Influence of Active Power Gradient Control of an MMC-HVDC Link on Long-Term Frequency Stability

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Abstract—**This paper presents a frequency stability analysis of two power systems coupled by a high-voltage direct current (HVDC) system, based on modular multilevel converter (MMC) technology. The effect of the active power gradient (APG) control scheme attached to MMC on the long-term frequency response (time frame of 1 s to 2 min) of the AC synchronous areas is analyzed by considering a typical disturbance like a load shedding, which helps in clearly observing the frequency deviation produced in the power systems considered. The frequency responses are assessed through deterministic software experiments in the time domain, focusing on 1) power systems with similar and different inertias and 2) the effect of varying the APG of the MMC-HVDC system. The simulation results reveal a correlation between APG and the long term frequency response, which becomes more prominent for low-inertia systems.**

Index Terms—**High-voltage direct current (HVDC), modular multilevel converter (MMC), active power gradient (APG), long-term frequency stability.**

I. INTRODUCTION

Most current HVDC links are based on Voltage Source Converter (VSC) technology, which has been evolving progressively in different types of converter topologies [1],[2]. One of the last topologies developed, the Modular Multilevel Converter (MMC) technology, has caused great interest in the scientific community as it is being considered as the most appropriate to boost massive integration of renewable energy sources and remote AC power systems interconnections through the development of HVDC systems, considering its several advantages with respect to previous VSC generations [3],[4]. Some of these advantages are converter losses reductions, a reduction on total harmonic distortion and an increment on the operability and reliability, due to its modular design [5]. For instance, the MMC technology has been employed for the transnational HVDC point-to-point link interconnection between Spain and France, INELFE project, achieving 2000MW exchange between these countries [6]. In the same way, it is expected that the second transnational HVDC point-to-point link in Europe, the COBRAcable project, integrates the Dutch and Danish power systems thought a point to point offshore MMC-HVDC link [7] before the end of this decade. Among the topics of greatest interest of the VSC technology analysis are the dynamic interactions associated with the integration of MMC-HVDC links and large AC networks. Different average MMC models have been developed to consider relevant aspects of the AC/DC interactions, like transients responses under single and three phase faults [8], [9], [10] and inter-area oscillations [11], [12]. Nevertheless, the studies conducted so far have not evaluated the active power gradient (APG) features of the VSC stations from the long-term frequency stability regulation perspective. This becomes a very relevant aspect especially when low inertia or weakly meshed power systems are connected through an HVDC system.

This work is focused on the study of the APG influence on the long-term frequency stability of two AC networks coupled by an MMC-HVDC link. In order to develop this analysis, an average MMC model was used based on [13] and [14]. A power balance disturbance is defined in order to determine the degree of support of the APG control on the frequency regulation. The experimental analysis considers two study cases: one where the AC networks have different constants of inertia and one where the AC networks have similar constants of inertia. The paper is organized as follows: In Section II, the theoretical background on long-term frequency stability, HVDC control and average models (AVM) is given. Section III describes the study proposed case and discusses simulations results. Finally, conclusions based on the results of this paper are drawn in Section IV.

II. THEORETICAL BACKGROUND

A. Long-Term Frequency Stability

Long-term frequency stability refers to the ability of a power system to maintain steady frequency following a severe network disturbance that result in a significant unbalance between generation and load [15]. In a classic power system, without power electronic converters, this steady frequency can be achieved by using a load-frequency regulation function which is one of the main operations that the Secondary Frequency Control or Automatic Generation Control (AGC) in a Power System has to manage. In that sense, AGC and the prime mover or governor system (GOV) models have a relevant influence on the long-term frequency stability studies where it is considered that the system frequency is uniform and the fast dynamics are not significant assuming that the time frame of interest (more than 30 seconds) is extended beyond the transient period sufficiently [16]. Furthermore, the addition of MMC-HVDC links as interconnectors of AC networks can contribute in the load-frequency regulation of the power systems, where the AVMs of the HVDC components have a highlighted relevance, since they allow to develop AC/DC systems integration studies (through a suitable representation of long-term frequency responses) [13].

B. HVDC system modeling

1) Average modeling of an MMC-HVDC station and DC cable: There are several models to represent the dynamic behavior of the MMC [10]. However, in this work, the MMC representation and controls associated will be mainly based on the AVM type 6 presented in [13] and model type 4 based on [14], which were developed for long-term power system dynamic studies. In these AVMs, the converter representation is done in a similar way to the classic 2 and 3 levels VSC technology, where voltages and current sources are used to represent the AC/DC power balance respectively. Figure 1 shows the adopted average MMC model representation.

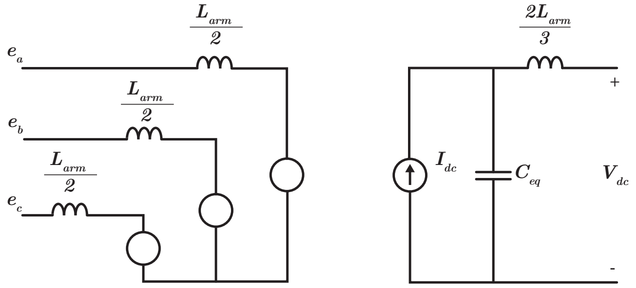

Fig. 1. MMC average model representation from [14].

In this model, it is assumed that the Internal Energy Balance Controls (IEBC) of the MMC (voltage capacitor balancing and circulating current controls) are working perfectly [14] which means that the third (energy) circuit loop presented on [17] for representing the internal dynamics of the converter and its respective IEBC systems can be neglected. Furthermore, as it is recommended in [14] for improving the accuracy of the average MMC model, *Larm* reactors will be represented simultaneously at the AC and DC networks and the equivalent capacitor *Ceq* which is a function of the number of submodules (*N*) and the capacitor value of the submodule (*C*) will be represented on the DC side network as it is shown in Figure 1. The respective mathematical relationship between theses variables is presented in equation (1). For the HVDC cable, an equivalent resistance model was considered, since the time frame of this study is large enough to avoid the representation of the energy storage elements of the DC cable.

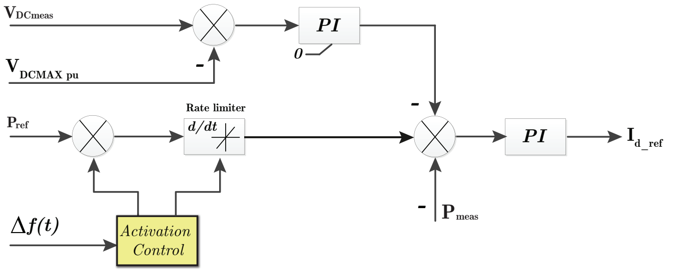

Fig. 2. Modified Active Power Control Mode from [13]. The block highlighted in yellow concerns with the addition of signals to regulate the active power reference and the APG used by the converter station.

$$C_{eq} = \frac{6C}{N} \tag{1}$$

2) Controls of the HVDC system: Fig. 4, shows the main control structures implemented for the HVDC system in this work. The P control, Q control, V_{dc} control, and V_{ac} control modes (used by the converter to regulate the power distribution and voltage levels of the AC/DC networks) are contained inside the block highlighted in yellow shown in Figure 4. The active power control scheme from [13] was incorporated into the AVM and adapted by creating a control block which allows to modify the active power rate limiter (APG) and adjusts the active power reference signal to compensate the frequency deviations registered by the respective converter station. In Figure 2, the adaptation of the control scheme is shown.

3) Active Power Regulation in a point-to-point MMC-HVDC system: In the MMC technology, AC current control can be developed by using the vector control principle [9], which nowadays is the most widespread method for the classic two and three level VSC technology. This method allows to independently regulate the active and reactive power supplied by the converter station [1] by using the *dqo* transformation and the phase loop locked system. The active power provided by the converter station can be described by equation:

$$P_{VSC} = v_d i_d + v_q i_q \tag{2}$$

Where P_{VSC} represents the active power of the VSC station and v_d, v_q, i_d, i_q represent the respective *direct and quadrature voltages and currents* on the *Synchronous Reference Frame* employed by the conveter stations. Moreover, the power distribution in an HVDC grid is regulated by the V_{dc} control structure, that due to the very low electrostatic inertia of the HVDC system [18] has to be set in order to compensate the fast dynamics characteristics of the HVDC system, which are considerably fast, so they can be obviated for the long-term frequency stability study performed on this work.

III. SIMULATION STUDY

A. System Description

The long-term frequency stability study developed in this work was conducted through time domain simulations. The simulation study was implemented in DIgSILENT PowerFactory v15.2. The dynamic model of generators and its controls, as shown in [15], are also used and this study. However, the automatic control generation and load controller effects of the synchronous machines were modeled in a similar way to the frequency control models described in [19] and [20], where

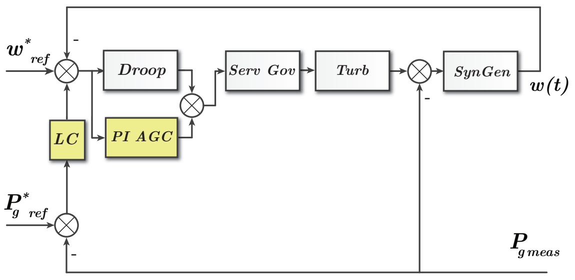

Fig. 3. AGC and load controller loops (highlighted in yellow) added to the simplified frequency control system in [15].

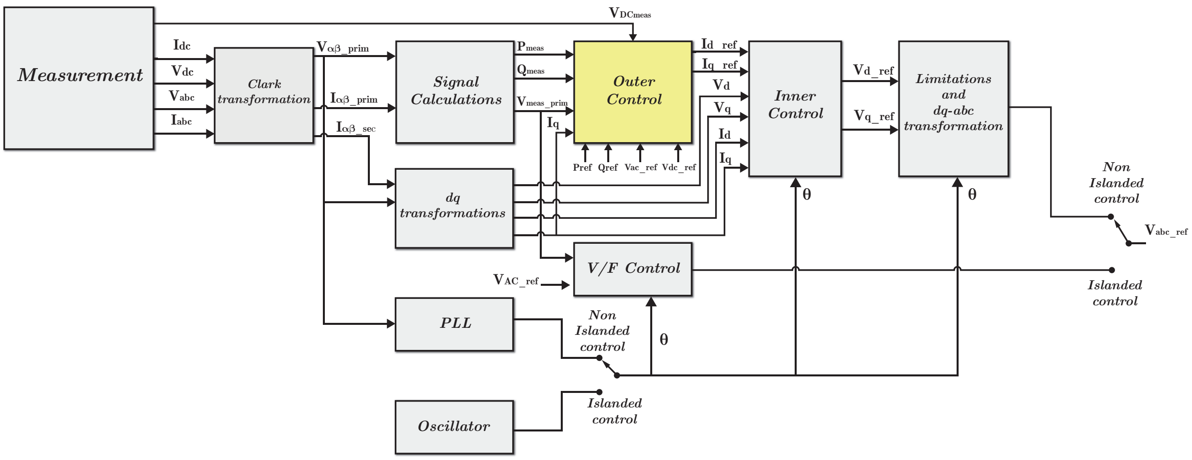

Fig. 4. Main Control Structures implemented based on [13].

PI regulators and proportional controllers are used to regulate the frequency deviations and the active power references of the synchronous machines in a power system. In Fig. 3, the frequency control blocks incorporated in the AC generator model considered [15] are highlighted in yellow.

Fig. 5 shows the power system under study, which is a modified version of the generic two area system presented in [16], where the synchronous machines have been modeled by using a 6^{th}order generator model and the main difference lies on the coupling between the AC networks, which has been based on an MMC-HVDC link connected between Bus 07 and Bus 08 through transformer units P_{CCA} and P_{CCB}, respectively. Furthermore, the respective parameter values for the MMC stations (nominal power, DC voltage level, number of submodules, capacitor and inductances values) were defined based on reference values provided in [10].

In this work, the long term frequency stability study will be assessed by considering a power unbalance generated in AC network A. This power disturbance is produced by a load shedding in the AC network A, specifically $Load\ A1$. This perturbation will generate a 20% power imbalance in power system A which is a criteria used in [21] to study over frequency deviation in a power system.

TABLE I
GENERATORS INERTIAS AND LOAD FLOW DESCRIPTION

Generation-Demand Balance	System Element	Scenarios I & II. Load Flow Conditions (MW)	Scenario I. Generator Inertia (s)	Scenario II. Generator Inertia (s)
Power Generation on Area B	G4	1337	20	6.7
	G3	450	2.5	2
Power Demand on Area B	Load B1	250	N/A	N/A
	Load B2	1000	N/A	N/A
	MMC station 2	500	N/A	N/A
Power Generation on Area A	G2	348	6.7	6.7
	G1	450	2	2
	MMC station 1	462	N/A	N/A
Power Demand on Area A	Load A1	250	N/A	N/A
	Load A2	1000	N/A	N/A

B. Scenario and Case Descriptions

The long-term frequency stability study is assessed by considering two different scenarios. In the first scenario, the configuration of the system under study is adjusted such that the AC network B has more inertia (which represents a system predominated with synchronous machines) and the AC network A has less inertia (representing a power system with more penetration of renewable energy resources). The second scenario represents a futurist situation, where the inertia of power system B has been reduced due to an increment of the renewable energy resources penetration. The inertias of A and B power systems have been assigned equal value.

The generator inertias and the load flow conditions (for the scenarios previously defined) can be observed in the Table 1. Here it can be noted that the load flow conditions are the same for both AC network scenarios, and the AC network B is providing power to the AC network A through the HVDC link in both scenarios as well.

TABLE II
RELATIONSHIP BETWEEN SYSTEM SCENARIOS AND APG CASES

System Scenarios	APG Case I	APG Case II	APG Case III
Scenario I $H_B > H_A$	APG $\Rightarrow$ Deactivated	APG $\Rightarrow$ Bypassed	APG $\Rightarrow$ Activated
Scenario II $H_B = H_A$	APG $\Rightarrow$ Deactivated	APG $\Rightarrow$ Bypassed	APG $\Rightarrow$ Activated

The APG effects on the long-term frequency stability are then addressed by considering three active power gradient cases or APG cases that are explained as follows. In the first APG case, the activation control block (shown in Fig. 2) is not reacting to any frequency system deviation, which is defined in this work as an APG deactivated state. This means that the activation control block is not generating any change on the current active power reference or APG value on the respective converter station. In the second APG case, the activation control block produces simultaneously a change in the active power reference and the APG value on the HVDC link. This change will reduce the active power supplied to the AC network A and it will increase the APG value in such way that the change in the active power reference is directly perceived by the PI regulator in Fig. 2 which is defined in this work as an APG bypassed state. In the third APG case, similar

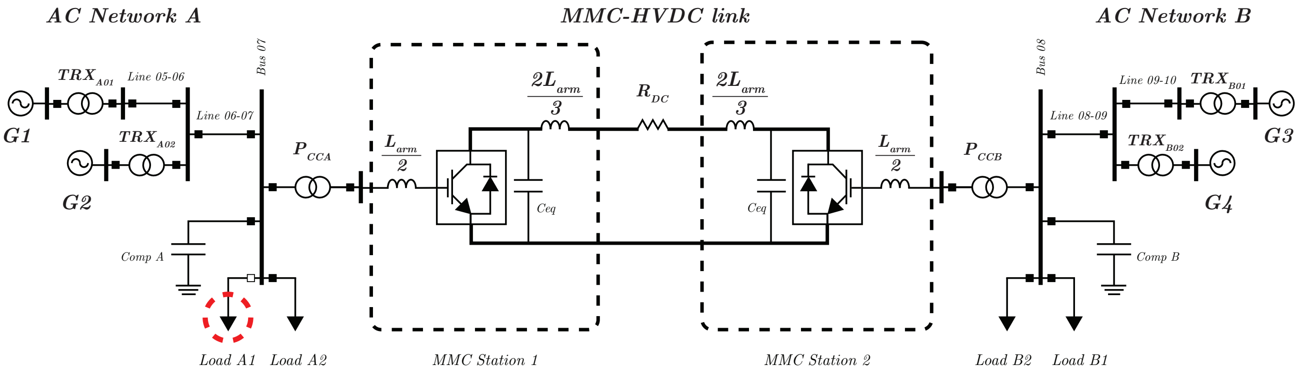

Fig. 5. Generic two area system from [16] coupled by an MMC-HVDC link.

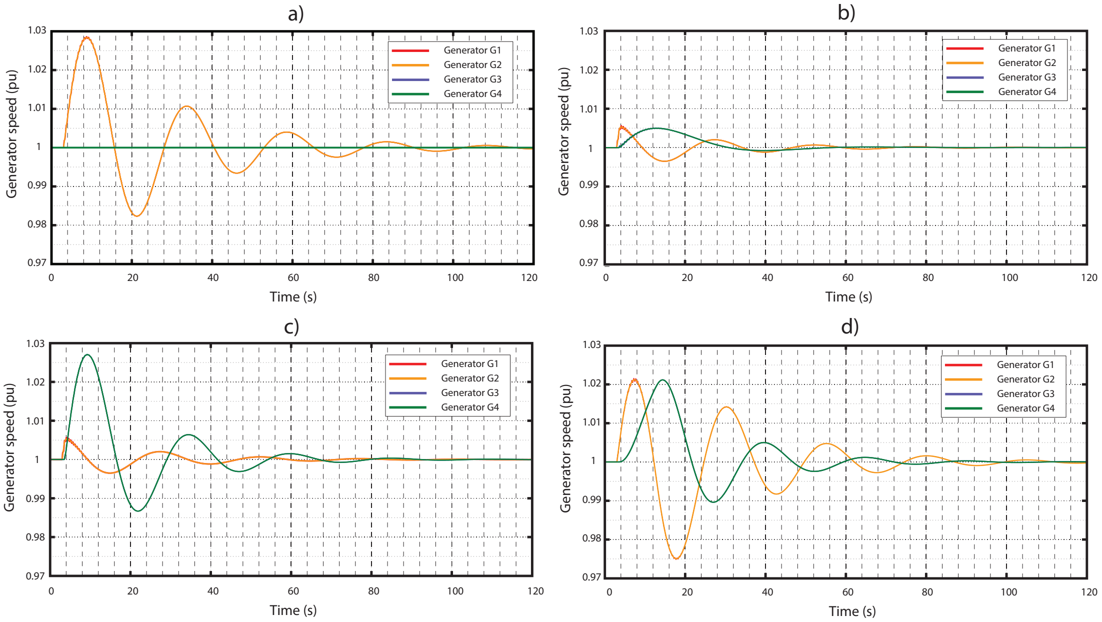

Fig. 6. Frequencies responses after a load shedding (in Load A1) considering two power system scenarios and different APG cases and. a) Scenarios 1 and 2 Case 1 (SC1C1 & SC2C1): Frequency responses of considering no active power reference changes in the HVDC system b) Scenario 1 Case 2 (SC1C2): Frequency responses considering an active power reference change using APG function bypassed. c) Scenario 2 Case 2 (SC2C2): Frequency responses considering an active power reference change using APG function bypassed d) Scenario 2 Case 3 (SC2C3): Frequency responses considering an active power reference change using APG function activated.

to the second one, the HVDC link reacts to the frequency deviation in the AC network A by reducing the active power supplied to it. However, in this case, the activation control block will set up the APG value to compensate the frequency deviation in the AC network A, and simultaneously, to mitigate the effects produced by this compensation in the frequency deviation produced in the AC network B. In this work, this operation mode is defined as an APG active state. Table II shows the relationship between the scenarios and cases previously defined.

C. Results

Simulation results reflect the frequency response of the power systems coupled by the MMC-HVDC link considering the scenarios, cases and the load shedding event defined in the previous sections. These simulation results are shown in Fig. 6. Here the *Load A1* disconnection occurs at 3 s for each simulation result. In the Fig 6a the APG function is deactivated (SC1C1 and SC2C1), which means that the MMC-HVDC link is not providing any frequency support to the AC network A, or in other words, the MMC-HVDC link is behaving as a constant power source in the affected AC network A. In this circumstance, the frequency perturbation is exclusively compensated by the frequency regulators of the synchronous machines in the respective system. Fig 6b shows the frequency response of the first scenario defined and the second APG case (SC1C2). Here, the active power reference in the MMC-HVDC link is reduced 250 MW due to the frequency deviation produced on the AC network A. This active power reference modification is triggered 0.5 s after the load shedding occurs (because of the continuous frequency gradient registered). In this result, the frequency deviation in the AC network A has been reduced significantly regarding the Fig 6a where the APG function was deactivated. In Fig 6b there is also a frequency deviation produced in the AC network B. Nevertheless, the amplitude of the frequency oscillation in system B is smaller than in system A which reveals that the inertia of system B is a relevant factor in the frequency deviation produced by the power imbalance transferred from the AC network A to the AC network B through the MMC-HVDC link. Similarly to Fig 6b, Fig 6c shows the frequency responses of the power systems considering the APG function bypassed (second APG case) but now, the inertias of both power systems are equal (second scenario). In this case, the frequency deviation in the AC network A presents the same frequency deviation observed in Fig. 6b. However, in Fig 6c, the frequency deviation registered in the AC network B is slightly smaller than the frequency deviation registered in Fig 6a for the AC network A. This is because part of the energy contained in the power unbalance (transferred though the MMC-HVDC link) has been consumed by the HVDC cable. The last simulation result shown in Fig 6d presents the frequency deviation of both power systems when their inertias are equal and the APG case is activated (SC2C3). In this configuration, the frequency deviations in the power systems are more sensitive to the APG regulation. In this simulation result, the APG value (27 MW/s) has been set up such the amplitudes of the first swing are similar. Here, the frequency deviation in AC network B has been reduced if it is compared with the frequency deviation of the same power system shown in Fig 6c. However, the frequency deviation in the AC network A has been increased if it is compared with the frequency deviation of the same power system shown in Fig 6c, becoming the APG selection criteria an relevant aspect for the frequency stability of power systems with similar inertias coupled by an MMC-HVDC link.

IV. CONCLUSIONS

In this paper a long-term frequency stability study of two synchronous power systems coupled by an MMC-HVDC link was developed. The active power control scheme of the MMC-HVDC system was adapted in order to assess the active power gradient (APG) influence of the MMC-HVDC link in the long-term frequency responses analyzed. In this assessment, a load shedding of 20% of the total power demand in one of the AC network was considered. Also two different scenarios which contemplate different inertia constants for the AC networks were defined. It was shown that the APG effects in the frequencies responses becomes critical, specially when these AC grids have similar constant of inertia and load levels. Depending on the APG value selected, the power disturbance can be transfered between the power systems through the MMC-HVDC system. This means that the APG setting determines the degree of frequency support that one power system can bring to another across an MMC-HVDC link. The criteria that determine an optimal APG is a topic that is being currently investigated.

V.

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