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INTEGRID – Impact of new Grid Codes on the local distribution network of nuclear power plants

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Abstract--This paper describes the key outputs of the INTEGRID project related to the impact of the new Grid Codes and the implementation of new technologies on the electrical systems and equipment of Nuclear Power Plants (NPPs). The project is funded by the European Commission under the NUGENIA+ umbrella as a pilot project, and carried out by EDF (leader), the University of Manchester, Areva GMBH, and TECNATOM. INTEGRID investigates the increased stresses on the equipment of NPPs that could result from the newly proposed modifications of the Grid Codes by the ENTSO-E, specifically the impacts of wider voltage and frequency ranges. In particular, this paper discusses the impact of these new frequency and voltage operating ranges, and the corresponding code modifications, on different aspects related to the regulation of machines, overheating and vibrations of the equipment, and the appearance of electrical transients in the plant distribution network. The implementation of new technologies, replacing the existing equipment, is also discussed.

Index Terms—Grid-Codes, NPPs, Renewable, stability, stresses, transients, energy mix, NUGENIA+.

I. INTRODUCTION

New Grid-codes [1] have been developed with an aim to allow for greater integration of Renewable Energy Sources (RES), particularly electrical power from the wind farms of the Nord-sea on the European electrical network. However, these new Grid-codes require increased flexibility from existing power plants including Nuclear Power Plants (NPPs). The INTEGRID project, developed under the NUGENIA+ work programme [2] and related to the point “Efficient integration of NPPs in the energy mix”, addressed the impact of these Grid-codes on NPPs.

The impact on existing NPPs is a critical

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topic, considering that nuclear power contributes nearly 30% of electrical production in Europe, and also considering their average age of nearly 30 years. The outputs of the project are expected to provide guidance towards the integration of future NPPs in the energy mix in the next decades, where different types of generation technologies, (e.g., nuclear, hydro, wind, photovoltaic) will be involved.

II. NUGENIA AND NUGENIA+ FRAMES

The INTEGRID project [3] is developed in NUGENIA+, under the FP7 NUGENIA frame [4], and has a connection in those platforms to the following aims:

- Improve modelling of phenomena in NPPs.
- Prepare the future to avoid technology obsolescence.

Furthermore, it has a link to the Strategic Research Agenda (SRA) of NUGENIA, and specifically to Technical Area 1 “Plant Safety and risk assessment”, and the Sub-area 1.4 “Effect of electrical Grid disturbances”.

The need for further research on identifying the effect of grid disturbances is also highlighted in the SRA Sub-area 1.4 which states that among external hazards, particular attention has to be paid to grid disturbances on the plant through the internal electric buses and other equipment important to safety [5]. New equipment is also mentioned, with a reference made to “modern electronics” and “digital equipment”. It is stated that the design of plant control and protection systems has to be based on an “increased understanding of these effects and the sources of these effects have to be investigated” [5]. These aspects are addressed in the INTEGRID Project.

III. DESCRIPTION OF THE INTEGRID PROJECT

A. Scope

The newly proposed modifications of Grid Codes, with wider voltage and frequency ranges, could lead to increased stress of the equipment of NPPs. INTEGRID – Impact of New TEchnologies and GRId codes on the local Distribution network of nuclear power plants – addresses the different issues associated with this new context, such as:

- The impact on the regulation of machines.
- Overheating and vibrations of the equipment.
- The appearance of electrical transients in the plant

distribution network.

- The implementation of new technologies, replacing the existing equipment.

These aspects are described in the following chapters.

B. Organization

This project includes four Partners, AREVA GmbH (Germany), EDF (France), TECNATOM (Spain), and The University of Manchester (UK), with EDF leading the project activities. The Project started in March 2015, with a project duration of 1.5 years, with two milestones defined and two Deliverables (technical reports) released in December 2015 and August 2016. Three meetings have been held, the kick-off meeting in Paris, France, in May 2015 [8], with subsequent meetings in Madrid, Spain, in October 2015, and in Manchester, UK, in April 2016.

C. Description of the different items

The main issues addressed by the project are described below:

1. New Grid codes and past codes review.
2. Impact of the stability aspects addressed by the new Grid-Codes (new voltage and frequency ranges).
3. Stresses on generators due to fluxes and thermal stresses on all components.
4. Stresses due to vibrations on generators.
5. Development of tools and review of existing ones.
6. Development of monitoring systems.
7. Measurements on generators sensors and other data acquisition.
8. Mitigating solutions for NPP generator and equipment.
9. Mitigating solutions of NPP network related issues.
10. Identification of NPP's distribution network equipment with issues owing to the new Grid codes.
11. Impact of the new Grid code on NPP distribution network and studies to be performed.
12. Evolution of the NPP electric distribution equipment including new technologies and DC.
13. Impact of new equipment on the Distribution Network and studies to be performed.
14. Design and operation Recommendations related to new grid codes and how to improve NPP reliability.

D. Description of project delivery

Among these items, nine were selected for initial investigation and were reported on in Deliverable 1 (items 1, 2, 3, 5, 6, 7, 10, 11, and 12). The second deliverable addressed the remaining items (4, 8, 9, 13, and 14) and was released in August 2016. Five items, 1, 2, 5, 6 and 11, are described within this paper to highlight the main contributions of the work completed.

IV. ASPECTS OF GRID CODES IMPACT

A. New Grid codes and past codes review

Both past and newly proposed grid codes by the ENTSO-E have been thoroughly reviewed. Both have been established in the face of new challenges raised by the development of renewable energy sources (RES). Electrical networks are facing new challenges since the 1990s mainly due to issues caused by deregulation [1] and the separation of Producers, Transporters and Distributors. This has led to the development of new entities called Transmission Systems Operators (TSOs), which may deliver ancillary

services to the Producers. In Europe, the ENTSO-E [3] has been created, which gathers the European TSOs.

From 2000 onwards, there has been considerable development of RES with an aim to reduce CO2 emissions resulting in the development of wind power plants [6] and photovoltaics. The development of smart grids [7] has also affected the energy mix with distributed generation playing a significant role in power networks. Another point to consider is the ageing of the actual centralized electrical networks, typically being nearly thirty years old. These ageing assets will have to be replaced in the coming decades and this must be considered in the light of these new challenges.

The ENTSO-E new Grid codes [1] define the conditions for the different types of producers to be connected to the European Network. This is illustrated in Fig. 1.

Fig. 1: Grid Codes (old and new frames)

It is important to note that the voltage and frequency stresses may be considerably higher at the equipment inside the NPP even if values are limited to contractual values reported in Fig. 1 at the Delivery point. For example, voltages may reach 1.2 or 1.3 p.u. at the generator terminals when the voltage reaches 1.1 p.u. at the Delivery point. The new frequency ranges may have a significant impact on the stability of the generators connected to the network.

B. Impact on the stability aspects addressed by the new Grid-Codes (new voltage and frequency ranges)

The new grid codes will result in wider frequency and voltage tolerances for new generation sources. This may have a significant impact on the nuclear power plants (NPPs) that are connected to the grid with respect to the stability of the machines and their voltage and frequency regulation [8]. The impacts on currently implemented control schemes must be thoroughly evaluated across the full range of possible operating conditions.

Following a thorough scenario-based analysis of all possible conditions, those resulting in worst-case performance could be identified. In order to identify the potential stability aspects that may be affected by the new Grid-Codes [9], [10], [11], [12], [13] an illustrative study has been performed using a generic nuclear power plant, with a generation net power output of 1000 MW, using IEEE standard models for the regulation. It has been

modelled and examined under normal and faulty conditions, as described in Fig. 2.

Fig. 2: Fault ride through (FRT) in the ENSO-E grid code.

The resulting voltage and frequency responses indicate that, in the worst cases, the frequency is found also to be very close to the upper margin of the codes. This indicates that additional studies would be required for the cases when the initial conditions (prior to the fault) are not ideal (i.e., when they are not 1 p.u. and 50 Hz for the voltage and the frequency respectively) at the 400 kV bus.

C. Development of tools and codes

1) Development of tools

The use of tools in order to address this new topic is an important issue to consider. Different types of electrical tools may be used in order to address the following points:

- Impact on the stability of the electric system, when new frequency ranges must be considered. In this area, dynamic simulation packages like PSS/E or DlgSILENT PowerFactory (and others) may be considered [14].
- Impact of the fast transient phenomena generated in networks and their impact on the equipment.
- Impact on the non-linearities involved in electrical networks [15], [16].

For b), the new voltage and frequency ranges may affect the steady-state voltage of the step-up transformers, either with load or no-load tap-changers. Higher voltages on the TSO side may lead to a higher voltage at the generator side. This could subsequently have an impact on insulation coordination. Higher voltages on the distribution side of the NPP, at the secondary side of the auxiliary transformers, may also have an impact on the steady-state operating conditions, on the saturation of MV/LV transformers in the electrical systems, and possibly on the operating conditions of the motors in the distribution network. The tools to be used to assess these phenomena are Electromagnetic Transients Programs (EMTPs) [17], [18]. Note that this is also relevant to items 2, 11 and 12 of the study previously mentioned.

2) Development of simulation codes

The development of software code and algorithms is also an important issue that has been considered within INTEGRID. This development will enable automated analysis of the stresses generated in the equipment [19], such as fluxes, temperatures and vibrations. Fig. 3 illustrates an example of the electromagnetic stresses formulated on the generator that are determined through 3D electric field programs [20], [21].

Fig. 3: Section of a 3D electromagnetic model of a 125 MW synchronous machine.

This point can inform «Mitigating solutions for NPP generator and equipment» (item 8), by identifying possible upgrades on the actual equipment. In the cases where the upgrade is not sufficient enough, mostly due to very severe stresses, mitigation through network redesign for example might be used. This has been addressed under «Mitigating solutions of NPP network related issues» (item 9). In the case where more detailed studies are necessary to capture the network modelling as well as the equipment, then coupling of tools may be required.

3) Measurements on Generators and NPPs main equipment /sensors

This investigation is performed through simulations based on the TECNATOM's training and engineering simulator of NPPs connected to a 50 Hz electrical grid. It could be possible to gather the measurements issued from the elementary systems (Hydrogen, Electrical, etc.) [22], [23] for different generators on the same site or different sites. Such an investigation may enable the acquisition of many sensor temperatures, vibrations, etc, for generators at a given site.

The studies are performed by introducing a transient on the high voltage grid side and starting at normal operating conditions with the NPP stable and operating at nominal power. The disturbance is propagated through the NPP equipment. To analyse the information provided and obtain results it is very convenient to select representative variables in order to survey the status of components. Based on the criticality of such variables and the existing sensors in most plants, a preliminary set of parameters were recorded during simulations. These were temperature, vibrations, coolant flow, instantaneous power consumed or generated, current, voltage, frequency, speed, transformation ratio, hydrogen pressure, and oil pressure.

Fig. 4 shows the outputs of one of the many scenarios simulated. In this case, the voltage is maintained at 1.00 p.u. The frequency varies with an initial value of 51.5 Hz for the first 30 minutes. Then the grid frequency changes to 51 Hz for the next 30 minutes. Finally, the frequency returns to its nominal value (50 Hz) for 7 hours.

The variables selected for monitoring are chosen based on the representativeness for some typical degradation mechanisms, but also for their availability in the real plant and in the simulator. An analysis of these variables could lead to the determination of the critical combinations of several changes and also the identification of new sensors

required to follow the changes in the most critical variables with higher accuracy in order to predict plant degradation.

Fig. 4: HP Turbine temperatures considering a scenario with varying frequency.

A preliminary review of the obtained values shows that changes in frequency may be the most critical issue. The combination of high frequencies and low voltages increases the temperatures in the components and also in bearings. It is necessary to incorporate new (actual or virtual) sensors to analyse in detail the values reached by those variables and also parameters changes in some critical locations. Some critical variables already identified include the generator windings displacement, humidity inside the motors and generators, and detailed internal temperature maps. This extra information could help further analyse and predict the influence of such changes in voltage and frequency.

4) Impact of new Grid code on the Distribution Network

Different variations of NPP distribution networks are possible depending on the safety and process requirements and national nuclear safety standards [5], however a typical NPP electrical distribution system is shown in Fig. 5.

Fig. 5: Single line diagram of a 1000 MW NPP modelled for studies.

The new voltage ranges may have an impact on the studies to be performed [24]. New steady-state conditions have to be evaluated that may, during long times of up to a few hours, stress the insulation of the different equipment (such as auxiliary transformer, cables, MV/LV transformers, and motors). This can be analysed using partial discharge measurement devices, or studies using detailed modelling as

mentioned in item 5. The impact on the distribution network in terms of overheating and vibrations has to be checked also. Electromagnetic transients may appear on the network due to new voltage ranges. The may have impact on the aspects listed below:

- Impact on higher voltages on the auxiliary transformers and MV/LV transformers, in terms of the generation of harmonics.
- Impact on higher voltages on voltage dividers, as they may lead to ferroresonance phenomena.
- Impact of faulty conditions in the Distribution network [25] [26].
- Impact of MV circuit- breakers operations in the network, especially vacuum circuit- breakers [27], especially when interrupting small inductive currents.
- Impact of load rejections.
- Impact on AC/DC converters [28].
- The impact of new frequency ranges have to be investigated.

The distribution network has changed substantially over the last several decades due to the proliferation of power electronic converters and end-use devices. These changes are particularly important as they might have affected different safety aspects which need to be assessed and verified by appropriate tests. New equipment as vacuum circuit-breakers, now replacing SF6 equipment, have to be investigated as they may generate re-ignitions when the poles open near a zero crossing of the circulating current.

V. DESCRIPTION OF RELEVANT POINTS

From the work completed in INTEGRID in the different items (as described above for some items) the main points and outputs of the project are identified are as follows:

- A detailed description of the challenges and issues introduced for NPPs by the new Grid Codes, particularly points needing further attention.
- Discussions surrounding these challenges written by experts in their area with complementary skills (University, Designer, Utility, Nuclear expertise).
- Provision of a list of suitable tools (stability and transient programs, 3D codes, non-linear tools).
- Initial simulations showing that the new Grid-Codes may affect the actual functioning of the power plants.
- A list of monitoring systems to be installed.
- A description of the studies to be performed considering their impact of the equipment of the Distribution electrical system.
- The collection of more than 100 relevant references on the topics covered.

VI. FUTURE DEVELOPMENTS

Further to the actual INTEGRID project, additional aspects related to this area (such as transformers etc.) may be considered in the future with respect to this topic. There are numerous aspects related to the power delivery side and also the distribution side which are described in the INTEGRID project. To this extent, future work has been identified to extend the studies on the dynamic response of the generator, aiming to identify the impact of governor and

excitation controls, and the size of different pumps and loads within the NPP. The impact on the equipment should also be investigated, with the installation of additional sensors, and also the impact on the distribution side of the NPP through detailed studies.

VII. CONCLUSIONS

This paper describes and highlights key aspects of the work completed on the NUGENIA+ INTEGRID project, from March 2015 to August 2016. This paper has addressed several items of the project related to the impact of the New Grid Codes provided by the ENTSO-E on the Power Delivery side or to the Electrical Distribution side of existing NPPs. Specifically it has discussed stability aspects, the impact on generators, palliative solutions, monitoring aspects, and the electrical distribution system. These items are described including two specific studies (stability and measurements issues). This first study related to stability aspects, shows that, in the worst cases, the frequency is found also to be very close to the upper margin of the codes. It has also been shown in the second study that the temperatures in the equipment may increase further and that additional sensors may be required. Future work by the authors will address an extension of this project and will complete more studies related to the items mentioned in the project.

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BIOGRAPHIES

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Jimmy Lorange received the PhD- Engineering Diploma of the "Institut National Polytechnique" de Grenoble in 2000. In 2008, he joined AREVA GmbH. He is responsible for the licensing of the electrical system of the EPR in UK (with EDF Counterpart).

Waldemar Geissler received his diploma as Electrical Engineer at the University of Applied Science in Nurnberg in 1991. After a joint venture between Framatome and Siemens, he now works for AREVA GmbH. Since 2010 he has worked in the area of Electrical System Design Authority, participating in IEC standardization and IAEA working groups.