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Research Article

STATCOM Contribution for Improving the Dynamic Performances of HVDC Link with Low SCR under Phase Opening Faults

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Abstract:

In this paper, a new application of STATCOM in HVDC system with low short-circuit ratio SCR has been proposed to solve the disturbance faults due to the interaction between HVDC and AC systems. These interactions generate inevitable drawbacks such as high temporary overvoltage's, low-frequency resonances, risks of voltage instability, long fault recovery times and risk of development of commutation failures. In this paper, the treatment of the phase opening fault at inverter side is studied by integrating of the STATCOM device in HVDC connection. The choice of this application has been justified by several tests at inverter AC side, and this with the aim of improving the performance of the system against commutation failures, re-establishment of functioning and limits the impact of this fault. The performance of the proposed system has been validated by several simulation results under MATLAB / SIMULINK.

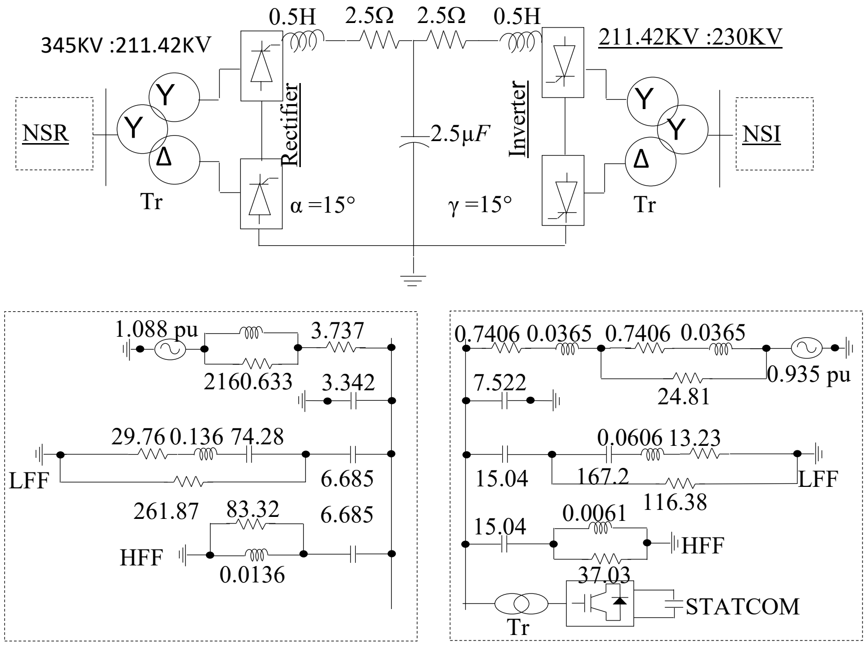
1. Introduction

Advances HVDC high voltage direct current transport technology is becoming increasingly required to ensure reliable, healthy and sustainable power supply and to meet the growing needs of the electrical power market, by providing support to the AC connected network.
The advantage of HVDC transmission over long distances has allowed its use on air and submarine domains, as well as in the field of the interconnection of two networks with the same frequency or different frequencies [1], [2].
However, the application of the LCC uses thyristor technology at the line frequency, which requires a large reactive power estimated at 50 % to 60 % of the transported power and also the injection of harmonic currents of low order and the risk of commutation errors at the inverter and their reliance on relatively strong alternative systems to provide commutation voltages [3].
HVDC systems can be classified according to their strengths in the short-circuit ratio (SCR) categories. SCR>3, 2<SCR<3, and SCR<2 correspond respectively to strong, weak and very weak links [4],[5] and [6]. The problems recognized with low and very low HVDC systems are high temporary overvoltage, the risk of voltage instability, low-frequency resonances, harmonic instability and commutation failures [7] and [8].
The majority of the previous phenomena are closely related to the AC side voltage regulation. Therefore, a special control strategy is adopted by the introduction of FACTS devices (STATCOM and SVC), allowing to provide appropriate solutions to improve the voltage stability of the supply system [9] and [10].
The STATCOM adopts the technology of the voltage source converter (VSC), for regulating a voltage via a transformer connected in shunt to the network. It allows a more robust control than the SVC and it delivers reactive power even in the presence of a very weak voltage. Given its characteristics, the maximum current of the STATCOM is independent of the voltage of the node [11] and [12].
Many faults can occur either at the AC network or at the converter (open circuit) [13]. The AC side faults of the inverter affect the HVDC system, such as those related to short circuit (SC), phase opening (OP) and the voltage drop (VD). Consequently, these defects have always affected the stability of the power conversion systems which minimizes their reliability.
Several researchers have dealt with the subject of the integration of the HVDC system inverter

STATCOM by various techniques to treat the faults mentioned previously [3], [14], [15], [16], [17] and [18]. They have led to an effective control of the magnitude of the fault current as well as the control of commutation failures problems.
However, a minority of researches concerning phase-opening faults related to converter- and AC-side voltage imbalance have not been sufficiently treated.

2.1 Description of CIGRE HVDC benchmark model

The CIGRE HVDC system is a single pole HVDC link (500 kV - 1000 MW) of two converters 12 pulses, one works as a rectifier and the other as an inverter.



NSR: AC Network Side Rectifier NSI: AC Network Side Inverter

***Figure 1.** HVDC-STATCOM system.*

In this article, a new application of phase opening fault at the inverter side is proposed. This contribution can respond favourably to the problem mentioned above and improve the stability of the HVDC system. Firstly, STATCOM device integration at the AC side of the CIGRE HVDC model inverter is performed, next applying several faults to test the performance of this integration. Finally, the faults effect in HVDC with and without STATCOM system is discussed.

2. Methodologies

The proposed system (HVDC-STATCOM) is presented in Fig.1 It consists of an HVDC LCC link based on the first CIGRE HVDC benchmark model and a connected STATCOM device, which is connected to the inverter node via a transformer [14], [16] and [19]. The purpose of the STATCOM integration is to set the switching voltage required to the HVDC inverter, by the compensation of the reactive power to the AC grid, in steady state, and under dynamic conditions.

These converters are connected to the AC systems, and each system has a short-circuit ratio SCR of 2.5 at a frequency of 50 Hz, which represents the degree of system strength. The model also includes AC filters and capacitor banks for reactive power compensation. The DC transmission line is modeled in "T", with high shunt capacitance and low series inductance. More details of the CIGRE HVDC model have been addressed in the references [19].
Table 1 presents CIGRE HVDC benchmark system parameters.

***Table 1.** Different characteristics CIGRE HVDC.*

parameters	Rectifier	Inverter
AC Voltage Base	345 KV	230 KV
Base MVA	100M VA	100 MVA
Transf. Tap (HV side)	1.01 pu	0.989 pu
Nominal DC Voltage	500 KV	500 KV
Nominal DC Current	2 KA	2 KA
Nominal DC Power	1000 MW	1000 MW
Voltage Source	1.088 pu	0.935 pu
Transf. Xl	0.18 pu	0.18 pu
Frequence	50 Hz	50 Hz
Angle Min	$\alpha=15^0$	$\gamma=15^0$

2.2 STATCOM Operation

In this study, the synchronous static compensator (STATCOM) is connected to the inverter node of the HVDC link. It consists of a two-stage, three-phase inverter and a 3000 μF capacitor which behaves as a variable DC voltage source.

Fig.2 shows an equivalent single-phase circuit of STATCOM where VL is the phase source voltage. The models of the transmission line are the shunt resistor rsh and the leakage inductance Lsh of the transformer. Vsh is the AC output voltage of the STATCOM.

In addition, the transmission system is assumed to be symmetrical, the saturation of the transformer, the delays of the regulator and the non-linearities caused by the switching of the semiconductor devices are also assumed to be negligible in the equivalent circuit [10], [20] and [21].

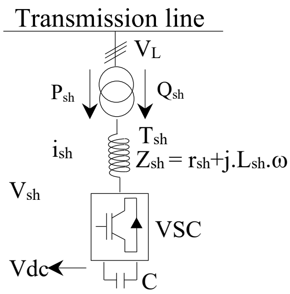


***Figure 2.** Configuration of STATCOM.*

The equations of system in Park's transformation model are presented as follows:

$$\frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} \frac{r_{sh}}{L_{sh}} & \omega \\ -\omega & \frac{r_{sh}}{L_{sh}} \end{bmatrix} \cdot \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \frac{1}{L_{sh}}\left(\begin{bmatrix} V_{shd} \\ V_{shq} \end{bmatrix} - \begin{bmatrix} V_{rd} \\ V_{rq} \end{bmatrix} \right) \quad (1)$$

The active and reactive powers are expressed by the following equations:

$$\begin{cases} P_{sh} = \frac{3}{2}(V_{shd} i_{shd} + V_{shq} i_{shq}) & (2) \\ Q_{sh} = \frac{3}{2}(V_{shd} i_{shq} + V_{shq} i_{shd}) & (3) \end{cases}$$

3. Strategies of HVDC control

3.1 Rectifier current control

Fig.3 shows the control of the rectifier current by a PI regulator. The output of this regulator is known as the delay angle or firing angle that generates the firing pulses of the rectifier. This angle is limited in the interval [α_{min} α_{max}], α_{min}= 5° and α_{max}= 165° [1].

3.2 Inverter control system

The control system of the inverter is shown in Fig.4 It consists of two regulators: one for voltage control and the other for transient current control [1-4]. The direct current Idi is compared with the current I_r and the result, in turn, is compared with the margin of the current I_m (0.1). The regulator PI generates the control angle α_1 which is limited between α_{min} = 92° and α_{max} = 165° [1].

The voltage controller compares the measured voltage with the reference value V_{ref} (1pu). The error is transmitted to a PI regulator which generates the control angle α_2, limited between α_{min} and α_{max} [1-5]. The smaller of the values α_1 and α_2 are used to generate the ignition pulses. In normal operation, α_1 is greater than α_2 and in transient, α_1 is less than α_2.

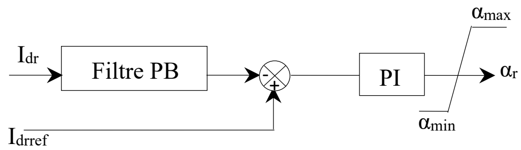


***Figure 3.** Rectifier current control.*

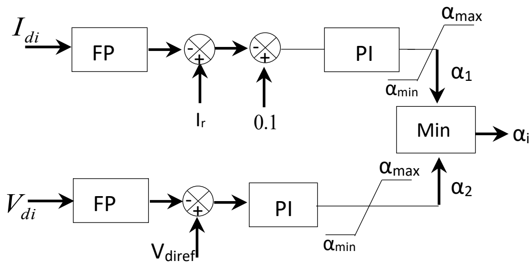


***Figure 4.** Inverter control system.*

4. STATCOM control strategy

In this strategy, the voltage of the shunt converter STATCOM is decomposed into two components. One component is in phase and the other in quadrature with the voltage at the connection point of the STATCOM (VL). The decoupled control system is used at the same time to control the voltage VL and the DC voltage Vdc of the capacitor [21] and [22].

4.1 Current regulation

The Figure 5 describes the circuit for adjusting the current in which the coupling terms are injected with opposite signs in order to make the two currents (I_{dsh} and I_{qsh}) completely independent and that in order to separate between the active and reactive powers injected.

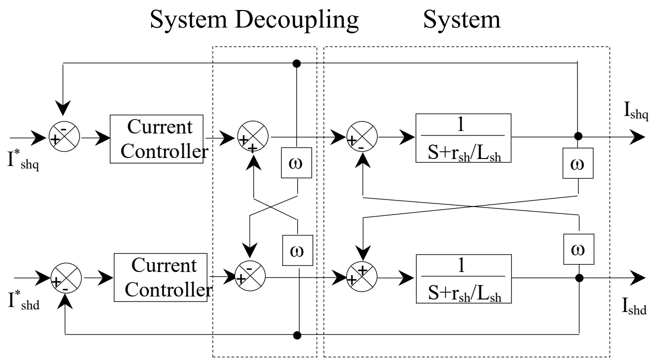


Figure 5. *System Decoupling*

Equation (1) shows the interaction between the current loops caused by the coupling term ωL [10], [22] and [23]. The principle of this control strategy is to convert three-phase measured currents and voltages into dq values to compute the current references from equations (4) and (5) based on equations (2) and (3):

$$i^{*}_{shd} = \frac{2}{3}\frac{(P^{*}_{sh}V_{shd} - Q^{*}_{sh}V_{shq})}{V^{2}_{shd} + V^{2}_{shq}} \quad (4)$$

$$i^{*}_{shq} = \frac{2}{3}\frac{(P^{*}_{sh}V_{shq} - Q^{*}_{sh}V_{shd})}{V^{2}_{shd} + V^{2}_{shq}} \quad (5)$$

4.2 DC voltage regulation

The DC voltage of the STATCOM is expressed by:

$$V^{2}_{dc} = \frac{P_{sh}}{CS} \quad (8)$$

Fig.6 describes the control of the DC voltage

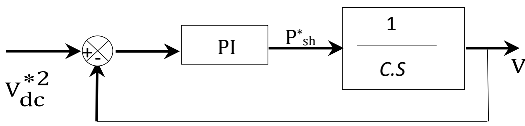


Figure 6. *Dc voltage control.*

Figure 7. shows the overall control of STATCOM

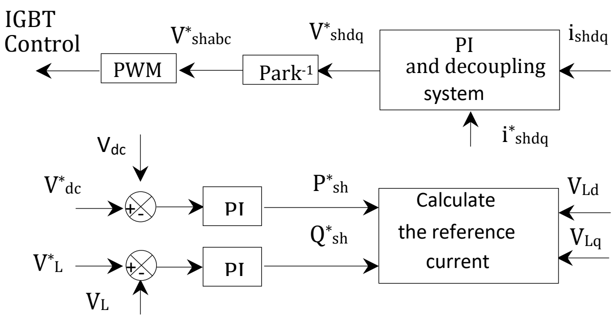


Figure 7. *Overall control of STATCOM.*

5. A comparative study between HVDC and HVDC-STATCOM under phase opening faults.

In this part, a fault is applied in the AC line at the inverter side (phase opening fault). There are two faults: single-phase fault and three-phase fault. This fault is experienced on the one hand with the HVDC and on the other hand with the HVDC-STATCOM in order to know their behavior. A comparison between the performances of the two systems is made to judge their efficiency.

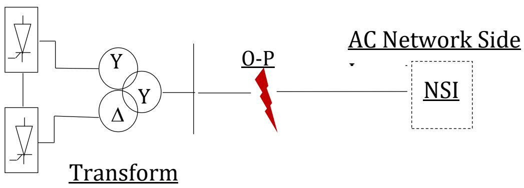


Figure 8. *HVDC and HVDC-STATCOM under phase opening faults.*

5.1 HVDC with and without STATCOM under phase open fault (single phase)

From Fig.9a and Fig.9b, it is noted that during the steady state, the voltages Vrms and the currents Irms retain their behavior and remain stable. After applying the fault at the moment 1s for the duration of 100 ms, the Vrms reaches a peak of 2pu and takes recovery time of 0.6s in the case of HVDC alone. On the other hand, the voltage approaches peak value of 1.9 pu and a recovery time of 0.3s in the case of HVDC-STATCOM. For the current Irms, we note that the recovery time for both systems (HVDC, HVDC-STATCOM) has the same behavior as the case of Figure 9a.

It is also observed that the HVDC system generates undulations whose period is less than 0.08 s compared with HVDC-STATCOM system.

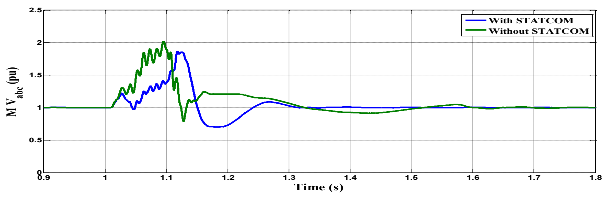


Figure 9a. *Voltage with and without STATCOM due to single-phase opening fault at inverter AC side.*

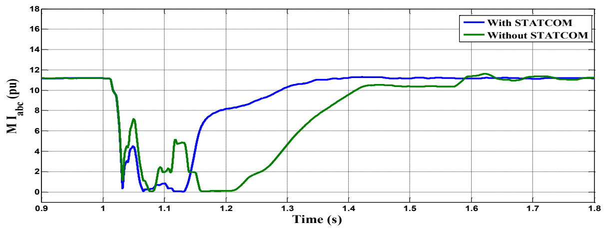


Figure 9b. *Current with and without STATCOM due to single-phase opening fault at inverter AC side.*

In Fig.10a and Fig.10b, note that the voltage supplied by the affected AC grid, drops the DC voltage at the input of the inverter and the current Id has peaks of 2.6 pu for both systems (HVDC, HVDC-STATCOM). In this case, the rectifier goes into inverter mode (the angle α exceeds 90°) and the reference current Id decreases to 0.3 pu, following the intervention of the VDCOL after detection of a DC voltage drop below 0, 6 pu (threshold voltage).
The recovery times (Tr) of the DC voltage and current (V_d, I_d) in both systems (HVDC, HVDC-STATCOM) are respectively (0.53s, 0.25s) and (0.58s, 0.3s). It is also noted that the current I_d in the case of the HVDC system alone, has high peaks around the value 1.8 contrary to the peaks presented by the HVDC-STATCOM system which have smaller values and tend towards zero.
In Figure 10c, it is clearly seen that the recovery time of the continuous power transported for the HVDC-STATCOM system is faster than that of the HVDC system alone with a difference of 0.3s.

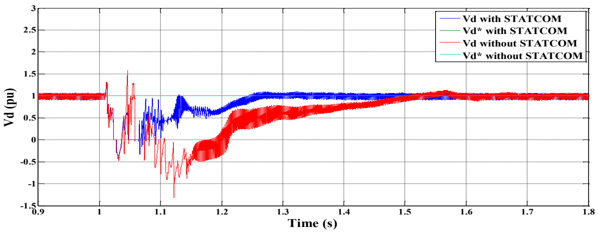


Figure 10a. *HVDC link voltages with and without STATCOM due to single-phase opening fault at inverter AC side.*

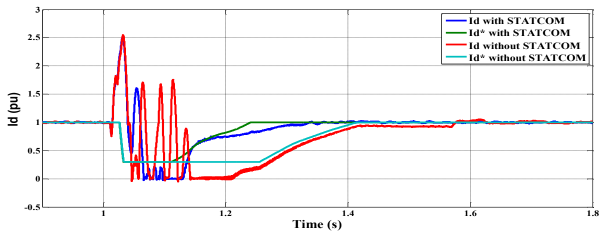


Figure 10b. *HVDC link currents with and without STATCOM due to single-phase opening fault at inverter AC side.*

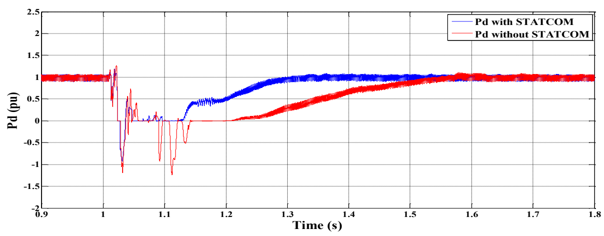
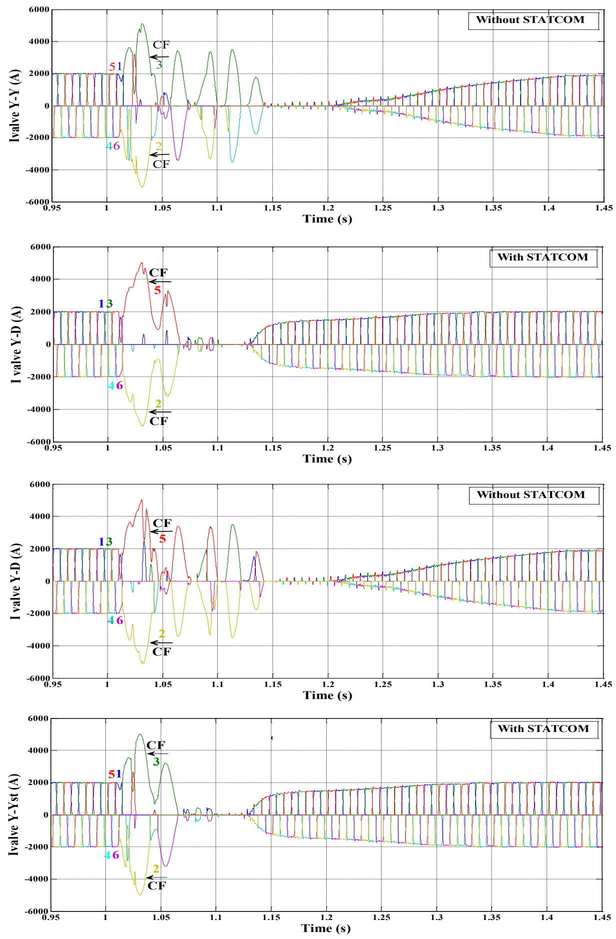


Figure 10c.*HVDC link power with and without STATCOM due to single-phase opening fault at inverter AC side.*

Fig.11a indicates that the functioning of valves 1 to 6 is ordered and stable before the fault. After the fault appearance, a malfunctioning is observed at the valves 3 and 2 because of the direct current I_d increase (Fig 9b), which generated significant peaks of the current of these valves. This fault, in turn, created a disorder of functioning at the other valves for a duration of 0.18 s. Beyond t = 1.2 s, the functioning restoration of the valves is noticed and the steady state is happening from t = 1.4 s.
In Fig.11b, the same observation of Fig.10a is drawn for the behavior of valves 3 and 2 with a time interval of malfunctioning of t = 0.11 s and the correct functioning re-establishment (orders of valves) from 1.13s and maintaining of the steady state from t = 1.15s.Fig.11c shows that the valves 5 and 2 work in concordance, so they conduct the current at the same time, which represents a failure commutation compared to the standards of the real regime. This failure is interpreted as a significant increase in DC current Id followed by disturbances during 0.18 s and re-establishment of the correct functioning (valve orders) from 1.2 s and maintaining of the steady state from 1.4s.In Fig.11.d, the same observations are drawn as those in Fig.10.c with disturbances whose duration is less than that of the case HVDC (0.05s). The re-establishment of the correct functioning (orders of valves) is faster (1.13 s) and maintaining of the steady state from t = 1.15s.



Figures 11a, b, c, d*. Currents in the valves of the two bridges Graëtz (YY and YΔ) with and without STATCOM.*

5.1 HVDC with and without STATCOM under phase open fault (three phases)

In Fig.12.a, the three-phase fault is applied at the moment 1s for the duration of 100 ms. The insertion of STATCOM has a perfect reduction effectiveness. The voltage Vrms peak and the recovery time are respectively reduced (from 3.8 pu to 1.5 pu) and (from 1s to 0.22 s).

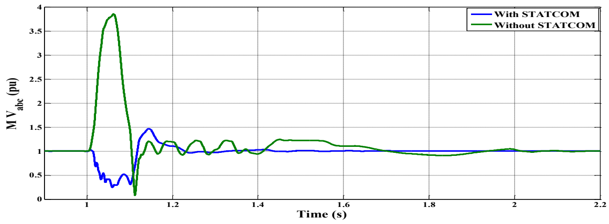


Figure 12a. *Voltage with and without STATCOM following an opening fault of 3 phases on the AC side of the inverter.*

Fig.12.b shows clearly that the presence of the STATCOM has reduced the undulations and recovery time of the current I_{rms} (from 1s to 0.22 s), compared to the HVDC system alone.

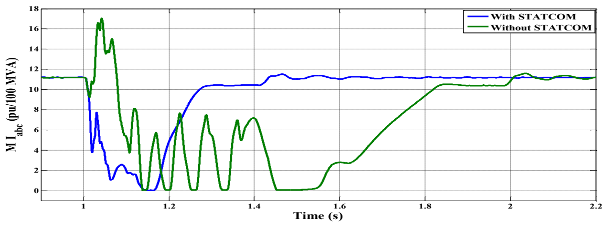


Figure 12b. *Current with and without STATCOM following a fault opening of 3 phases on the AC side of the inverter.*

In Fig.13a, Fig.13b and Fig.13c, it is observed that the use of STATCOM improves, on the one hand, the recovery time of the functioning after the elimination of the fault (the time recovery time goes from 1s to 0.4s) and on the other hand, it reduces the undulations appearing on the V_d, I_d and P_d magnitudes of the HVDC system alone.

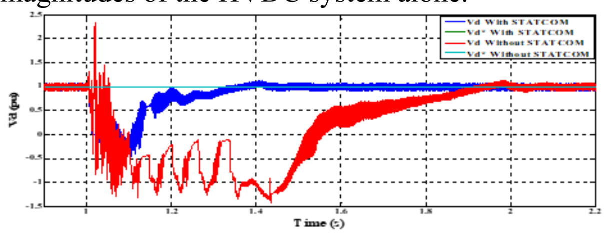


Figure 13a. *Voltage of the HVDC link with and without STATCOM due to a fault in the 3-phase AC side opening of the inverter.*

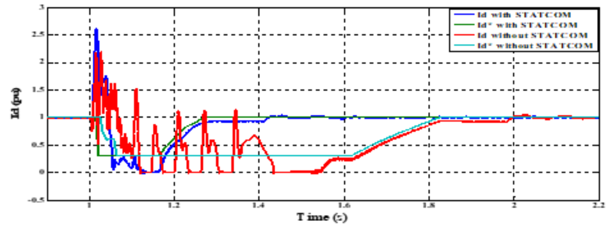


Figure 13b. *Current of the HVDC link with and without STATCOM due to a fault in the 3-phase AC side opening of the inverter.*

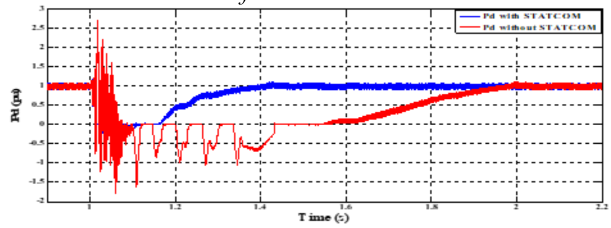
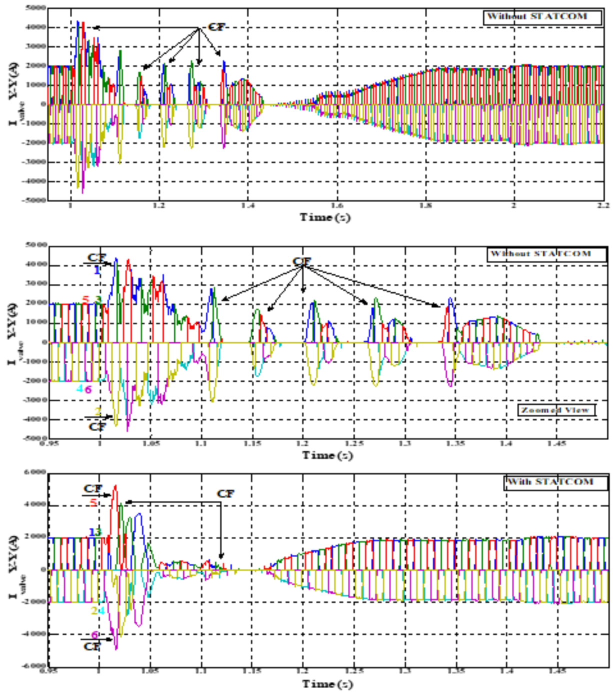


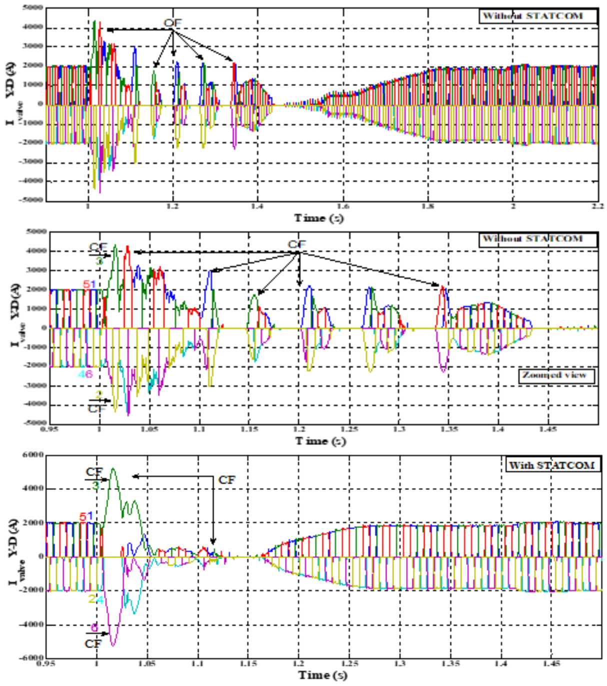
Figure 13c. *HVDC link power with and without STATCOM due to a fault in the 3-phase AC side opening of the inverter.*

In Figs.14.a, b,c, and Fig.15.a, b,c, the normal and stable functioning of all the valves is observed before the fault occurrence.



Figures 14.a, b, c. *Currents in the valves of bridge Graëtz (YY) with and without STATCOM due to 3 phase opening faults at inverter AC side*

After that, the increase of the DC current Id has created significant peaks of the current and consequently a disorder of valves functioning.
The functioning recovery of these valves is better in HVDC-STATCOM case whose steady state is re-established from the moment t = 1.25 s compared to that of HVDC alone which is from 1.8s.



Figures 15a, b, c. *Currents in the valves of bridge Graëtz (YΔ) with and without STATCOM due to 3 phases opening fault at inverter AC side*

6. Conclusion

In this paper, a new technique based on the application of STATCOM in HVDC system with low SCR is proposed. This technique solved the disturbances caused by the interaction between the HVDC and AC systems during the phase opening faults by adding the STATCOM to the HVDC system at the inverter AC side. The solutions carried by the new HVDC-STATCOM system have improved the dynamic performance during various faults.

The results of the simulation demonstrated the robustness and efficiency of this technique by obtaining satisfactory responses: faster recovery time after the fault as well as a better minimization of currents and voltages disturbances in the case of HVDC-STATCOM system.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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