

Control and Protection of Hybrid LCC-VSC HVDC Transmission System based on VDCOL Strategy

Mohamed Amine Kazi¹, Radouane Majdoul¹, Adnane El-almi¹, Ibrahim Baraka²,
Nadia Machkour¹

¹Department of Structural Engineering, Intelligent Systems & Electrical Energy, University Hassan II Casablanca, Morocco

²Advanced Science and Technology, University Abdelmalek Essaadi, ENSA, Tetouan

Abstract: The combination of line combined converter LCC and voltage source converter VSC technology provides the benefits of both techniques by constituting a hybrid LCC-VSC HVDC system. In this paper to discover the potential and the performances of this system a control design is adopted for both converter considering the protection by using Voltage dependent current order limiter (VDCOL). This technique used to decrease the current reference of LCC HVDC converter station when the voltage at that station is depressed during disturbances. Different case studies are proposed starting with normal operation, DC current variation, reactive power variation, and finally system operation under AC and DC faults. The responses of the system during faults demonstrate the tracking performance and also its ability to protect the stations and limit the references during AC and DC faults. The control strategy is examined by simulations using Matlab/Simulink software.

Keywords: high voltage direct current (HVDC); line commutated converter (LCC); voltage source converter (VSC); Voltage dependent current order control (VDCOL)

1. Introduction

Industrialization and population growth are the primary factors for the steady increase in electrical energy consumption. In addition, more and more electricity is produced far from urban areas and therefore has to travel long distances. Thus, in order to have a balance between production and consumption, the complexity of the electrical networks increases regularly and is accompanied by strong constraints related to the stability of the networks [1]. In addition to this, there are problems related to the liberalization of the electricity market, which creates various operating scenarios. These factors therefore also require systems to operate as close to their limits as possible while ensuring maximum safety. In addition, the quality of electrical power has become a major concern for consumers and suppliers. Therefore, rigorous criteria for the development and operation of networks are required.

High-voltage direct current (HVDC) technology, which has been used for more than 70 years [2], is suitable for transmitting large amounts of energy over long distances with minimal losses. In 1954, the first commercial HVDC link, with a capacity of 20 MW/±100 kV, was installed between Sweden and the island of Gotland. Since then, the cumulative capacity of HVDC transmission installed around the world has steadily increased [3], and recently a huge increase in volume is in progress [4]. To date, most of the HVDC systems installed worldwide are of the LCC (Line-Commutated Converter) type and use thyristor valves.

LCCs are the oldest technology for HVDC links. The converters use thyristors. The thyristor-based HVDC line commutated converter (LCC) is used for bulk power transfer [5] (more than several GW) over long distances due to its mature, efficient, reliable, and cost-effective technology. However, LCC-HVDC technology has some inherent problems, such as switching failure [6], difficulty in connecting weak AC systems [7], interconnection problems with renewable energy sources such as turbine-generator shafts [8] that are subject to high stresses during faults such as through fire, misfire, short circuit through the inverter station, flashover, and a three-phase short circuit in the AC system, which can result in severe damage to the entire system [9] and the need to reverse the polarity of the DC voltage during power flow reversal.

These obstacles make this technology difficult to implement on large-scale DC networks. HVDC based on a voltage source converter (VSC) [10] is a more current technology that offers greater operational flexibility, such as separate control of active and reactive power and black start capabilities [11-12]. VSCs, but in the other hand, have larger switching losses and construction costs than LCCs.

Overall, LCC-HVDC leads VSC-HVDC in terms of maturity and cost efficiency, but VSC-HVDC offers greater operational flexibility and the capacity to operate in extremely weak systems. LCC-HVDC, on the other hand, lacks islanded operation and voltage support, necessitating synchronous sources and huge bulk reactive power compensation devices on the ac side.

Hybrid HVDC using LCCs and VSCs has been proposed as a promising alternative solution [13] that incorporates the benefits of both converter topologies: lower power losses and costs, as well as greater control flexibility. Furthermore, by replacing one of the terminals with VSC, the hybrid LCC-VSC HVDC [14-15] concept can be used to improve an existing LCC-HVDC connection. The LCC-HVDC and VSC-HVDC systems can also be linked to create a new hybrid network. The control approach and operation method of the LCC and VSC are, however, completely different.

Many research works have dealt with hybrid systems [16-18] and have proposed many contributions including control laws in order to improve their performances also the possibility of integrating renewable energy sources and offshore parks to constitute multi-terminal systems [19] using LCC and VSC structures together, without forgetting the evaluation and control of these systems during the different probable faults on the networks as well as their protection systems

In this paper the hybrid LCC-VSC HVDC system employs one converter using LCC technology as the rectifier while the other converter uses VSC technology as the inverter, the two stations are interconnected via a DC cable. The control modes of the rectifier and the inverter are realized and implemented by a PI control to guarantee good performance and ensure the stability and reliability of the system. The first part of this paper will be devoted to the structure of the hybrid system by detailing the topology used for the LCC station and the topology for the VSC station and secondly the proposed controls for each station using the VDCOL strategy and finally for the rest of the paper a simulation of the hybrid LCC-VSC HVDC system under different cases including normal operation, DC current variation, reactive power variation and with the presence of the AC and DC default

2. Structure of hybrid HVDC systems:

Figure 1 shows the basic structure of a point-to-point hybrid HVDC. The rectifier station is the conventional LCC based on two 12 pulse rectifier. The inverter station is VSC converter which utilizes the three-level neutral point clamped (NPC).

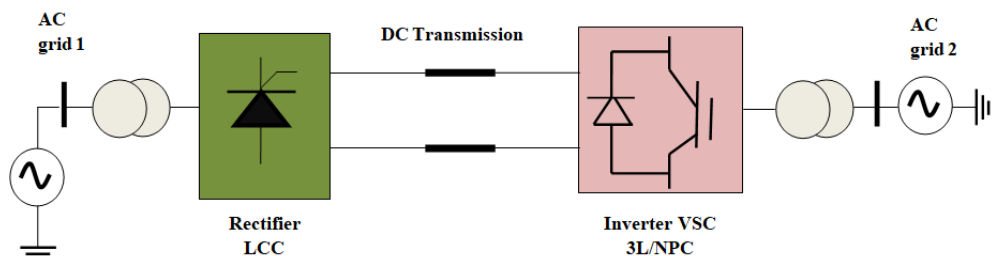


Figure 1. Hybrid LCC-VSC transmission system

A. Structure of LCC

The major component of an LCC is the six-pulse bridge (Graetz bridge) consisting of six controlled thyristor switches or valves. To operate the converter at the desired nominal voltage, the thyristors are usually connected in series to create a suitable thyristor switch. The

disadvantage of the six-pulse bridge is that considerable harmonics of the AC current and DC voltage are produced because of the phase change at every 60° . To overcome this problem, two six-pulse bridges are connected in series to form a twelve-pulse bridge. In this way, each of the two six-pulse bridges is connected to a DC rail, whose phase change at every 30° helps to eliminate some of the harmonics.

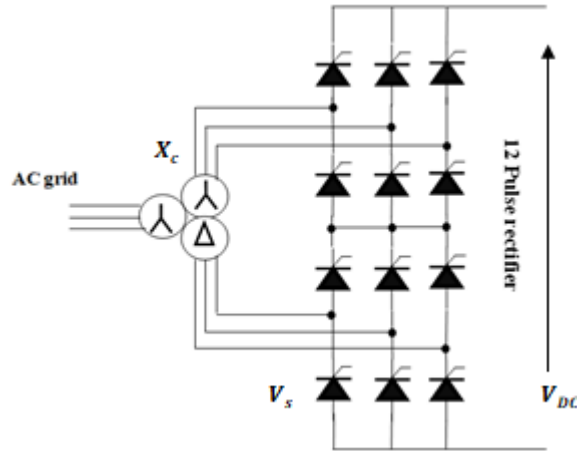


Figure 2. 12-pulse rectifier

$$V_{DC} = B \frac{3\sqrt{2}}{\pi} V_s \cos \alpha - B \frac{3}{\pi} X_c I_{DC} \quad (1)$$

Where V_{DC} , I_{DC} are respectively the output voltage and current of the converter, α the firing angle, V_s are the RMS (Root Mean square) AC voltages of the primary and secondary side of the converter. X_c is the converter transformer reactance. The parameter B is one ($B = 1$) for six-pulse HVDC systems and B equals two ($B = 2$) for twelve-pulse units

B. Structure of VSC:

The second generation of HVDCs uses VSC technology. The main difference with VSCs is that other components are used instead of thyristors. Most of the time, IGBTs are used in combination with antiparallel diodes, but GTO thyristors can also be used. These components offer a new freedom: their activation and deactivation can be controlled, which was not possible with thyristors, whose activation was only controlled. This additional freedom offers new possibilities to the user, such as independent control of active and reactive power. As the name indicates, a VSC link acts as a voltage source. This means that the voltage on its link never changes polarity, and remains fixed at a reference value.

VSC topologies are developing to increase the power transferred, and they are classified into three types, namely; two-level converter, three-level converter, modular multi-level converter (MMC). The three-level VSC topology, shown in figure 3, is called Neutral Point Clamped converter (NPC).

Each phase of the VSC can switch to three different voltage levels, specifically; the positive DC terminal, the negative DC terminal and the midpoint. The three-level NPC converter minimizes harmonics to bring the output signal closer to the reference. In addition, the three-level NPC allows for a lower switching loss than a two-level VSC technology. This topology can be extended to more voltage levels, resulting in reduced harmonics and lower switching losses. However, increasing the number of levels using the NPC topology becomes more complicated and requires cooling equipment for the converter devices.

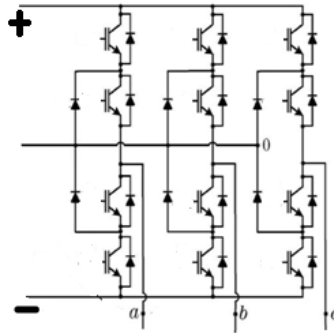


Figure 3. Three level NPC converter

3. Control strategy of hybrid LCC-VSC HVDC system

Figure 1 represents an LCC-VSC HVDC grid, with LCC acting as rectifier and VSC acting as inverter. The advantages of hybrid structure in terms of technical maturity, high power rating, low manufacturing cost, and reduced power losses are all utilized in this architecture. without forgetting it's capacity to reduce the danger of commutation failure. [17-21] investigated the operation, control, and protection of LCC/VSC hybrid DC networks [22].

The rectifier based on LCC structure ensures constant dc current control combined with minimum firing angle control and voltage dependent current order limiter (VDCOL) [23]. During normal operation, the rectifier converter is under the constant dc current control. During a fault, VDCOL try to reduce the dc current order in accordance with dc voltage drop, thus the fault current progressively decreases to a new dc current order as shown in figure 4.

The inverter based on VSC structure ensures direct voltage control, including inner loop current control and outer loop voltage control. The inner loop current controller regulates the amplitude and phase of AC current. The outer loop voltage controller includes an active power class control and a reactive power class control, which are chose as the constant dc voltage control and the constant reactive power control respectively in this paper.

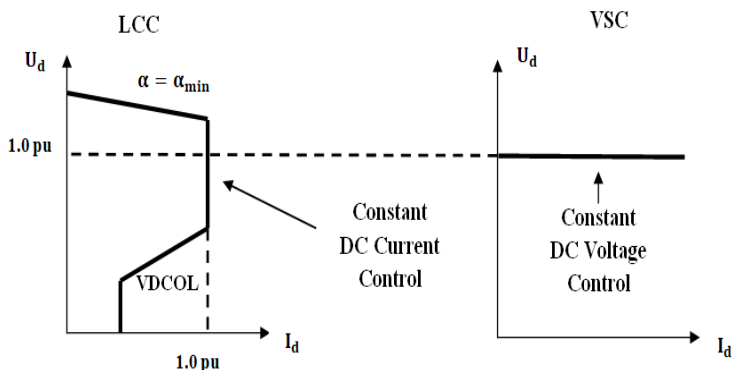


Figure 4, characteristic of VDCOL control

A. LCC control system

We describe below the control method of the LCC, the basic schematic of the rectifier is shown in figure 5.

We applying Kirchhoff theorem we have:

$$V_{dcr} = V_{dor} \cdot \cos \alpha - R_{cr} I_{dc} \quad (2)$$

With:

$$R_{cr} = \frac{3X_{cr}}{\pi}$$

$$V_{dor} = \frac{3\sqrt{2}}{\pi} V_{eff}$$

α : Firing angle

V_{eff} RMS value of the voltage between phases

X_{cr} : Rectifier switching reactance

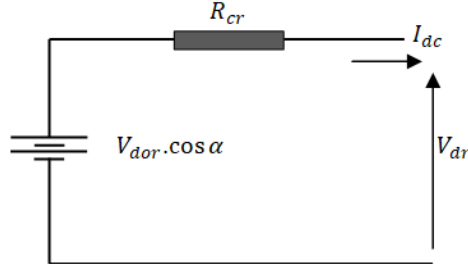


Figure 5. Schematic of LCC rectifier

The current I_{dc} in the DC line is given by the expression:

$$I_{dc} = \frac{V_{dcr} - V_{dci}}{R_{dc}} \quad (3)$$

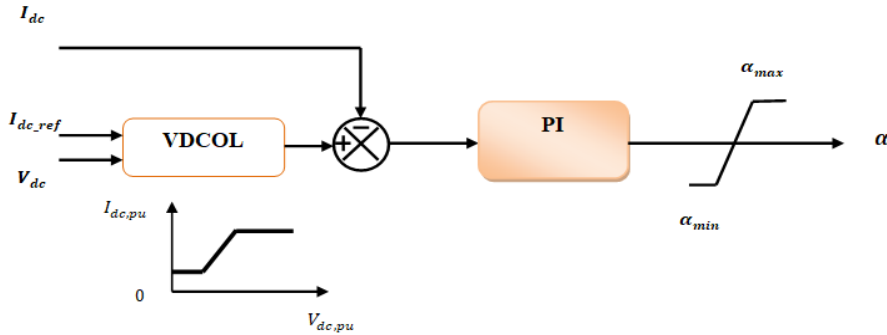


Figure 6. LCC rectifier general control scheme

Where R_{dc} and V_{dci} is the total resistance of the DC cable and DC output voltage at the VSC converter. According to (2) and (3) the parameters in the denominator being constant, the only way to modify the current I_{dc} is to control the angle α because the voltages V_{dcr} and V_{dci} are exposed to unpredictable fluctuations on the AC side.

The current controller is shown in Figure 6. The measured DC current I_{dc} of the system compared with the current reference I_{dc-ref} . The output of the PI controller is the firing angle. This angle limited in the range $[\alpha_{min}, \alpha_{max}]$ is used to generate the rectifier firing pulses.

B. VSC Control system

For any VSC-HVDC system, the control objectives are to compensate for disturbances and ensure good transient and performance. The vector control method is the most widely used control approach in power system applications. This control technique has a cascade control structure. It is composed of two loops: the internal current control loops and the external control loops. Figure 7 shows the structure of the station based on VSC converter.

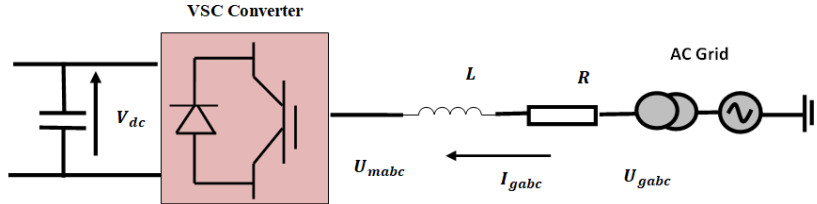


Figure 7. Structure of VSC station

Applying Kirchhoff's laws we find:

$$L \cdot \frac{di_j}{dt} + R \cdot i_j = u_{gj} - u_{mj} \quad (4)$$

The system (4) can be written as:

$$u_{gabc} = R \cdot i_{gabc} + L \cdot \frac{di_{gabc}}{dt} \quad (5)$$

Applying the park transformation we find the state representation of the station:

$$\begin{cases} \frac{di_d}{dt} = \omega \cdot i_q - \frac{R}{L} \cdot i_d + \frac{(u_{gd} - u_{md})}{L} \\ \frac{di_q}{dt} = -\omega \cdot i_d - \frac{R}{L} \cdot i_q + \frac{(u_{gq} - u_{mq})}{L} \end{cases} \quad (6)$$

B.1 Outer loop control

The outer control loop can control several variables; the current i_d can regulate the DC bus voltage or the active power while the current i_q can regulate the reactive power or the AC voltage

Power control:

Active and reactive power can be controlled independently. They are used to generate the reference currents of the internal loops. The dq reference frame is selected that the d-axis is synchronized to the AC source voltage. This results in $u_q = 0$.

$$P_{dq} = \frac{3}{2} \cdot (u_d \cdot i_d + u_q \cdot i_q) = \frac{3}{2} \cdot (u_d \cdot i_d) \quad (7)$$

$$Q_{dq} = \frac{3}{2} \cdot (u_q \cdot i_d - u_d \cdot i_q) = -\frac{3}{2} \cdot (u_d \cdot i_q) \quad (8)$$

Figure 9 shows the structure of the power control loops. PI correctors are used to regulate the dynamic responses of the power loops.

DC Voltage Control:

The DC voltage control loop is required to control the DC bus voltage by ensuring the balance between the power injected to the DC network and the power absorbed by the AC network. The structure of the controlled system is shown in Figure 1.12. The output of the control loop provides the reference input for the forward current.

AC voltage control:

This control loop is particularly designed for VSC converters connected to a weak AC network, which is sensitive to interactions between AC and DC because of its high impedance compared to the rated DC power. Moreover, any disturbance on the DC or AC side of the converter can induce AC voltage instability (e.g. voltage drop, overvoltage, etc.). To avoid these problems, an AC voltage control loop can ensure the regulation of the low AC voltage of the network at fixed amplitude.

B.2 Inner loop control

The internal control is responsible for generating the reference signal for the voltage V_{dq} -ref. This reference is provided in the dq0 frame. It must be translated into the abc frame to inform the PWM which controls the IGBT gates. Figure 8 shows the control scheme of inner current loop.

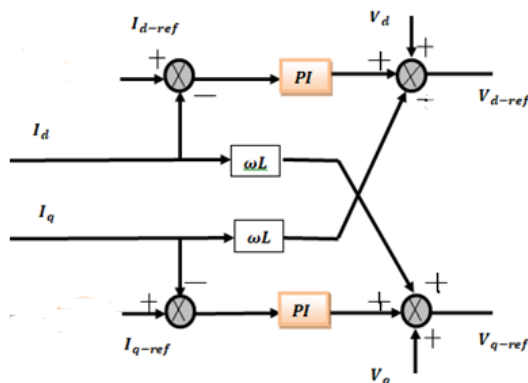


Figure 8. VSC Inner loop scheme

Figure 9 describes completely the control structure of the VSC station; we can see the outer and inner control loops as well as the controlled variables. As mentioned before, the VSC station of the Hybrid LCC-VSC system controls the DC voltage and the reactive power.

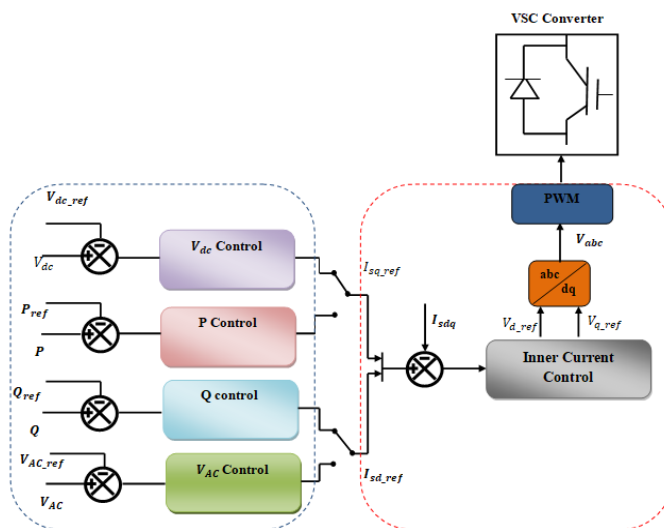


Figure 8. Control architecture for VSC station

3. Simulation Analysis and Results

In order to test and verify the validity of the hybrid LCC-VSC HVDC system and to see its different performances, a simulation was performed using Matlab/Simulink software.

Table 1. Simulation Parameters

	Parameters	value
LCC Station	Rated power	200 MVA
	AC side voltage	500 kV
	DC Voltage	230 kV
	DC Current	1kA
	AC reactance and resistor	$R=30\Omega$; $L= 48,86$ Mh
	AC filters	4*150 Mvar
	DC Link capacitors	$C1=80\mu F$; $C2=80\mu F$
	LCC	two 12-pulse

	Parameters	value
VSC Station	Rated power	200 MVA
	AC side voltage	230 kV
	DC Voltage	230 kV
	AC reactance and resistor	$R=900\text{m}\Omega$; $L= 31\text{ mH}$
	DC link capacitors	$C1=70\mu\text{F}$; $C2=70\mu\text{F}$
	VSC type	NPC Three Level

Table 2. DC Line Parameters

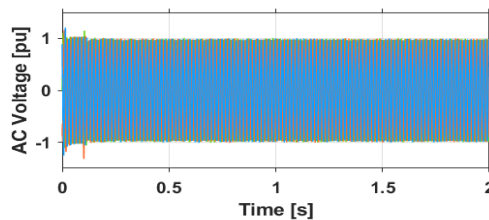
Length of transmission line	300 Km
DC cable resistance	15 $\text{m}\Omega/\text{km}$
DC cable inductance	0,792 mH/km
DC cable capacitance	0,144 $\mu\text{F}/\text{km}$

To demonstrate the effectiveness of the system structure three scenarios were established:

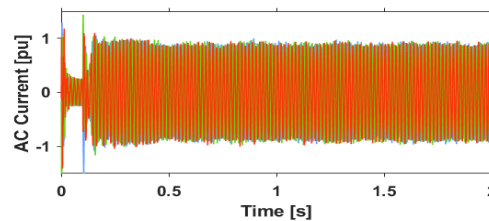
1. Normal operating conditions
2. Tracking performance (DC current reference variation, reactive power variation)
3. Performance during AC and DC faults. Other faults such as misfire, firethrough on VSC converters are the subject of several studies [24-25].

A. Steady-state:

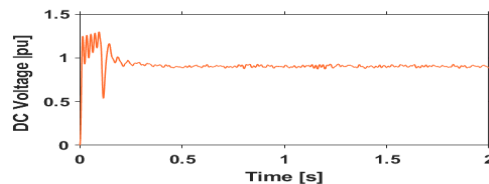
During normal operation of the Hybrid LCC-VSC HVDC system, the converter station based on LCC technology (rectifier) operates in current control mode ($i_{dc_ref}=1\text{kA}=1\text{p.u.}$) and the other station based on VSC technology (Inverter) operates in DC volt control mode ($V_{dc_ref}=220\text{kV}=1\text{p.u.}$). Figure 10 shows the behaviour of the system.



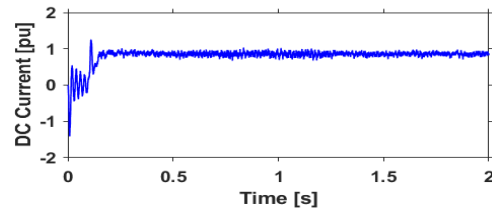
(a).



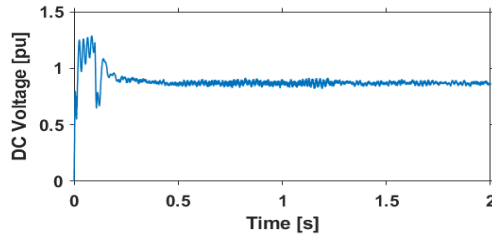
(b).



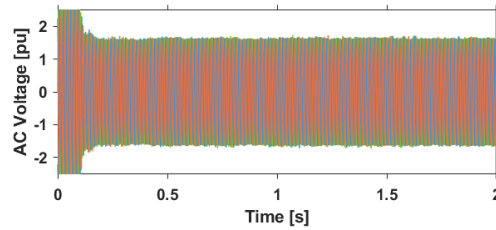
(c).



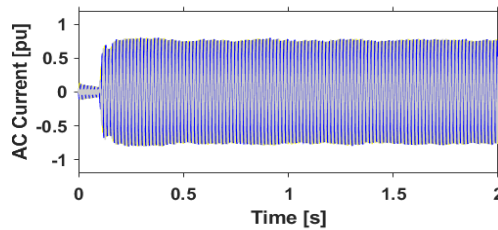
(d).



(e).



(f).



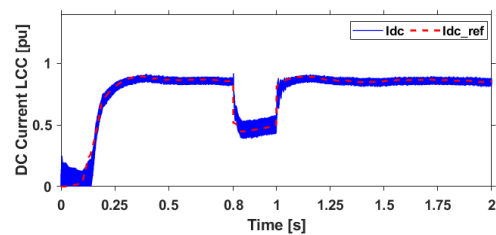
(g).

Figure 9. Steady state of Hybrid LCC-VSC: a). AC grid VSC b). AC Current VSC c). DC Voltage LCC d). DC Current e). AC Current LCC f). AC grid LCC g). DC Voltage VSC

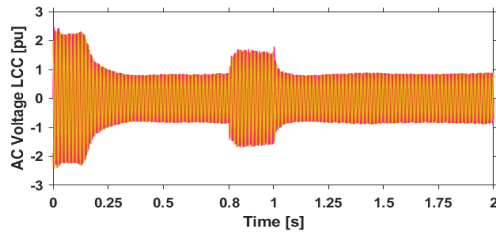
B. Performances in Tracking

B.1. Current reference Change:

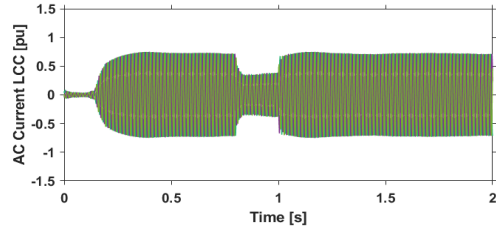
To test the performance of the rectifier LCC side current controller, a decrease of 0.5 applied to the current reference during the interval [0.8s 1s] is applied as shown in figure 11 (a). The figure shows the active powers of the two stations, the DC voltage is properly controlled and remains stable with acceptable oscillations during the duration of the change in the current reference, note also that the firing angle has increased because it is determined by the current regulator



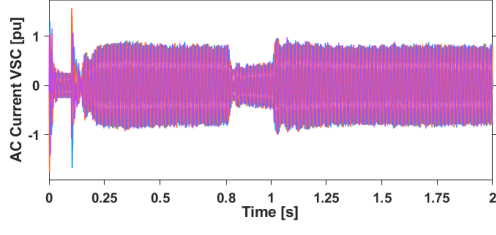
(a).



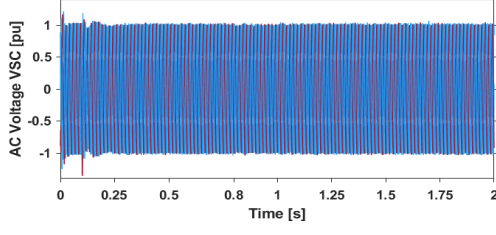
(b).



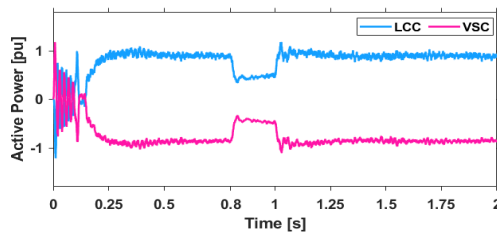
(c).



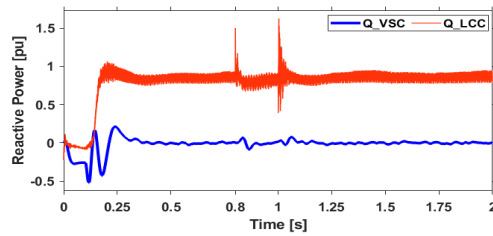
(d).



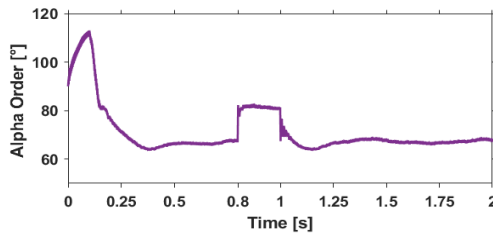
(e).



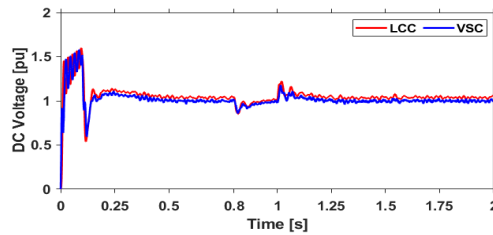
(f).



(g).



(h).



(i).

Figure 10. DC Current reference change: a). DC Current b). AC Voltage LCC c). AC Current LCC d). Active Power e). Reactive Power f). DC Voltage g). AC Current VSC h). AC Voltage VSC i). Firing Angle of LCC

B.2. Reactive Power change:

At $t=1s$ the reactive power of the VSC station is decreased from 0 p.u to -0.5 p.u, figure 12 shows the responses of the hybrid LCC-VSC HVDC system, we notice that the DC voltage and current remain constant during the change of reactive power with small oscillations. The change of the reactive power has no impact on the LCC station, which guarantees more reliability.

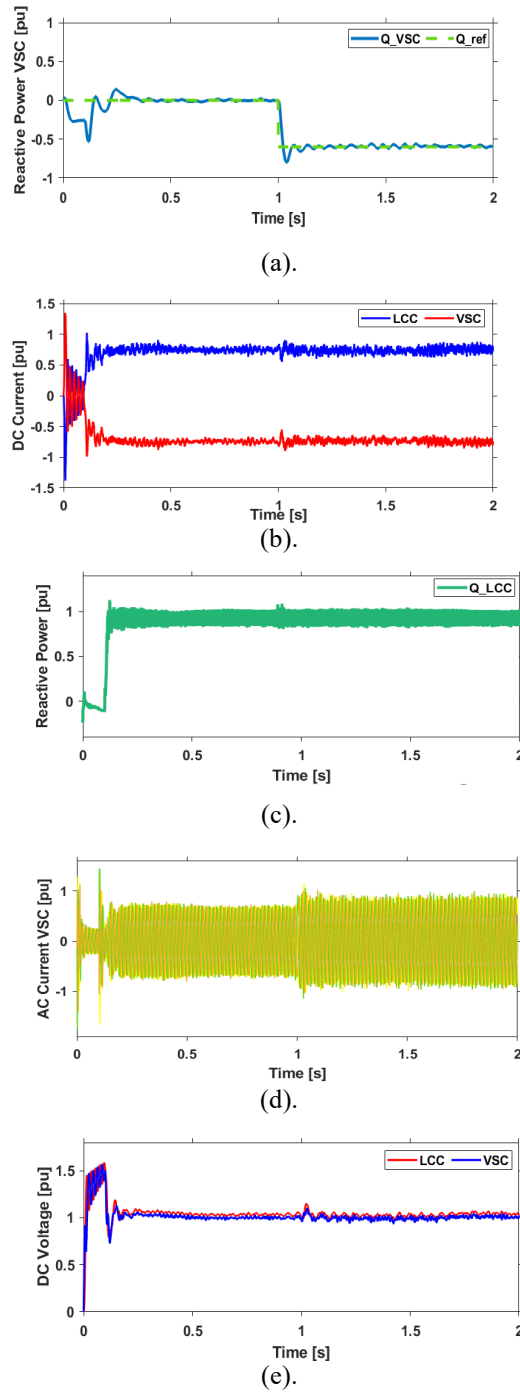


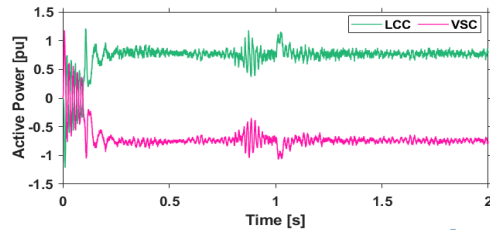
Figure 11. Reactive Power change a). Reactive Power VSC b). Reactive power LCC c). DC Current d). Active power e). AC Current VSC f). DC Voltage

C. Performances under AC and DC faults

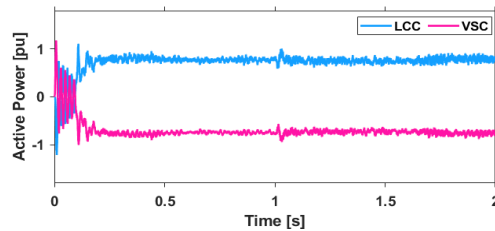
C.1. AC fault

AC faults are very common in electrical networks and cause many problems and failures, hence the need to correct them quickly. Figure 13 shows the global behavior of the hybrid LCC-VSC HVDC system following a fault in the AC network on the LCC side. A line break on phase

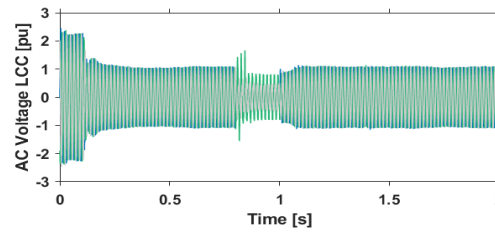
1 during 200 ms causes power oscillations as shown in figure 13, DC voltage returns to its reference value after a phase of oscillations. The integrator of the dc current controller will be reset to 0 to clearing AC fault and to increase the firing angle at $t=1$ s to return to normal operation.



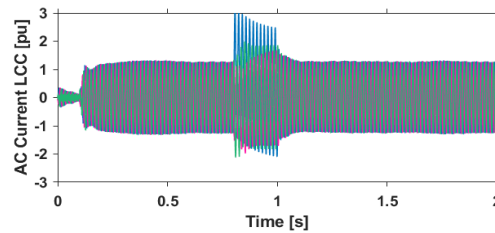
(a).



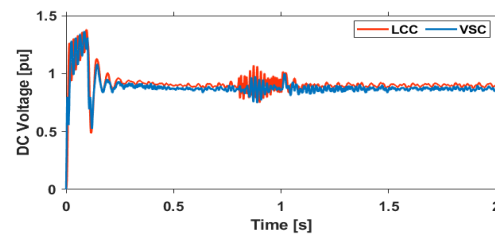
(b).



(c).



(d).



(e).

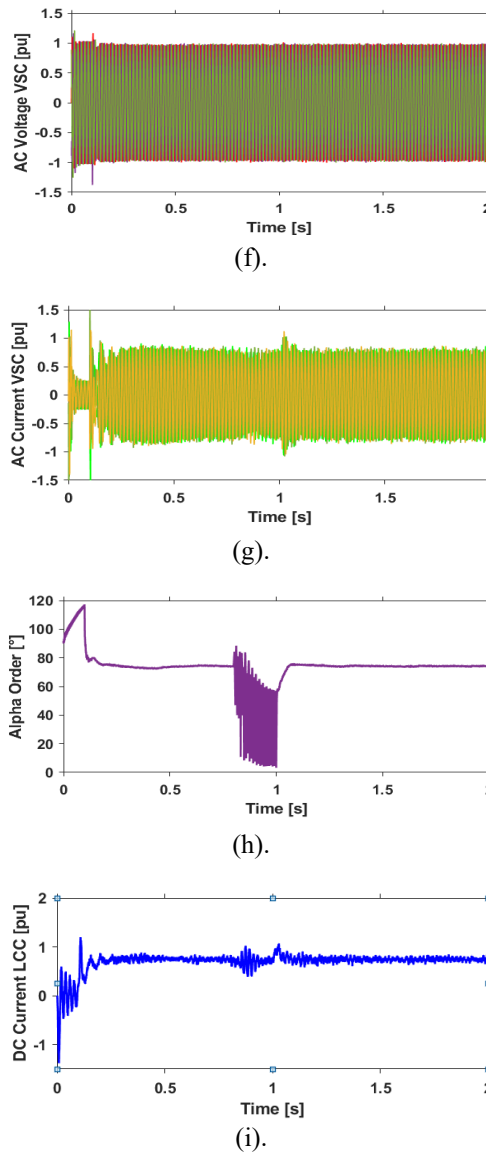


Figure 12. AC Fault in LCC Station a). Active Power b). DC Voltage c). AC Voltage LCC d). DC Current LCC e). AC Voltage VSC f). AC Current LCC g). AC Current VSC h). Firing Angle of LCC

C.2. DC Fault

At $t=1$ s a line to line fault in DC side as shown in the following figure.

This fault results a rise in DC current, the DC voltage drops to zero at the rectifier. This DC voltage drop is detected by the voltage dependent current limiter (VDCOL) which reduces the reference current to 0.3 pu at the rectifier as shown in figure 15 (a), which shows the great importance of the VDCOL in limiting the reference current in case of a fault and therefore protecting the electronic switches. The active power of both LCC and VSC stations tends towards 0 during the fault detection it should also be noted that the firing angle is increased to keep the DC current constant.

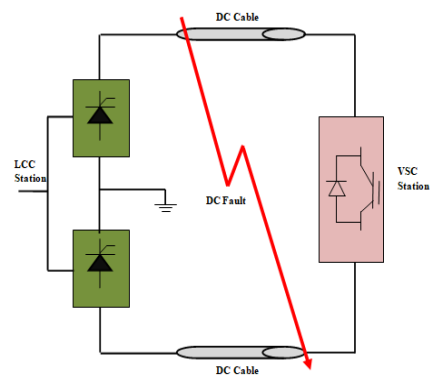
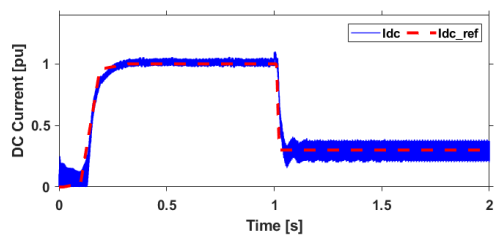
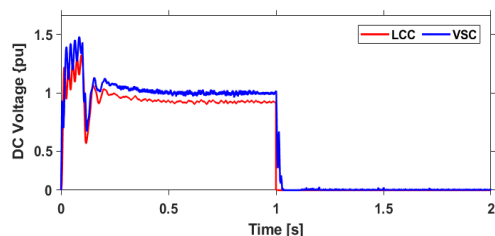


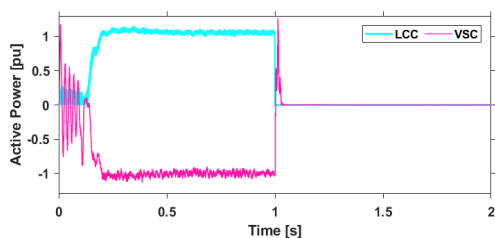
Figure 13. Circuit of Hybrid LCC-VSC system under DC Fault



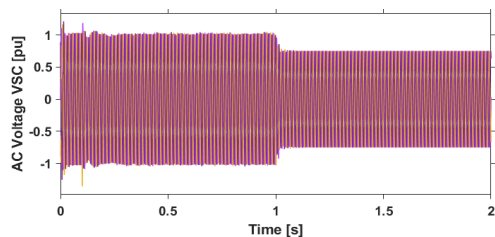
(a).



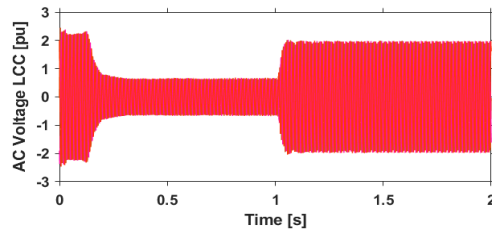
(b).



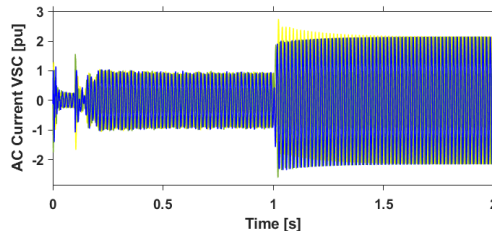
(c).



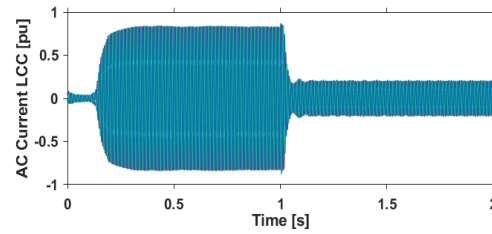
(d).



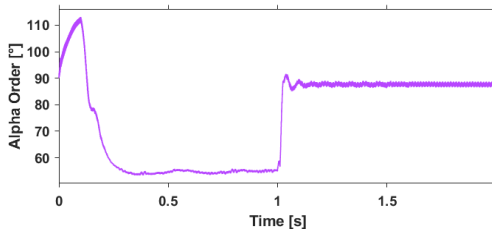
(e).



(f).



(g).



(h).

Figure 14. DC Fault in the Hybrid LCC-VSC system a). DC Current b). DC Voltage c). Active Power d). AC Voltage VSC e). AC Current VSC f). Firing Angle of LCC g). AC Voltage VSC h). AC Current LCC

5. Results Analysis

The figures 10-15 show the evolution of the different variables of the system, the transient regime starts from 0 until about 10ms, then the system stabilizes until a disturbance occurs, observing the simulation results it should be noted that the transient regime of the system is related to the chosen parameters of the controller and also to the parameters of the VDCOL block. The VDCOL function has only one relationship between the input DC voltage and the current order of the VDCOL. Since a drop below 0.3 p.u. of the DC voltage automatically leads to the modification of the transient aspect as can be seen in figures 10 to 15, it should also be noted that the reference current ramp starts only after 10ms, so the choice of the VDCOL parameters is crucial and must be well chosen. The choice of the VDCOL parameters is the subject of several research studies [25-26] the transient regime can be improved by modifying the reference current ramp and by adapting the VDCOL function as studied in [27-28] with a suitable delay.

Under the conditions of disturbance such as the variation of the reference current Fig 11 we can see at $t=80\text{ms}$ that the current decreases from 0p.u to the value of 0.5 p.u which directly causes the increase of 80 degree of the firing angle to ensure the continuation of the current reference point. Fig 13-15 shows the variables of the system following AC and DC defaults here the VDCOL block must intervene and set a new current step, at fault application the DC current quickly increases above 1 p.u and the DC voltage falls to zero at the rectifier. This DC voltage drop is seen by the Voltage Dependent Current Order Limiter (VDCOL) which reduces the reference current to 0.3 p.u at the rectifier reached during 10 ms , a direct current then still flows during the default and at the same time protects the converters as studied in [29-31]. The dynamic response proposed by the control presents overshoots and oscillations compared to non-linear controls [32-34] which offers the consideration of the system parameters and give smoother responses.

6. Conclusion

This article studied a hybrid HVDC transmission system that used an LCC as a rectifier and a VSC converter as the inverter station, respectively. Verification and validation of the performance of the hybrid LCC-VSC system using widely established HVDC operating standards is conducted by analytical selection of system parameters and consideration of various system operating situations. The results from a LCC-VSC hybrid HVDC system show that the proposed hybrid HVDC system can operate under various conditions and includes the protection of the converters, using the (VDCOL) Voltage Dependent Current Order Limit, this notion is used to detect a probable fault or a disturbance by reducing the reference current, The recovery after a DC line fault is problematic and especially for VSC-HVDC transmission system for this reason, hybrid systems remain a possible solution to avoid over voltages and over currents during dc line fault.

As future work many elements can be approached and will be of great importance as the elaboration of advanced control techniques, the extension of the system to a multi-terminal configuration by integrating renewable energy sources.

7. References

- [1]. C. Bayliss, B. Hardy. Transmission and Distribution electrical engineering. Elsevier, 2007.
- [2]. K. Meah, S. Ula, "Comparative evaluation of HVDC and HVAC transmission systems," *In IEEE Power Engineering Society General Meeting*, pages 1–5, 2007
- [3]. M.P. Bahrman, B.K. Johnson, The ABCs of HVDC transmission technologies, *IEEE Power Energy Mag.* 5 (2) (2007) 32–44,
- [4]. Jovicic D, Ahmed K (2015) High voltage direct current transmission – Converters, systems and DC grids. Wiley, p 43
- [5]. G. Li, J. Liang, T. Joseph, T. An, J. Lu, M. Szechtman, B.R. Andersen, Q. Zhuang, Feasibility and reliability analysis of LCC DC grids and LCC/VSC hybrid DC grids, *IEEE Access* 7 (2019) 22445–22456,
- [6]. C. Meyer and R. W. De Doncker, "LCC analysis of different resonant circuits and solid-state circuit breakers for medium-voltage grids," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1414–1420, Jul. 2006.
- [7]. L Feng, "Study on Difference Between Two-Terminal LCC-HVDC and Three-Terminal LCC-HVDC Control and Protection System", *IOP Conference Series Earth and Environmental Science* 701(1):01 2013
- [8]. HAMMONS, Unbalanced Operation of HVDC Converters in Asynchronous Links in Torsional Stressing of Turbine Generator Shafts, *Electric Power Components and Systems* (June 2010)
- [9]. A. Abu-Siada, S. Islam, Application of SMES Unit in Improving the Performance of an AC/DC Power System, *IEEE Transactions on Sustainable Energy*, Vol. 2, No. 2, April 2011

- [10]. Khan, F. I., and Massoud, A. M. (2016). Twelve-Pulse Line Commutated Converter Drive System with VSI for Starting up and Active Power Filtering. 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016)
- [11]. Alcaso, A.N.; Cardoso, A.J.M., "Remedial Operating Strategies for a 12-Pulse LCI Drive System," in *Industrial Electronics, IEEE Transactions on*, vol.55, no.5, pp.2133-2139, May 2008
- [12]. N. Flourentzou, V. G. Agelidis, and G. D. Demetriades, "vsc based HVDC power transmission systems: An overview," *IEEE Trans. Power Electronics*, vol. 24, no. 3, March 2011.
- [13]. Nagwa F. Ibrahim, Sobhy S. Dessouky, VSC-HVDC Control System, of *Design and Implementation of Voltage Source Converters in HVDC Systems* (pp.15-30)
- [14]. G. Zhang, Z. Xu, and H. Liu, "Supply passive networks with VSC HVDC," *IEEE Power Engineering Society Summer Meeting*, 2001.
- [15]. Guo C, Liu W, Zhao C Research on the control method for voltage-current source Hybrid-HVDC system, *Science China*, 56(11): 2771-2777 (2013)
- [16]. Pingyang Sun*, Harith R. Wickramasinghe, Georgios Konstantinou, "Hybrid LCC-AAC HVDC transmission system *Electric Power Systems Research* 2020
- [17]. Andersen, B. R. and Xu, L.: 'Hybrid HVDC system for power transmission to island networks', *IEEE Trans. Power Del.*, 2004, 19, (4), pp. 1884-1890
- [18]. Xu, Z., Wang, S. and Xiao, H.: 'Hybrid high-voltage direct current topology with line commutated converter and modular multilevel converter in series connection suitable for bulk power overhead line transmission', *IET Power Electronics*, 2016, 9, (12), pp. 2307-2317
- [19]. Li G, Liang J, Joseph T, An T, Lu J, Szechtman M, Andersen BR (2019) Feasibility and reliability analysis of LCC DC grids and LCC/VSC hybrid DC grids, *IEEE Access*, 7: 22445-22456
- [20]. R. Zeng, L. Xu, L. Yao, S. J. Finney, and Y. Wang, "Hybrid HVDC for integrating wind farms with special consideration on commutation failure," *IEEE Trans. Power Del.*, vol. 31, no. 2, pp. 789–797, Apr. 2016.
- [21]. Jingbo Zhao and Yan Tao "Control Characteristic Analysis and Coordinated Strategy Design for Hybrid HVDC with Multi-Infeed MMC Inverters", *Front. Energy Res.* 9:737294. (2021)
- [22]. Juanjuan Wang, Menghua Huang, Chuang Fu, Huan Li, Shukai XU, Xiaohua Li, "A New Recovery Strategy of HVDC System during AC Faults," *IEEE Transactions on Power Delivery* Volume: 34, Issue: 2, April 2019
- [23]. Zeng R, Xu L, Yao L, Finney SJ, Wang Y (2016) Hybrid HVDC for integrating wind farms with special consideration on commutation failure, *IEEE Transactions on Power Delivery*, 31(2): 789-797
- [24]. C.-H. Lin, Impact of fire-through and misfire in rectifier valves on a turbine generator neighboring to a HVDC inverter station, *Journal of Marine Science and Technology* 16(4):241-248, December 2008
- [25]. H. A. Darwish, A. M. I. Taalab, M. A. Rahman, Performance of HVDC converter protection during internal faults, *Power Engineering Society General Meeting*, 2006. IEEE
- [26]. Aimin Li, Zexiang Cai, Qizhen Sun, Xiaohua Li, Dayong Ren, Zeming Yang, "Study on the Dynamic Performance Characteristics of HVDC Control and Protections for the HVDC Line Fault," *IEEE Power & Energy Society General Meeting* 2009
- [27]. W. Liu, C. Zhao, C. Guo, The control strategy for hybrid HVDC using voltage margin control and voltage dependent current order limiter control, in: *2nd IET Renewable Power Generation Conf. (RPG 2013)* (2013) pp. 1–4. 10.1049/cp.2013.1794.
- [28]. M. Nguyen, T. Saha, M. Eghbal, Master self-tuning VDCOL function for hybrid multi-terminal HVDC connecting renewable resources to a large power system, *IET Gener. Transm. Distrib.*, 2017, Vol. 11 Iss. 13, pp. 3341-3349

- [29]. Y. Li, J. Wang, Z. Li, Z. Liang, M. Huang, Z. Wang, VDCOL parameters setting influenced by reactive power characteristics of HVDC system August 2017 Dianli Xitong Baohu yu Kongzhi/Power System Protection and Control 45(16):16-23
- [30]. L. Liu, Y. Wang, X. Li, B. Zhang, Design of variable slope VDCOL controller based on fuzzy control July 2015
- [31]. D. He, J. Wen, X. Geng, Study on HVDC commutation failure and voltage compensated variable slope VDCOL control, Conference: 2018 2nd *IEEE Conference on Energy Internet and Energy System Integration (EI2)* October 2018.
- [32]. JM. S. Fuentes-Burrue, E. Lenymirko Goytia, Auxiliary Protection Scheme for Assembly Hybrid HVDC Breakers, Conference: 2021 *IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*, November 2021
- [33]. M. Riaz, Y. Fan, J.Ahmad,M.khan,M.Khan,E.Ahmed, Research on the Protection of Hybrid HVDC System, 2018 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET), September 2018
- [34]. D. Zhang, C. Wu, J. He, C. Liang, A new protection scheme for transmission line of three-terminal hybrid HVDC system, *International Journal of Electrical Power & Energy Systems* 134(1):107446 (January 2022)



Mohamed Amine Kazi born on August 01, 1993, holder of a master's degree in automatic signal processing and industrial computer science from the University Hassan I FST of Settlat Morocco. Currently PhD student in the field of electrical networks and HVDC technology at the University Hassan II of Casablanca (Morocco) in the laboratory Complex Cyber Physical Systems.



Radouane Majdoul was born in Meknes, Morocco, in 1969. In 1997, he successfully passed the external aggregation contest. He received her PhD degree in Automatic Signal Processing and Industrial Computing Automation and Industrial in 2017 from Hassan I University-FST ofSettat Morocco. Currently he is Research Professor Laboratory of Structural Engineering Intelligent Systems & Electrical Energy ENSAM, hassan II University, Morocco



Adnane El-alami was born in Morocco on December 14, 1990. He received the Master in Automatic, Signal Processing, and Industrial Computing from the Faculty of Science and Technology, Hassan 1st University, Settlat, Morocco in 2019. And received the Aggregation in Electrical Engineering from CRMEF Settlat in 2018. Currently, he prepares his PhD titled: Topologies, modulation and control strategies of multilevel converters in complex cyber-physical systems laboratory, at university Hassan II ENSAM Casablanca, Morocco.



Ibrahim Baraka was born on December 10, 1987, holds a master's degree in microelectronics from the University ibn Tofail Kenitra Morocco, currently PhD Student in the field of Electrical Engineering and New Technologies at the University Abdelmalek Essadi Tetouan Morocco in the laboratory Sciences and Advanced Technologies



Nadia Machkour was born in 20 January 1974, she is an associated professor at Hassan II university of Casablanca (Morocco), PhD in electrotechnics at the Blaise Pascal University in Clermont Ferrand (France), a former researcher at the NIST (National Institute of Standards and Technology) in Maryland (USA), and a professor at the University of Auvergne (France). Industrial expert in the field of industrial management, Engineering of complex systems and renewable energies.