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Making VSC-HVDC Control Robust to Geomagnetically Induced Current

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Abstract— Solar storms can affect the terrestrial power grid by inducing potential differences between points on the earth. These can couple into the power system through earthed structures such as transformer earths, which in turn can result in transformer saturation through geomagnetically induced current (GIC). For systems such as voltage-source converter (VSC) HVDC, this causes a variety of problems. This paper discusses the phenomenon, system modelling to assess the resulting problems and presents a compensate strategy to ameliorate GIC effects for VSC-HVDC.

Index Terms—HVDC Transmission, Inverters, Power Grids, Power Systems Dynamics, Transformers.

I. INTRODUCTION

Voltage-source High Voltage DC Transmission has been proposed for connecting long distance AC networks. Typically this is for distances of 100km or more for submarine cables, or 500km or more using overhead lines. Applications include the connection of large offshore wind farms to shore, interconnecting two unsynchronized networks or as ‘embedded links’ strengthening an AC network by reinforcing existing AC transmission. In such applications VSC-HVDC is subjected to a variety of effects.

A type of event which may cause severe unbalanced disturbance to the three-phase voltage, but yet to be studied comprehensively in the context of HVDC, is known as the Geomagnetically Induced Current (GIC) caused by Geomagnetic Disturbances (GMDs). During solar flares, coronal mass ejections and other solar events, huge amounts of radiation, charged particles and plasma are ejected by the Sun [1]-[3]. This intense outflow of electromagnetic fields and plasma is defined as the solar wind [1], [4] and usually takes 28 to 100 hours to travel to Earth if it blows in Earth’s direction. Extreme solar storms can take less, such as the 2003 “Halloween storm” which took only 19 hours [5].

When the charged particles and plasma in the solar wind reach the Earth’s magnetic field, they generally descend to and circle around at the altitudes of approximately 100 km above the magnetic poles, where they are then ionized. The complex interactions between these ionized particles and the

geomagnetic field produce auroral currents, or electrojets which flow horizontally in the ionosphere [2]-[4]. It is possible for these fluctuating currents to reach a magnitude of 1 million amperes or more [4], [6], and thus cause strong disturbances to the geomagnetic field. The intensity of solar activities is correlated with the sunspot cycle, which has a period of about 11 years. The peak of solar activity usually lags the sunspot cycle peak by 3-5 years [3]. While it is difficult to accurately predict when a major GMD event will appear, near real time space weather data is now available, for example, on the website of the National Weather Service Space Weather Prediction Center (USA). More recent research also suggests that it is now possible to detect emerging sunspot regions in the solar interior before they appear on the surface of the sun [7], [8].

When the geomagnetic field is fluctuated by the strong electrojet currents, the change of flux will induce Earth Surface Potential (ESP). The magnitude of the ESP is very much related to the geography of the affected regions: being proportional to the distance between neutral grounding points [9] and inversely proportional to the earth conductivity [6]. The current resulting from the presence of the ESP and conductors is known as GIC. The GIC enters the power system via neutral grounded star-connected transformers [9]-[11]. Since the frequency of the GIC is usually in the range of milli Hertz, viewed from a normal frequency power grid (50 Hz or 60 Hz), the GIC can be considered as quasi-dc current [2],[3],[10],[11]. Predominantly high latitude areas are sensitive to solar storm induced GIC, but regions located in lower latitude areas, such as the southern coast of China, Australia and South Africa, do experience adverse GIC effects as well [12]-[14].

The most vulnerable components in a power system to GIC are the power transformers. Since GIC appears as quasi-DC in the AC power system and can last for minutes to hours, it stresses the transformers into half-cycle saturation which is considered as the root cause of nearly all GIC-related problems in the power system [3], [9]. During this state the abnormally high transformer excitation current will introduce extra odd and even harmonics into the power system, while at

the same time, causing stray flux to impinge on the conductive parts of the transformer, including the oil tank, flux shields, clamps, windings and other structural components. This will induce eddy current in these components and may cause excessive temperature rise [3],[9].

GIC effects in the context of HVDC systems have been studied before, but almost exclusively on Line Commutated Converter (LCC) HVDC systems. GIC may cause commutation failures in LCC-HVDC systems and overload harmonic filters and protective devices [15], [16], [17]. The reactive power consumption of LCC-HVDC is usually compensated with capacitors banks, which are low impedance paths for harmonics and have been tripped out by relay protection in past GIC events [15], [17].

Information of GIC impacts on VSC-HVDC systems is significantly less than LCC-HVDC systems. This is partially due to the fact that VSC-HVDC is a relatively new technology, the total installed capacity of VSC-HVDC is substantially lower than LCC-HVDC and there has not yet been any reported major VSC-HVDC disruption caused by GIC. In fact, VSC-HVDC is considered to be immune to GIC events in certain research [18], since the converters operate at much higher voltage levels than the induced potential. However, the effects of abnormal harmonics generated by saturated converter transformers were not discussed in [18]. This paper addresses this issue.

II. MODELLING VSC-HVDC FOR GIC STUDIES

A. Transformer Connection

Figure 1 Concept of the UMEC Transformer Model (a) Core structure of the single phase transformer (b) The unified magnetic equivalent circuit of the single phase transformer (c) Implementation in EMTDC [21],[23]

Since the transformer is considered as the most vulnerable component in the power grid during GIC related events, the transformer model needs to be selected carefully, specifically

the transformer model used must be able to represent the electrical aspects of transformer saturation. If the transformer model is able to simulate hysteresis, then a more accurate result is likely to be achieved.

In software packages, such as PSCAD/EMTDC, two types of transformer models are typically provided, which can model saturation. The more well-known is the Steinmetz model [19], sometimes known as the “General Transformer Model”. The other is a Norton circuit based model, such as the “Unified Magnetic Equivalent Circuit (UMEC) Transformer Model” [20] derived directly from magnetic equivalent circuit analysis [21], [22]. The UMEC model offers a number of advantages when compared with other similar magnetic circuit equivalent based transformer models: the need for a proximity criterion is removed; the division of magnetising current is not arbitrary; uniform core flux is not assumed and leakage reactance is not lumped. When configured appropriately, the UMEC model is capable of simulating transformer saturation and hysteresis. This model is therefore used here.

A single-phase UMEC model is shown in Figure 1 [21], [23]. The primary and secondary voltages are used to calculate the winding limb flux ϕ_1 and ϕ_2 , respectively. The two Magnetomotive Force (MMF) sources $N_1 i_1(t)$ and $N_2 i_2(t)$ shown in Figure 1(b) represent the primary and secondary windings respectively. Since leakage flux and limb flux are both represented, a uniform core flux is not assumed. Figure 1(c) is the Norton equivalent and implementation of the single-phase UMEC transformer model. More details of the UMEC model can be found in [21], [23]. The model used was parameterized based on a normalized to a per-unit system [21]. Details of the derivation of the normalized core can be found in [21], [24].

Figure 2 Simulated magnetising current for UMEC model

The simulated magnetizing current, was validated against results from [21].

B. System Model

As shown in Figure 3, the test model comprises of the following components: a high impedance ‘weak’ network, the transformers, the GIC injection units, the MMC converters (and their controls), the PLLs, a low frequency DC network

model based on power balance with the MMC model, and a strong network. This test model is designed to simulate and investigate the scenarios during which the weak network converter encounters during GIC events. Since the goal of the model is not to study the detailed behaviours of the AC networks and due to the narrow bandwidth of GIC events (from milli Hz to about 1 Hz), a high fidelity network model is not required as a first pass. Both AC networks are thus modelled as three-phase voltage sources behind impedances.

Figure 3 Schematic of the test model

As shown in Figure 3, the MMC model used in the GIC tests is the Averaged Value Model (AVM) [25]. To investigate the inner dynamics of the MMC, a detailed model is necessary. However, since the bandwidth of GIC events is much slower than the inner dynamics of the MMC converter, the AVM is more suitable than the computationally demanding full detail model.

DQ current control is used for the MMC, since real power and reactive power can then be controlled separately. Constant power control is used on the high impedance network (rectifier) side while DC voltage control is implemented on the strong AC network (inverter) side to maintain the DC link voltage, i.e. the strong AC network absorbs power fluctuations on the DC network. The HV side AC voltage in the model is 400 kV line-to-line, while the LV side AC voltage is 333 kV line-to-line. The DC link voltage is ± 320 kV with capacity of 1000 MW [26].

C. GIC Model

DC currents are injected into the UMEC transformer neutrals to simulate GIC events. This modelling method is based on the procedure outlined in [20]. The desired amount of GIC injection is controlled via a feed-back PI controller connected with a controlled voltage source and a resistor, whose value is chosen according to [27]. A controlled current source is not used due to its high impedance (which theoretically would be infinite), since this would effectively make the transformer floating.

III. SIMULATION

To examine the performance of the model under GIC conditions, a GIC of 224A (74.67A per phase) was injected into the grounded transformer neutral on the rectifier side. This particular amount of GIC is chosen because it was the estimated total amount of GIC during the 1989 Québec event [15]. The rectifier is set to delivery 900MW constant power (0.9 p.u.) while the inverter is set to V_{dc} control.

Figure 4 Three-phase voltages on rectifier side transformer before GIC

Figure 5 Three-phase voltages on the rectifier side transformer after about 15s of GIC injection

The three-phase voltages of the rectifier side transformer before GIC injection are shown in Figure 4. Signs of harmonics can be seen in the voltages since the transformer is working near the knee point of the B-H characteristic.

Figure 5 and 6 show the three-phase voltages and three-phase currents of the rectifier side transformer after about 15s of GIC injection, respectively. Saturation effects can be clearly observed. A harmonic analysis of the secondary currents shows that DC currents are blocked by the delta winding, however, even harmonics and other non-triplen harmonics are not blocked.

Figure 6 Three-phase currents on the rectifier side transformer after about 15s of GIC injection

IV. ENHANCING PERFORMANCE

This section explores the use of what will for simplicity be referred to as an Enhanced Fundamental Positive Sequence Control (EFPSC) under GIC conditions. This is essentially a combination of PLL selection, appropriate tuning of the VSC-HVDC controller and positive sequence fundamental frequency current control.

The first step is identifying the appropriate Phase-Locked Loop (PLL) to use to ensure the robustness of this part of the control. A number of commonly used PLLs [28] were tested.

Figure 7 PLL Average Absolute Frequency Errors (%) in GIC test

These include the Synchronous Reference Frame (SRF) PLL, which uses a dq control structure, and PLLs which use the SRF with additional filtering (the Lead-Compensation SRF and the Window SRF). The Enhanced PLL (EPLL) generates a quadrature set of signals from each phase and then extracts the positive sequence. The Double Second-Order Generalised Integrator (DSOGI) PLL generates a

quadrature set of signals from the $\alpha\beta$ signals and then extracts the positive sequence. The Decoupled Double Synchronous Reference Frame (DDSRF) PLL extracts positive sequence components from the rotating dq reference frame. The bottom four PLLs were considered further, Figure 7, on the basis of being very robust to GIC. Of these, when other factors, such as dynamic performance, harmonic rejection, interfacing requirements etc [28] were considered, the DSOGI-PLL was considered most appropriate.

During the voltage ramp-up period, the dq current controllers are disabled and the corresponding grid voltages are used as reference signals for the Nearest Level Modulators (NLMs) to produce firing signals for the two converters. A perfect DC source is used to charge up the DC link to full voltage during voltage ramp-up. This DC source is disconnected after voltage ramp-up. The dq current controllers are then enabled to produce reference signals for the NLMs. At this moment, the dq voltage components are calculated directly from the transformer secondary voltages. After system start-up, the fundamental positive sequence components of the voltages (generated by the DSOGI-PLL) are manually switched into the Clarke Transform while the power transfer is set to zero.

Figure 8 Three-phase voltages on the rectifier side transformer after about 15s of GIC injection

The bandwidth of the real power controller on the rectifier side is set to 370Hz, while the damping ratio is set to 1. The bandwidth of the reactive power controller is set to 200Hz with a damping ratio of 1. The inverter side is set as V_{dc} control with a bandwidth of 10Hz and a damping ratio of 1. The two power controllers on the inverter side are both set to 200Hz of bandwidth and damping ratio of 1. An excessively fast bandwidth results in higher demand being placed on the converter. A slower bandwidth may result in insufficient

response and even instability. After the positive sequence control is engaged, the rectifier is ramped up to delivery 900MW constant power (0.9 p.u.). A GIC of 224A is then injected to the grounded transformer neutral on the rectifier side. Figure 8 and Figure 9 show the three-phase voltages and three-phase currents of the rectifier side transformer after about 15s of GIC injection, respectively. Compared with the results shown in Figure 5 and 6, the waveforms in Figure 8 and 9 are much less distorted and a lot more sinusoidal.

Figure 9 Three-phase currents on the rectifier side transformer after about 15s of GIC injection

V. SUMMARY

The impacts of GIC on a VSC-HVDC system based on MMC converters are assessed using the AVIM and the UMEC transformer model. The simulations confirm that the use of delta winding in the transformer is not capable of blocking the DC offset caused by GIC completely. A control strategy, the EFPSC, is developed using PLLs as advanced phase sequence extractors and is shown to be capable of reducing the stress caused by GIC on transformers.

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