Grid Support Functionalities based on Modular Multilevel Converters with Synchronous Power Control

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***Abstract*— High voltage direct current (HVDC) transmission networks is one of the most interesting systems for the application of modular multilevel converters. Stability improvement of large interconnected systems is essential which has been largely studied in AC systems but still under development in DC networks.**

This paper presents a control strategy to provide support to the grid against disturbance in a HVDC system implemented with a modular multilevel converter (MMC). The main idea behind this work is to replace the classical power controller by a new control strategy, which emulates the characteristics of a synchronous generator. The control proposed is known as Synchronous Power Control (SPC) and it is able to emulate inertia, damping and droop characteristics required by the grid. To validate this work, simulation results are presented in a HVDC-MMC system connected to a weak grid.

***Index Terms*—High voltage direct current transmission, Modular Multilevel Converter, Synchronous Machine, Synchronous Power Control, Virtual Admittance.**

I. Introduction

Multilevel converters are becoming an interesting configuration in medium and high voltage application due to their large number of output voltage levels and their high power quality. The modular multilevel converter (MMC) is a subfamily of the multilevel converters, and its characteristics makes this topology interesting for high voltage direct current transmission (HVDC) applications, instead of the classical two level voltage source converters [1]. The modularity, high quality of the output voltage, fault operation and capacity of connecting a high voltage in the dc bus, are some characteristics of this converter which are considered attractive for HVDC applications [2].

The large interconnected system increases the complexity to ensure the reliability and the stability of the electrical network, When the HVDC system is connected to a weak grid, the system is not able to work in its optimal operation point [3]. The strength of the electrical network is defined by the short-circuit ratio (SCR), which defines the ability of the system to keep the voltage and the frequency constant at the point of common coupling (PCC) during the injection of reactive and active power. As the SCR represents the behavior of the grid interaction between the electrical network and the generator system, with a lower SCR the grid is weaker and the voltage and frequency variations are higher. On the other hand, with a higher SCR the grid is stiffer and the voltage and frequency variations are lower.

Thus, considering a grid with low SCR, it is necessary to implement a control strategy to fulfill the grid code requirements in order to provide support to the electrical network. For this reason the MMC converter should be robust enough to remain operative in case of faults or unusual operation of the grid and guarantee in all possible situations the stability of the system. In order to fulfill with these requirements it is possible to emulate the features of synchronous generators by appropriately controlling the MMC converter, which contribute to support the transient stability of the grid through virtual inertia and damping.

The distributed generation systems based on converters which emulate the effect of inertia of synchronous generators and provide frequency regulation under grid conditions, have been researched in literature. In [4] the support of a weak grid is implemented through inertia emulation, but this strategy presents some constraints due to limits in load angles and the requirement of a higher dc capacitance to maintain a lower variation of the DC bus voltage. In [5] a virtual synchronous generator (VSG) is proposed in which the PLL is modified to emulate inertia effect to support the grid frequency, but the control strategy does not provide an improvement under short circuit faults.

The works presented in [6] introduce the Synchronous Power Controller (SPC), which represents an enhanced synchronous machine. This control strategy emulates inertia, damping, droop characteristics and providing grid support services under different operation scenarios.

This paper presents a HVDC system based on MMC with the Synchronous Power Control (SPC) introduced in [6]. The idea is to control the current references of the output current control loop to provide grid support funcionalities. The paper structure is organized as follow. Section II introduce the MMC converter and the general control structure. Section

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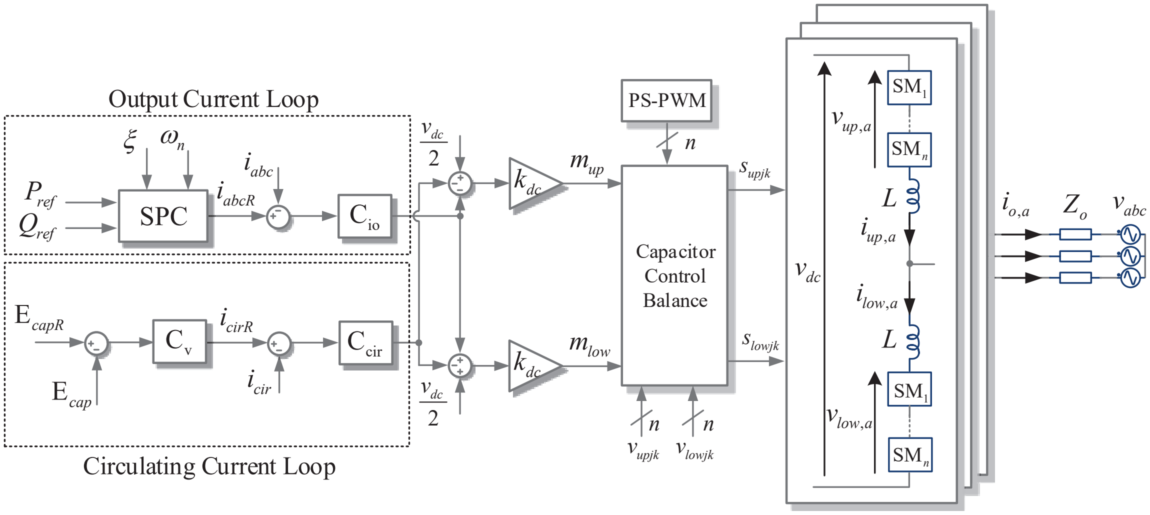

Fig. 1: Three phase Modular multilevel converter and control strategy

III presents the Synchronous Power Controller. Section IV provides simulation results and finally section VI concludes the paper.

II. MMC Converter and Control Structure

The configuration of the MMC consists of several modules connected in series, which is commonly found in literature as a half bridge or a full bridge converter [7]. The series connection of modules is connected to a couple inductors in each arm, and the connection between two of them make up a phase which can be paralleled for several phases.

In HVDC applications, the MMC is considered one the most attractive configurations to be implemented by the industry [8]. The highest degree of modularity, large number of output voltage levels and high voltage in the dc bus are some of the characteristics considered in this converter. In Fig.2, a HVDC configuration with two MMC connected through a dc bus is shown. In this figure MMC1 operates in DC bus voltage control state while being connected to a stiff grid (Grid1) on the AC side through a low frequency transformer. On the other side MMC2 operates in power control state and is connected to a weak grid (Grid2) with a load at the point of common coupling (PCC).

The work presented implements a control strategy to support the weak grid of the HVDC system by means of MMC2.

A. Control Strategy of MMC

The scheme in Fig.1 represents MMC2 converter and its control strategy. It can be observed from the figure that two current control loops generate the modulation indexes of the upper and lower arm. These modulation indexes are adjusted by means of the capacitor control balance to send the switching states of the modules [9].

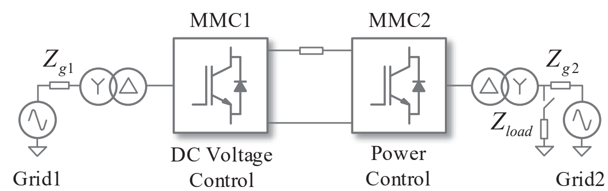

Fig. 2: HVDC configuration based on MMC

In literature several control strategies for the MMC can be found. Some of them use the structure implemented in [10], where the output current loop depends on the power references, and the circulating current loop depends on the energy stored in the capacitors. The definition of both variables are given by:

$$i_{o,i} = i_{up,i} - i_{low,i} \tag{1a}$$

$$i_{circ,i} = \frac{i_{up,i} + i_{low,i}}{2} - \frac{i_{dc}}{3} \tag{1b}$$

Where $i_{o,i}$ is the output current, $i_{up,i}$ and $i_{low,i}$ the upper and lower current arm respectively, and $i_{circ,i}$ the circulating current. The subindice i represents the phase a, b, c.

The equations that represent the dynamic behavior of the MMC are:

$$Ri_{cir,i} + L\frac{i_{cir,i}}{dt} = \frac{v_{dc}}{2} - \frac{v_{up,i} + v_{low,i}}{2} - \frac{i_{dc}}{3} \tag{2a}$$

$$v_{c,i} = -\frac{R}{2}i_{o,i} - \frac{L}{2}\frac{di_{o,i}}{dt} + \frac{v_{low,i} - v_{up,i}}{2} \tag{2b}$$

Equation (2a) is the dynamic model of the circulating current and equation (2b) shows the dynamic of the output current. Both model depend on the coupling inductance L, the resistance R of the arm and the equivalent capacitor voltage of the upper and lower arm.

Assuming that the energy stored in each arm is distributed evenly across each capacitor, the power processed by each arm can be represented as follows:

$$P_{up,i} = \frac{dE_{up}}{dt} = \frac{C_m}{2NV_{dc}} \frac{dv_{up,i}^2}{dt} \tag{3a}$$

$$P_{low,i} = \frac{dE_{low}}{dt} = \frac{C_m}{2NV_{dc}} \frac{dv_{low,i}^2}{dt} \tag{3b}$$

Where N is the number of modules per arm and C_m the capacitance. With the energy control loop is possible to generate the circulating current reference, while the output current references are defined by the synchronous power control.

The novelty of this work is to replace the classical power control by the Synchronous Power Control in order to emulate a synchronous machine and make use of the advantages of supporting the weak grid against different drawbacks.

III. Synchronous Power Control

The control strategy used to generate the output current references is the Synchronous Power Control (SPC). This control method is based on the main operation principle of a synchronous machine, where the relation of magnitude and phase-angle between the internal electromotive force (emf) and grid voltage, determine the active and reactive power flow of the system. Considering this characteristics, it is possible to emulate the behavior of a synchronous machine in the MMC converter in order to control the emf and therefore generate the active and reactive power required.

The connection between the synchronous generator and the grid is represented in Fig.3.a. The synchronous machine is defined by the electromotive force $e(t)$ in series with a impedance RL, while grid voltage is represented by $v(t)$.

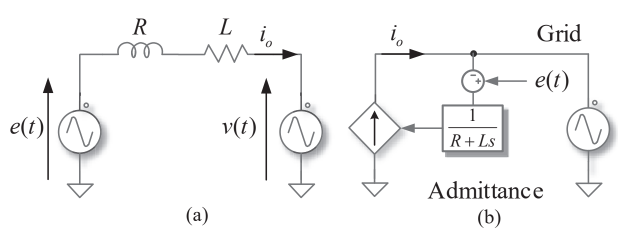

Fig. 3: (a) Representation of a synchronous generator connected to the grid. (b) Virtual admittance implementation in the Synchronous Power Control

From the representation of the synchronous generator connected to the grid, it is possible to find the expression in complex frequency domain of the current injected. This expression is depicted in the equation (4) and shows how the current depends on the difference between the grid and the emf voltages multiplied by the admittance.

$$i(s) = \frac{1}{R + Ls}(v(s) - e(s)) \tag{4}$$

The admittance can be defined as a first order low-pass filter because of the distortion in the voltage difference. The implementation of the admittance concept can be seen in Fig.3.b, where the error between the emf and the grid voltage generates the current reference in the system. This representation is the base of the synchronous power control and the idea of this control strategy is to define a virtual admittance for emulating the behavior of the synchronous machine with the capacity of changing the parameters according to the operation conditions of the system.

A. Power Loop Controller

The SPC control can be divided into three blocks. The power loop controller which is able to generate the virtual synchronous frequency, the reactive power controller which generates the voltage amplitude of the emf and the virtual admittance block. The virtual synchronous frequency is self-synchronized with the electrical grid, and it does not require external synchronization like a Phase-Locked Loop (PLL) or a Frequency-Locked Loop (FLL) [6].

The active power exchange between the synchronous generator and the grid can be represented by means of voltage magnitude and difference of phase-angle between both voltage sources. Considering the electrical characteristic of the synchronous machine, active power generated can be approximated by the equation (5). This expression considers the output impedance of the synchronous machine is mainly inductive [11].

$$P_e = \frac{EV}{X_L}\delta = K_p\delta \tag{5}$$

Variables E and V represent the RMS voltages of the emf and grid respectively, as long as X_L is the output impedance of the virtual admittance provided by the SPC.

In the synchronous machine unbalance between electrical and mechanical torque generates an acceleration or deceleration in the rotor. Considering inertia and damping of the generator, the expression that represents the rotor acceleration is given by.

$$T_m - T_e - D\Delta\omega_s = J\frac{d\Delta\omega_s}{dt} \tag{6}$$

Where J represents the inertia moment, D the damping, $\Delta\omega_s$ the angular speed and T_m - T_e the difference between the mechanical and electrical torque respectively. Using the equation (5) and (6) it is possible to represent the power control loop based on the synchronous machine as represented in Fig.4(a) using the relationship between mechanical and electrical power injected to the grid.

In case of SPC control, the closed loop between angular speed and power difference is replaced by the Power Loop Controller (PLC), which can be designed using the expression

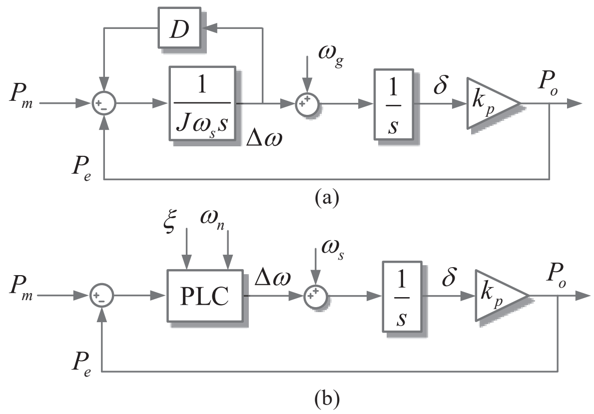

Fig. 4: (a) Active Power control of the synchronous machine, (b) Active Power control of the SPC

of the inertia constant H defined as the kinetic energy at rated speed divided by the nominal power [11]. The transfer function of the closed loop is given by:

$$\frac{\Delta\omega}{\Delta P} = \frac{\omega_s}{2HS_B s + w_s^2 D} \tag{7}$$

The closed loop between the mechanical and the electrical power, can be written as a second order transfer function, which has the expression presented in (8a). This transfer function is defined by means of damping and natural frequency shown in equation (8b) and (8c) respectively.

$$\frac{P_e}{P_m} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{8a}$$

$$\xi = \frac{D\omega}{2}\sqrt{\frac{\omega_s}{2HS_B K_p}} \tag{8b}$$

$$\omega_n = \sqrt{\frac{\omega_s K_p}{2HS_B}} \tag{8c}$$

Both parameters depends on the damping D and the angular speed ω_s of the synchronous generator, which can be used in the SPC to emulate the generator behavior and determines the angular position of the virtual rotor through the phase-angle of the emf. The difference between the phase-angle of the emf and the grid angle gives the δ angle, which allows to calculate the active power injected to the grid by means of the equation 5.

The representation of the power loop controller in the active power control of the SPC is shown in Fig.4.b, where it can be observed that the PLC depends on the damping and the natural frequency. These parameters are defined by the system requirement and not necessarily are tuned with a fixed parameter given by a real synchronous machine. This is due to the fact that the damping action provided by the mechanical rotor in the generator is limited by electrical and mechanical constrains, therefore the synchronous generator does not have a high damping performance. Hence the SPC control can be considered as an enhancement of the synchronous generator.

There are several ways to represent the power loop controller, in [12] it can be observed three different control strategies, where the dynamic performance of each one are analyzed regarding inertia and damping variations. The zero error tracking in steady state operation of the PI controller is an useful characteristic to be considered, for this reason this work implements a PI as a power loop controller. Its expression is represented by.

$$PLC_{PI} = \frac{k_{po}s + k_{io}}{s} \tag{9}$$

Considering the relationship between the mechanical and the electrical power, it is possible to define the proportional and the integral parameters of the PI controller based on the inertia H, the damping ξ and the natural frequency ω_s. These expressions can be written according to the equation 6 by means of.

$$k_{po} = 2\xi\sqrt{\frac{\omega_s}{2HS_B K_p}} \tag{10a}$$

$$k_{io} = \frac{\omega_s}{2HS_B} \tag{10b}$$

Where k_{po} represents the proportional gain and k_{io} the integral constant. It can be noticed that by changing inertia, damping, natural frequency and virtual admittance (K_p) it is possible to modify the proportional gain, whereas the integral constant only depends on the inertia and the natural frequency.

B. Reactive power controller

The variation of the electromotive force amplitude $e(t)$ has a direct relation with the reactive power injected. Therefore this power control has the capacity of keeping the emf voltage amplitude in a specific level required. The PI controller is the structure selected to implement this control loop, and its architecture is the same as in 9.

As it was mentioned before, SPC has a similar behavior of the synchronous generator. Therefore with the phase-angle generated by the power control loop and the emf voltage amplitude determinated by the reactive power control, the three phase emf are generated through a voltage controlled oscillator (VCO), which is compared to the grid voltage and later used by the transfer function of the virtual admittance to generate the current references. The general scheme of the SPC is shown in the Fig.5, where it can be observed that the SPC system depends on the power references, damping and natural frequency provided by the requirements.

C. Frequency and Voltage Droop Controller

The integration of distributed generation systems is conditioned to fulfill grid code requirements of the grid operator. Stability of the system should be supported under different frequency and voltage conditions, due that, frequency and voltage droop controller are required in the control strategy to support these eventually problems [13].

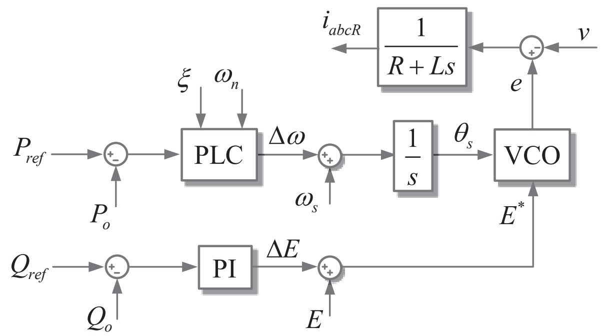

Fig. 5: Synchronous Power Control considering the active and reactive power control

IV. Simulation Results

The configuration described in Section II is simulated to validate the proposed control strategy in the HVDC-MMC system. The main parameters are presented in the Table I and both MMC have the same characteristics related to the coupling indutance and number of modules per arm. The system is evaluated by three different scenarios. The first one shows the response of a weak grid when a load is connected at the PCC. The second test presents a short circuit of 95% in the three phases, and the third test evaluate the behavior of the control strategy against a grid frequency change.

TABLE I: Simulation Parameters

Parameters	Symbol	Value
Grid1 Voltage	v_{g1}	95kV
Grid1 frequency	f_{g1}	60Hz
Grid2 Voltage	v_{g2}	85kV
Grid2 frequency	f_{g2}	50Hz
DC bus Voltage	v_{dc}	160kV
Nominal Power	S_B	20MVA
Short Circuit Ratio	SCR	5
Virtual Resistance [p.u.]	R	0.1
Virtual Inductance [p.u.]	L	0.3
Damping Coefficient [p.u.]	ξ	0.7
Switching Frequency	f_c	1000
Inertia	H	5s

A. Load Connection

The performance of the test is shown in Fig.6. The idea is to evaluate the system when there is a sudden change in the load connected close at the PCC. The load of 20MVA with a power factor of 0.9 is connected at t=1.4s. As it can be noticed in Fig.6(a), the voltage of the PCC decreases its amplitude, but due to the characteristics of the SPC, the active and reactive power injected present a change for a short time in order to support the voltage sag. After the transient, the active power return to its reference value and the reactive power keeps its value because of the Q-V droop implemented in the control. The effect of the power change can be observed in the output and circulating current (Fig.6(d) and Fig.6(e) respectively),

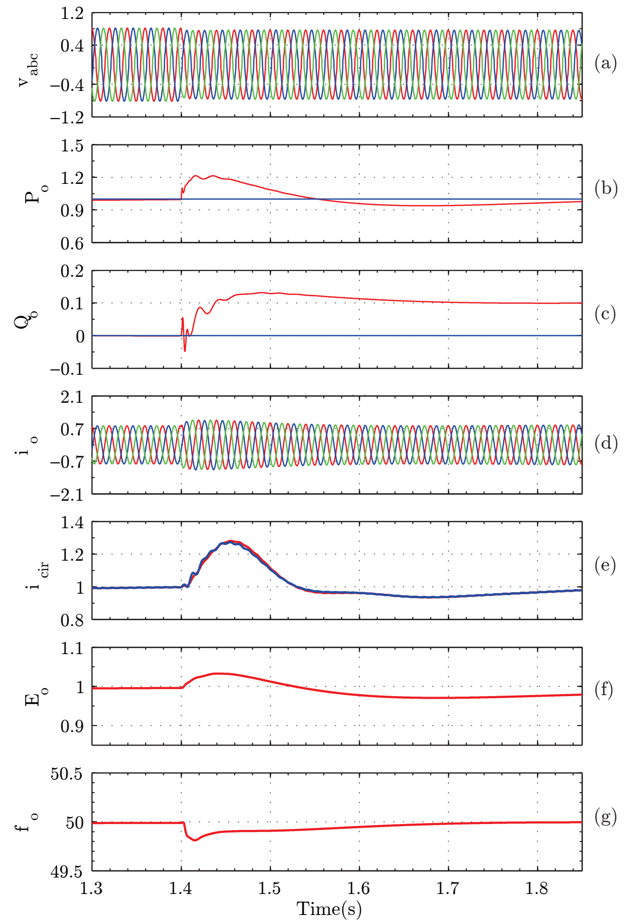

Fig. 6: Simulation results when a load is connected. (a) Grid voltage, (b) Output active power, (c) Output reactive power, (d) Output current, (e) Circulating current, (f) Electromotive force (emf), (g) virtual synchronous frequency

where it can be shown an increase in both currents. The fig.6(e) and Fig.6(f) show the response of the electromotive force (emf) and the virtual synchronous frequency of the power loop controller. Since the drop voltage at the PCC produces a power change, the virtual frequency and the voltage amplitude of the emf change to compensate this effect.

B. Short circuit

Fig.7 shows the response of the system when there is a short circuit in the grid. Between 1.5s and 2s, the amplitude of the electrical network decreases to 95% of nominal value because of a short circuit. The plots in Fig.7(a) shows the behavior of the voltage at the PCC and it can be noticed that the control strategy is able to support the grid against this issue. The active power decrease meanwhile the reactive power increase to keep the voltage, thus the MMC keeps injecting current to the grid. Fig.7(d) and Fig.7(e) depict the increase in the output current and a decrease in the circulating current due to the active and reactive power changes. It is important to highlight that this performance is achieved without any frequency and voltage droop controller.

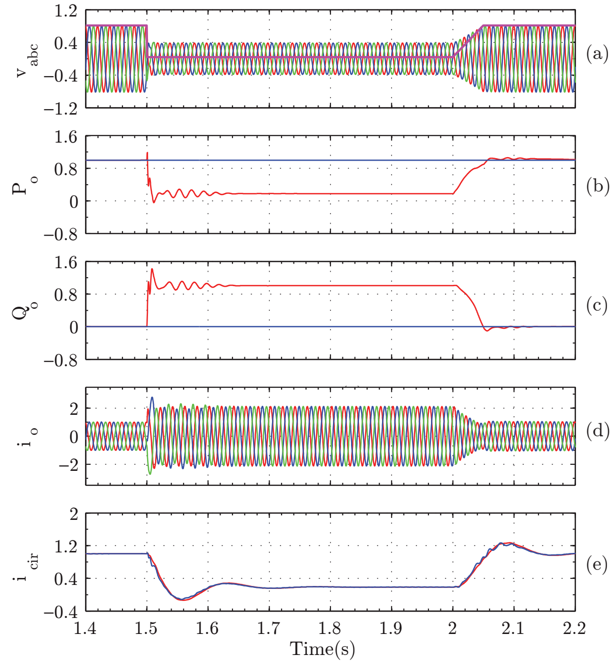

Fig. 7: Short circuit in the grid. (a) PCC Voltage. (b) Output active power. (c) Output reactive power. (d) Output current. (e) Circulating current.

C. Grid frequency change

The variation in the grid frequency is depicted in Fig.8. In this case the frequency is reduced gradually at 1.2secs from 50Hz to 49.5Hz in 0.3secs then maintains this value for 0.5secs and returns back to 50Hz gradually in 0.3secs. The behavior of the active and reactive power are shown in Fig.8(b) and Fig.8(c) respectively, meanwhile the virtual synchronous frequency is depicted in Fig.8(d). Since active power has a direct effect on the frequency, its value presents a higher change with the grid frequency change, as long as the reactive power is close to 0. Furthermore it can be observed that the virtual synchronous frequency presents a similar behavior of the grid frequency.

V. Conclusion

This paper presents a control strategy to support a HVDC system connected to a weak grid. The HVDC is based on the modular multilevel converter and the control used in the output current loop is called Synchronous Power Control. The inertia, damping and droop effect emulate a synchronous machine behavior which is an interesting strategy to be used in many applications. The different scenarios presented in this work demonstrate that the active and reactive power changes depends on the frequency and voltage amplitude in the grid, and their responses are defined by the parameters of the power loop controller and the reactive power control of the SPC.

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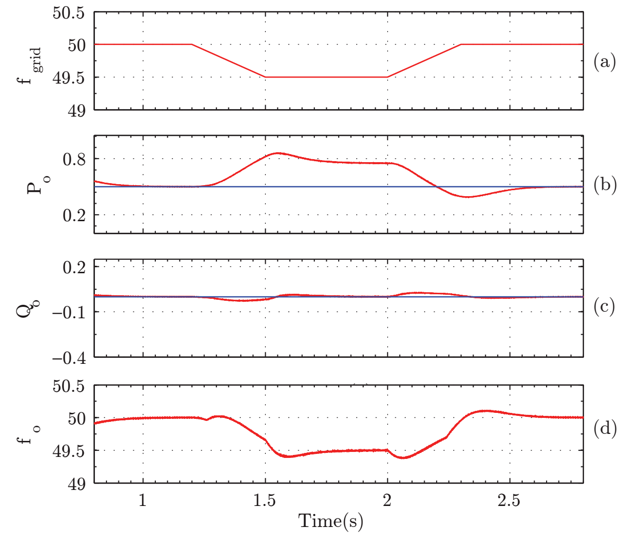

Fig. 8: Frequency change. (a) Grid frequency. (b) Output active power. (c) Output reactive power. (d) Virtual synchronous frequency.