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Interconnection of two very weak AC systems by synchronverter based HVDC

¹Raouia AOUINI ²Bogdan MARINESCU ¹Khadija BEN KILANI ¹Mohamed ELLEUCH

¹University of Tunis El Manar, ENIT- L.S.E.-LR 11 ES 15-BP 37-1002 Tunis le Belvédère, Tunisia

²SATIE-ENS Cachan, 61 Avenue du Président Wilson 94235 Cachan Cedex, France

and IRCCyN-Ecole Centrale Nantes, BP 92101 • 1, rue de la Noë, 44321 Nantes Cedex 3 • France

Email: aaouinii@yahoo.com, bogdan.marinescu@irccyn.ec-nantes.fr, khadijakilani@yahoo.fr, melleuch2008@gmail.com

Abstract-- In this paper, the HVDC emulation by the synchronverter concept is investigated for interconnection of two very weak AC systems. A specific tuning method for the parameters of the regulators based first on the sensitivity analysis of the system poles to the control parameters and, next, on their placement using residues. The use of the synchronverter control allowed us to improve the dynamic transmission capacity of a HVDC connection of two weak AC systems. This improvement is analyzed both from the point of view of the emulation that the synchronverter provides and from the dynamic (control) point of view. In addition to the analysis of the stability and capacity, the proposed control structure is also compared with the vector current control in terms of dynamic performances. The simulations tests in Matlab/Simulink are done with two very weak AC systems with a short-circuit ratio (SCR) of 1 interconnected by a HVDC line.

Index Terms-- HVDC, synchronverter, regulator parameters tuning, stability

I. INTRODUCTION

For High Voltage Direct Current (HVDC) transmission, the strength of the AC system is important for normal operation [1]. An AC system can be considered as weak either because its impedance is high or its inertia is low. A typical high-impedance system is when an HVDC link is terminated at a weak point of a large AC system where the short-circuit capacity of the AC system is low. Substantial research has been performed in this field [1]–[3]. The most outstanding contribution on this subject is [2], which recommends to use short-circuit ratio (SCR) as a description of the strength of the AC system relative to the power rating of the HVDC link. Compared to the conventional thyristor-based HVDC, the Voltage Source Converter (VSC) based HVDC has a number of technical merits: reactive-power support to the AC system, possibility to connect to very weak ac systems and black-start capability [4, 5]. Examples of such applications can be found when an HVDC link is powering an island system, or if it is connected to a wind farm.

Several control methods of VSC-HVDC have been proposed. Among them, vector-current control has been mostly investigated [6]. However, some difficulties have been

experienced by VSC-HVDC based on vector-current control in weak AC system connections [8], [11]. First, reference [8] shows that the maximum power that a VSC-HVDC link using vector current control can transmit to the AC system with SCR = 1.0 is 0.4 p.u. Next, the recently proposed synchronverter concept has been adapted to the converters of a VSC-HVDC link [12]. The concept of the synchronverter control is to mimic the behavior of a synchronous generator (SG) along with its voltage and frequency regulations [13]. More specifically, the sending-end rectifier emulates a synchronous motor (SM) and the receiving end inverter emulates a synchronous generator (SG). This resulting Synchronverter based HVDC was called SHVDC.

In this paper, the SHVDC system is tested for the interconnection of two very weak AC systems. At the tuning stage, the SHVDC control allows one to analytically take into account dynamic specifications to obtain better dynamic performances than the vector control. The impact of the control parameters and the inertia emulation on the dynamic transmission capacity of a HVDC connection of two weak AC systems is analyzed. The rest of the paper is organized as follows: in Section II, the SHVDC structure is recalled. An analytic method to tune the parameters of the controllers of the SHVDC in order to meet the desired performances is given in Section III, while validation tests are presented in Section V.

II. SYNCHRONVERTER BASED HVDC CONNECTED TO WEAK AC SYSTEMS

Fig. 1 shows the main-circuit diagram of a VSC-HVDC converter connected to an AC system. L_s and R_s are the inductance and resistance of the phase reactor of the VSC, and L_g and R_g are the inductance and resistance of the AC system. C_f is the AC capacitor connected at the point-of-common-coupling (PCC). The bold letter symbols, E , V and e represent the voltage vectors of the AC source, the PCC and the VSC. P and Q are the active power and reactive power generated by VSC to the AC system. The converters of the HVDC line are designed to emulate synchronous machine. The synchronverter proposed in [13] is an inverter of which regulations are chosen such that the resulting closed-loop mimics the behavior of a conventional synchronverter generator (SG).

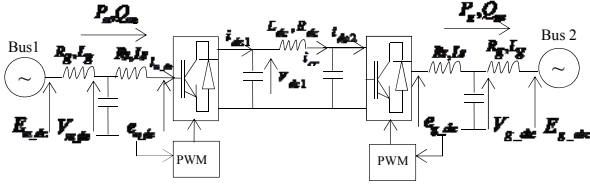


Fig. 1. Two terminal HVDC-VSC link

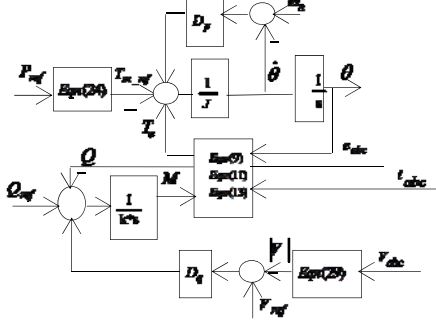


Fig. 2. Model of the synchronverter electronic parts [13]

As a result, the DC power is sent from the rectifier emulating a synchronverter motor (SM) to the inverter working as SG [12]. The resulting system in Fig. 1 is called Synchronverter High-Voltage Direct Current (SHVDC) [12].

A. Modeling of AC systems

The phase terminal voltage of the SG and SM are $V_{g_abc} = [V_{ga} \ V_{gb} \ V_{gc}]^T$, $V_{m_abc} = [V_{ma} \ V_{mb} \ V_{mc}]^T$ respectively

$$V_{g_abc} = -R_s i_{g_abc} - L_s \frac{di_{g_abc}}{dt} + e_{g_abc}, \quad (1)$$

$$V_{m_abc} = R_s i_{m_abc} + L_s \frac{di_{m_abc}}{dt} + e_{m_abc}. \quad (2)$$

The SHVDC given in Fig. 1 is connected to the grid via the impedance (L_g, R_g) such that

$$V_{g_abc} = \frac{1}{C_f s} (i_{g_abc} - i_{g_123}), \quad (3)$$

$$i_{g_123} = \frac{1}{(R_g + L_g s)} (V_{g_abc} - E_{g_abc}), \quad (4)$$

$$V_{m_abc} = \frac{1}{C_f s} (i_{m_123} - i_{m_abc}), \quad (5)$$

$$i_{m_123} = \frac{1}{(R_g + L_g s)} (E_{m_abc} - V_{m_abc}). \quad (6)$$

where $i_{g_abc} = [i_{ga} \ i_{gb} \ i_{gc}]^T$, $i_{m_abc} = [i_{ma} \ i_{mb} \ i_{mc}]^T$, are respectively the stator phase currents of the SG and the SM, L_s, R_s are, respectively, the inductance and the resistance of the stator windings and $e_{g_abc} = [e_{ga} \ e_{gb} \ e_{gc}]^T$, $e_{m_abc} = [e_{ma} \ e_{mb} \ e_{mc}]^T$ are respectively the back emf of the SG and the SM.

B. Characteristics of weak AC systems

A weak AC system is typically characterized by its high impedance [2]. As the AC-system impedance increases, the voltage magnitude of the ac system will become ever more sensitive power variations of the HVDC system. This difficulty is usually measured by the short-circuit ratio (SCR),

which is ratio of the AC-system short-circuit capacity versus the rated power of the HVDC system. SCR is directly related to the AC system inductance. According to [2], SCR is defined as

$$SCR = \frac{S_{ac}}{P_{dN}} \quad (7)$$

where S_{ac} is the short-circuit capacity of the AC system including the VSC at the PCC bus, while P_{dN} is the rated dc power of the HVDC link.

Based on this parameter, the AC system is considered strong or weak. If the $SCR > 3.0$ the AC system is considered strong and control systems stability and robustness is not a problem. If $SCR < 3.0$, the AC system is considered weak.

The short-circuit capacity of the AC system can be expressed as

$$S_{ac} = \frac{|V|^2 (L_g + L_s)}{\omega L_g L_s} \quad (8)$$

where ω is the angular frequency of the ac system, $|V|$ is the voltage magnitude of the PCC, and the resistances R_c and R_g have also been neglected.

C. Synchronverter based HVDC

The SHVDC system is a SM/SG connected by a DC line. In Fig. 1 and Fig. 2 we depict respectively: (i) the power part of the SG/SM which consists of the inverter/rectifier plus LC filter (all equations are presented in the Appendix 1) (ii) the controls which are ensured by the electronic part.

The frequency droop loop included in the SHVDC structure is defined by the following equations

$$T_{gn} = T_{gn_ref} + D_{gp} (\omega_n - s \theta_g), \quad (9)$$

$$T_{mn} = T_{mn_ref} + D_{mp} (\omega_n - s \theta_m), \quad (10)$$

The SG (respectively the SM) thus shares load with the other generators of the AC grid to which it is connected in proportion with the static droop coefficient D_{gp} (respectively D_{mp}). T_{gm_ref} is the mechanical torque applied to the rotor of the SG and it is generated by a PI controller as shown in Fig. 2 to regulate the real power output P_g . In the SM case, T_{mm_ref} is generated by a DC voltage control for power balance.

$$T_{mn_ref} = (k_{p_vt} + \frac{k_{i_vt}}{s}) (V_{d_ref} - V_{d1}), \quad (11)$$

$$T_{gn_ref} = (k_{p_Pg} + \frac{k_{i_Pg}}{s}) (P_g - P_{g_ref}). \quad (12)$$

The reactive power Q_{gm} (respectively Q_{mm}) is controlled by a voltage droop control loop using a voltage droop coefficient D_{gq} (respectively D_{mq}), in order to regulate the field excitation M_g (respectively M_m), which is proportional to the voltage generated.

$$Q_{gm} = Q_{g_ref} + D_{gq} (V_{g_ref} - V_g), \quad (13)$$

$$Q_{mm} = Q_{m_ref} + D_{mq} (V_{m_ref} - V_m). \quad (14)$$

$$M_g = \frac{1}{k_g s} (Q_{gm} - Q_{gc}), \quad (15)$$

$$M_m = \frac{-1}{k_m s} (Q_{nm} - Q_{me}), \quad (16)$$

where V_g (respectively V_m), is the output voltage amplitude is computed by

$$V_g = \frac{2}{\sqrt{3(V_{ga}V_{gb} + V_{ga}V_{gc} + V_{gb}V_{gc})}}, \quad (17)$$

$$V_m = \frac{2}{\sqrt{3(V_{ma}V_{mb} + V_{ma}V_{mc} + V_{mb}V_{mc})}}. \quad (18)$$

III. TUNING OF THE SHVDC PARAMETERS

The SHVDC parameters should be tuned simultaneously and in a coordinated way such that the global stability performances of HVDC are ensured i.e.:

- satisfy HVDC local dynamics. The SHVDC parameters are calculated to reach desired modes starting from HVDC specifications control. The connections between the dynamics of interest and the modes are based on the participations factors [14].

- enhance the transient stability of the neighboring AC system. This is done such that the dynamics of the neighbor zone are taken into account at the synthesis stage via the oscillatory modes. The gains of the SHVDC controllers are computed to damp these modes and thus to reduce the swing of the zone.

For this tuning, the SHVDC shown in is put into the feedback system structure presented in Fig. 3 where $H(s)$ is the linear approximation of the system in Fig.1. All control parameters are grouped in the following diagonal matrix and tuned based on the following result.

$$K(s,q) = \text{diag}(D_{gp}, D_{mp}, K_{p_vdk}, K_{i_vdk}, D_{sq}, D_{mq}, K_{p_p_e}, K_{i_p_e}) \quad (19)$$

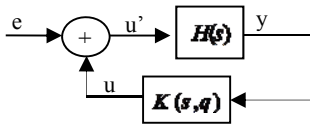


Fig. 3. Feedback system

Proposition [14]: The sensitivity of a pole λ of the closed-loop in Fig. 2 with respect to a parameter q of the regulator K_{ii} is

$$\frac{\partial \lambda}{\partial q} = r_\lambda \frac{\partial K_{ii}(s,q)}{\partial q} \quad (20)$$

where r_λ is the residue of $H_{ii}(s)$ at pole λ .

Note that, for our case, (19), $\left. \frac{\partial K_{ii}(s,q)}{\partial q} \right|_{s=\lambda} = 1$.

The contribution of each control gain in the shift of the pole is

$$\lambda_i = \lambda_i^0 + \sum_{j \in \Lambda} r_{ij} K_j, \quad (21)$$

where λ_i^0 is the initial (open-loop) location of the pole λ_i and r_{ij} is the residue of $H_{ij}(s)$ in λ_i . Finally, the pole placement is the solution of the following optimization problem

$$\{K_j^*, j = 1..8\} = \arg \min_{K_j} \sum_i \|\lambda_i^* - \lambda_i\|^2, \quad (22)$$

where λ_i is given by (22) [12].

IV. SIMULATIONS AND INTERPRETATIONS

The SHVDC structure is investigated in this section on the simple system of Fig. 1. A 200 MW, ± 100 kV VSC-HVDC link is used to interconnect two very weak AC systems, having equal SRC=1. Simulation tests are performed using MATLAB SIMULINK software. The performances of tuned SHVDC parameters technique presented in Section 3 and the classic vector control are tested and compared for VSC-HVDC links connected to weak ac systems. The two controllers are tuned to satisfy the same performance specifications of a HVDC link.

A. Results with the vector current control

For weak grid connection, the d-q inner current of vector control was provided by a PI-type active power controller for the I_d component and by a PI-type AC voltage controller for the I_q component. The vector current control parameters are obtained to meet HVDC specification in Appendix 2. The SCR of the AC system imposes a theoretical limitation on the maximum power that the VSC-HVDC system is possible to transmit to or from the AC system. For instance, in [8] it is shown that it is not possible to operate a VSC with vector control at a higher power than approximately 0.4 p.u if the SCR of the AC systems are 1.0. Indeed, Fig. 4.a and b show poor performance of the vector current control and the maximum power is 0.4 p.u in this case. In addition, the filter-bus voltage is more sensitive to power variation of the VSC-HVDC link.

B. Results with the SHVDC control technique

For the same case of weak interconnection, the SHVDC structure of Fig.1 is analyzed. The SHVDC parameters are tuned with the control method presented in section III. First, desired locations λ_i^* were computed for each pole λ_i starting from control specifications given in Appendix 2. The desired poles and the results for the dynamics of interest for the SHVDC are given in Table I. The optimal parameters K_i in the first column of Table III were obtained with (22) solved for the desired locations in Table I. Fig. 5.a shows that the SHVDC structure enables a maximum power transmission of 0.82 p.u. As a consequence, the SHVDC control allows us to improve the dynamic power transmission capacity of a HVDC link of two weak AC systems. It is noted that better dynamic responses are provided with the new coordinated control. Fig. 5.b shows that the variations of the filter-bus voltage are much smaller when using the SHVDC control in response to the same power changes.

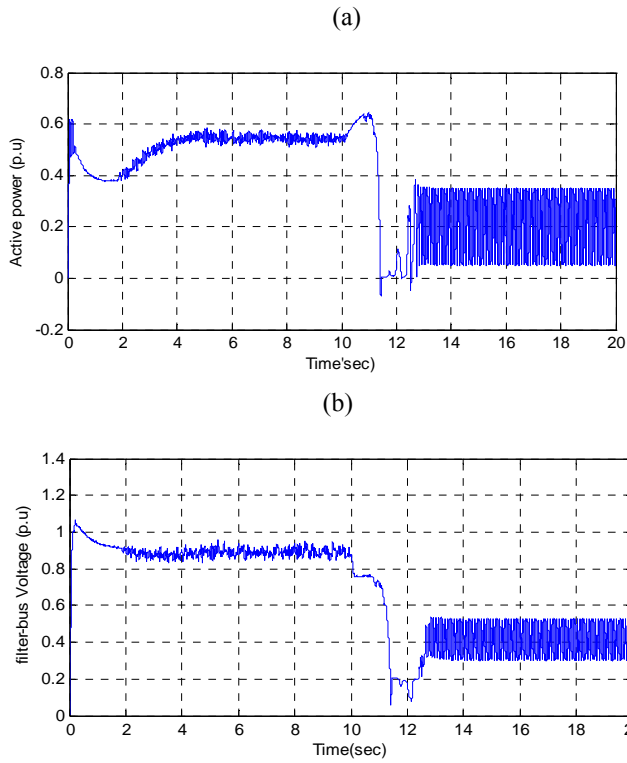


Fig. 4. Step response of P_{g_ref} for vector current control at $P_g = 0.4$ p.u. with SCR = 1.0. (a) Response of P_g to a +0.1 step in P_{g_ref} (p.u.); (b) Response of filter bus voltage to +0.1 step change in P_{g_ref} (p.u).

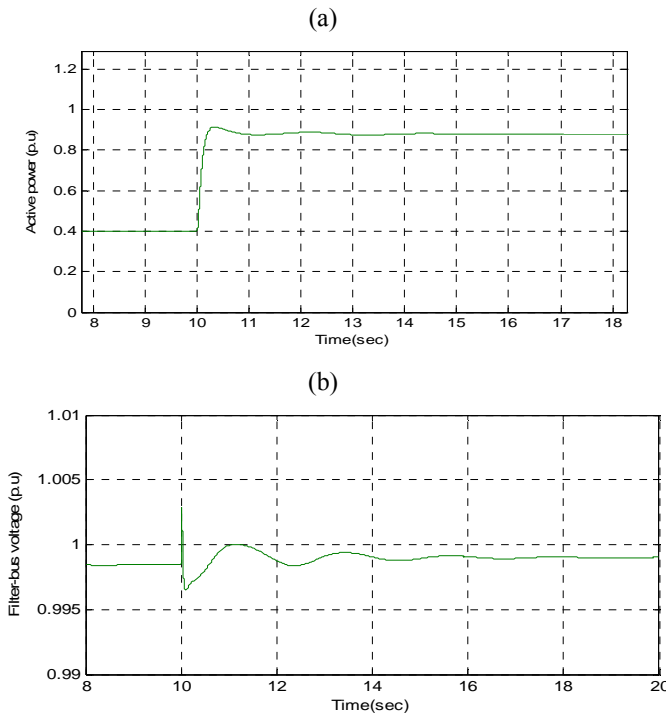


Fig. 5. Step response of P_{g_ref} for SHVDC control at $P_g = 0.4$ p.u. with SCR = 1.0. (a) Response of P_g to a +0.44 step in P_{g_ref} (p.u.); (b) Response of filter bus voltage to +0.1 step change in P_{g_ref} (p.u).

TABLE I
DESIRED MODES MEETING THE HVDC SPECIFICATIONS
CASE 1: H=3.2 s

Dynamics interest	of	λ_i^0	λ_i^*	r_{λ_i}
Voltage V_m		-5.2	-10	-0.26
Voltage V_g		4.2	-10	-0.19
Active Power P_m		$2.8 \pm 5.3i$	$-21 \pm 21.4i$	$-0.07 \pm 0.1i$
Active Power P_g		-2.8 ± 5.3	$-21 \pm 21.4i$	$-0.05 \pm 0.1i$
Reactive Power Q_m		-5.2	-10	-0.543
Reactive Power Q_g		4.2	-10	-0.19

TABLE II
PARTICIPATION FACTORS
CASE 1: H=3.2 s

%	$P_{a_V_m}/Q_m$	$P_{a_P_m}$	$P_{a_V_g}/Q_g$	$P_{a_P_g}$
λ_{V_m/Q_m}^0	41.29	34.1	0.34	0.16
$\lambda_{P_m}^0$	29	66.66	0.15	0.22
λ_{V_g/Q_g}^0	0.16	0.2	31.06	42.57
$\lambda_{P_g}^0$	0.25	0.2	34.9	57.35

TABLE III
SHVDC PARAMETERS

K	SHVDC optimal parameters for case 1	SHVDC optimal parameters for case 2
D_{mp}	15.06	10.38
D_{mq}	84.12	84.07
$K_{p_V_{dc}}$	0.38	0.41
$K_{i_V_{dc}}$	0.87	0.81
D_{gp}	200.8	2250.52
D_{gq}	375	400
$K_{p_P_g}$	32.33	30.27
$K_{i_P_g}$	20.45	24.35

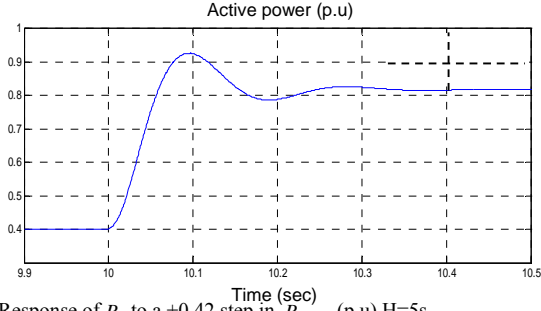


Fig. 6. Response of P_g to a +0.42 step in P_{g_ref} (p.u) $H=5s$

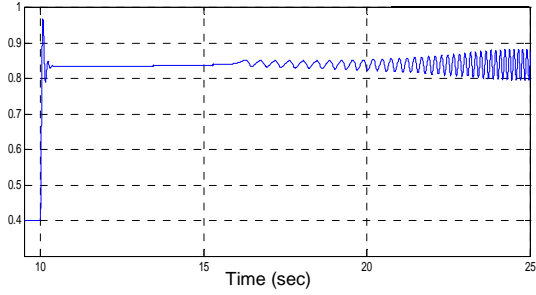


Fig. 7. Response of P_g to a +0.43 step in P_{g_ref} (p.u) with an inertia $H=5s$

C. Effect of the Inertia emulation

The advantage of the SHVDC structure is to mimic the closed-loop of a standard synchronous generator. Thus inertia emulation is provided, and it is well known that the inertia has a positive impact on the stability of the AC system. For this reason, we have analyzed the SHVDC structure for two different constant inertias:

- case 1: $h=3.2$ s (case in section V.B).
- case 2 : $h=5$ s.

For the two cases, we have placed the poles of the closed-loop at the same desired locations of dynamics of interest (Table I). For case 2, the obtained tuned SHVDC parameters K_2 are given in the second column of Table III.

For the same case 2, Table IV presents the initial location λ_i^0 of λ_i for each dynamic of interest and the final location λ_i^* . The response of the SHVDC of case 2 to a 0.42 p.u step changes in active power reference is given in Fig. 6. The system is unstable for a greater step in power reference (Fig.7). As a consequence, the maximum power capacity for case 2 is equal also to 0.82 p.u as for the case 1. We can thus conclude that the improvement of the dynamic power capacity is due to the control manner (the way on which the closed-loop poles are placed) and not to the inertia emulation provided by the SHVDC structure.

D. AC-System Faults

The fault ride-through capability of the VSC-HVDC link is tested by applying three-phase ac-system faults with 0.2 s duration at the rectifier station. Fig. 8.a and b show the response of active power and the filter bus voltage. Again better dynamic performances are obtained with the proposed controller: the transient oscillations with the SHVDC control are more damped.

TABLE IV
DESIRED MODES MEETING THE HVDC SPECIFICATIONS
CASE 2: $H=5$ s

Dynamics interest	of	λ_i^0	λ_i^*	$r_{\lambda_i^*}$
Voltage V_m		-4.2	-10	-0.16
Voltage V_g		3	-10	-0.3
Active Power P_m		$5.1 \pm 8.3i$	$-21 \pm 21.4i$	$-0.03 \pm 0.1i$
Active Power P_g		-1.8 ± 8.3	$-21 \pm 21.4i$	$-0.01 \pm 0.1i$
Reactive Power Q_m		2.6	-10	-0.5
Reactive Power Q_g		1.36	-10	-0.2

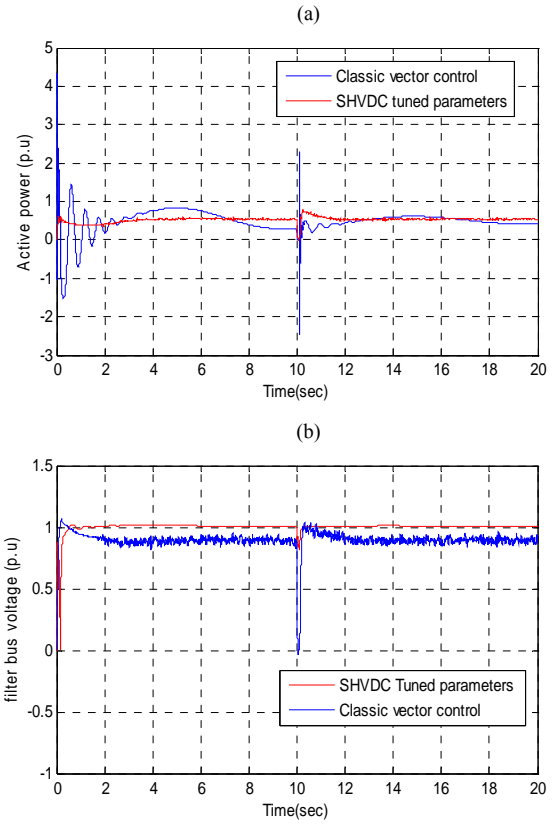


Fig. 8. Responses to 100 ms short circuit at the rectifier station. (a) Response of P_g ; (b) Response of filter bus voltage.

V. CONCLUSION

In this paper, a HVDC link has been emulated using the synchronverter concept. A control strategy of the converters has been proposed based on a specific tuning method which uses, the sensitivity analysis of the system poles with respect to the control parameters. The control strategy has been tested for the interconnection of two very weak AC systems. Better results than the vector current control were obtained (i) better dynamic performances because this approach allows one to analytically take into account dynamic specifications at the tuning stage. (ii) better dynamic transmission capacity of the

HVDC connection in the sense that the link capacity under stability constraints is higher than the one obtained when using the standard vector control. This improvement of the dynamic transmission power is due to the way in which the SHVDC parameters are tuned and not to the inertia emulation provided by the SHVDC structure. The advantage of this emulation is to get on a structure well-known by the operators (standard synchronous generator plus its standard voltage and frequency regulators). However, this kind of tuning under emulation is under optimal in the sense that the constraints to keep the structure of the classical generators and their regulations imposed by the synchronverter principle limits the performances of the resulting closed-loop.

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VII. APPENDIX

APPENDIX 1: POWER PART OF THE SHVDC SYSTEM

As shown in Fig. 2, the SHVDC include the mathematical model of a three-phase round-rotor synchronous machine described by

$$\dot{\theta}_g = \frac{1}{J_g}(T_{gm} - T_{ge} - D_{gp} s \theta_g), \quad (1)$$

$$\dot{\theta}_m = \frac{1}{J_m}(T_{me} - T_{mm} - D_{mp} \dot{\theta}_m), \quad (2)$$

$$T_{ge} = M_g \langle i_{g_abc}, \tilde{\sin} \theta_g \rangle, \quad (3)$$

$$T_{me} = M_m \langle i_{m_dc}, \tilde{\sin} \theta_m \rangle, \quad (4)$$

$$e_{g_abc} = M_g s \theta_g \tilde{\sin} \theta_g, \quad (5)$$

$$e_{m_dc} = M_m s \theta_m \tilde{\sin} \theta_m, \quad (6)$$

$$P_g = M_g s \theta_g \langle i_{g_abc}, \tilde{\sin} \theta_g \rangle, \quad (7)$$

$$Q_{ge} = -M_g s \theta_g \langle i_{g_abc}, \tilde{\cos} \theta_g \rangle, \quad (8)$$

$$Q_{me} = M_m s \theta_m \langle i_{m_dc}, \tilde{\cos} \theta_m \rangle, \quad (9)$$

$$P_m = M_m s \theta_m \langle i_{m_dc}, \tilde{\sin} \theta_m \rangle. \quad (10)$$

where T_{gm} and T_{mm} are, respectively, the mechanical torque applied to the rotor of the SG and the SM. T_{ge} and T_{me} are, respectively, the electromagnetic torque applied to the rotor of the SG and the SM. θ is the rotor angle, J_g and J_m are the combined moment of inertia of generator and turbine.

$s=d/dt$ is the derivation operator. P_g (respectively P_m) and Q_g (respectively Q_m) are the active and the reactive power, respectively, of the SG (respectively of the SM).

M_g and M_m are, respectively, the field excitation of the SG and the SM.

The equations of $\tilde{\sin} \theta$ and $\tilde{\cos} \theta$ are

$$\tilde{\sin} \theta = \begin{bmatrix} \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix}^T \quad (11)$$

$$\tilde{\cos} \theta = \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \end{bmatrix}^T \quad (12)$$

The operator $\langle \cdot, \cdot \rangle$ denotes the conventional inner product in \mathbb{R}^3 .

APPENDIX 2 : VSC-HVDC SYSTEM PARAMETERS

Bus system 1 & 2: line voltage=100 kV, frequency=50 Hz, Short circuit power=200 MVA, $R_s=0.75\Omega$, $L_s=0.2$ H.

27th AC filter in AC system 1 & 2: reactive power=18 MVAR, tuning frequency=1620 Hz, quality factor=15.

54th AC filter in AC system 1 & 2: reactive power=22 MVAR, tuning frequency=3240 Hz, quality factor=15.

DC system: voltage= ± 100 kV, rated DC power=200 MW, Pi line $R=0.0139 \Omega / \text{km}$, $L=159 \mu\text{H}/\text{km}$, $C=0.331 \mu\text{F}/\text{km}$, Pi line length= 150 km, switching frequency=1620 Hz, DC capacitor=70 μF , smoothing reactor: $R=0.0251\Omega$, $L=8\text{mH}$.

Parameters of the classic vector control: current loop: $k_p=5$, $k_i=1$, AC voltage control: $k_i=20$, active power control: $k_i=20$, DC voltage control: $k_p=5$, $k_i=2$.

HVDC control specifications: Set-points for the transmitted active power, the reactive power and the voltage at the points of coupling have to be tracked with the following transient performances [15]:

- the response time of the active/reactive power is normally in the range of 50 ms to 150 ms.

- the response time for voltage is about 100 ms to 500 ms.