dynamic thermal rating then the temperature of this line will not exceed the maximum operating temperature but will eventually reach a temperature that is perilously close to it. This will make this line very vulnerable to any further changes in weather or loading.

The benefit of this alarm signal is that it can be used to inform the operator that certain transmission lines will exceed their maximum operating temperature if remedial action is not taken. This will improve the situational awareness of the operators and improve the security of the system by allowing operators to pre-empt problems with corrective actions rather than responding after a fault has occurred. A further update of this alarm scheme will be presented in Section 6.3, where the estimated temperature violation time will become available and enables innovations in selection of OTS actions.

### 4.2.3 Design of the Novel Transmission Line OTS Tripping Logic

The inclusion of the DTLR comparison scheme and the Alarm scheme into the E-OTS creates an improved OTS (N-OTS), the block diagram of which is depicted in Figure 4-4.
The signal $a$ is generated by the E-OTS logic based on the status of the 14 circuit breakers that are monitored. The signal $b$ indicates if the conductor temperature is violating the maximum limit. If the temperature on a single transmission line exceeds the pre-set thermal limit then the signal $b$ will be 1. Signal $e$ is the alarm signal. The signal $c$ is calculated using a Boolean and operation on $a$ and $b$.

$$
c = a \land b
$$

The signal $d$ is a delayed version of $c$. It is the final tripping signal that will be sent to a group of pre-determined generators.

The N-OTS that is proposed here will only trip the generators if both $a$ and $b$ are equal to 1. This will prevent unnecessary tripping by only allowing a trip signal to be transmitted when both of the following two conditions are met:

1. The E-OTS has issued a Trip signal, based on the breaker status of the monitored transmission lines.
2. One of the monitored lines will violate their temperature limits if no generators are disconnected.

The N-OTS can prevent the unnecessary tripping of generators and afford system operators more flexibility during contingency conditions. In contrast to the E-OTS, which was a purely event based scheme, the N-OTS uses a combination of event and response-based decision making. The following section presents several examples that demonstrate the benefits of the DTLR controlled OTS.
### 4.3 Inputs for the Novel DTLR Controlled OTS

To implement full functionality of N-OTS, the protected part of the system must be fully observable and its real-time status including its loading, current, etc. should be accessible at any time. The SMT previously mentioned in Section 2.4 would be an essential technique to provide inputs for the N-OTS.

Phasor Measurement Units (PMUs) are power system devices that provide real-time measurements of voltage and current phasors at a rate of up to once per cycle with precise time synchronization [65]. Three PMUs have already been installed in the SmartZone area of the GB network and more will be installed in the near future. One of the roles of the SmartZone is to create a test bed in the GB system for the advanced trialing of PMU enabled applications, examples of which are described in [36]. These devices will provide the power system measurements required by the novel OTS, i.e. current flow on the transmission lines in the SmartZone. Furthermore, PMUs could be used to report the CB status at the monitored substations to the novel OTS using digital channels. In the existing OTS the CB statuses are obtained via the dedicated logic units. To simplify the examples presented here for the novel OTS, it is assumed that there are sufficient PMUs installed to monitor the current on all of the transmission lines in the SmartZone.

For instance, in the DTLR control block, PMUs are used to provide the real-time line current measurements necessary for the DTLR calculation. This decision was motivated by the availability of modern, high accuracy PMUs in the SmartZone of the GB National grid and the fact that an essential element of the N-OTS is delaying generation tripping, where it is important to remember that this tripping is a protection action.

The synchronized nature of PMU measurements means that they have precise time tags assigned to the measurements taken from across a wide area. These time tags would help ensure confidence when delaying protection actions based on estimates of the time available before a thermal overload will occur. This is because precise time tags reduce the uncertainty in the time available, as it would be known relative to the exact, common reference used by the PMUs and no assumptions would have to be
made about the relative time difference between individual measurements, as would be the case with unsynchronized measurements.

Furthermore, the standardized nature of PMU data (governed under the IEEE C37.118.2 std [66]) means that using data from multiple PMUs as inputs to single monitoring and control scheme (like the N-OTS) is a far simpler proposal than it is for the existing monitoring devices in the SmartZone, many of which use different, proprietary formats for data exchange.

4.4 Performance of the Novel DTLR Controlled OTS

To demonstrate the benefits of the N-OTS that is proposed in this thesis, two case studies have been presented. Both Case 1 and Case 2 involve the loss of three transmission lines with the N-OTS armed.

The weather conditions that are used in this test are updated every 300 s, as it is assumed that the weather parameters will not vary significantly in this period. The weather data for line L4 is given in Table I. This group of weather parameters was selected as they are representative of a warm summer day in the SmartZone. The weather data selected for these tests was extracted from the Met Office Data Point Service [67].

<table>
<thead>
<tr>
<th>Time(s)</th>
<th>Wind direction (deg)</th>
<th>Wind Speed (m/s)</th>
<th>Ambient Temp (deg)</th>
<th>Time(s)</th>
<th>Wind direction (deg)</th>
<th>Wind Speed (m/s)</th>
<th>Ambient Temp (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>133</td>
<td>4.31</td>
<td>19.8</td>
<td>1200</td>
<td>125</td>
<td>5.91</td>
<td>18.2</td>
</tr>
<tr>
<td>300</td>
<td>133</td>
<td>4.31</td>
<td>19.8</td>
<td>1200.1</td>
<td>125</td>
<td>5.31</td>
<td>19.8</td>
</tr>
<tr>
<td>300.1</td>
<td>145</td>
<td>4.61</td>
<td>20.1</td>
<td>1500</td>
<td>125</td>
<td>5.31</td>
<td>19.8</td>
</tr>
<tr>
<td>600</td>
<td>145</td>
<td>4.61</td>
<td>20.1</td>
<td>1500.1</td>
<td>232</td>
<td>5.0</td>
<td>18.2</td>
</tr>
<tr>
<td>600.1</td>
<td>130</td>
<td>5.61</td>
<td>19.8</td>
<td>1800</td>
<td>232</td>
<td>5.0</td>
<td>18.2</td>
</tr>
<tr>
<td>900</td>
<td>130</td>
<td>5.61</td>
<td>19.8</td>
<td>1800.1</td>
<td>133</td>
<td>5.31</td>
<td>18.7</td>
</tr>
<tr>
<td>900.1</td>
<td>125</td>
<td>5.91</td>
<td>18.2</td>
<td>2100</td>
<td>133</td>
<td>5.31</td>
<td>18.7</td>
</tr>
</tbody>
</table>

The weather conditions on other transmission lines are given in the same format.
This weather data assumes uniform weather conditions along the path of each of the transmission lines. In the future this assessment of the weather conditions may need to be extended to incorporate the known issues of non-uniform thermal limits (i.e. hot spots) on the transmission lines (e.g. spans of the line or fittings that constrain the thermal loading of the line due to a smaller maximum sag or lower thermal tolerance, respectively) and significant weather variations within the area due to its geographical properties (it spans across an estuary).

4.4.1 Case 1: Outage of $L_{10}$, $L_8$, and $L_1$ with N-OTS armed

In this case, lines $L_{10}$, $L_8$, $L_1$ were tripped at 300 s, 305 s and 310 s, respectively. The N-OTS has been enabled. The lines are marked in Figure 4-5 in this case are exactly same as the case in Section 3.4.2.1 and 3.4.2.2. The duration of the case is longer to demonstrate the ongoing temperature variation of the conductor. In Cases 4 in Section 3.4.2.4, the E-OTS is believed to execute an unnecessary tripping.

![Figure 4-5: Fault locations for Case 1 with N-OTS](image)

The test results are presented in the following figures. It can be seen in Figure 4-6, that after losing three transmission lines the loading of the other lines in the system increases. The N-OTS does not initiate tripping in this case. This is in contrast to Case 2 in Section 3.4.2.2 (the results of which are repeated in Figure 4-8), in which the E-OTS did trip the generation assets.
Figure 4-6: The loading of L4, L5, and L11 for Case 1 with N-OTS

Figure 4-7: The loading of L4, L5, and L11 for Case 1 with N-OTS (Enlarged for outage period)

Figure 4-8: Traditional loading of transmission lines for Case 2 with E-OTS

Figure 4-9 shows that this is because the DTLR temperature violation logic did not approve the generator tripping. The N-OTS detected the loss of the three transmission lines but no temperature violation signal was generated. It can be seen from the temperature (Figure 4-10) and DTLR line loading (Figure 4-11) for these lines that this was the correct decision for the OTS to make.
Figure 4-10 presents the variation in conductor temperature after the line outages occurred. No conductor temperatures exceeded the maximum allowable temperature of 80 °C, which means from the thermal point of view, that the lines were operating safely after line outages. Here, the maximum allowable temperature is a pre-determined value based on the profile provided by the conductor manufacturer. It varies between conductors according to factors such as the materials used, the conductor diameter, and the conductor pattern. In the case studies here the maximum allowable conductor temperature is 80 °C, which is an NG standard. Changing this value would influence the specific operation of the OTS (i.e. if it will trip or not trip) but, provided a suitable value is selected, it would not prevent the OTS from operating properly. Note that the selection of an incorrect value could have severe consequences, as it may prevent the OTS from protecting the lines properly.

Figure 4-9: Breaker status and temperature violation signal of N-OTS (Case 1)

Figure 4-10: Conductor temperatures of L4, L5, and L11 for Case 1 with N-OTS
The fluctuations in the temperature that can be seen in Figure 4-10 are caused by changes in the weather conditions. Figure 4-11 shows the variation in the DTLR current limits for a temperature limit of 80 °C, these are updated according to the changes in the monitored weather conditions that are assumed here to change every 300 seconds. The real-time loading currents of the transmission lines do not exceed their DTLR limits, so the conductor temperatures will never reach 80 °C.

Figure 4-12 directly presents a comparison of the conductor temperature on the monitored transmission lines under pre-disturbance condition, after outages but before N-OTS operation and after N-OTS operates (No tripping actions for this case, but the N-OTS continuously monitor the conductor temperature). It reflects the N-OTS impact on system operation.
Given that no transmission lines are overloaded there is no need for the N-OTS to trip the pre-determined generators. The N-OTS proposed here has proven to be reliable for this case and successfully prevented unnecessary tripping.

4.4.2 Case 2: Outage of lines L₈, L₁₁ and L₇ with N-OTS armed

In this case, lines L₈, L₁₁ and L₇ were tripped at 300 s, 305 s and 310 s respectively. The N-OTS has been enabled. Compared to Case 1, the outages will occur at different locations which will result in different post disturbance conditions. The fault locations are shown in following Figure 4-13.

The test results of this case are shown in Figure 4-14 – Figure 4-17. Immediately after losing three transmission lines, one (L₄) of the three monitored lines (L₄, L₆ and L₉) is within 10 % of its DTLR (shown in Figure 4-15). This means that the conductor temperature will eventually become very close to 80 ℃, so the system is vulnerable. An alarm signal, the pink dash line in Figure 4-16, was generated to make operators aware of this threat.

Figure 4-15 shows the variation in the DTLR current limits for a temperature limit of 80 ℃. They are updated every 300 s due to the changes in weather conditions. The real-time loading of L₄ exceeded its DTLR limit 900 s after the test started, due to a combination of the line outages and a change in the weather conditions. This resulted in a further temperature increase that reached 80 ℃ at 919.53 s.
Figure 4-14: Conductor loading of L4, L6, and L9 for Case 2 with N-OTS

Figure 4-15: Conductor currents of L4, L6, and L9 for Case 2 with N-OTS

Figure 4-16: Breaker status and temperature violation signal of N-OTS (Case 2)

Figure 4-17 depicts the variation of conductor temperature. Without further action, L_4 will eventually trip off and potentially initiate a cascade of line tripping. As soon as the temperature limit is violated, the DTLR temperature violation scheme approves the tripping of the generators that the original OTS logic had suggested based solely on
CB status signals. This temperature violation signal has been shown as a red solid line in Figure 4-16.

The generators were successfully disconnected from the system after a short delay (0.1 s in this case) and the loading of the monitored transmission lines was reduced immediately (Figure 4-14). The conductor temperature also began to fall; this fall in temperature is delayed in the same way that the heating of the conductor is delayed due to the thermal time constants.

**Figure 4-17:** Transmission line conductor temperature (losing L8, L11 and L7)

The N-OTS has increased the operation time of the OTS from 1.18 s to 609.3 s, without compromising system security. The inclusion of the alarm scheme in the N-OTS means that the system operator will have ten minutes, in this case, to identify corrective actions that would be more efficient than the pre-planned generator tripping.

**Figure 4-18:** Transmission line conductor temperature comparison for Case 2 with N-OTS
Figure 4-18 directly presents a comparison of the conductor temperature on the monitored transmission lines under pre-disturbance condition, after outages but before N-OTS operation and after N-OTS operates. It reflects impact of the N-OTS on system operation.

4.4.3 Summary of Case Studies

Two case studies have been carried out in this group of tests. Each of which demonstrates one of the benefits offered by the N-OTS.

*Preventing unnecessary tripping*

Case 1 in Section 4.3.1 is designed to test the performance of the N-OTS compared to the E-OTS in Case 2 from Section 3.4.2. The tests cases are the same except that the test duration is different to demonstrate the temperature variation of the conductors. Therefore, the system is expected to experience the same post-disturbance conditions.

In Section 3.4.2 the E-OTS detected the sequential outage of three transmission lines and tripped the pre-selected generation only after a short delay. As it has been discussed before, this tripping is believed to be ‘unnecessary’ as none of the monitored transmission lines exceed their maximum operational temperature during the test. This tripping would be very costly and this behaviour from the E-OTS is undesirable.

The N-OTS performance for this case is given in Section 4.3.1. As with the E-OTS, the N-OTS detected the sequential loss of transmission lines but, unlike the E-OTS, the N-OTS did not generate a tripping command. This is because the comparison scheme in the N-OTS determined that no single element was overloaded, relative to its DTLR. The comparison scheme blocked the decision made by the E-OTS and left the system in normal operation. It can be concluded that the N-OTS has the ability to adaptively judge overloading using real-time inputs instead of using conservative offline estimates. Therefore, ‘unnecessary’ tripping can be avoided by adopting the N-OTS.

*Extending the operating margin under contingency conditions*
The case presented in Section 4.4.2 simulated a different set of line outages to demonstrate the ability of the N-OTS to extend the operation margin during stressed system conditions. The fault locations have been changed and the disturbances had a more severe impact on the transmission line loading. Several of the monitored transmission lines exceed their static loading limit after the disturbances occurred within the network. However, the N-OTS did not operate because no transmission line is experiencing overheating as the comparison block found no temperature violation at this initial stage. Moreover, by comparing the real-time transmission line current and its real-time dynamic thermal loading, the alarm scheme predicted that the temperature of the transmission line will violate its limit if no further protective actions are taken into account in the future. This means that the N-OTS will eventually need to operate if remedial actions are not taken.

In the case studies, the temperature of the transmission line reached its limit 619 s after the first outage occurred. The N-OTS immediately approved the tripping command generated by the E-OTS when the temperature exceeded the limit. Therefore, the N-OTS extended the tripping time from the predefined 0.1 s to the 619 s that was available for the actual system conditions. The time this delay makes available to operators may, with further research, allow them to replace costly and intrusive tripping with an optimal re-dispatch that alleviates the overload within the estimated time available.

**Summary**

The Novel OTS could provide the following benefits compared to the existing OTS:

- Block costly ‘unnecessary’ tripping caused by E-OTS
- Execute tripping function only when required
- Delay tripping to provide time for less intrusive remedial actions than tripping
  - Generate an alarm signal to improve the situational awareness of operators

**Impact of N-OTS on System Security**

This tripping delay does not reduce system security, as the E-OTS tripped generation on the assumption that the outages of three lines would result in a cascade thermal overload of the remaining lines, as the outages of each line increases the loading on the
neighbouring lines until they also trip and eventually the entire transmission corridor is lost. Instead, the N-OTS uses DTLR to actually determine if a thermal overload will occur. This allows the N-OTS to manage the decision to initiate generation tripping after a line outage in a more intelligent way, with three possible outcomes:

- The DTLR comparison scheme blocks the generation tripping, as it identifies that no thermal overload will occur and, as such, no immediate tripping is necessary as there is no threat of a cascade (although re-dispatch may be necessary to return the system to an operating condition that is secure, thermally or otherwise, against any further outages)
- The DTLR comparison scheme approves the generation tripping, as it identifies that a thermal overload is imminent
- The DTLR comparison scheme determines that a thermal overload will occur after some periods, and sends an alarm signal to notify the system operators. The N-OTS will wait till there is temperature violation occur to approve the tripping commands.

4.5 Chapter Summary

This chapter presents the development of a novel transmission line OTS (known as N-OTS) that may enhance the performance of the E-OTS within the National Grid Humber SmartZone. The design of the N-OTS is presented and case studies are used to illustrate the improved performance of the N-OTS.

The development of N-OTS is based on the theory of the DTLR. Its core idea is to raise the usage of transmission line capacity by changing its loading limit from the conservative static limit to a more flexible dynamic thermal limit. The equations used to calculate both the static thermal limit and dynamic limit are introduced and from the basis of the N-OTS decision making. Furthermore, indirect monitoring of the conductor temperature using real-time weather and electrical measurements is presented.
The design of the N-OTS that integrate DTLR technique is presented in details in this chapter. The N-OTS consist three main parts:

- **E-OTS.** The E-OTS is kept as it is now in the N-OTS and used as source for generating tripping command.
- **DTLR comparison scheme.** It is the major innovation of the N-OTS and used as the source for approval signal of tripping command.
- **Alarm scheme.** This the addition function enabled by DTLR comparison scheme which issue alarm signals when system is under danger.

The benefit of the proposed novel integration of the real-time calculation of DTLRs into an OTS is that it allows a more informed decision to be made about the generation tripping initiated by the OTS. The dynamic ratings can be used to identify if a thermal overload will actually occur after a line outages, rather than the existing conservative practice of assuming it will. The real-time conductor temperature estimated by using the DTLR technique will determine the behavior of the novel OTS instead of only using the detection of line outages as in the existing transmission line OTS. When a disturbance occurs, the fluctuation of the conductor temperature can be tracked and whenever the limit is violated, an approval signal will be sent to the E-OTS, which enables the generator tripping. Another function within the novel OTS enabled by DTLR is the generation of an alarm signal, which alerts the operator to the threat of a thermal overload in the near future.

The novel transmission line OTS has been verified through case studies that demonstrate that it may significantly improve the performance of the E-OTS. The N-OTS has successfully prevented the unnecessary tripping seen in the previous chapter for the E-OTS. The N-OTS only allows generator tripping to occur when a transmission line is above its temperature limit. This allows the time of the tripping to be delayed from milliseconds to minutes depending on the pre-fault conditions and thermal constants of the conductor. With further work, described in Section 6.3, this time could be used to benefit the system by enabling the design of adaptive optimal actions instead of costly generation tripping.
5. **Using Real Time Temperature Estimation for Improving an Operational Tripping Scheme for Transformers**

There is an increasing emphasis on keeping transformers in service longer than has been the practice in the past, for economic reasons [70]. Therefore, there might be a higher possibility for a transformer to suffer a fault. The transformer OTS protects transformers from overloading and helps keep them in operation as long as possible when the system is experiencing faulty conditions. This is realized by disconnecting of the pre-defined generators which would reduce the loading of the overloaded transformer and return the system to a secure state of operation. This chapter starts with an explanation of the theory of transformer heating. The temperature within a transformer tank varies by location and to protect the transformer the location that experiences the highest temperature, the hot spot, must be found. Section 5.2 presents how the existing transformer OTS in NG works and Section 5.3 proposes a novel transformer OTS that integrates a real-time temperature estimation technique into the existing OTS. This update would make the novel transformer OTS a responded based SIPS. The performance of this novel transformer OTS is presented in Section 5.4. It will be compared to the original transformer OTS and the benefits of employing the novel transformer OTS will be demonstrated. The contents of this section are summarised in Section 5.5.

### 5.1 Transformer Thermal Protection – an Overview

Power transformers are some of the most expensive components within the modern electricity network. They are widely used in the transmission network, distribution network and power plants. A failure in a transformer will not only result in enormous economic loss, but will also be a huge disturbance to all costumers connected to it and create the threat of voltage failure across multiple busbars [71]. The protection of a transformer is complex as it may depend on their importance, winding connections, earthing, loading, operation modes and ambient environment, etc.

The power transformers are conventionally protected from faults or being damaged by one of differential protection schemes: High Speed phase Overcurrent (HSOC), Two
Stage Overcurrent relay, Winding Temperature Indicator (WTI) and etc. These relays detect abnormalities of voltages and currents in the differential zones. For example, the appearance of a short circuit or large fault currents will cause the protection relays to trip and isolate the transformer by opening the relevant breakers [72]. However, for some contingencies, like overheating due to overloading of the transformer, immediate protective actions might not be required, as each transformer has its pre-set continuous, emergency and even short term emergency ratings to help the device survive faults. Whilst this potential overheating may not require immediate action, it still requires quick identification and accurate estimation of transformer status.

There exist two types of thermal protection methods in modern power system: first group is ‘mechanical’, where physical sensors and relays are utilized to detect over-temperature, and take actions through alarms and tripping. Though this is the direct path of transformer thermal protection, it is not applicable to the transformers manufactured decades ago and the phasor could only detect the top-oil temperature. The second group is overcurrent based transformer protection schemes. It uses combinations of measurements including measured current, ambient temperature, and transformer oil temperature to identify a presence of overheating condition of transformer [73]. This protections scheme has wider applications as it did not require advanced sensors within the transformer and top-oil temperature could be estimated. In this thesis, the second group of transformer thermal protection scheme are adopted as a key method of improving a SIPS aiming to protect transformer from overheating.

The estimation of transformer heating progress has been a subject of great interest over the past decades and many methods and results have been published [69]-[81]. Among them, there are two standards, the IEEE loading guide for oil-immersed transformers (Std 57.91) [74] and the loading guide for power transformers defined by British standard (BS IEC 60076-7) [69]. In [70] the thermal modelling of a transformer and a method for the estimation of oil temperature are both presented. The methodologies for transformer temperature calculation mentioned in these references are commonly adopted around the world for the calculation of transformer short term emergency ratings and overheating protection.

Except for the methods for temperature estimation, the existing publications discuss the application of these temperature estimates during the operation of an overloaded
transformer. In [75] the design of an adaptive transformer overload relay is presented; [76] and [77] describes how to use transient transformer over load ratings in thermal protection; [78] proposes the replacement of pre-set emergency loading with on-line estimations; [79] describes the economic benefits of ensuring that transformer continue to operate under overloaded conditions. All of these papers have a common pre-condition of incorporating new techniques into transformer thermal protection schemes, which require detailed understanding of the thermal behaviour of transformers and the real-time estimation of transformer temperature.

In this chapter, the thermal protection scheme for transformers in the NG network will be tested and analysed. New modern techniques will be proposed that can be integrated into the existing scheme and would significantly improve the effectiveness and accuracy of the transformer thermal protection algorithm.

5.2 Transformer Heating Process

To better understand the method of temperature estimation within a transformer, it is worth explaining the general heating process within the transformer.

The heating and cooling processes within a larger power transformer and its cooling equipment are not simple. The temperature of the transformer will vary depending on where it is measured within the transformer. A thermal diagram shown in Figure 5-1 is commonly used to describe the temperature differences inside the transformer oil bank and its windings. Note, some assumptions have been made when creating this diagram including [69]:

- The oil temperature inside the tank increases linearly from bottom to top, whatever the cooling mode. This is to simply the expression of the heating process.
- The temperature rise of the conductor at any position on the winding is assumed to increase linearly, parallel to the top oil temperature rise. The winding temperature is marked with a dashed line that is parallel to the solid line between D and B. $g_r$ is the constant difference between the winding temperature and oil temperature.
The hot-spot temperature rise is higher than the temperature rise of the conductor at the top of the winding. This assumption allows for possible temperature increases due to stray losses or extra paper on the conductor. Therefore, a new parameter $H \times g_t$ is introduced here to describe the difference between the hot-spot and the top oil temperature.

The meaning of each point is explained as follows [69]:

- **A** is at the top of the oil. The temperature at this point stands for the *top-oil temperature* derived as the average of the tank outlet oil temperature and the tank oil pocket temperature.
- **B** is at the top of the winding. The temperature at this point stands for the *mixed oil temperature* in the tank at the top of the winding (often assumed to be the same temperature as A).
- **C** is at the middle of the oil tank. The temperature at this point stands for the *average temperature of the oil* in the tank. This is due to the assumption that oil temperature inside the tank increases linearly from bottom to top.

Figure 5-1: Transformer Thermal Diagram [69]
❖ **D** is at the bottom of the winding. The temperature at this point stands for the *Oil temperature at the bottom* of the winding.

❖ **E** indicates the location of the bottom of the tank. No specific temperature is monitored here.

Except for the above locations within the oil tank, there are also extra parameters and points shown in the figure [69]:

- **g_r** is the parameter that describes the difference between the average winding temperature and the average oil (in tank) temperature at rated current
- **H** is the hot-spot factor
- **H × g_r** describes the temperature rise between the top-oil and the hot-spot.
- **P** is the location where the transformer has the hottest temperature. It is the Hot-spot temperature
- **Q** is assumed to be located at the middle of the winding. The temperature here stands for the average winding temperature determined by the resistance measurement.

Figure 5-1 depicts the assumed relationships between different temperatures within the transformer for steady state. In general, the temperature inside a transformer increases from the bottom to the top and the reason for this will be explained in the later paragraphs.

The hot-spot temperature is the temperature that has the most crucial influence on the transformer’s operation. The transformer emergency loading capability and the aging rate of the oil paper insulation is determined by this temperature [80] [81]. Therefore, an accurate prediction and estimation of this temperature is important for both consumers and network operators. If the transformer’s hot-spot temperature is higher than its limit, there will be higher losses and reduction of insulation life.

There are a few reasons for why the hot-spot temperature appears at point P in Figure 5-1:

1. **Oil Density**
   The findings from physical tests indicate that the oil density decreases as the temperature increases. This means that the higher the oil temperature, the lower
the oil density. Therefore, the hotter, lighter oil will be pushed higher up the oil bank.

2. Eddy Loss

Based on the transformer electrical test results, the maximum leakage field appears at the top of the winding. Eddy currents are electric currents induced within conductors by a changing magnetic field in the conductor. This current will heat the part of the winding it appears in and increase the temperature around it. To reduce the eddy current, laminations of magnetic cores of transformer are commonly adopted. Insulation painting is applied on each level to increase the resistance of the core which will limit the eddy current.

3. Heat Superposition

Due to the different thickness and resistance throughout a multi-layer winding, the heat distribution varies between turns. In the case of Zigzag-cooled windings, the washers reduce the heat transfer into the fluid and instead, keep the heat superimposed within the winding.

The combined effects of these three phenomena cause the hot-spot temperature of the transformer to appear at, or close to, the top of winding.

Knowing the transformer heating process under steady state and the locating of the hot-spot within the transformer, the following part of this section will explore the method of calculating the real-time transformer temperature.

Figure 5-2 shows the thermal model represented as an electrical equivalent circuit. From this equivalent, the basic heat transfer equation can be deduced. The equations (5-1) to (5-9) all describe the heating progress within a transformer. In general, the oil heats up slower than the winding and the winding temperature is the issue for transformer protection. The difference between top-oil temperature and hot-spot temperature must be understood.
The differential equation for the equivalent circuit is [70]:

\[ q_{fe} + q_{cu} = C_{oil} \frac{d\theta_{oil}}{dt} + \frac{1}{R_{oilR}} \left[ \theta_{oil} - \theta_{amb} \right]^{1/n} \]  \hspace{1cm} (5-1)

where \( q_{fe} \) is the heat generated by iron losses; \( q_{cu} \) is the heat generated by copper losses within the conductor; \( C_{oil} \) is the thermal capacitance of the oil in Ws/°C; \( \theta_{oil} \) is the temperature of the oil; \( \theta_{amb} \) is the ambient temperature and \( R_{oilR} \) is the thermal resistance of the oil under rated conditions.

Furthermore, the heat transfer through a wall next to a moving fluid is (e.g. the heat transfer through the transformer wall between the insulating oil and surrounding air):

\[ q = 1 / R_{thR} \cdot \theta^{1/n} \]  \hspace{1cm} with \( 1/n > 1.0 \)  \hspace{1cm} (5-2)

\[ \theta = R_{thR} \cdot q^n \]  \hspace{1cm} (5-3)

Figure 5-2: Thermal model of oil-to-air transformer heat transfer [70]
where $R_{thR}$ is the rated value of the thermal resistance; $\theta$ is the temperature difference and $1/n$ is a constant that describes the forced air flow or other cooling used, for example n=0.8 if no fans are installed and n=1.0 if fans are employed to force the air to move faster [70].

If we introduce: $\beta = \text{ratio of } q_{cu} \text{ to } q_{fe} \text{ at rated load } (I_{pu}=1.00)$; $\tau_{oil} = R_{oilR}C_{oil}$; $\Delta \theta_{oil} = \theta_{oil} - \theta_{amb}$; equation 5-4 will be converted to 5-5:

$$\frac{l^2_{pu} \beta + 1}{\beta + 1} \cdot [\Delta \theta_{oilR}]^{1/n} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + \left[\theta_{oil} - \theta_{amb}\right]^{1/n} \quad (5-4)$$

where $\Delta \theta_{oilR}$ is the rated load, rated ambient value of $\Delta \theta_{oil}$.

The difference equation for 5-4 is:

$$D\theta_{oil} = \frac{Dt}{\tau_{oil}} \cdot \left[\frac{l^2_{pu} \beta + 1}{\beta + 1} \cdot [\Delta \theta_{oilR}]^{1/n} - \left[\theta_{oil} - \theta_{amb}\right]^{1/n}\right] \quad (5-5)$$

Equation 5-5 is the initial model of the transformer estimation methods that developed in the standard BS IEC 60076 [69]. The following method will be used to estimate the top-oil temperature in the novel dynamic thermal technique controlled transformer OTS.

Equation 5-6 presents how the top-oil temperature is estimated in [69]:

$$\theta_o(t) = \theta_a + \Delta \theta_{oil} + \left\{\Delta \theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^t - \Delta \theta_{oil}\right\} \times f_1(t) \quad (5-6)$$

where $K$-load factor; $R$-ratio of load losses (copper loss) at rated current to no-load losses (iron loss); $X$-oil exponent; $\theta_o$-Top-oil temperature at the load considered; $\theta_a$-ambient temperature; $\Delta \theta_{oil}$-Top-oil (in tank) temperature rise at start; $\Delta \theta_{or}$-Top-oil (in tank) temperature rise in steady state at rated losses (no-load losses + load losses).
Except for those parameters that have been explained in previous equations, a new formula \( f_1(t) \) is introduced in (5-6). It is used to describe the relative increase of the top oil temperature rise corresponding to the unit of the steady state value.

\[
f_1(t) = \left( 1 - e^{(-t)/(k_{11}\tau_0)} \right) \quad (5-7)
\]

where \( k_{11} \) is a constant controlling the difference between the top-oil and average oil temperature; \( \tau_0 \) is the average oil-time constant and \( f_1 \) is used to simulate the exponential model of the top-oil temperature.

Equation 5-8 presents how the hot-spot temperature is estimated in [69]. The hot-spot temperature is calculated by adding top-oil temperature and the estimation of the top-oil and hot-spot-top-oil temperature difference.

\[
\theta_h(t) = \theta_o + \Delta\theta_{oi} + \left\{ \Delta\theta_{or} \times \left[ \frac{1+R\times K^2}{1+R} \right]^t \right\} - \Delta\theta_{oi} \times f_1(t) + \Delta\theta_{hi} + \{Hg, K^\gamma - \Delta\theta_{hi}\}* f_2(t) \quad (5-8)
\]

where \( Y \) is the winding exponent; \( g_r \) is the average winding to oil gradient; \( \theta_h \) is the hot-spot temperature and \( H \) is the hot spot factor.

The \( f_2(t) \) in equation 5-9 describe the relative increase of the hot-spot-top-oil gradient change. It is expressed as:

\[
f_2(t) = k_{21} \times \left( 1 - e^{(-t)/(k_{22}\tau_w)} \right) - (k_{21} - 1) \times \left( 1 - e^{(-t)/(\tau_o/k_{22})} \right) \quad (5-9)
\]

where \( k_{21} \) and \( k_{22} \) are thermal constants; \( \tau_o \) is the average oil-time constant and \( \tau_w \) is the average winding time constant.

\( f_2(t) \) describes the difference between the rates at which the winding temperature and oil temperature will increase when they are heated. From Figure 5-3, the rate at which the temperature increases of a winding, is larger than the rate at which the oil temperature will increase. The hot-spot-oil temperature difference is calculated as the
winding temperature minus the oil temperature at the same time. So \( f_2(t) \) contains an overshoot due to the different rate of temperature change in the winding and the oil.

Figure 5-3: Transformer heating progress winding vs oil

After the introduction of the fundamental equations used to estimate transformer temperature at various points, the following sets of formulas present a method for solving the differential equations above. They are achieved by applying forward Euler method to 5-8. The resulting expression for the transformer temperature equations is as follows:

\[
\left[ \frac{1 + K^2 R}{1 + R} \right]^2 \times (\Delta \theta_{or}) = k_{11} \tau_w \times \frac{d \theta_o}{dt} + [\theta_h - \theta_o] \]  
(5-10)

\[
k_{21} \times K^y \times (\Delta \theta_{hr}) = k_{22} \times \tau_w \times \frac{d \Delta \theta_{h1}}{dt} + \Delta \theta_{h1} \]  
(5-11)

\[
(k_{21} - 1) \times K^y \times (\Delta \theta_{hr}) = (\tau_w / k_{22}) \times \frac{d \Delta \theta_{h2}}{dt} + \Delta \theta_{h2} \]  
(5-12)

\[
\Delta \theta_h = \Delta \theta_{h1} - \Delta \theta_{h2} \]  
(5-13)

\[
\theta_h = \theta_o + \Delta \theta_h \]  
(5-14)

where \( K \) is the load factor; \( Y \) is the winding exponent; \( k_{21}, k_{22} \) are thermal load constants, \( \tau_w \) is the winding time constant; \( \theta_o \) is the top-oil temperature at the loading considered; \( \theta_h \) is the hot-spot temperature; \( \Delta \theta_h \) is the hot-spot-to-top-oil gradient at the loading considered \( \Delta \theta_{hr} \) is hot-spot-to-top-oil (in tank) gradient at rated current.
Equation 5-10 shows the result of the differential equation for top oil temperature. The hot-spot temperature rise is solved though the sum of two differential equations (5-11)-(5-12). They are a discrete form of a continuous function \( f_2(t) \). Equation (5-14) is the final equation that provides the hot-spot temperature.

These equations will be integrated into the novel transformer OTS to estimate the top-oil and hot-spot temperature.

5.3 Sensitivity Analysis of Transformer Heating

Mentioned in previous section, the time constants that will have an impact on the transformer heating process are fixed when manufactured. In this section, tests have been carried out to explore the sensitivity of the transformer thermal behaviour under different pre-fault loading, post-fault loading and manufactured parameters.

5.3.1 Test 1: Sensitivity of Transformer Thermal Process- to Different Pre-fault Loading

In this test, the monitored transformer will have different pre-fault loading levels of 60%, 72% and 84%. In each case the post-fault loading of the transformer is 120%.

The results are given in the Figure 5-4. It can be summarized that the post-fault temperature of the transformer is determined by the post-fault loading and that, no matter how large the pre-fault loading is, this post-fault temperature will be reached at the same time after the fault. For example, in this test, the hot-spot temperature of the transformer will reach 123 °C 230 minutes after the load increase for all three pre-fault loadings.
However, the time at which the transformer will reach intermediate temperatures, e.g. 110 °C, will vary for different initial loadings. The higher the pre-fault loading, the shorter the time it will take for the transformer to reach this intermediate temperature and violate any temperature limit that is below the final steady state temperature. It is not difficult to understand this phenomenon, because the transformer with higher pre-fault loading will contain more heat energy than those who have lower loading. This means that the pre-fault loading will have more significant influence on the transformer temperature during the initial temperature increase after the loading change.

5.3.2 Test 2: Sensitivity of Transformer Heating Process- to Different Post-fault Loading

In this test, the monitored transformer will have the same pre-fault loading which is 72% in all cases. The post-fault loading of the transformer is varied between the cases and 120%, 140% and 160% are the values tested.
The test results are shown in Figure 5-5. The post fault loading of a transformer will impact on the new heat balance that the transformer will reach. The higher the post overloading, the more severe the overheating that the transformer will suffer.

Moreover, the transformer with the higher post-fault loading will reach any temperature limit faster, as the higher loading causes a larger temperature gradient.

**5.3.3 Test 3: Sensitivity of Transformer Heating Process- to Different Transformer Time Constant**

In this test, the monitored transformer will have the same pre-fault loading of 72% and a post fault loading 140%. In each case different oil and winding time constants will be used.

The test results are given in Figure 5-6. By comparing the red case and the green case, in which the transformers have the same winding time constant but different oil constants, it can be understood that the lower the oil time constant, the higher the gradient of the hot spot temperature increase. Similarly, comparison of the blue case and the red case reveals that the lower the winding constant, the higher the temperature gradient will be for the transformer.
Figure 5-6: Transformer temperature trend for different transformer design

It is worth noting that the influence of the winding constant is most significant during the initial stages of the temperature increase (e.g. the first 20 minutes) and the oil constant mostly affects the later stages (e.g. after the first 20 minutes). This has been proven in equation (5-9) on page 118.

The results of these three tests can be summarized in the requirements for the design of the transformer OTS. The transformer OTS should be able to automatically identify different levels of pre and post loading and response to each contingency with adaptive solutions. The model of the transformer should also be considered within the transformer OTS, as its time constants will have a major impact on the transformer thermal behaviour.

5.4 Overview of the Existing Transformer OTS

Similar to the protection scheme for transmission lines used in the GB network, there is another type of OTS that is commissioned in part of the GB network. It is used to protect transformers from overheating and is referred to here as the transformer OTS.

There are some similarities between the transmission line OTS and the transformer OTS:
  - Both of the OTSs are examples of a SIPS
  - Both of the OTSs protect elements from overheating
Both of the OTSs realize their function by disconnecting pre-determined generation assets.

However, the differences between these two types of OTS are obvious as well. The transmission line OTS protects transmission lines from overloading while the transformer OTS prevents transformers from overheating. This means the OTSs are based on different underlying equations, as the thermal progress during transmission line and transformer overheating are different. Therefore, the upgrading on the transformer OTS needs specific technique rather than the novel transmission line OTS.

The transformer OTS is armed during a maintenance outage of one of the 4 Creyke Beck 400/275kV SGTs (super grid transformers) which could be for a few weeks each summer. It would also be armed if a fault appears on a SGT during any time of the year. The scheme prevents a thermal overload of a single remaining SGT if there is a single circuit fault on the opposite circuit.

For example, in the case illustrated in the Figure 5-7 below, a single circuit fault on the Creyke Beck – Salt End North circuit during an outage of SGT5B would result in SGT5A being overloaded if the transformer exceeds its short term rating. The MVA flows shown on the circuit are the worst case flows simulated using DIgSILENT. The SGT5A pre-fault loading of 603 MVA gives a short term 3 minute rating of 1130 MVA. This value is fixed and pre-calculated. The meaning is addressed in later paragraphs.
Figure 5-7: Transformer OTS Application Example on CREYKE BECK SGTs (Provided by NG)

The existing scheme is relatively un-intelligent and has been designed to be as simple as possible so there is minimal risk of it failing. It simply monitors the circuit breaker status of the transmission lines and transformers in order to determine which circuits are in service. If a certain circuit is lost, it automatically trips off pre-selected generation to prevent the thermal overload on the transformer.

Moreover, this scheme utilizes a time delay that waits for a Delayed Auto-Reclose (DAR) to attempt to bring the faulted line back in service. This delay reflects the fact that a very high percentage of faults are transient and there is sufficient short term, 3 minute, rating in the transformer to wait for a successful DAR. This prevents any unnecessary generator tripping.

However, waiting for a DAR is only applicable to the existing 1100 MW of CCGT (Combined Cycle Gas Turbine) generation at Saltend South. In the case of generation from the proposed wind farms it is impossible to wait for DAR, which means they need to be tripped off if a transformer is exceeding the 3 minute SGT. Instead of instantaneous trips, they will be tripped off via a de-load ramp down over a number of seconds to prevent excessive mechanical stresses on the turbines. This is now common for wind farm inter-trips due to thermal issue.
The existing short term ratings of a transformer are essentially based on two things – average ambient temperature of the season in the year and the SGT’s pre-fault loading. An example is given in Figure 5-8. Different versions of this chart exists for different pre-fault loading (%Nom) and different season.

![Figure 5-8: Transformer Short term ratings example (Source: NG input)](image)

Here is an illustration of the table. If the pre-fault loading is 95% of the transformer’s nominal capacity, and the post fault loading is 835MVA, this transformer can be in operation normally for 20 minutes before further protections take effects.

![Figure 5-9: Existing Transformer OTS working process](image)
Figure 5-9 explains the operation of the existing transformer OTS. It can be explained in following sub points:

1. The OTS system will first detect the loss of selected transformers or transmission lines by monitoring circuit breaker status changes on the terminals of those elements. If the tripping logic inside CB status block has been approved, a trip signal will be generated to protect the transformer.

2. The selected transformer’s pre-fault loading will be recorded and sent to the *transformer post-fault rating selection block*. Inside which, a pre-determined form like Figure 5-8 has been integrated as a function. The pre-fault loading will decide which part of the form will be applied, as shown in the purple circle in Figure 5-9 and then 5 different levels of short term emergency ratings corresponding to the pre-fault loading as given in green circle will be output from this block.

3. After comparison between these five pre-set emergency ratings and the real-time post fault loading, the *loading comparison block* sends a time delay signal (red circle).

4. After this time delay, if no further protection has been made on this transformer, the transformer OTS tripping signal will be approved and the pre-selected generation will be tripped. The loading of the monitored transformer will be reduced to acceptable conditions.

It is concluded from the working process that the pre-calculated data in the table determines the behaviour of the OTS. This may result in the transformer OTS lacking awareness of the system operation status and issuing unnecessary tripping commands. Additionally, the existing transformer OTS does not know what generation is on, what the generation output is and the demand levels. There is the possibility that the OTS will send out a tripping signal to a generator that is not generating.

A more intelligent automatic decision could determine if it was necessary to trip the wind farms instantly or wait for a DAR, which could reduce the cost of inter-trip compensation payments and keep renewable energy connected to the system. It is expected that, if the temperature of the SGT and pre-fault loading was monitored, that the SGT short term rating could be assessed more accurately and fed into the OTS. By doing so, the decision from the OTS would be more accurate and cost-effective.
5.5 Design of a Novel Transformer OTS

The design of a novel transformer OTS has been presented in Figure 5-10. Compared to the existing transformer OTS shown in Figure 5-9, a few changes have been made to make the transformer OTS more intelligent.

![Figure 5-10: Working process of novel transformer OTS](image)

There are two main blocks newly designed in the novel scheme shown in green cubical of Figure 5-10. Their functions are explained as follows:

**Transformer Temperature estimation block**

- **Utilizing new inputs.** In the novel transformer OTS, ambient temperature measurements have been introduced into the system. As the ambient temperature has a major influence on transformer cooling, this new measurement will enhance the accuracy of transformer temperature estimation. The ambient temperature is included in the operation of the existing OTS in the form of assumed temperatures for each season when the short-term transformer emergency is calculated. It is not hard to understand that using the average...
ambient temperature for each of the four seasons would hardly satisfy the requirements for an accurate assessment of the pre-fault transformer situation.

- **Enabling real-time transformer temperature estimation.** In the Transformer temperature estimation block, the equations (5-10)-(5-14) are integrated which enables the real-time temperature to be assessed. The pre-fault temperature of the transformer could be assessed with accurate information based on the pre-fault loading. In the previous OTS, the pre-fault loading has been divided into a small number of discrete levels, which significantly reduces the precision of the analysis. After the disturbance occurs, the novel OTS will continuously monitor the temperature rise due to the loading change. The output of the transformer temperature estimation block will be an accurate real-time estimated value of the transformer hot-spot temperature.

- **Generating an alarm signal.** In the transformer temperature estimation block, an alarm signal will be generated to indicate the operator that the transformer is potentially overheated if no further actions are taken. This function is realized by an independent program that designed to quickly estimate the transformer temperature trend and compare it to the temperature limit. If the temperature limit is going to be violated, the alarm signal will be issued and make the operator aware of this potential dangerous situation. The existing transformer OTS does not have this function but simply detects the faults and trips the generation if pre-conditions are met.

**Temperature Comparison block**

- **Utilizing new method identifying transformer overheating.** The temperature comparison block is designed to identify if the transformer is overheating through the real-time hot-spot temperature received from temperature estimation block and its threshold. In the novel transformer OTS, the real-time transformer temperature becomes the judgement which will decide if the transformer is overheating. If the transformer’s temperature increase up to a danger level after system losing assets, the transformer OTS will send out an approval signal which finally approve the tripping command comes from the CB status block.

Besides the two novel blocks from the novel schemes, the signal approval scheme has also been upgraded. New blocks are shown in blue cubical of Figure 5-10.
A new signal approval block.

The tripping decision made by temperature estimation scheme (signal $b$) will be sent into an approval block, where it will be combined with the tripping signal $a$ from the existing transformer OTS.

$$ c = a \land b $$

$$ e = c \land d $$

(5-15)

(5-16)

If the real-time temperature is not violating its temperature limit, $b'$ will be 1 and $b$ keeps equaling to 0. This will block the generator tripping as there is no transformer overheating. If the real-time temperature is violating its limit, a trip block signal $b'$ will be 0 and after a ‘not’ logic, $b$ will be 1. If both $a$ and $b$ are equal to one, $c$ will be 1 which approves the tripping signal $d$ from CB status block. This will finally trip the pre-determined generations.

The reason for introducing this not block and signal $b'$ is to avoid potential failure of new temperature estimation scheme. For example, if signal is lost in temperature estimation block, the signal $b'$ will keep as 0 which will make $b$ equal to one. The signal come from existing transformer OTS will always be approved and make the transformer OTS work. Therefore, the existing transformer OTS can be performed as the backup for the novel part of transformer OTS.

A new generator selection scheme.

In the existing transformer OTS, the generator statuses (such as if they are connected or what amount is the output) are not known. This may result in invalid operation like the OTS decides to trip a generator which is not connected in the system before fault occurs. This problem will not exist in the novel transformer OTS as a generator selection scheme has been introduced. By monitoring circuit breaker status on the terminal of generators will help the OTS to avoid sending tripping signals to those who are offline. The novel transformer OTS will take effect to the connected generations only through OTS scheme. Also, this block would be ready for development of functions that enables intelligent selection of operation of OTS instead of tripping only strategy. Details are given in the next chapter.
With all the improvements mentioned above (novel temperature estimation scheme and approval scheme), the novel transformer OTS will not only protect the transformer from overheating, but also operates more accurately, necessarily and efficiently.

5.6 Test Results for the Novel Transformer OTS

In this section, a few case studies will be carried out on the part of NG model shown in Figure 5-11 that was simulated using DIgSILENT. The model is based on Creyke Beck station which is located on the East coast of England.

There are four super grid transformers (SGT) in the test network. Each of them is rated at 750MVA. Before the test starts, there is one transformer (marked by a red circle) that is assumed to be under maintenance. It will not be available during the whole test. The two SGTs circled in brown will be disconnected due to a fault on CREB2B-CREB2A circuit at 60 minutes after the test starts. This will result in the situation that only one SGT (circled in green) carries power flow from all four transformers. This is the worst case that transformer OTS needs to protect against and the remaining SGT may easily become overloaded.

The parameters that describe the transformer thermal progress are:
\( \Delta \theta_{or} = 45 \text{ K} \) (top-oil temperature rise in steady state at rated load loss);

\( \Delta \theta_{hr} = 35 \text{ K} \) (hot-spot-top-oil gradient at rated current)

\[ \tau_o = 150 \text{ min.} \quad \tau_w = 7 \text{ min.} \quad R = 8 \quad x = 0.8 \]

\[ y = 1.3 \quad k_{11} = 0.5 \quad k_{21} = 1 \quad k_{22} = 2 \]

Maximum allowable temperature limit: \( \theta_{lim,ir} = 110 ^\circ \text{C} \)

The ambient temperatures of the remaining transformer are given in Table 5-1 and Figure 5-12 for 249 minutes in 3 minutes step. This represents a warm summers day.

<table>
<thead>
<tr>
<th>Time</th>
<th>( \theta_a )</th>
<th>Time</th>
<th>( \theta_a )</th>
<th>Time</th>
<th>( \theta_a )</th>
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</table>

**Figure 5-12: Ambient temperature trend**
5.6.1 Case 1: Test of Effectiveness of Novel Transformer OTS - No System Status Change during Fault

In this case, it is assumed that there was no system status change (generator tripping, load shedding, etc.) after the fault occurs until the transformer OTS operated. One transformer is under maintenance since the start of the test and two of the SGTs are lost due to faults on the transmission line at 60 minutes since the test started. The test results are given in the following three figures.

![Transformer load factor trend (case 1)](image1)

Figure 5-13: Transformer load factor trend (case 1)

![Real-time transformer temperature trend (case 1)](image2)

Figure 5-14: Real-time transformer temperature trend (case 1)
Immediately after the fault on the other two transformers occurred, the loading on the monitored transformer increased to approximately 130% of nominal (shown in Figure 5-13). This loading exceeds its nominal rating which breaks the steady state heat balance established before the fault. Both the hot-spot temperature and the top oil temperature start to increase sharply. All the progress of temperature change has been observed and recorded by the novel transformer OTS system.

The first reaction from the novel transformer OTS system is detecting the loss of the two transformers and the issuing of a time signal from the existing transformer OTS, which makes up part of the novel OTS. The existing transformer OTS recorded the pre-fault loading which is 480 MVA (65% of nominal loading) and the post fault loading which is 967.5 (129.6% of the nominal loading). By analysing this data, the existing OTS generated a time signal of 10 minutes from the fault till a tripping by identifying the input in Figure 5-16. The 10 minutes time signal is shown in green in Figure 5-15. However, this time signal is not approved by the novel OTS due to the function performed by the temperature estimation block.
Figure 5-16: Pre-set transformer short-term loading guide by NG (case 1)

Figure 5-14 shows that 36.5 minutes after the fault occurred the hot spot temperature has increased to the pre-defined limit 110 °C (shown in Figure 5-14). If there are no further actions, the transformer temperature will continue to increase and the overheating will start to cause damage to the insulation and affect the contents inside the oil like generating gases. Also, this high temperature will expose the tap changer and cable-end connections higher stresses that encroach upon their design and application margins. This will reduce the operational life of the transformer.

The novel transformer OTS acted, as expected, when the transformer temperature reach the temperature limit. An approval signal, shown in Figure 5-15, was generated and enabled the pre-determined generation tripping. As some of the generation shown in Figure 5-11 was disconnected from the CREB bus, the transformer loading has been reduced to below 100% (around 97% in this case shown in Figure 5-13). It took some time for the transformer temperature to respond to this change of loading, but it is clear that the temperature started to decrease after the generation was disconnected. Though the transformer is still heavily loaded, the temperature is under its limit which means
from the thermal point of view, this transformer is operated safely. The novel transformer OTS has saved the transformer from overheating.

Except for saving the transformer from damage, the other benefit afforded by the novel OTS is delaying the tripping of the generators. The existing transformer OTS will initiate tripping 10 minutes after the fault occurs, while the novel transformer OTS delayed this to 36.5 minutes after the fault, without violating any thermal constraints. This is quite similar to the benefits of the novel transmission line OTS. It will not security of operation but will allow the asset to operate as long as possible.

5.6.2 Case 2: Test of the Effectiveness of Novel Transformer OTS-
System Status Change after the Initial Fault

In this case, it was assumed that there will be a load change on the monitored transformer 7 minutes after the fault on the SGTs has occurred (e.g. unexpected generator loss of its step and tripped). The change of transformer loading will happen before the novel transformer OTS acts and will have an impact on the thermal behaviour of the transformer. Otherwise, the test conditions are the same as Case 1: one transformer is under maintenance from the start of the test and two of the SGTs are lost due to faults on the transmission line at 60 minutes. The test results are given in the following three figures.

![Figure 5-17: Transformer load factor trend (case 2)](image-url)
Figure 5-17 shows the reduction in transformer loading from 1.3 to 1.18 at 67 minutes into the test. This resulted in a reduction of the rate of temperature increase, as shown in Figure 5-18. Figure 5-19 shows that the existing transformer OTS did not respond to the change in the loading and generated its approval at the same time as Case 1, which is 10 minutes after the fault occurred.

The transformer hot spot temperature finally increased up to its limit after 58 minutes, instead of the 36.5 minutes it took in Case 1. The approval tripping signal was generated at this time and generation was disconnected to reduce the temperature of the transformer.

The change of tripping time has proved that the novel transformer OTS has observed recorded and responded to the changes in the system before, during and after the fault. The existing transformer OTS will only respond based on the pre-fault loading and has no ability to react to loading changes after the fault. The delay in the generation
tripping offered by the novel transformer OTS could enable the implementation of more complex and efficient actions.

5.6.3 Summary of Case Studies

Two case studies have been carried out in this group of tests. There are two types of benefits can be summarized from the results:

*Delaying the tripping*

The novel transformer OTS has been shown to be effective in preventing transformers from overheating. With the input of real-time loading and weather data, the accurate real-time transformer temperature has been successfully estimated. This transformer temperature is then used to determine if it has overheated, which allows a more accurate understanding of the threat posed to the transformer than that the table used by the existing transformer OTS. The novel scheme allows the transformer to operate under overloaded conditions for 36.5 minutes for Case 1 and 58 minutes for Case 2, compared to 10 minutes in both cases for the existing transformer OTS. This means the novel transformer OTS has successfully delayed the tripping without violating system constraints. This delay could have a significant impact on the actions available to resolve the overload. For example, the time it makes available to operators may allow them to replace costly and intrusive tripping with an optimal re-dispatch that alleviates the overload within the extra time available. A novel approach for exploiting this additional time is presented in Chapter 6.

*Adapting to the system change during faulty conditions*

Real-time transformer temperature estimation allows the changes before, during and after any fault to be monitored by the novel transformer OTS. This will afford improved understanding and situational awareness, which could enable more flexibility and efficiency when dealing with the overloaded transformer.

For example, if changes in the system cause the overloading to become worse before the OTS operates, the novel OTS will automatically detect it and reduce the delay
between the fault and approval of the generation tripping, as the increase in the overload will cause the temperature to increase faster. Furthermore, if generation re-dispatch has been scheduled to reduce the original overload, the tripping can still be performed if there is not enough time for the re-dispatching to finish due to the increased overload. Conversely, if the overloading is reduced by changes in the system after the fault, the operation time will be extended and the operator may have more options to reduce the overload, instead of costly tripping as stated above.

5.7 Chapter Summary

This chapter has demonstrated a protection scheme that prevents overloaded transformers from overheating by coordinated inter-trips of generation assets within the network. It is a SIPS and the scheme is referred to as the transformer OTS.

The chapter starts with an overview of the transformer thermal protection theory, followed by an extended introduction on transformer thermal behaviour. Detailed thermal process within a transformer is expressed in theoretic description and mathematical expressions. Two exponential equations have been commonly utilized to estimate two typical temperatures inside the transformer: the top-oil and hot-spot temperature. They have been adopted as the main methodology enables the function of real-time transformer temperature estimation within the novel transformer OTS.

The existing transformer OTS scheme commissioned within the GB transmission network is an event based SIPS. It simply protects transformer from overheating by reducing its loading through cutting off pre-selected generations when certain contingency happens. The advantage of this existing scheme is simple and quick. However, its disadvantages are obvious that the pre-calculated data (offline simulation) in the operation table determines the behaviour of the OTS. This results in the existing transformer OTS lacking awareness of the system operation status and issuing unnecessary tripping commands.

A novel transformer OTS which is aiming to address the weakness of the existing OTS is proposed in this chapter. The most significant enhancement of the upgrading is the integration of the real-time temperature estimation block into the tripping decision
system. Moreover, new inputs supported by WAMs or SMT system, new generator selection scheme, and new alarm signals all make the novel transformer OTS more intelligent and effective than the existing one. This is realized by estimating and monitoring of the real-time transformer temperature based on its real-time conditions. Instead of pre-fault loading, the pre-fault temperature can be assessed; instead of post fault loading, the post-fault temperature trend can now be tracked by the novel transformer OTS. The whole heating processes of an overloaded transformer become achievable which will significant improve the accuracy of the operation of OTS.

The above mentioned benefit expected from the design of novel transformer OTS has been demonstrated through case studies. Moreover, there are more merits shown from the test results. One of the benefits afforded by the novel OTS is the delaying in the generator tripping. This delay would allow the operator with more flexibility in fault handling and possibilities of conducting actions which may replace the costly tripping. The other benefit achieved by the novel OTS is the ability of responding to any load change after the fault occurs. If the overloading becomes worse, the novel OTS automatically reduces the delay between detection of thermal threat and operation. The novel OTS possess much better ability to adapt to any levels of pre-fault and post fault loading, any change during contingency conditions and real-time weather conditions than the existing transformer OTS.

The development of the novel transformer OTS has left a same issue as the novel DTLR transmission line OTS which is the chance of better estimation and utilization of the alarm signal. The following chapter is going to focus on the economic optimization of the operation of OTS where the alternative actions rather than tripping will be explored.
6. **Economic Optimisation of the Actions of the Novel Transmission Line OTS**

This chapter provides a detailed description of the design of the novel economic optimisation function that has been proposed to further improve the novel transmission line OTS (N-OTS). This optimisation function is enabled by the assessment of time to temperature violation, finds the cheapest way to reduce overloading of transmission without risking security.

Section 6.1 discusses the definition, objective and requirements to be met in a general optimization problem. Examples of optimisation problems in non-power system and power system applications are given. The motivation for integrating the Economic Optimization (EO) into an OTS is presented in Section 6.2. Section 6.3 presents how the alarm block of the N-OTS (introduced in Section 4.2) is improved to estimate the time to temperature violation. Section 6.4 gives the transmission line OTS related specific economic optimization problem definition, functions and requirements in the actual power system operation. The constraints in solving the optimization function are also presented in details. Case studies are carried out in Section 6.5 which will present the different types of benefits achieved by including EO in the OTS. Finally, Section 6.6 summarizes the contents of this chapter.

### 6.1 Optimization Problems

Optimization theory is commonly used in many subjects and research areas. They can be defined as “*finding an alternative with the most cost effective or highest achievable performance under the given constraints, by maximizing desired factors and minimizing undesired ones*” [21]. To put it simply, it helps the designer to select the best possible solution of a problem from a set of candidate choices.

Optimization problems can be divided into two types according to the nature of the decision variables [21]:

- Continuous [21]
The variables are allowed to take values from a continuous range. A typical solving method would be ‘iterates’ which is algorithm that generate sequences of values of the variables.

- **Discrete**

  The variables are limited to a finite number of values within a range, e.g. binary (0 or 1) or integer. It deals with problems where an optimal solution is chosen from a finite number of possibilities.

For many optimization problems, an ‘iteration’ method may become unacceptable, so it becomes necessary to limit the solution space. A discrete optimization problem is also known as a combinatorial optimization problem. It is concerned with the high efficient distribution of limited resources or limiting the utilization of consumption to meet desired goals. Some typical methods for solving this type of optimization problem are ‘integer programming’ and ‘tree span’ search.

Very often, complex problems will not be solved in a single step and, instead, the solution process will be separated into a series of steps which will be executed one by one. The common procedure in solving an optimization problem is:

1) Recognizing optimization purpose  
2) Defining the optimization problem  
3) Setting up the models  
4) Define the constraints  
   a. Equivalent constraints  
   b. Non-equivalent constraints  
5) Solving the model  
6) Evaluating each of the solutions  
7) Identifying the best or optimal solution  
8) Implementing the selected solution and output  

In steps 1) and 2), the optimization problem for a specific purpose must be defined. The decision variables, the relevant evaluation criteria, and the constraints must be determined. The more decision variables need to be considered, the more complex the optimization problem will be and the more difficult it will be to find the optimal solution. Also, in some cases, there is more than one goal. The proper selection of the goals which may co-ordinate with each other will result in a proper solution;
otherwise, if the goals are conflicted, there will be no solution and the optimal problem will become meaningless.

In the steps 3) and 4), a model that represents the problem essence will be constructed. The decision variables will be turned into decision variables (mathematic expression) and formulated to express the links between them. It is an abstraction from a realistic problem into mathematical expression. The requirements for this new model are:

- It must be ‘solvable’ which means that the model should be able to be solved by existing optimization methods like the branch-bound technique or simplex method [21];
- All the constraints must be reflected within the model as failure to faithfully include a constraint may make the solution unacceptable;
- The model parameters should be reasonable and achievable, as there must be known variables within formulas and equations;
- Result testing system should be included, as data must be verified before identified as ‘optimal’.

Only when all of the above requirements are fulfilled can the mathematical model be believed to accurately reflect the optimization problem.

Step 5) are to solve the model above. It is most like a mathematical procedure. The methods in solving this model include the branch-bound technique or simplex method [22]. Results for each of the decision variables will be passed to the next step.

Step 6) of the optimization procedure is to evaluate and validate the results achieved by solving the model. A sensitivity analysis may be performed here, which learns how the optimal solution varies with changes in the model parameters. In some cases, retrospective tests can help. These tests evaluate the new solutions by comparing the current case and historical cases. This can only be used as a reference, because the historical data may not accurately predict future behaviour.

The last steps 7) and 8) of the optimization procedure are to implement the solution. Only a validated solution or data will pass through this step. There are two typical types of implementation:
• The result will be implemented only once. After implementing the selected ‘optimal’ solution, the optimization procedure terminates. For example, the optimal distance selection for off-shore wind turbines. (Once settled, the assets are unlikely to move again.)

• The result will be implemented repeatedly. Implementing the latest solution may result in a change in the system parameters, values or decision alternatives. Thus, the optimization model needs to be redesigned and modified to determine another round of solutions. For example, the optimal planning for a distribution network (Once a transmission line is set between two areas, this will influence on selection of other connections.)

After finishing all the above steps, an optimized solution for the problem will be generated. This can be considered as the best possible solution for the problem that has been chosen from a set of candidate solutions. Though the optimization problem itself is typically a mathematical problem, the application of optimization theory appears in many fields of industry and research, including power systems. Examples of power system applications are:

• Optimal transmission line routes [90]
  This process is to find the optimal route for a new transmission line. With modern technology, a transmission line will have various ratings for different seasons and weather conditions. The optimized route will fulfil the construction requirements; have the minimum cost and the highest available capacity.

• Optimal power flow [91]
  This process is to find the optimal power dispatch within a power network. It involves the network model, load flow analysis and enormous mathematical analysis. The optimal power flow has the minimum cost of generation and conforms to system operation requirements like nodal voltage, ratings of transmission assets and the operational limits of generators.

### 6.2 Cost Optimization of OTS Operation

The thermal time constants of a transmission line mean that there will be a delay between the increased electrical loading of the line and the resulting increase in the lines temperature, see Section 4.1 for a detailed description of this process.
This means the N-OTS may delay the issuing of a trip signal, without compromising security, and provide improved situational awareness by issuing an alarm (Section 4.2.2) that will warn the operator of any impending thermal violation. However, the alarm signal introduced in Section 4.2.2 only indicated that a violation would occur and not when it would occur.

Accurate knowledge of when the violation will occur (i.e. the delay between the electrical overload and the temperature violation) would allow more intelligent actions to be designed to alleviate the overload, e.g. generator rescheduling, rather than resorting to generator tripping. This rescheduling can be optimized and the action taken may include a combination of tripping and rescheduling.

The N-OTS integrated with economic optimization function is referred as Economic optimized N-OTS (EN-OTS). Figure 6-1 show four typical cases that the EN-OTS must accommodate:

a) No violation will occur, the security of the original OTS should not be undermined for this case
b) The time to violation is sufficient for optimal rescheduling to be calculated and implemented.

c) The time to violation with no actions ($t_{c1}$) is short. So, a small amount of generator tripping at $t_{c0}$ is used to provide sufficient time ($t_{c2}$) for optimal rescheduling.

d) The violation occurs very quickly, pre-defined tripping is implemented and the EN-OTS must not compromise reliability for this scenario.

![Figure 6-1: Typical cases for operating the EN-OTS](image-url)
In general, the length of the delay ($t_{violate}$) before a temperature violation occurs (e.g. $t_b$) determines the complexity of the actions that can be considered.

Extending the alarm signal to provide this time information is an essential enable for this cost optimisation and the delay until the violation will be a key input to the cost optimization problem. This extension of the alarm signal to estimate the delay before the change in loading will cause a temperature violation ($t_{violate}$) is presented in the next section.

6.3 **The Extension of the Alarm Signal**

As mentioned above, the alarm signal with time information will afford system operator many benefits. This information can be extracted from the transient heat balance equation, as is described below.

Transient heat balance equations can be used to describe the delayed variation in conductor temperature in response to a change in the current loading on the transmission line. This delay is due to the existence of the thermal time constants. There will be no step change in a conductor temperature and the heating procedure is undergoing with an all-time changing rate. An example of the delayed response of the conductor temperature to a change in line current is depicted in Figure 6-2. This delay and the mechanisms behind it (the thermal time constants and specific heat capacity of the line) are described in Section 4.1.2.
If the time when the conductor temperature of OHL reaches $T_f$ is named as $t_f$, the time for the conductor heating progress can be defined as $t_h$ which is the time between the event at $t$ and the time that the conductor reached a pre-defined temperature point $t_{lim}$.

If this time $t_h$ can be estimated, which means the system operator will be able to know when the disturbance will cause the line to reach the temperature limit. This information will allow an informed decision to be made about the viable solutions for this overload, e.g. generator re-dispatch, rather than simply tripping generation. The re-dispatch of generation will be a cheaper solution for relieving the overloading but it takes time to ramp the output of generation.

The estimation of the time needed for thermal overheating (referred as temperature violation time) is based on the transient heat balance equations:

$$q_c + q_r + mC_p \frac{dT_c}{dt} = q_s + I^2 R(T_c)$$

$$\frac{dT_c}{dt} = \frac{1}{mC_p} \left[ R(T_c) I^2 + q_s - q_c - q_r \right]$$

where $q_c$ is the heat loss from convection; $q_r$ is the radiated heat loss; $q_s$ is the heating effect of the sun; $R(T_c)$ is the AC resistance of the conductor at temperature $T_c$, $I$ is the conductor current and $mC_p$ is the total heat capacity of the conductor.
The time for the conductor temperature violation to occur is influenced by several factors, including: the initial conductor temperature, the magnitude of the change in the conductor current, the new steady state temperature and the weather conditions. An example for the thermal progress for a conductor with different post-fault current is presented in Figure 6-3. The conductor has same initial temperature which is 40 °C but it has different post fault loadings.

![Figure 6-3: Temperature rise for different post fault loadings](image)

Figure 6-3 shows that the different post fault loading resulted in different post fault temperature rise. If the conductor is 30% overloaded, it takes 448 s to heat the conductor to its temperature limit and the final temperature is 114 °C. If the conductor is 20% overloaded, it takes 801 s to heat the conductor to its temperature limit and the final temperature is 91°C. When the post fault loading is only 5% overloaded, it takes 1370 s to heat the conductor to temperature limit. So, it can be summarized that the larger the post-fault current, the shorter the time for the conductor to become overheating.

There are a few points worth mentioning about the above test:

- The percentage overloading is calculated as the real-time conductor current over its real-time dynamic thermal ratings. Weather conditions have been reflected in the DTLR ratings and it is always likely to be higher than the conductor’s original static rating.

- It is assumed that the weather conditions did not change during the test. In reality, changes in the weather data will also influence the heating progress.
• In practice, there may be an allowance for errors. This is because the system needs to perform in the presence of bad data, communication loss, or element failure. For example, in this case the temperature limit it is set to 78.4 °C, which is 2% below the actual maximum conductor temperature (80 °C).

If the temperature violation time (e.g. 448 s for a 30% overload or 1370 s for the 5% case) can be estimated after the increase in loading, it can be used as part of the alarm signal that is issued by the EN-OTS.

The calculation of DTLR and the estimation of temperature violation time are all performed in the alarm block of the EN-OTS. This enhanced alarm signal will enable the economic optimization of the OTS operation.

6.4 Definition of the Cost Optimization Problem

The estimated temperature violation time offers the system operator a chance to design a more intelligent OTS instead of a simple mode OTS with only tripping as solution. The selection of new types of actions such as generation re-dispatch, must comply with the optimal economic cost with respect to the system requirements including system operating codes, allowed ramping rate, minimum stable generation, commercial factors, settlement arrangements, etc.

Economic optimization will be achieved by minimizing the cost of the re-dispatch \( \Delta P_{r,i} \), tripping \( \Delta P_{t,i} \) and associated penalty costs \( C_{p,i} \) necessary to reduce the line loading by \( P_{tar} \).

\[
\begin{align*}
\min C &= \sum_{i=1}^{n} \Delta P_{r,i} C_{r,i} + \Delta P_{t,i} C_{t,i} + C_{p,i} \alpha_i \\
\text{s.t.} \sum_{i=1}^{n} (\Delta P_{r,i} + \Delta P_{t,i}) \varepsilon_i &\geq P_{tar} \\
\Delta P_{r,i} / \varepsilon_i &\leq \Delta_i, \quad i = 1, \ldots, n \\
P_{tar} &= P_{post} - P_{limit}
\end{align*}
\]

(6-3) (6-4) (6-5) (6-6)
where $P_{tar}$ is the reduction needed in the line loading and, for the $i$th generator, $e_i$ is a weight factor that defines the contribution of a reduction in generation to the reduction in the loading of the line being protected (this is calculated based on the optimal power flow). $P_{tar}$ is calculated from the post-fault loading $P_{post}$ minus the real-time DTLR limit of the transmission line $P_{limit}$. $rr_i$ is the ramp rate and $\alpha_i$ is a binary variable that is 1 if the generator is asked to change its output and is 0 otherwise. $\Delta t$ is the time available for the generation re-dispatch.

Solving the objective function (6-3) through mixed-integer linear programming, subject to following constraints, minimizes the cost of eliminating the risk of a thermal overload. It involves different types of costs depending on how the generator participates in the actions initiated by the enhanced OTS. The selection of constraints is all based on real system operation requirements. The optimizer used within this chapter is considered as global optimization method [92].

The constraint in (6-4) ensures that the total power reduced on the targeted transmission line must be greater than or equal to $P_{tar}$, i.e. the reduction in generation is sufficient to eliminate the risk of a thermal overload. $P_{tar}$ has no relation with the time signal and is only calculated based on the DTLR limits. If this target is met then the transmission line will not become thermally overloaded for the initial weather conditions; note, it is assumed here that these will not change during the course of the generation reduction.

The second constraint in (6-6) ensures that each generator can achieve the targeted reduction in generation in the time available without exceeding its maximum ramp rate, $rr_i$. A typical value of $rr_i$ for a CCGT generator would be between 5-10 MW/min. For some special fast ramping units, the rate can be increased up to 50 MW/min [94] [95].

A constraint is also included to ensure that no generator is asked to both trip and re-dispatch as part of the ‘optimal’ solution, as this is not possible. Finally, constraints are included to ensure that no generator is required to operate above its rated output or below its minimum stable generation (MSG) [101] [102].
Solving the objective function (6-3) subject to these constraints minimizes the cost of eliminating the risk of a thermal overload. It involves different types of costs depending on how the generator participates in the actions initiated by the EN-OTS.

The cost of re-dispatch is different for each generator. Each generator will prepare a ‘bid-offer’ pair for each operating window to show the price they are willing to pay to reduce their contracted generation (bid) or get paid to produce more power than contracted (offer). However, if the re-dispatch is required by the EN-OTS, the transmission network operator will also pay compensation to the generator for reducing their output from the contracted level. The bid-offer price varies in each operating window (settlement period) and is expected to reach the maximum during the peak demand in everyday time. An average value of offer price is around £25-40/MWh and the price for peak hours could be up to £140/MWh. The bid price is slightly lower than the offer price [99].

The cost of tripping contains two parts: the price for the energy reduction, which is currently set to £1.72/MWh, and a one-time penalty cost or compensation to the generator if it is disconnected from the network by the operator. The penalty cost can be far higher than the payment for energy reduction and is on the order of hundreds of thousands of pounds. It is this penalty cost that makes the actions of the original OTS particularly expensive and makes the introduction of optimized ramping attractive [103].

Each of these constraints and input parameters are included to represent one or more system requirements. Some of these requirements are described in the following subsections.

6.4.1 Grid Codes

A grid code is a technical specification, which defines the requirements for a facility to connect to a public electric network. Facilities include power stations, consumers, protective devices, or other networks. The requirements are complex and specific for each kind of facilities. For example, for a generator, the code may define its active and
reactive power limits, behaviors during system disturbances and responses to any contingencies. The actions of OTSs must obey these grid codes.

This grid code enables the system to operate normally, safely and securely. The contents of a grid code vary depending on the network operators’ requirements. Each country may develop various unique grid codes, and for the case of the UK, the National Grid is the code administrator. All changes to the code must include industry consultation and be approved by Ofgem [93].

The NG grid code defines the operating procedures and principles governing the relationship between the National Grid Electricity Transmission plc (NGET) and all the users of the National Electricity Transmission System (NETS) [93]. It specifies the daily procedures from planning to real-time operation and covers normal condition and contingency cases.

There are seven sections which forms the grid code:

- **Planning code**
  *This part of grid code describes the supply of information by users to NGET for commissioning planning and development of NETS.*

- **Connection Conditions**
  *This defines the minimum technical, design and operation scenarios that must be complied to by NGET and the users connected to the NETS.*

- **Compliance Processes**
  *This defines the process that must be followed by NGET and power suppliers to demonstrate their compliance with the Grid Code.*

- **Operating Code**
  *These codes define the requirements imposed on system operation for all aspects, including: demand forecasting, testing and monitoring of users, establishment of system tests, or contingency planning.*

- **Balancing Code**
  *This describes the pre-gate closure and the post gate closure process and the requirements relating to system frequency control.*

- **Data Registration Code**
  *This presents the data required by NGET from users and by users from NGET.*
General Conditions

The connection conditions, operating code and the balancing code parts of the grid code are most relevant to a system to generator operational tripping scheme (OTS). The official definition of an OTS given in the Grid Code [93] is: ‘A Balancing Service involving the initiation by a System to Generator Operational Inter-tripping Scheme of automatic tripping of the User’s circuit breaker(s), or Relevant Transmission Licensee’s circuit breaker(s) where agreed by NGET, the User and the Relevant Transmission Licensee, resulting in the tripping of BM Unit(s) or (where relevant) Generating Unit(s) comprised in a BM Unit to prevent abnormal system conditions occurring, such as over voltage, overload, System instability, etc., after the tripping of other circuit-breakers following power System fault(s).’

6.4.2 Ramp Rates

A ramp rate is defined as the rate at which generating units can increase or decrease their output while they are synchronized to the system. It is normally expressed in megawatts (MW) per minute [94] [95].

Each of the individual generating units has its own design, pre-determined parameters, optimal operation points and various strategies for dealing with abnormal conditions. If the ramp rate of every generator is known, then these generators can be coordinated by the system operator to deliver an appropriate response to a contingency.

There are two types of ramp rates.

- Ramp Up Rate
  It is the rate that a generator can increase its active power output. This rate varies depends on the current power output. There could be up to three ramping rates for a single generator and two threshold points of active power where the ramping rate will change. This design is to enable safe startup of the generator and fulfill its own technical requirements until synchronized and to deliver the different requirements from the grid operator after it is synchronized to the network. Typically, the ramp up rate before synchronization is high, as the generator need to quickly reach a sufficient output to synchronize with the
network. Just after synchronization, there is a relatively small ramp up rate as the generator and network need to get well coordinated to avoid disturbance on system caused by new power injection. After passing this threshold, the ramp up rate will be higher so that the generator can respond to the changes in the load demand over the day.

- **Ramp Down Rate**

  It is the rate that a generator can decrease its active power output. This rate changes according to its current loading. Similar to the ramp up rates, there can also be up to three rates for any single unit. These different rates enable a unit to shut down without violating its technical requirements and execute the commands received from grid operators under a contingency. For most cases, a generator will have a larger ramp down rate when synchronized, followed by a relative low rate for disconnection from the main network.

The ramp rate will be considered in the optimization process of the EN-OTS. Including this factor is used to guarantee the most economical solution for relieving the load constraint is achievable.

The ramp rate for National Grid case is presented in [95].

**Ramp Up**
- Rate 1: Period from no output to the value ready for synchronization
- Rate 2: Period for generator to get synchronized with network
- Rate 3: Period for generator connected to the network

<table>
<thead>
<tr>
<th>Type</th>
<th>Rate 1</th>
<th>Rate 2</th>
<th>Rate 3</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Fired (cold start)</td>
<td>1-5</td>
<td>0.2-5</td>
<td>5-10</td>
<td>MW/min</td>
</tr>
<tr>
<td>Coal Fired (hot start)</td>
<td>5-50</td>
<td>0.2-10</td>
<td>5-10</td>
<td></td>
</tr>
<tr>
<td>CCGT (cold start)</td>
<td>0.3-10</td>
<td>0.2-5.5</td>
<td>2-20</td>
<td></td>
</tr>
<tr>
<td>CCGT (hot start)</td>
<td>2.1-10</td>
<td>0.2-20</td>
<td>5-20</td>
<td></td>
</tr>
</tbody>
</table>

(CCGT: Combined Cycle Gas Turbine
OCGT: Open Cycle Gas Turbine)
These data are summarized from different power units.

*Ramp Down*

- Rate 1: Period from current output to the value ready for separation from the network
- Rate 2: Period for generator to get disconnected from network
- Rate 3: Period for generator to slow down or shut down

<table>
<thead>
<tr>
<th>Type</th>
<th>Rate 1</th>
<th>Rate 2</th>
<th>Rate 3</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Fired</td>
<td>5-10</td>
<td>4-20</td>
<td>10-45</td>
<td>MW/min</td>
</tr>
<tr>
<td>CCGT</td>
<td>9-30</td>
<td>0.7-53</td>
<td>4.5-22</td>
<td></td>
</tr>
<tr>
<td>OCGT</td>
<td>5-40</td>
<td>0-10</td>
<td>0-10</td>
<td></td>
</tr>
</tbody>
</table>

These data are summarized from different power units.

For the security of system integrity protection, there is also a limit for ramp rate change for the whole power station or connection point to the network. This is because excessively fast changes in generation injection may result in significant fluctuations in the frequency.

The setting for National Grid is given as follows:

<table>
<thead>
<tr>
<th>MW Change</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 300 MW</td>
<td>No limit</td>
</tr>
<tr>
<td>300 MW-1000 MW</td>
<td>1-50 MW/min</td>
</tr>
<tr>
<td>Over 1000 MW</td>
<td>1-40 MW/min</td>
</tr>
</tbody>
</table>

These requirements are integrated into the optimization problem.

### 6.4.3 Balancing Price

There are many reasons for an imbalance between the active power generated and consumed by the power system. This includes loss of transmission assets, load...
shedding or connection, actions of protective devices, etc. System operator is responsible to reconfigure the system if there is an imbalance of power within the network.

The transmission system is referred to as being ‘long’ if there is too much power injection, i.e. there is more generation than demand, and ‘short’ if there is not enough power injection, i.e. there is more demand than generation [99].

In Great Britain, National Grid is responsible for balancing the system. They may command increases or decreases in the amount of electricity being supplied to the system at different locations. The costs incurred have been defined as the constraint costs and transferred equally to generators and suppliers as the Balancing Services Use of System (BSUoS) charge [96]. This charge is to recover the following fees [97]:

- The Total Costs of the Balancing Mechanism
- Total Balancing Services Contract costs
- Payments/Receipts from National Grid incentive schemes
- Internal costs of operating the System
- Costs associated with contracting for and developing Balancing

An explanation of each cost can be found in National Grid documents [97]. In 2013-14, the total cost of balancing services amounted to £1,002 million. This converted to the BSUoS is equivalent to between £1 and £3 per MWh [98].

In National Grid, the balancing activity is operated on a half-hourly basis. Therefore, there are 48 half hour operating windows in each single day. Each of the half hour units is called a Settlement Period. The participating suppliers for load and generators will negotiate agreements with each other and inform the transmission network operator National Grid with details of their contract one hour before each settlement period. The contract information may contain their contractual positions and an accurate estimation of their likely actual generation output and demand in the next period. The time line of the system balancing service is given in Figure 6-4.
Other important information is the price they would charge or be prepared to pay for altering their level of generation or demand ('bids and offers') [99]. Here, a bid is a proposal to reduce the generation or increase demand and in contrast, and an offer is the proposal to increase generation or decrease the demand. National Grid can then take any balancing actions necessary by selecting and using these bids and offers or series of other services available [98].

For more details, the bid and offer always appears as a ‘Bid-Offer’ pair. It includes four elements:

- **Offer price**: the price for the generator to be paid per MWh for an increase in output or for the supplier to decrease their load.
- **Bid price**: the price the generator wants to pay per MWh for a decrease in output or for the supplier to increase their load.
- **Active time**: the settlement period for which this ‘bid-offer’ price applies. According to the historic data, the bid/offer price is the highest during the peak load hours.
- **Range of Power Output/Load for which bid-offer pair applies**: A bid-offer is normally set to be available only when the power output is within a specific range. For example, a generator may propose price-1 for the first 30 MW change in output and price-2 for the following 50 MW from its Final Physical Notifications (FPN). (FPN represent the information on expected output provided by generators to the System Operator at gate closure, 1 hour ahead of delivery)
An example of a bid-offer is given in Figure 6-5:

![Figure 6-5: A set of bid and offer pairs][99]

Except for the bid-offer price, there are two reference prices in the real-time electricity market: the system buy price (SBP) and system sell price (SSP). These prices are used as an important indicator for network users to set individual bid-offer pairs. If a Party has under-generated or over-consumed compared to its contracted volume it will have to buy that shortfall of energy at SBP. If a Party has over-generated or under-consumed compared to its contracted volume it will have to sell that extra energy at SSP.

Example of the SBP and SSP are given in Figure 6-6 and Figure 6-7.

![Figure 6-6: Real-time systems buy and sell prices example 1][99]
Figure 6-6 and Figure 6-7 show that the peak value for SSP and SBP appear during the morning peak hours (7 am-10 am) and evening peak hours (6 pm-9 pm). This means the pre-determined contract have more effectiveness during these periods as the penalty in violating the contract would be costly. In another word, the cost for a system operator to conduct balancing service within these times would be more expensive than other hours.

There are two types of balancing actions conducted by National Grid. They vary in terms of the operating scope and the costs they may incur:

- **System imbalance actions** tackle local or regional constraints in the capacity of the transmission network, as well as short-term variations between demand and supply. All actions are employed within a settlement period.

- **Energy imbalance actions** address the general imbalance between the generation and demand at a national level across the settlement period as a whole.

Constraint actions will result in compulsory compensation ('constraint payments') for generators as they may be forced to obey a constraint barrier [98].

The actions commanded by a system operator aiming to relieve the imbalance within the network are called Balancing Services Adjustment Actions. The SO will consider and prepare an individual Balancing Services Adjustment Action for each of the following balancing services:

- **Forward Contracts**
  The contracts will include the energy related products, pre-gate closure balancing transactions and system to system services.

- **Maximum Generation**
  The Maximum Generation Service allows system operator utilize capacity which is outside of the Generator's normal operating range in emergency
circumstances. This emergency utilization fee have been agreed on a bilateral basis and detailed in commercial agreements. Generator will get paid if this service is activated.

- **System to Generator Operational Intertripping**
  This Intertrip will automatically disconnect the pre-selected generators or demand from the network when a predefined event occurs. The requirements for a System to Generator Operational Intertrip have been settled at the time that the Connection Agreement is entered into. The generators will be paid for each required tripping operation on a £/MW and a £/trip basis.

- **Emergency de-energization instructions**
  The generators, loads or other user of the network may be requested to de-energize by the system operator if their connection poses an immediate threat of injury for people or damage to the network. This can be realized by directly disconnecting the user’s equipment or sending request to the distribution network owner to de-energize the connected element.

These actions are performed on different time scales, objectives and at different operation costs. They are also suitable for specific circumstances.

### 6.4.4 Minimum Stable Generation

The minimum stable generation (MSG) is defined as the minimum amount of generation output that a conventional power plant can sustain [94] [101]. In the GB network, according to the grid code it is known as “the minimum output (in whole MW) which a Gen set can generate or DC Converter at a DC Converter Station can import or export to the Total System under stable operating conditions, as registered with NGET under the PC (and amended pursuant to the PC). For the avoidance of doubt, the output may go below this level as a result of operation in accordance with BC3.7” [102].

The MSG is a key item of data that must submitted by the generator to the grid operator before it is connected to the network. The generation assets should not be instructed to operator below its MSG. This means that the re-dispatch scheme designed by the EN-OTS should not cause any generator to violate its MSG.
The typical value of MSG is 65% of the nominal rating in GB network [102]. This value varies for different generator assets under different operating conditions. For example, the MSG is around 260 MW for a ‘hot’ start coal fired unit with 500 MW rating, this is 52% of the rating [94].

6.4.5 Tripping Price

An intertrip will automatically disconnect the pre-selected generators or demand from the network when a predefined event occurs. In April 2005 the capability and intertrip payments were specified at **1.72 £/settlement period** and **400,000 £/trip**. These prices are subject to indexation [103].

*A Capability Payment* shall be paid in respect of each Intertripping Scheme as follows: The Company shall pay to the User an amount (“the Capability Payment”) in consideration of the installation of the System to Generator Operational Intertripping Scheme and the User’s obligations under Paragraphs 4.2A.2.1(a) and (b), being an amount per month determined by reference to the number of Settlement Periods during the month in question (and in respect of which the requirement for System to Generator Operational Intertripping is stated in Appendix F3 of the relevant Bilateral Agreement) and the payment rate (£/Settlement Period) specified in Schedule 4 to this Section 4.

*An intertrip payment* shall be paid in respect of each operation of the OTS as follows: Each generator to system Intertripping Scheme, where the Circuit Breaker(s) are tripped upon receipt of a signal from the System to Generator Operational Intertripping Scheme, The Company shall pay to the User an amount (“the Intertrip Payment”) being an amount (£/Intertrip Contracted Unit/trip) specified.

Based on the historic data of the balancing service cost, the tripping penalty has made up more than 90% of the total cost of the OTS. This is despite the fact that the tripping cost it is only paid when the tripping is performed, unlike the capability cost that is always paid, which is indicative of the extremely high cost of actually tripping
generation. Therefore, there is a demand for an economic optimized solution for the OTS which would possibly avoid tripping and avoid this cost.

### 6.5 Performance of the Economic Optimized N-OTS

In this section, case studies are presented that illustrate the performance of the cost optimization functions for different inputs and parameters.

A part of network of GB transmission network is shown in Figure 6-8. This area is armed with the EN-OTS and the cost optimization functions. It is assumed that the transmission line L8, L11 and L7 are lost which resulted in overloading on L4. There are three generators at stations S3, S4 and S5 that are chosen to take part in the actions of enhanced OTS. So, nine generators participate in the optimization.

![Figure 6-8: National Grid SmartZone Substations](image)

#### 6.5.1 Case 1: Base Case (high penalty cost, no fast ramping)

In this case all parameters values (e.g. the penalty cost) are selected from the normal range and no fast ramping units are involved. The generator parameters are given in Table 6-4.
### Table 6-4: Parameter of generators

<table>
<thead>
<tr>
<th>Sta.</th>
<th>G.</th>
<th>Trip (MW)</th>
<th>Up (MW)</th>
<th>Down (MW)</th>
<th>$rr$ (MW/min)</th>
<th>Price Up (£/MW)</th>
<th>Price Down (£/MW)</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>G1</td>
<td>228</td>
<td>42</td>
<td>87.6</td>
<td>5</td>
<td>25</td>
<td>10</td>
<td>0.307</td>
</tr>
<tr>
<td>S3</td>
<td>G2</td>
<td>228</td>
<td>42</td>
<td>87.6</td>
<td>7</td>
<td>20</td>
<td>15</td>
<td>0.307</td>
</tr>
<tr>
<td>S3</td>
<td>G3</td>
<td>228</td>
<td>42</td>
<td>87.6</td>
<td>10</td>
<td>15</td>
<td>12</td>
<td>0.307</td>
</tr>
<tr>
<td>S4</td>
<td>G4</td>
<td>140</td>
<td>33</td>
<td>50.0</td>
<td>5</td>
<td>25</td>
<td>10</td>
<td>0.320</td>
</tr>
<tr>
<td>S4</td>
<td>G5</td>
<td>140</td>
<td>33</td>
<td>50.0</td>
<td>7</td>
<td>20</td>
<td>15</td>
<td>0.320</td>
</tr>
<tr>
<td>S4</td>
<td>G6</td>
<td>140</td>
<td>33</td>
<td>50.0</td>
<td>10</td>
<td>15</td>
<td>12</td>
<td>0.320</td>
</tr>
<tr>
<td>S5</td>
<td>G7</td>
<td>179</td>
<td>71</td>
<td>49.0</td>
<td>5</td>
<td>25</td>
<td>10</td>
<td>0.217</td>
</tr>
<tr>
<td>S5</td>
<td>G8</td>
<td>179</td>
<td>71</td>
<td>49.0</td>
<td>7</td>
<td>20</td>
<td>15</td>
<td>0.217</td>
</tr>
<tr>
<td>S5</td>
<td>G9</td>
<td>179</td>
<td>71</td>
<td>49.0</td>
<td>10</td>
<td>15</td>
<td>12</td>
<td>0.217</td>
</tr>
<tr>
<td>Price for Trip</td>
<td>1.72</td>
<td>MSG</td>
<td>52% of Rating</td>
<td>Penalty Cost</td>
<td>£400000/trip</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An example of the information contained in this table is: Generator G3 is located in station S3; its pre-fault output is 228 MW, which means its output can reduce by 228 through tripping or 87.6 through re-dispatch (a MSG of 52% rating is assumed); its output can increase by 42 MW as 228 is not its maximum rating; its ramp rate is 10 MW/min; the price to pay it to output more is £15/MWh and produce less for £12/MWh; by decreasing 1 MW output of this generator will reduce 0.307 MW on L4; if it is selected to be tripped, the penalty cost will be £400000 plus £1.72 per MW disconnected.

Three tests are carried out based on these parameters. The differences between these tests are the amount of power to be reduced. The $P_{tar}$ in Table 6-4 was set to 300 MW, 200 MW, and 100 MW, respectively. For the purposes of these tests the estimated time to violation was varied between 0 and 20 minutes and the optimization problem defined in Section 6.4 were solved. The cost of the optimal action for each of these tests is presented in Figure 6-9.
A clear step change in cost has been captured for the cost-time curves of all three $P_{tar}$ values. As the tripping penalty is extremely high, compared to re-dispatch, if there is enough time for generator re-dispatch the optimal solution always replaces tripping with generation re-dispatch. This step change can also be seen from the operation plan generated by the optimization scheme. Two examples of which are given in Table 6-5 for $P_{tar}$=200 MW.

The data in Table 6-5 presents the reason for the price step change. If the temperature violation time is estimated to be 4.1 minutes then the economic optimization process will avoid one generator tripping compared to 4 minutes, as the coordinated ramping of the other generators can achieve the same power reduction as the additional tripping. It is also noticed that all of the un-tripped generators reduce their power output. The same situation happens between 10.7 and 10.8 minutes where there are one more step changes for the green curve ($P_{tar}$=200 MW).

<table>
<thead>
<tr>
<th>$P_{tar}$</th>
<th>200</th>
<th>Time</th>
<th>4 min</th>
<th>Power</th>
<th>200</th>
<th>Time</th>
<th>4.1 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generators Needed for Tripping</td>
<td>Generators Needed for Tripping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G1</td>
<td>-228</td>
<td>G2</td>
<td>-228</td>
<td>G1</td>
<td>-228</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>-228</td>
<td></td>
<td>In MWs</td>
<td>G2</td>
<td>-228</td>
<td></td>
<td>In MWs</td>
</tr>
<tr>
<td>Generators Needed for Re-dispatch</td>
<td>Generators Needed for Re-dispatch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td>G3</td>
<td>-41</td>
<td>G4</td>
<td>-21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>G5</td>
<td>-29</td>
<td>G6</td>
<td>-41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>G7</td>
<td>-21</td>
<td>G8</td>
<td>-29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>G9</td>
<td>-37</td>
<td></td>
<td>In MWs</td>
</tr>
<tr>
<td>Total Cost</td>
<td>£ 1.2m</td>
<td>Total Cost</td>
<td>£ 0.8m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The results presented here can be classified using the definitions given in Figure 6-1 (page 145). For the 200 MW case the period from 0.1 min to 4.1 minutes is type d, where tripping is the only solution. The time between 4.1 minutes and 20 minutes is type e, tripping is necessary but some tripping can be replaced with re-dispatch to deliver the same result at reduced cost. There is no type b for this case as the $P_{tar}$ cannot be met only by generator re-dispatch. The maximum power reduced on L4 by generator re-dispatch is 195.21 MW. Details of the calculation are given in Table 6-6.

### Table 6-6: The generator re-dispatch and its impact on L4

<table>
<thead>
<tr>
<th>Sta.</th>
<th>G.</th>
<th>Down (MW)</th>
<th>$\varepsilon$</th>
<th>Impact on L4</th>
<th>Sta.</th>
<th>G.</th>
<th>Down (MW)</th>
<th>$\varepsilon$</th>
<th>Impact on L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>G1</td>
<td>87.6</td>
<td>0.307</td>
<td>26.893</td>
<td>S3</td>
<td>G2</td>
<td>87.6</td>
<td>0.307</td>
<td>26.892</td>
</tr>
<tr>
<td>S3</td>
<td>G3</td>
<td>87.6</td>
<td>0.307</td>
<td>26.893</td>
<td>S4</td>
<td>G4</td>
<td>50.0</td>
<td>0.320</td>
<td>16.000</td>
</tr>
<tr>
<td>S4</td>
<td>G5</td>
<td>50.0</td>
<td>0.320</td>
<td>16.000</td>
<td>S4</td>
<td>G6</td>
<td>50.0</td>
<td>0.320</td>
<td>16.000</td>
</tr>
<tr>
<td>S5</td>
<td>G7</td>
<td>102.2</td>
<td>0.217</td>
<td>22.177</td>
<td>S5</td>
<td>G8</td>
<td>102.2</td>
<td>0.217</td>
<td>22.177</td>
</tr>
<tr>
<td></td>
<td>G9</td>
<td>102.2</td>
<td>0.217</td>
<td>22.177</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td><strong>195.2118 MW</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MSG</td>
<td></td>
<td></td>
<td></td>
<td>52 %</td>
</tr>
</tbody>
</table>

However, if the $P_{tar}$ is reduced to 100 MW, and the estimated time to violation is longer than 5.6 minutes, no tripping is required and becomes type b, where the violation can be avoided using only generator re-dispatch. Table 6-7 present the crucial time slots that type b becomes available which is the cheapest operation cost.

### Table 6-7: Comparison of Operations of different fault time Case 1 (5.5 mins Vs 5.6 mins)

<table>
<thead>
<tr>
<th>Power</th>
<th>100</th>
<th>Time</th>
<th>5.5 m</th>
<th>Power</th>
<th>100</th>
<th>Time</th>
<th>5.6 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Generators Needed for Tripping</td>
<td>Generators Needed for Tripping</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>-228</td>
<td>In MWs</td>
<td></td>
<td>G1</td>
<td>-28</td>
<td>G2</td>
<td>-39.2</td>
</tr>
<tr>
<td>G3</td>
<td>N/A</td>
<td>G4</td>
<td>-27.5</td>
<td>G3</td>
<td>-56</td>
<td>G4</td>
<td>-28</td>
</tr>
<tr>
<td>G5</td>
<td>0</td>
<td>G6</td>
<td>-40.1</td>
<td>G5</td>
<td>-39.2</td>
<td>G6</td>
<td>-50.0</td>
</tr>
<tr>
<td>G7</td>
<td>0</td>
<td>G8</td>
<td>0</td>
<td>G7</td>
<td>-28</td>
<td>G8</td>
<td>-37.0</td>
</tr>
<tr>
<td>G9</td>
<td>0</td>
<td>In MWs</td>
<td></td>
<td>G9</td>
<td>-49</td>
<td>In MWs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total Cost</td>
<td>£ 401423.9</td>
<td>Total Cost</td>
<td>£ 4431.6</td>
</tr>
</tbody>
</table>
Seen from the Table 6-7, if tripping is avoided, the operation cost of EN-OTS will be reduced significantly.

6.5.2 Case 2: Hypothesis Case (low penalty cost, no fast ramping)

Case 1 showed that the **tripping penalty** is the most significant part of the operation cost of the OTS. For this case, the penalty cost is varied to study its impact on the operating behaviour. Five tests have been conducted using the parameters in Table 6-4, except for the change in penalty cost. The penalty costs in these tests are £500, £1000, £2000, £5000 and £10000, respectively. The cost-time curves are given in Figure 6-10 and Figure 6-11 for $P_{tar}$=200 MW.

It can be seen from all five curves that the total operation cost has been reduced significantly. However, there are some differences in the shape of the curves.

When the tripping has a very low-cost, e.g. £500/trip, the overall cost is lower than the cost of generator re-dispatch; so, in the economic model used here tripping is always the best option. When the tripping price is between £1000-2000/trip, which is close to the cost of generator re-dispatch, the optimization function responded with the cheapest mixed operation plans. For the tripping prices higher than £5000/trip, where the tripping penalty is much higher than the re-dispatch cost, the cost-time curve will have clear step changes, like those seen in Case 1. Furthermore, the step changes in the cost curve occur at the same times as in Case 1, i.e. for penalty costs of £5000 and £10000 per trip only the total cost is changed and not the actual nature of the solution. It is worth noting that the reduction in cost between these steps appears larger in Figure 6-11 than it does in Figure 6-9, this is purely due to the scale of the y-axis of Figure 6-11.
Therefore, it can be summarized from this case that for the scenario considered here, the tripping penalty will only have an impact on the operational decisions of the EN-OTS if it is less than £5000/trip, which is 1.25% of the actual tripping penalty of the existing OTS. However, in practice, it seems highly unlikely that the tripping penalty will ever be this low, which means that the intelligent balancing of tripping and ramping based on the time available is necessary.

6.5.3 Case 3: Alternative Case (high penalty cost, with fast ramping)

Another factor which will influence the behaviour of the cost optimization function is the ramping rate of generators.
In the previous two cases, the generator data in Table 6-4 is used and all generators are assumed to be CCGT or coal fired, which means a tight limit on ramping rate is applied. However, if three different generation assets that have fast ramping rates are assumed to exist at S5, the cost-time curve will be changed as well. The new generator data for S5 is shown Table 6-8.

<table>
<thead>
<tr>
<th>Sta.</th>
<th>G.</th>
<th>Trip (MW)</th>
<th>Up (MW)</th>
<th>Down (MW)</th>
<th>Rr (MW/min)</th>
<th>Price up (£/MW)</th>
<th>Price down (£/MW)</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>S5</td>
<td>G7</td>
<td>280</td>
<td>62</td>
<td>102.2</td>
<td>50</td>
<td>125</td>
<td>110</td>
<td>0.31</td>
</tr>
<tr>
<td>S5</td>
<td>G8</td>
<td>280</td>
<td>62</td>
<td>102.2</td>
<td>50</td>
<td>120</td>
<td>115</td>
<td>0.31</td>
</tr>
<tr>
<td>S5</td>
<td>G9</td>
<td>280</td>
<td>62</td>
<td>102.2</td>
<td>50</td>
<td>115</td>
<td>112</td>
<td>0.31</td>
</tr>
<tr>
<td>Price</td>
<td>1.72</td>
<td>MSG</td>
<td>52 %</td>
<td>Penalty Cost</td>
<td>£ 400000/trip</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Two tests are carried out in this case. The targeted amount of power reduction is kept as 200 MW. The first case will use the data in Table 6-4 only and the second test will use the data from Table 6-8. The cost curves are presented in Figure 6-12.

![Figure 6-12: Cost-time curve for alternative case 3](image)

It can be seen in Figure 6-12 that there is the same number of step changes in the cost for both tests but the changes occur at different times. The fast ramping units allow the tripping to be replaced sooner by the generator re-dispatch, which will allow the cost of the EN-OTS operation to be significantly reduced for the more severe examples of type c. Furthermore, it should be noted that the fast ramping units reduce the number of cases that are of type d. A comparison of the EN-OTS actions for the time at which the first step change in each curve occurs is given in Table 6-9.
Table 6-9: Comparison of Operations of different step change time

<table>
<thead>
<tr>
<th>Power</th>
<th>200</th>
<th>Time</th>
<th>1.5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generators Needed for Tripping</td>
<td>Generators Needed for Tripping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G1</td>
<td>-228</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>-228</td>
<td>In MWs</td>
<td>-228</td>
</tr>
</tbody>
</table>

G Re-dispatch With fast Ramp units | G Re-dispatch without fast ramp units

<table>
<thead>
<tr>
<th>Power</th>
<th>200</th>
<th>Time</th>
<th>4.1 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generators Needed for Tripping</td>
<td>Generators Needed for Tripping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G1</td>
<td>-228</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>-228</td>
<td>In MWs</td>
<td></td>
</tr>
</tbody>
</table>

Whilst the operation of fast ramping units is more expensive than the normal CCGT, the significant cost of tripping means that they still offer a significant benefit to the cost effectiveness of the OTS actions. This suggests that when selecting generators to participate in an EN-OTS, fast ramping units should be favoured, despite their apparently larger cost.

6.5.4 Case 4: Alternative Case (High MSG vs Low MSG)

As discussed in Section 6.4, the MSG will influence the behaviour of the cost optimization function by limiting its operating flexibility. Modern operating strategies enable the possibility of lower MSG [101], which provides opportunities for reducing operation costs.

In this case, two tests will be carried out based on different generator parameters. The $P_{tar}$ is kept as 200 MW for both cases. Test 1 will use the generator data in Table 6-4 (where the MSG was 52 % for all units) and Test 2 will use the data from Table 6-10. The MSG is different between these two groups of data but all other parameters are same.

Table 6-10: Parameter of generators Case 4 Test 2

<table>
<thead>
<tr>
<th>Sta.</th>
<th>G.</th>
<th>Trip (MW)</th>
<th>MSG (%)</th>
<th>Up (MW)</th>
<th>Down (MW)</th>
<th>$rr$ (MW/min)</th>
<th>Price Up (£/MW)</th>
<th>Price Down (£/MW)</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>G1</td>
<td>228</td>
<td>48%</td>
<td>42</td>
<td>98.4</td>
<td>5</td>
<td>25</td>
<td>10</td>
<td>0.307</td>
</tr>
<tr>
<td>S3</td>
<td>G2</td>
<td>228</td>
<td>48%</td>
<td>42</td>
<td>98.4</td>
<td>7</td>
<td>20</td>
<td>15</td>
<td>0.307</td>
</tr>
<tr>
<td>S3</td>
<td>G3</td>
<td>228</td>
<td>48%</td>
<td>42</td>
<td>98.4</td>
<td>10</td>
<td>15</td>
<td>12</td>
<td>0.307</td>
</tr>
</tbody>
</table>
The cost curves for both tests are presented in Figure 6-13. Step changes in cost are recorded as expected. It can be seen that for the first 7.8 minutes, the operation cost for generators with high MSG and low MSG are exactly same. From two crucial times, which are 7.9 minutes and 15.4 minutes into the test, the cost curves begin to diverge. The details of operation at these two times are expanded as follows.

<table>
<thead>
<tr>
<th>Generators Needed for Tripping</th>
<th>Power</th>
<th>Time</th>
<th>7.9 min</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>-228</td>
<td>79</td>
<td>-39.5</td>
<td>£ 824660.2</td>
</tr>
<tr>
<td>G2</td>
<td>-228</td>
<td>40</td>
<td>-50.0</td>
<td>£ 406289.7</td>
</tr>
<tr>
<td>G3</td>
<td>-79</td>
<td>0</td>
<td>-39.5</td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>-55.3</td>
<td>55.7</td>
<td>-52.1</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6-13: Cost-time curve for alternative case 4**
The operation actions for a 7.9 minute temperature violation time for both tests are given in Table 6-11. For the test with high MSG generator sets, two generators are tripped and seven generators are re-dispatched while there is only one generator tripped for the test with low MSG generators. The operation cost for low MSG is halved compared to the cost of high MSG assets conditions.

The reason for this difference of operation strategy to occur is the MSG constrains the solution until the time to violation increases enough to allow other units to ramp down, see where the curves become equal to one another again. For example, G6 for Test 1 is limited to a 50 MW change due to its MSG requirement and the same generator can reduce 74.3 MW if lower MSG is applied. The larger change in generator re-dispatch provides the higher possibility of replacing generator tripping and achieving the power reduction required without tripping. A similar explanation can be used for the divergence in cost at 15.4 minutes. The detailed operation strategies are presented in the Table 6-12.

<table>
<thead>
<tr>
<th>Power</th>
<th>200</th>
<th>Time</th>
<th>15.4 min</th>
<th>Power</th>
<th>200</th>
<th>Time</th>
<th>15.4 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tripping</td>
<td></td>
<td></td>
<td></td>
<td>Tripping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>-228</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Re-dispatch</td>
<td></td>
<td></td>
<td></td>
<td>High MSG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G1</td>
<td>-77.0</td>
<td>G2</td>
<td>N/A</td>
<td>G1</td>
<td>-77.0</td>
<td>G2</td>
<td>-98.4</td>
</tr>
<tr>
<td>G3</td>
<td>-87.6</td>
<td>G4</td>
<td>-50.0</td>
<td>G3</td>
<td>-98.4</td>
<td>G4</td>
<td>-74.3</td>
</tr>
<tr>
<td>G5</td>
<td>-50.0</td>
<td>G6</td>
<td>-50.0</td>
<td>G5</td>
<td>-74.3</td>
<td>G6</td>
<td>-74.3</td>
</tr>
<tr>
<td>G7</td>
<td>-49.0</td>
<td>G8</td>
<td>-47.7</td>
<td>G7</td>
<td>-69.0</td>
<td>G8</td>
<td>-68.5</td>
</tr>
<tr>
<td>G9</td>
<td>-49.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>£ 405858.2</td>
<td>Total Cost</td>
<td>£ 8720.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-12 shows that if the fault violation time is 15.4 minutes, there will be no tripping needed for the test with lower MSG. Six of the nine generators reach their MSG for this time, but the total power re-dispatched from all generators has successfully reduced the 200 MW on the targeted transmission line. The operation cost reduced to 2.14% of the cost for high MSG. The reason for this significant reduction is that the lower MSG settings afforded the system operator more flexibility in power re-dispatch which enables the tripping to be avoided entirely.
6.5.5 Summary of Case Studies

Case 1 shows that the tripping penalty is the largest part of the cost of operation for the OTS. Therefore, there is a strong motivation to reduce the number of tripping commands from the E-OTS and N-OTS.

The results in Case 2 explored the impact of the *tripping penalty* on the operation of the EN-OTS. However, it has been shown that only if the tripping penalty is reduced to 1.25% of its real value, which seems unlikely, will the penalty influence the selection of the operation strategy.

The results in Case 3 explored the impact of *fast ramping* on the operation of the EN-OTS. If more fast ramping units are involved in the OTS operation, there is higher possibility of reducing the operation cost for a short temperature violation period. The fast ramping units will replace the tripping more quickly by allowing more power to be re-dispatched.

The results in Case 4 explored the impact of *Minimum Stable Generation* on the operation of the EN-OTS. If a lower MSG is applied, the flexibility of the generator re-dispatching will increase and this results in more opportunities for replacing generator tripping with generator re-dispatching.

Overall, the temperature violation time information which enables multi-type operation of EN-OTS, allow enormous cost reduction from tripping only solution. For example, in Case 1, if the target power is 100 MW, tripping only action will cost £ 0.8 m. However, if the temperature violation time is estimated to be longer than 5.6 minutes, the operation cost can be reduced to £ 4431. The EN-OTS save 99.994% operation cost from tripping only solution. Also, the more flexibility of the generator involved in EN-OTS, the better performance EN-OTS will have in cost reduction. In modern power system, the increasingly use of new generation technique e.g. PV and load participation, can all contribute to the flexibility of EN-OTS operation.

6.6 Further Benefits from EN-OTS
The improvement in the OTS offered by the Economic Optimized (EO) technique will not only be seen in the reduced operation cost but also by avoiding tripping it will reduce the risk of unforeseen consequences of the OTS action. This is because the simple trip of a generator is a contingency in itself that may in certain circumstances result in undesirable consequences, e.g. frequency fluctuations or adjacent generators going out of step, particularly when the system is already operating in a stressed condition.

To explore the impact of OTS operation on the frequency and rotor angle of adjacent generators, two tests have been conducted. The first test assumed that the three generators mentioned in Table 6-4, G1, G2 and G3 in station S3 were disconnected at 5 s, 5.5 s, and 6 s. The electrical frequencies on the adjacent generators are recorded in Figure 6-14 and relative rotor angles are presented in Figure 6-15. S3_1, S3_2, S3_3 are the other generators in the S3 station that are not involved in the OTS operation. G4 and G7 are selected from stations S4 and S5. These generators are selected because the action of the OTS will not only influence the local stations but also have a global impact on generators across the system.

Figure 6-14: Frequency change for generator tripping
Figure 6-14 shows that the frequency of all five monitored generators went down immediately from 49.997 Hz to 49.942 Hz which is over 0.1 % of nominal frequency. Though the frequency recovered from the initial fast drop to a new stable level which is 49.948 Hz, the operating point of the whole network has been changed. The relative rotor angles of generators are shown in Figure 6-15. The rotor angle of G1 dropped to zero soon after it is tripped from the network and the angle of rest generators started to fluctuate. The range and scale of the angle oscillations vary between the generators. The rotor angle of generator S33 is only slightly oscillated due to the effect of its controller and the generator G7 has experienced severe oscillation. It can be concluded that, the tripping of generators will immediately reduce the power flow on the targeted transmission lines; however this fast action of generators may result in potential cascade tripping due to unforeseen interactions during stressed conditions or by exposing hidden failures. This means, that generator tripping should be avoided if alternative actions could satisfy the same operational requirement.

In contrast to Test 1, there will be no generator tripping in test 2. Instead, the generators G1, G2 and G3 will be re-dispatched gradually by ramping. Due to the limit of ramp rate, there will be four simulated power re-dispatch in generators. These occur at 5 s, 6 s, 7 s and 8 s since the test start respectively. The electrical frequencies on the adjacent generators are recorded in Figure 6-16 and relative rotor angles are presented in Figure 6-17.
Given in Figure 6-16, the frequency change of adjacent generators during or after the generators dispatching procedure is much smaller compared to the previous test involving tripping from the same sets of generators. The average frequency dropped from 49.997 Hz to 49.987 Hz which means the maximum drop is only 0.02% of its normal value. The rate of rotor angle change is similar to the frequency. As there is reduction in output of G1, the rotor angle of G1 decreased by moves quickly to a new stable state after the operation. For the other generators, there occurs slight oscillation during the dispatching progress but both the amplitude and length of time are much less than the fluctuation caused by the direct generator tripping.

By comparing the results achieved from these two tests, it can be concluded that the tripping of generator operation commanded by the OTS may pose new threats to the secure operation of adjacent generation assets and if the tripping can be replaced by multiple generator dispatching, the risk of collapse of rest of generators will reduce significantly.


6.7 Chapter Summary

This chapter has presented the creation of a novel economic optimization methodology for further improving the operation of the novel OTS. It is referred to as the EN-OTS. The new scheme is providing the OTS with the ability to tailor its actions to the operating conditions and relieve the overload at minimum cost. It is realized by replacing costly tripping actions with cheaper generation dispatch program without violating the security constraints of network. The EO scheme structure and its practical application parameters, the difference of system performance under the N-OTS and the N-OTS with EO, have all been explored.

The chapter starts with introduction of the theory of the optimization problem, followed by an exploration of its application in designing optimal operation for OTS. Due to the longer time constant of thermal progress, the time delay between the overload occurring and the transmission line exceeding its maximum temperature could be used for generator dispatch. If the generator dispatch could be finished before the temperature violation time, the transmission line will not become overheated as its loading has been reduced. Four types of operations have been defined here: no OTS needed (type a in Figure 6-1); generator dispatching only (type b); mixed operation of generator dispatching and tripping (type c); generator tripping only (type d). In reality, only a few urgent cases will require generator tripping immediately after the disturbance, and the rest of the cases can be an optimized mixture of tripping and rescheduling.

Given the possibility of optimizing the OTS operation, the novel transmission line OTS will be equipped with a new EO function where the cost optimization function will be performed. The input of this cost optimization includes: the estimated temperature violation time which is also the available time for generator re-dispatch, which is estimated through an extension of the alarm scheme in the novel transmission line OTS; the target power reduction, this is calculated based on DTLR theory; generator limits, such as ramp rates, minimum stable generation; other limits and concerns, like grid operation codes or electricity market rules. The output of the optimization function will be a schedule of generation output changes that prevent the transmission line from overheating at the minimum cost.
Case studies are presented that examine the benefits of the EO for the operation of the novel transmission line OTS. It has been concluded from the results that, the penalty cost of generator tripping has formed the largest part of the operation cost of OTS and the OTS with EO would significantly reduce this cost by replacing generator tripping with generator re-dispatch within the limited time available. The more flexibility of the generator has in EN-OTS, such as faster ramping units and lower MSG settings, the better performance EN-OTS will have in cost reduction. Besides the cost reduction, the new combined operation strategy in which tripping will be replaced by ramping will have far less impact on the operation of the system. Therefore, the actions of the OTS with EO function will reduce the likelihood of the OTS action causing the disturbed conditions to further propagate through the system.

In summary, this chapter presents the novel use of economic optimisation as part of the operation of a OTS, which will enhance its performance by reducing the impact on the rest of network and significantly reducing the cost of preventing thermal overloads.
7. Thesis Summary

This chapter summarises the ambition of this research (Section 7.1). It is followed by conclusions on the success of this research, comparative to its defined goals, (Section 7.2). The contributions and achievements reached are discussed in Section 7.3. Finally, possible opportunities for the further development of this research are proposed in Section 7.4.

7.1 Introduction

The research presented in this thesis dealt with the creation of novel SIPS that ensure thermal security of devices within a power system with reduced impact on the operation and economic performance in the power system. Conventional algorithms used for thermal protection of transmission lines and transformers are simple and fast. However, they lack accuracy and are inefficient. This is because the decisions made by conventional algorithms are based primarily on circuit breakers status, simple Boolean algebra and pre-determined settings from the planning stage (event based logic), rather than the actual thermal status of the transmission assets (real-time measurements based logic). Furthermore, the lack of accuracy of these existing schemes means that the protective actions they command are invasive and might lead to sequential disturbances. Therefore, the main objective of this research was to develop SIPS that should enable real-time assessment of the thermal behaviour of the monitored elements with support from synchronized measurements. This will give them the ability to classify the severity of different contingencies and respond with adaptive protective actions. The novel schemes are expected to enhance the situational awareness of the system operator during stressed conditions and allow actions that are less invasive and more cost effective.

The background of this research is the rapid evolution of modern power networks. The growing volume of renewable and intermittent generation that is being connected to power systems, the increasing demand for electricity, and the urgent need for CO₂ reduction have all created new challenges in modern power systems. These challenges include more load congestion, which forces the network to operate closer to capacity limits than ever before; more faults on the network, due to its increased complexity;
and the increasing importance of economic requirements in operation. These new challenges have made power systems increasingly vulnerable to cascading failures and blackouts. There is a high demand for contingency plans that can be optimally adapted to combat this increasing uncertainty and minimize the cost of operation, without compromising system security. The SIPS is selected to be a strong candidate to fulfil these requirements. They are well established in power systems and have become a valuable tool for improving system security. Unlike conventional protection devices, which were designed to protect individual elements from being damaged during faults, SIPS are designed to maintain the integrity of the entire power system or a portion of the power system under faulty conditions. One example of SIPS is the OTS that is employed in the GB transmission network to protect the system from abnormal conditions like thermal overheating after disturbances by tripping pre-selected generation assets.

The key enablers of this research are the advent and rapid development of WAMPAC and SMT. SMT, represented by PMUs, provide unprecedented real-time access to the measurements of current and active power on system elements that will enable the real-time assessment of their temperature, which is essential to the novel thermal OTSs proposed in this thesis. Using this real-time temperature assessment to delay the operation of tripping is an essential aspect of the new schemes. However, this may keep the system element under faulty condition for a longer time; therefore, highly accurate and reliable assessment of the real-time system status is necessary. Moreover, the synchronized nature of PMU measurements means that they have precise time tags assigned to the measurements taken from across a wide area. These time tags would help ensure confidence when delaying protection actions based on estimates of the time available before a thermal overload will occur. This is because precise time tags reduce the uncertainty in the time available, as it would be known relative to the exact, common reference used by the PMUs. Therefore, no assumptions would have to be made about the relative time difference between individual measurements, as would be the case with unsynchronized measurements.

The motivation of this research is to make the most of the time available due to the relative length of thermal time constants, by employing low-impact, low-cost actions as part of thermal protection schemes. The delay between the step increase in the loading of an asset and the resulting increase in its temperature after a disturbance
provides the opportunity to make more intelligent decisions about how to alleviate the threat posed to system operation by thermal overloads, rather than simple fixed generator tripping. More intelligent operation strategies, such as generator re-dispatching, is expected to offer enormous reductions in operational cost compared to only using expensive generator tripping.

An additional advantage of this research was the application to the full network model of the GB transmission network with all dynamic controllers built-in. Most simulation tests for the novel OTSs have been conducted using this realistic network, which provides a direct view into their effectiveness and the benefits they afford the operation of power system.

7.2 Thesis Conclusions

In summary of the whole thesis, novel OTSs that provide intelligent protection against thermal overheating are designed, demonstrated and verified. These OTSs use unprecedented data of synchronized system measurements provided by SMT and convert them into essential information deciding operation command of OTS through new functions developed within the OTSs. This smart protection uses the real-time temperature assessment to accurately determine if an asset will be thermally overloaded, to provide the system operator with improved awareness and create the opportunity to design adaptive cost-effective solutions to any thermal overloads.

7.2.1 Review of the Design of SIPS

The first goal of this research was to investigate the past experience with the design and application of SIPS. SIPS have become increasingly prevalent in recent years and this investigation was conducted through four separate aspects:

- Classification of SIPS
  
  *From scope of the area protected:* local (distribution network), local (transmission network), sub system and entire system wide
  *From decision making process:* event-based, parameter based, response based, and any combination of these three types
• Typical architecture of SIPS
  Four typical types: flat architecture, hierarchical architecture, centralized architecture and distributed architecture

• Design process of SIPS
  Eight steps: system study; hardware description and outage detection; scheme architecture; data acquisition, communication, networking and related tools; core logic function; operating methodology; cost considerations; testing procedure.

• Application of SIPS
  Examples including: generator rejection/re-dispatching; load rejection; underfrequency/undervoltage load shedding; adaptive load mitigation; voltage/ angular instability advance warning scheme;

Unlike conventional protection devices, which were designed to protect individual asset from being damaged during faults, SIPS are designed to maintain the integrity of the entire power system or a portion of the power system under faulty conditions. This approach enables SIPS to perform efficient and secure protection operations under specific conditions.

SIPS are realized by simultaneously monitoring and controlling multiple elements of the system. Searching for technologies that fulfil this requirement is the second task of the research. WAM and SMT are good options for supporting SIPS. They are believed to be the key enabler for the design of modern SIPS. The review of SMT and WAMPAC is given in Section 2.4 of Chapter 2. It revealed that these new technologies offer unprecedented real-time access to system measurements and provide highly accurate, reliable, synchronized data with high resolution. This data enables more accurate and comprehensive system state estimation. Complete observability of the system as well as fast and stable access to these measurements was assumed during the development of the novel SIPS presented here on the premise that the necessary communication channels and data processors will be available in the near future.

An OTS is an example of a SIPS that is already employed by National Grid to protect the system from abnormal conditions after a disturbance by disconnecting pre-selected generation assets. There are two types thermal OTSs installed in the GB network. One protects transmission lines from overheating and the other protects transformers from
overheating. Both existing OTSs will issue a trip signal to disconnect pre-determined generators if certain combinations of circuit breaker status occur.

7.2.2 Benefits of Transmission Line OTS

The performance of the existing OTS (E-OTS) for transmission lines was first investigated (Chapter 3). The functional structure of this scheme reveals that it is an event-based SIPS. The only effective input of the scheme is the status of circuit breakers. If the breakers of certain combinations of pre-selected transmission are open then this scheme will be activated and pre-determined generators will be tripped. This action is based on calculations performed at the planning stage that indicate that the loss of certain combinations of transmission lines will result in the thermal overloading of lines in the rest of the network. Several case studies are carried out on the test network and with the existing OTS scheme armed. It can be summarized from the results that this scheme has advantages, including: simple processing, fast response, and low possibility of failure. However, its weakness is obvious as well. Unnecessary tripping could be issued and this will results in huge expense to the customer.

Here, unnecessary tripping is deemed to have occurred when the loss of certain combinations of transmission lines occurs and the OTS initializes tripping, correctly according to its logic, when there is no transmission line that is actually violating its thermal loading limit based on real-time system measurements. This situation may happen when the system is lightly loaded during night time or weekends. As the existing OTS lacks effective inputs for analysing the true state of the power system, its actions are all decided during the planning stage. This scheme is unintelligent and hardly satisfies the expectations (e.g. low cost in operation, low impact in network, or adaptive to each contingency) in modern protection scheme.

Dynamic thermal line rating technology is chosen to be integrated into the existing OTS. Its nature, theoretical background and the equations for temperature estimation have been described in Chapter 4. With the real-time system measurements, available from SMT; the parameters when the transmission line is manufactured and constructed; and the real-time weather conditions from Met Office, the conductor temperature of the monitored transmission line can be assessed. There is no better
parameter to reflect the thermal status of the conductor than its real-time temperature. Therefore, the conductor temperature of transmission line has been adopted as the decisive factor in the decision making process of the novel transmission line OTS.

The novel transmission line OTS will trip generators only when the existing transmission line OTS has issued a trip signal based on the breaker status of the monitored transmission lines and one of the monitored lines will violate their temperature limit if no further protective actions are taken. In contrast to the existing transmission line OTS, which was a purely event based scheme, the novel transmission line OTS uses a combination of event and response-based decision making. There are many benefits expected from this novel scheme shown as follows.

- **Prevent unnecessary tripping.** As the real-time conductor temperature could be assessed, the thermal status of the transmission line could be well understood. Though the loss of a group of transmission lines (like N-3 contingency) may result in a dramatic load increase on certain circuit, there is the possibility that this increased loading will exceed its static rating but not its dynamic rating. This means that the conductor will never be heated to above its temperature limit. For this circumstance, the novel transmission line OTS will block the tripping issued by the existing OTS and prevent this unnecessary action, as the conductor is believed to be secure from the thermal point of view.

- **Extend the operating margin under system faulty conditions.** The loss of multiple assets would result in a dramatic load increase on certain circuits and this increased load may violate their dynamic thermal rating. For this circumstance, the novel transmission line OTS is required to react due to the risk of thermal overload. However, because of the relative length of thermal time constants, the conductor temperature would not suffer a step increase in temperature after the step increase in loading. Instead, the heating process will be delayed. This delay is decided by the severity of the overload, the thermal properties of the line and the weather and may vary from a couple of seconds to minutes. The existing OTS could not identify this time period and a fixed time delay of 0.1 s after the fault occurs is used. The novel transmission line OTS is able to delay the actions relative to the true nature of each contingency and would significantly extend the operation margin under system faulty conditions. If proper actions like generator/load rescheduling, which also
reduce the power flow on the monitored transmission line, are performed during this delay then the tripping of generators might be avoided.

- **Application of Alarm scheme.** The novel transmission line OTS affords the system operator an alarm signal that would improve their situational awareness under stressed conditions. This alarm signal will be issued when the novel transmission line OTS determines that the temperature limit of the conductor will be violated. The conductor is still safe in operation under alarm status but actions are required to relieve the dangerous condition. If the alarm signal is not issued, the conductor is believed to be thermally secure even though it might be heavy loaded or have exceeded its static limit after the disturbances within the network.

Case studies of the performance of the novel transmission line OTS have been carried out for the GB network model. Test results are presented in Chapter 4 that demonstrate the above benefits.

### 7.2.3 Benefits of Transformer OTS

After the development of the novel transmission line OTS for protecting transmission lines, a second type of OTS was developed for protecting transformers. This OTS is presented in Chapter 5.

The algorithm for the existing transformer OTS has some similarities with that of the existing transmission line OTS. They are both event based SIPS and triggered by the status of selected circuit breakers. The outputs of the OTSs are all tripping signals. However, the tripping signals for the transformer OTS include an extended time delay. The tripping is not executed immediately after the actions of the circuit breakers because the transformer is designed to have several short-term emergency ratings. Different overloading conditions can be endured for different periods of time. The existing way to decide these times is based on operational rules that have been pre-defined during the planning stage. An example of an operating chart is given in Figure 5-8 of page 125.
It is obvious that using the pre-calculated data in such a chart as the only determining factor for the existing transformer OTS is not an accurate basis for OTS operation. The existing transformer OTS lacks awareness of the system operation status and may issue unnecessary tripping commands.

The design of a novel transformer OTS starts with the enhancement of the inputs of the OTS scheme. To supplement the circuit breakers statuses, pre and post fault loading, the ambient temperature and continuous monitoring of the transformer loading is introduced. This new data is provided by SMT. With high quality synchronized measurements of transformer loading and weather conditions, as well as the thermal constants of the transformer, the real-time transformer temperature can be assessed. The top-oil and hot-spot temperature within the transformer would be used as the key trigger for the OTS operation. No matter what the loading is, if the temperature limit is not violated then the transformer is believed to be thermally secure and OTS actions will not be activated.

The benefits of integrating real-time transformer temperature assessment are as follows:

- *Delaying the tripping.* The novel transformer OTS will not only be effective in preventing transformers from overheating but will also extend the operating margin during system faulty conditions. With the real-time temperature data available, the novel transformer OTS will be activated only if the transformer is just about to suffer from overheating (temperature reached the limit but not over). The existing transformer OTS has only five modes of operation, which provides five time durations for keeping transformer stressful heavily loaded. They have been pre-calculated based on the worst case scenario, which makes sure it is effective under all cases but also ensure it will be overly conservative in almost all cases. In the novel transformer OTS, there is no specific number of operating modes, which means the OTS responds with actions specifically designed for each individual contingency.

- *Adapting to the true system state during stressed conditions.* With the technique of real-time transformer temperature estimation, all the transformer status changes before, during and after the disturbance are now continuously monitored. This improvement may afford them more flexibility and targeted actions to deal with faults. In the existing transformer OTS, the scheme only
records the pre-and post-fault loadings and then responds with a pre-set time signal for operation. If there is any change in the transformer loading after this, like generator rescheduling that reduces the loading of the transformer, the existing scheme would not recognize this change and could incorrectly initiate tripping according to the worst case loading after the disturbance. The novel transformer OTS would capture this change and keep monitoring the trend of the temperature within the transformer. If the overloading becomes worse, the novel transformer OTS will activate tripping earlier than the initially expected tripping time decided by the system condition just after the disturbance and vice versa.

♦ *Introduction of an Alarm scheme.* The novel transformer OTS affords the system operator an alarm signal that improves their situational awareness during stressed system conditions. This alarm signal is achieved by a prediction of the trend of temperature change within the transformer according to current loading and weather conditions. An alarm will be issued when this calculation determines that a temperature limit violation within the transformer will occur eventually. The transformer will remain in operation under alarm status but actions are required to relieve the overload. If the alarm signal is not issued, the transformer is believed to be thermally secure even though it might be heavily loaded or have exceeded its static limit after a disturbance within the network.

These benefits of the novel transformer OTS have been verified using simulations of the full GB network model in DIgSILENT Power Factory. It is the same network used when testing the novel transmission line OTS.

### 7.2.4 Benefits of Economic Optimization of OTS

Optimization theory has been widely used in many subjects and research areas. It is generally utilized as the way to find out solutions which are the best or optimal for a problem with respect to a specific goal and many types of constraints. There existing many applications of optimization theory in power systems, such as ‘optimal transmission line routing’ and ‘optimal power flow’. In this thesis, it is adopted as a tool to minimize the operation cost of OTS by optimizing its operation strategy.
Transmission line OTS is selected to demonstrate the benefits afforded by this new function.

The novel OTSs would significantly improve the situational awareness of the system operator during stressed conditions. The alarm signal and estimate of the time to temperature violation allows adaptive actions to be implemented that relieve the thermal overload with minimal generation tripping. However, tripping generators is the only mode of operation for the existing OTS. Due to the lack of reliable synchronized measurement data, the real-time system status and true states of power system could not be well assessed in the past. This forces the operation of the OTS to be simple but also guaranteed to be effective. Therefore, generator tripping is a strong candidate for relieving overloading across the network if operation cost is not a limiting factor. In the modern design of protection schemes, ensuring cost-effective operation has become an increasingly important requirement. Therefore, there is a demand for employing protective actions that could substitute the costly generator tripping.

The thermal time constants of a transmission line mean that there will be a delay between the increased electrical loading of the line and the resulting increase in the lines temperature. This enables opportunities for employing slower protective actions to replace fast generator tripping. For example, in this research, the additional time made available by the enhanced intelligence of the OTS was exploited to allow generation re-dispatch to replace generator tripping and reduce the operation cost of the OTS.

Re-dispatch is cheaper than tripping, as it avoids the large penalty cost associated with tripping, and can offer the same reduction in the loading of an asset with sufficient time. The operation cost of re-dispatch of generators will not be fixed, but varies for amount of power in ramping up/down and for different time of the day. The total cost will be decided by the real-time electricity market. However, the re-dispatch of generators has to obey various constraints, including: maximum ramping rate and minimum stable generation (MSG). These limits mean the re-dispatch procedure takes longer to relieve the overload than generator tripping. Therefore, generation re-dispatch could become an option for use by an enhanced OTS only if there is enough time for the procedure to be accomplished.
In order to combine generation dispatch and tripping as part of the OTS action, the time before a temperature violation will occur, i.e. the available time for the OTS to deliver the load reduction, must be assessed. This estimate of the time until a temperature violation is an extended function of the alarm signal and is performed using an independent temperature assessment program. This is also described in Chapter 6.

Another crucial input of the cost optimization function is the target power reduction that is necessary to relieve the overloading. This is also estimated as part of the alarm scheme using the real-time rating.

After estimating the time available and the target power reduction, the cost optimization function can be performed. Economic optimization will be achieved by minimizing the total cost of the re-dispatch, tripping and penalty cost. Case studies have been conducted for different contingencies, generator ratings, ramp rates, market prices, etc. The primary benefit of this approach to designing OTS actions is that it can dramatically reduce the cost of the OTS action by avoiding the larger penalty costs associated with tripping. Furthermore, the new combined operation strategy will reduce the impact on the operation of adjacent system assets.

### 7.3 Contributions

The research presented in this thesis focuses on the creation of novel Operational Tripping Schemes (OTSs) that explicitly satisfy both the functional and economic requirements. They are considered as intelligent, adaptive and efficient SIPS application in thermal protection of system elements.

The main contributions of this research can be separated into four parts:

1. Investigation of performance of the two existing thermal based National Grid OTSs under contingency conditions.
2. Creation of a novel transmission line OTS that provides enhanced protection against the cascading outage of a group of transmission lines due to the sequential overloading of these lines.
3. Creation of a novel transformer OTS that conducts on-line assessment of the temperature within a transformer and provides the system operator with adaptive actions that will prevent the assets from overheating.

4. Creation of a new functional block within the OTS structure that uses optimization theory to determine the lowest cost solution to overheating in the time available (temperature violation time as estimated by the OTS). This new function enriches the solutions for relieving thermal overloading generated by OTS.

These contributions are summarised as follows:

1. Investing performance of existing two types of OTSs under system faulty conditions.

Two types of OTSs currently in use in the GB transmission network are studied in this research: 1) is an OTS that protects transmission lines from thermal overload and 2) is an OTS that protects transformers from thermal overload. The design of the two existing schemes have some similarities, e.g. both schemes are triggered based on the status of circuit breakers and the protection actions initiated by both schemes are the tripping of pre-determined generation. The key difference between the schemes is the operation time after the disturbance occurs. The transmission line OTS reacts immediately after the detection of a change in circuit breaker status while the transformer OTS will respond with a pre-set delay (from 3 minutes up to 6 hours) due to the short-term emergency ratings of transformers.

The objective, design, functional structure and working algorithm of both OTSs have been reviewed in Chapter 3 and 5, respectively. Furthermore, their performance under system contingency conditions has been tested using simulations of the full GB network model in DiGSIILENT PowerFactory. Based on these tests the merits and flaws of the existing design can be summarised as:

- Pros: Simple operation, quick response and high reliability
- Cons: Simplicity prevents effective assessment of network status, fixed operation mode

The simplicity of the scheme allows unnecessary tripping to occur. These unnecessary actions could incur high financial costs or even initiate other
disturbances in the system. The existing schemes lack the ability to respond adaptively to each contingency. The pre-setting of transmission line rating and the short-term emergency loading of transformer are based on worst case scenarios, which means they are overly conservative for most cases and result in huge waste of capacity when system is under stressed conditions. The single tripping mode of OTS is also more aggressive than other protective actions, e.g. generator re-dispatch.

Developing this understanding of the merits and flaws of the existing OTSs was the starting point for creating the novel OTSs presented in this thesis.

2. Creation of a novel transmission line OTS which aims to protect the system from a cascading outage of a group of transmission lines due to the sequential overloading of these lines (Chapter 4).

The existing OTS is an event based SIPS that only uses the circuit breaker status of transmission lines as an input. So, the tripping condition of the OTS is based on a single condition:

- System losing three or more transmission lines simultaneously

Instead of depending solely on circuit breaker status, the novel OTS uses real-time measurements of current and weather provided by SMT to indirectly monitor the temperature of the transmission line. This allows the novel OTS to adaptively judge if a line will experience, or has experienced, a thermal overload and, based on this, approve the generator tripping that was proposed bases on the breaker status. Therefore the tripping condition of the novel OTS will be a combination of two conditions:

- System losing three or more transmission lines simultaneously
- The temperature limit is violated on the monitored transmission line

The generator tripping will be approved only when both conditions are met. The benefits that are expected from the design of this novel OTS are:

- Prevent unnecessary tripping. The enhanced OTS only allows generator tripping to occur when a transmission line will eventually experience a thermal overload for the current system conditions.
◆ **Extend the operating margin under contingency condition.** The novel OTS is required to react only when a temperature limit violation is actually occurring. The OTS will keep the asset in operation safely until its temperature reaches the defined limit. This means the operating time of the OTS may be increased from milliseconds to minutes, depending on the pre-fault conditions and thermal constant of the conductor. This time may allow alternative solutions for the overload to be considered that may be less severe and costly than generator tripping.

◆ **Alarm signal for operators.** The novel OTS offers the system operator an alarm signal that will improve their situational awareness. The alarm scheme was originally designed to indicate to the operator that a thermal overload will occur and, in a later stage of this research, it was extended with a function that estimates the time to temperature violation. Therefore, the operator could use the alarm signal with violation time information to determine the optimal operation strategy.

All the above points have been demonstrated through simulation of a full GB network model.

3. Creation of a novel transformer OTS which is able to conduct on-line assessment of temperature within a transformer and provide the system operator with adaptive operation commands to protect the asset from overheating (Chapter 5).

The delay in the operation of the existing transformer OTS is pre-defined during the planning stage. An example of this operating chart is given in Figure 5-8 (page 125). So, the tripping operation of the OTS is based on two conditions:

◆ System losing a pre-set combination of circuits simultaneously

◆ The pre-determined tolerance time of the transformer for the post-disturbance loading has passed

The existing transformer OTS lacks awareness of the operating condition of the system and this may cause it to have two defects:
- Issue tripping commands that are correct, according to the OTS logic, but unnecessary in practice.
- An generator that is out of service may be required to be tripped by the existing transformer OTS, as it has only one fixed operation mode. The operation becomes meaningless and could lead to the OTS failing to fulfil its function and allow the transformer to overheat.

The design of a novel transformer OTS starts with the enhancement of the inputs of the OTS scheme. The status of the relevant circuit breakers and the pre and post fault loading of the transformer are used as inputs by the existing transformer OTS. In the novel OTS these are supplemented with the ambient temperature and continuous monitoring of the transformer loading. This data is obtained from SMT. The real-time transformer temperature can be assessed if the real-time loading, weather conditions and parameters of the transformer are available. The enhanced transformer OTS uses this assessment to incorporate the top-oil and hot-spot temperature of the transformer into the OTS operation. No matter what the loading is, if the temperature limit is not violated, the transformer is believed to be thermally secure and the OTS actions will not be activated.

The benefits of integrating real-time transformer temperature assessment are as follows:

- *Delaying tripping*. Similarly to the novel transmission line OTS, the novel transformer OTS is able to propose adaptive protective actions for each contingency. The scheme is designed to make the most of the thermal constant of the transformer heating progress and keep it in operation longer under stressed emergency condition.
- *Adapting to the system change during stressed contingency conditions*. With the technique of real-time transformer temperature estimation, all the transformer status changes before, during and after fault are now continuously monitored by the OTS. If the overloading becomes worse, the novel transformer OTS will activate tripping earlier than the estimated tripping time based on system conditions at starting point of the disturbance.
Introducing an Alarm scheme. Similarly to the novel transmission line OTS, the novel transformer OTS affords the system operator an alarm signal which would improve their situational awareness under system contingency conditions. This alarm indicates if the transformer will eventually be overheated and can be extended to provide information on when the thermal overloading will occur based on current system situation.

These benefits of the novel transformer OTS have been demonstrated using simulations of a full GB network model in DIgSILENT Power Factory.

4. Creation of an additional functional block in the decision making procedure of the enhanced transmission line OTS that enriches the OTS by allowing the OTS to relieve thermal overloading at the minimum cost and disruption by replacing fixed, predefined actions with adaptive, optimal actions. (Chapter 6).

Generation tripping is the only operation action used by OTS in the past. This is due to the lack of effective system measurements, the past OTS operation could only be decided by data in planning stage. This action is considered to be a fast, reliable, effective solution for reducing power flow if operation cost is not crucial. In modern power system, cost-effective has been become an increasingly important requirement for system operation and therefore, there is a demand for employing protective actions offer the same level of reliability and dependability as before but at a lower cost in a more stressed system.

The generator re-dispatch scheme is a strong candidate for relieving power congestion within the network. The cost and impact on adjacent assets is also much lower for re-dispatch than it is for generator tripping. However, the re-dispatch of generators have to obey various constraints including maximum ramping rate, minimum stable generation (MSG) and the complex payment structure involved when dispatching generation during emergency conditions (i.e. commands after the market has balanced the system; details given in Section 6.2). However, generator re-dispatch is inevitably slower than tripping. Therefore, generator re-dispatch is only an option as part of OTS actions if there is enough time for the procedure to be accomplished. The thermal time
constants of a transmission line mean that there will be a delay between the increased electrical loading of the line and the resulting increase in the lines temperature. This delay provides opportunities for employing generator re-dispatch actions instead of fast generator tripping. This can be achieved by extending the alarm scheme to estimate the time until a temperature violation will occur and the power reduction that must be achieved in this time to prevent overheating.

The economic optimization of the OTS actions is achieved by minimizing the total cost of the re-dispatch, tripping and associated penalty costs using optimization theory. Case studies have been conducted to verify the performance of the optimization function under different contingencies, including various post-fault loadings, generator ratings, generator ramp rates, different tripping penalties. The primary benefit of this new approach for designing OTS actions is to drastically reduce the cost of OTS operation by replacing a tripping only scheme with a scheme that can combine tripping a re-dispatch without sacrificing security. Published data from NG shows that the tripping penalty cost makes up 99% of the operation cost of the OTS. Furthermore, the new combined operation strategy in which tripping will be replaced by ramping will have far less impact on the operation of the system.

7.4 Future Development

The achievements presented in this thesis has accomplished most of the goals set by this research and has made some contributions. However, there exist some possibilities to make further improvements on algorithms of the novel OTSs and their practical applications.

- For WAM data acquisition
  It is assumed that there are sufficient PMUs installed to monitor the current on all of the transmission lines in the SmartZone to realize the full functionality of novel transmission line OTS. The optimal PMU placement within this area is worthy furtherly explored. Besides, if the original data communication network
becomes unavailable due to disturbance, there should be backup data input to perform the novel OTS function.

- For transmission line modelling
  The transmission line within Humber Zone is considered as short lines which means the weather conditions are the same for both ends and the temperature are distributed averagely. If the novel transmission line OTS is expected to be implemented on long transmission lines, more factors including weather difference, sag and temperature distribution across the whole asset need to be considered. The hot spot temperature will be the decision factor to initialize the operation of OTS.

- For optimization methodology
  Future work can be done in building a close-loop control between the ramping solution and the thermal progress estimation. This is because, the temperature violation time would become longer during the generator ramping progress. This provides further opportunities in optimizing the OTS operation. Besides,

- For operation of OTS
  Before the novel OTS be implemented in the real network, the influence of its action to the rest of the network must be pre-assessed. It must not result in any further disturbance across the system.
8. References


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Appendix A. List of publication

Journal


Conferences
