5 th International Conference on Control & Signal Processing (CSP-2017)
Proceeding of Engineering and Technology –PET
Vol.25 pp.112-116

Dynamic performance of an HVDC link based on protection function against commutation failures

M.MANKOUR[#1], M. KHIAT[#2], L. GHOMRI[3], M. BENSALAH[#4]
[#]*Department of electrical engineering*
Laboratory SCAMRE (Simulation, commande,Analyse et maintenace des réseaux électriques)
Polytechnic school of ORAN (ENPO-MA, Ex:ENSET), Algeria
[1]`med_mank@yahoo.com`
[2]`Khiat2_2000@yahoo.fr`
`4mb.enpo@yahoo.com`
[3] *Department of electrical engineering*
University Abdelhamid Ibn Badis of Mostaganem, Algeria
[3]`Lilaghomri@yahoo.fr`

***Abstract*—Real time simulation of a 12-pulse HVDC (High Voltage direct Current) is presented in this paper using RTDS (Real time Digital simulator) by means of RT-lab platform with HYPERSIM (OP-5600) simulator. Main objective of the study is to reduce the probability of commutation failures at inverter station by adding a protection function to the control system. This real time simulation considers the strength of AC system and also the dependence of the protection function on the system behavior and recovery from AC faults. The protection function validity is demonstrated based on the obtained waveforms analyses from a real time simulation of an AC single phase to ground fault applied to the inverter side.**

Keywords—, RTDS (Real Time Digital simulation), HYPERSIM simulator, HVDC system, commutation failures, protection function.

I. INTRODUCTION

HVDC transmission is worldwide used in power systems for environmental, economical, and technical reasons. Addition to this, its application in long distance by means of submarine cables has became the best solution for linking two different grids whatever they have not same frequencies. [1]. Most of HVDC systems used are based on LCC (line-Commutated converter) using thyristor technology. However, some problems in their operation appear, especially in case of AC faults [2], where commutation failures are the commonest misoperation of an inverter, resulting from internal or external faults at the converter terminal. Furthermore, probability of commutation failure depends on interaction AC-DC and on SCR (short-Circuit ratio), the strength of AC system which the converter terminal is connected [3]-[4]. In literature, two main methods to reduce the risk of commutation failures after faults can be classified as follow: the first is achieved by modification of the control system [5], and the second one by introducing additional power electronic devices in the system [3].

In order to understand the behaviour the HVDC system under different kinds of faults, various simulations and comparison with different simulator and software are used to study HVDC systems such PSCAD/EMTDC, PSB/SIMULINK, and PSCAD/SIMULINK by Faruque. M. O and al [6] and with PSS/E by D. Kwon and al [5]. In this paper, a full DRTS (Digital Real Time Simulator) is used to analyze the electromagnetic transients of a 12-pulse HVDC system. This DRTS is HYPERSIM (OP-5600) developed by RT-LAB [7], Hypersim offers an extend software and hardware package designed to simulate on-line or off-line complex power system [8]-[9]. In fact, in domain of supercomputer and fast processors, the simulation of complex and dynamic systems are achievable in real time[4] and the real time simulation has its application in mainly three categories as follow: Hardware in the loop HIL, Rapid control prototyping RCP and Simulation in the loop SIL, more detail in [10]. A SIL is used in this paper to study the performance of the protection function to mitigate commutation failures in an inverter feeding week grid after single phase to ground fault.

The rest of paper is organized as follows: Section II presents the HYERSIM Environment. Section III introduces the commutation failure model. Section IV describes HVDC system under study and DC control function and the protection function is also presented. The simulation results are presented in section V. Conclusion is given in section VI.

II. HYPERSIM ENVIRONNEMENT

HYPERSIM is fully digital real-time simulator developed by IREQ, the Hydro-Quebec's research institute [19]. HYPERSIM uses the nodal approach and the trapezoidal integration method to solve equations of power network, control and protection systems [7]. The features of the HYPERSIM (OP-5600) used for simulation in this paper are: two CPU Intel Xeon Six-core 3.46 GHZ 12M cache, Four Memory 2GB and X8DTL-I-O Supermicro Motherboard, processor 5600/5500 series. The HVDC system implemented in simulation is modeled in single phase, both protection and regulation are included.

ISSN 2356-5608

III. COMMUTATION FAILURES DESCRIPTION

During commutation in normal condition, the valve current cannot change from one valve to the other suddenly and thus, commutation cannot be instantaneous (figure 1). In fact, for each valve, commutation process takes a period of time [1]-[3].

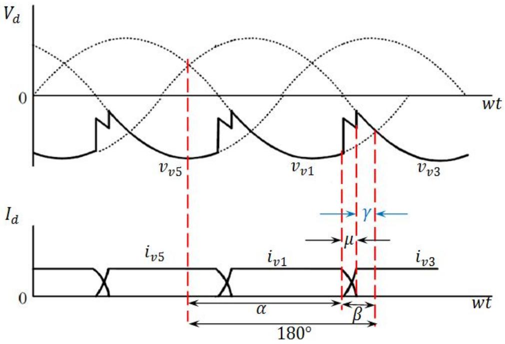


Fig 1. Inverter operation showing commutation

Commutation process between valve 1 and valve 3 in normal commutation condition is presented in fig 2. During commutation between the two valves, a short-circuit current I_{cc} is created through the two reactance X_c by voltage V_{ba}. Then this short circuit current will be decreased gradually even the current go out from the valve 1 to the valve 3 and that is explained by $(I_d = i_{v1} + i_{v3})$, the DC current rest constant during commutation .

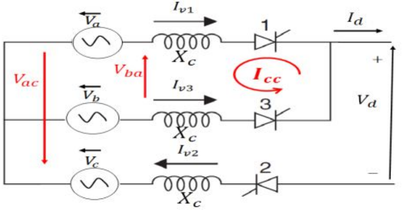


Fig.2 Equivalent circuit during conduction between valve 1 and 3

The time of short circuit current annulations is measured by commutation period between the two valves, known as the overlap angle μ given in equation 4. At the beginning of commutation when $wt = \alpha$, and assuming that inductances of transformer winding are equal, we can write:

$$v_{ba} - v_{ac} = \sqrt{2}(X_c/w)\, di_v/dt \tag{1}$$

After integration, the instantaneous expression for the commutating current is thus:

$$i_{cc} = \frac{V_{LL}}{2X_c}[\cos\alpha - \cos(wt)] \tag{2}$$

Therefore, at the end of commutation, $wt = \alpha + \mu$, the current valve 3 is equal to the DC current, then equation 2 gives:

$$i_{v3} = I_d = \frac{V_{LL}}{2X_c}[\cos\alpha - \cos(\mu + \alpha)] \tag{3}$$

Then, the overlap angle μ is expressed as:

$$\mu = arcos\left(\cos\alpha - \frac{X_c I_d \sqrt{2}}{V_{LL}}\right) - \alpha \tag{4}$$

Where: α represent delay angle, β is advance angle ($\beta = 180 - \alpha$), X_c reactance of transformer converter, I_d represent DC current and V_{LL} is the line to line RMS voltage dependent on AC system voltage.

The inverter is more prone to commutation failure and it presents the commonest fault because it firing angle is large $90 < \alpha < 180$, unlike to rectifier which his delay angle$\alpha < 90$, that's why rectifier rarely fails in commutation failure. For that, to make a successful inverter operation and to avoid any commutation failure and overshoot of current valve, an extinction angle γ must be taken in consideration because thyristor require a turn-off time for a successful commutation (figure 1) and this angle need to be maintained at the minimum value [1]-[2].therefore, a limit is imposed at the maximum value of the inverter firing angle:

$$\alpha_{\max\_inv} = 180 - (\mu + \gamma_{min}) \tag{5}$$

Rising of commutation failures is explicated by increasing of the overlap angle μ or decreasing of extinction angel γ_{min} which causes reduction in Voltage or increase in current or both. Basically, Commutation failures are causes by the following causes [2]-[3]:

a) Faults in connected AC systems causes decrease in the Voltage, disturbances and phase shift at AC System which create commutation failures.

b) Increase of DC current which is usually due to the system disturbance and too rapid control system or fault in AC connected system.

c) Malfunctioning in firing control which may be caused by an internal fault such a misfiring system or fault in converter valves.

IV. SYSTEM UNDER STUDY

As proposed in [6]-[17], a mono-polar 1000 MW (500KV, 2 KA) HVDC link is presented and implemented in the real-time simulator-Hypersim [17].A DC interconnection is used to transmit power from the strong AC system _1 (315 kV, 60 Hz and SCR of 4.5) to the weak AC system_2 (230 kV, 60 Hz and SCR of 2.3), as shown in Fig. 3. The element of POW (point-to-wave) is compulsory in the network to give a reference signal to clock the disturbance and to synchronize the data acquisition and breaker operations [9].

A. The AC system: The AC networks, both AC system_1 and AC system_2, are modeled to represent the AC supply networks of the rectifier and inverter sides. Each one has internal impedance and magnitudes of their impedances are represented as $R-R/L$ networks having the same damping function of frequency such the resonances at the fundamental and third harmonic [19].

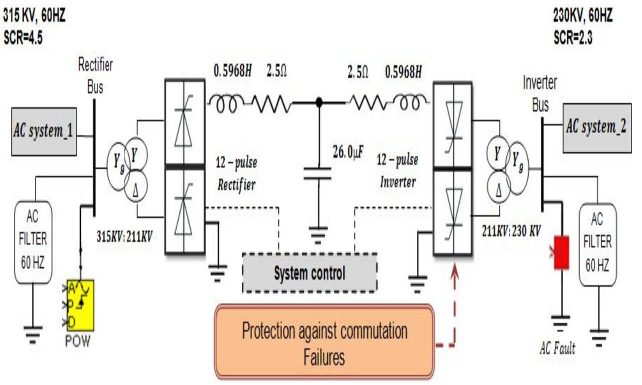


Fig 3. HVDC system

B. Converter transformer: The both converter transformers (rectifier and inverter) with tap changer control are modeled with three phase transformer (three-winding per phase): a Y primary with grounding impedance, a floating Y secondary and delta tertiary. The leakage resistances and inductances of windings are considered.

C. DC line: The DC line is modeled using an equivalent-T network with smoothing reactor 0.5968 H connected to both rectifier and inverter side**.** The reactor smoothing is represented by decoupling reactor to divide the task into two sub-tasks in order to decrease the calculation load [9].

D. AC Filters and reactive support: Current harmonics of the order of 11, 13, 25 and higher are generated on AC side of 12-pulse HVDC converters. For this reason, Damped filters are installed to limit the amount of harmonics to the level required by network. The capacitive banks are also installed to recompense the reactive consumed by converters in conversion process. Each filter and capacitors banks are installed on rectifier and inverter sides.

E. Converter: Two 12-pulses converter are used for both station rectifier and inverter side, each valve of converter is composed with many thyristors in series and has a RC parallel snubber.

F. Control System: The basic units of system control are tap changer control, synchronization regulation of firing angles (delay angle_ α and firing angle_γ), VDCOL (Voltage Dependent Current Order Limiter) and protection against commutation failures, as shown in figure 4. The function of the regulation system for both converters rectifier and inverter are two current and voltage regulators of the proportional and integral type (PI) operating in parallel to calculate and adjust delay angle α_{rec} of rectifier and maintain extinction angle of inverter γ_{inv} at a minimum values, the voltage is regulated with a slope determinate by current margin ($\Delta I_d = 0.1\, pu$) and voltage margin ($\Delta V_d = 0.05\, pu$).

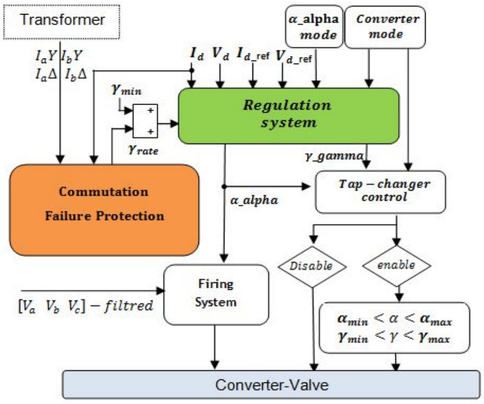


Fig. 4. Control system diagram of converter.

- **VDCOL function:** Voltage Dependent Current Order Limiter (VDCOL) is used to adjust the Current reference I_{d_ref} set point at the correspondent value of the DC voltage V_{d_line} in such type of disturbance. Another benefit of this function is good recovery from DC power transit and minimization of the risk of commutation failure [3]-[19].

- **Protection function:** To reduce the risk of commutation failures, a function control against commutation failure is added to the main control (figure 4). Comparison between both DC and AC current at valve side is done in normal condition, in fact they are nearly equal (in pu). Whereas in case of commutation failure, a short circuit on DC side is created instantaneously providing quick increasing of DC current (the thyristor valve oversteps his necessary time of commutating and left conducting). At this moment the Inverter has a null voltage and hence, drops of current on the AC side. The comparison between currents (I_{ac}) and (I_{dc}) is detected by the protection function if:

$$I_{dc} > I_{ac} \tag{6}$$

$$And \quad I_{ac} < 0.65\, pu \tag{7}$$

$$Where\ I_{ac\_CF} = 0.65\, pu \tag{8}$$

The function protection helps to take out the inverter from commutation failure by keeping away α_{inv} from the area where the risk of commutation failure is high especially in case of persistent commutation failures. As shown in fig 7, it action is by subtracting γ_{CF} from equation 5 to decrease the upper limit of α_{inv} , then the maximum firing angle is expressed as:

$$\alpha_{\max\_inv} = 180 - (\gamma_{min} + \mu) - \gamma_{CF} \tag{9}$$

V. SIMULATION RESULTS

The 12 pulse HVDC system is implemented in the simulator Hypersim, Real time simulation is taken with 50 μs step simulation. Two case studies after single phase to ground at inverter bus are carried out as fellow:

a. Normal control system (without protection).
b. With protection function.

a) Without protection function

A Single phase to ground is applied to the inverter bus at t=3s, and the duration of the fault is 10 cycles. Results are shown in fig. 5. An overshooting of the DC current on both side rectifier and inverter ($I_{d-rec} = 4200A$ and $I_{d-inv} = 4700A$) due to the reduction in DC voltage at inverter side. Delay angle of the rectifier is forced to the inverter side and reach ($\alpha_{rec} = 140°$) because the rectifier current controller react and attempt to reduce the pick of the current by increasing the delay angle. Commutation failure rise (figure 6) and the extinction angle fall to zero. The VDCOL then operates and limits the DC current at the minimum value($I_{d-min} = 600A$). The inverter delay angle reaches the maximum value ($\gamma_{inv-max} = 160°$) when the inverter voltage controller tries to restore the DC voltage, therefore, the inverter pass to control the extinction angle to avoid rising of commutation failures. Almost immediately after clearing the fault, second commutation failures appears in valves due to overshooting of the DC current but VDCOL reacts again to reduce it at the minimum value, and DC current is ramped up gradually to ensure the stability and system comes back to normal condition in 0.2 seconds.

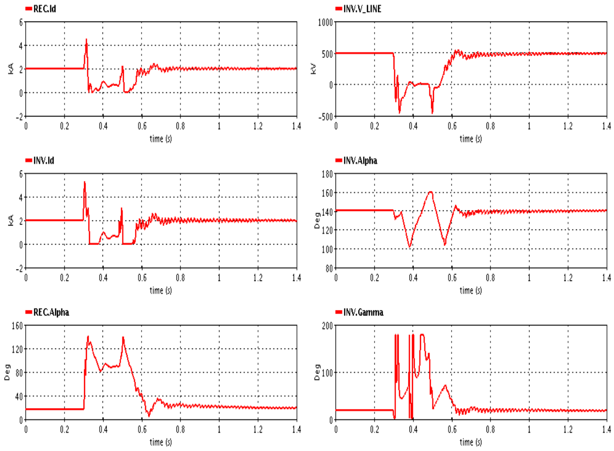


Fig 5. Single phase to ground, 10-cycle fault at inverter bus.

b) With protection function

The same fault was applied at inverter bus for the same duration of time, the goal of this case is to test the protection function role.

As shown in figure 7. When the fault is applied at t=3s, at the first time, same behavior is noticed like first case, but in this case, after adding protection function to the main system control, the angle rate imposed by the protection function (equation 8) decrease the inverter delay angle and keep it away from the maximum value ($\gamma_{inv} = 118°$). When the fault is cleared at t=4.48s, the recovery process is initiated, DC voltage restores and the VDCOL adjusts the DC current gradually. As shown in figure 9, no overshooting of the DC current, commutation failures are avoided by the protection function and the system comes back to stability condition but cost a little much time recovery.

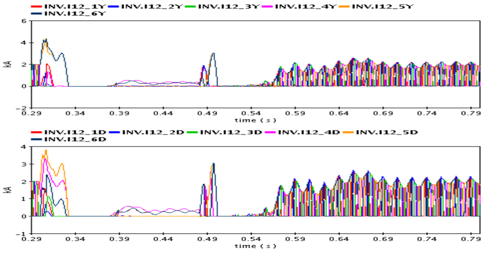


Fig 6. Waveform of inverter current valves during the fault (zoomed view).

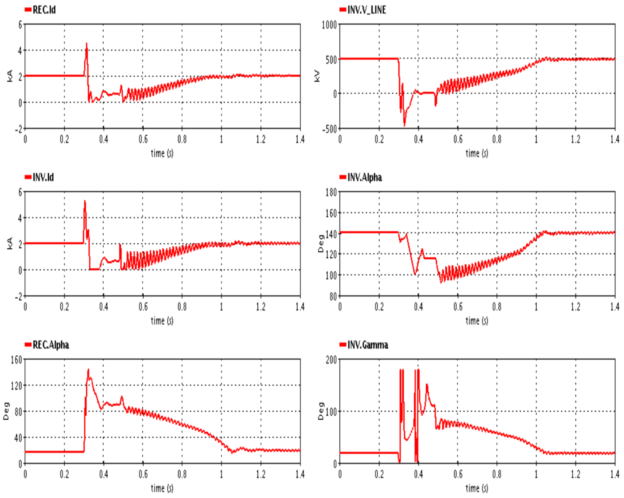


Fig 7. Single phase to ground, 10-cycle fault at inverter bus.

VI. CONCLUSION

In this paper, we present a real time simulation of an HVDC link in dynamic condition using HYPERSIM simulator, as shown in the above results, we show that not only the system control affects on commutation failures rising or inhibiting, but also protection function has a reliability to mitigate the commutation failure. In goal to improve the performance of HVDC system, a protection function is added to the main control system, its action is by decreasing the inverter delay angle and keeps it away from the maximum value to avoid commutation failure, and in consequence, decrease the consumption of reactive power by the inverter. This approach provides also a good recovery and a good stability after fault clearing.

Efforts will be made in the future work in developing other methods to mitigate the commutation failures problems or reduce its probability, and for studding other possibilities such as adding electronic devices/component in the system or by means of other mode simulation in real time studies.

ISSN 2356-5608

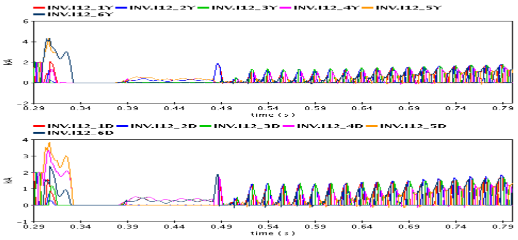


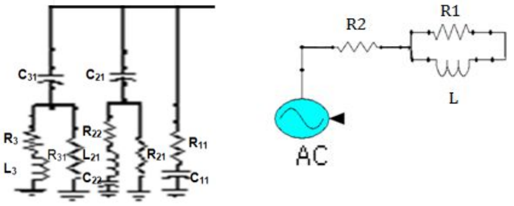
Fig 8. Waveform of inverter current valves during the fault (zoomed view).

APPENDIX

Table I gives the detailed parameters of the HVDC link, the diagram of AC system and the AC filter are shown in fig. 10.

Table I
PARAMETERS OF THE HVDC SYSTEM

Parameters	Rectifier	Inverter
AC Voltage base	315 KV	230 KV
System frequency	60 HZ	60 HZ
Nominal DC voltage	500 KV	500 KV
Nominal DC current	2 KA	2 KA
Transformer X_c	0.18 pu	0.18 pu
Minimum Angle	15	15
SCR	4.5	2.3
Power Supply	R1=19.88 Ω R2= 3.437 Ω L=0.151 H	R1=25.63 Ω R2=8.36 Ω L=0.0581 H
AC Filters	C11=2.7851F R11=0.001 Ω	C11=6.2681F R11=0.001 Ω
	C21=5.5711F C22=61.91F L21=0.1137H R21=0.2976 Ω R22=261.85 Ω	C21=12.531F C22=139.31F L21=0.0505H R21=0. 1323 Ω R22=116.38 Ω
	C31=5.5711F L31=0.01137H R31=0.001Ω R32=83.32 Ω	C31 =12.531F L31=0.00505H R31= 0.01 Ω R32=37.03 Ω



(a) (b)

Fig. 10 a) Diagram of AC Filter. b). AC system representation

REFERENCES

[1] Arrillaga, J, High Voltage Direct Current Transmission, *the Institution of Electrical Engineers, 1998*.

[2] K.R. Padiyar, HVDC Power Transmission Systems, *New Academic Science Limited, second edition, 2013.*

[3] CIGRE .Working group 14.05, Comutation Failures causes and consequences, Interaction between AC and dc Systems, *final report. November1995*.

[4] M. O. Faruque, T. Strasser, G. Lauss, V. Jalili-Marandi, P. Forsyth, C. Dufour, V. Dinavahi, A. Monti, P. Kotsampopoulos,J. A. Martinez, K. Strunz, M. Saeedifard, X.Wang, D. Shearer, M. Paolone,R. Brandl, M. Matar, A. Davoudi, and R. Iravani, Real-Time Simulation Technologies for Power Systems Design, Testing, and Analysis, *IEEE Power and Energy Technology Systems Journal, vol 2, no. 2, pp63-73 june 2015*.

[5] Thio.C.V, Davies, J. B, Kent.K. L."Commutation Failures in HVDC Systems," *IEEE Trans. Power delivery 11 No.2. (April 1996),pp 946–957*.

[6] Faruque. M. O, Yuyan Zhang, Dinavahi. V, Detailed Modeling of CIGRE HVDC Benchmark System using PSCAD/EMTDC and PSB/SIMULINK," *Power Delivery, IEEE Transactions Vol. 21 No. 1 (Jan 2006), 378–387*.

[7] A, O, Barry, F. Guay, S. Guerette, P. Giroux, Digital Real-time Simulation for Distribution System, *in Proc. 2000 IEEE International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance, pp. 252-258, Oct. 2000*.

[8] G. Sybille and P. Giroux, Simulation of FACTS controllers using the MATLAB power system blockset and hypersim real-time simulator, *in Proc. IEEE Power Eng. Soc. Winter Meeting, vol. 1. New York, NY, USA, Jan. 2002, pp. 488-491*.

[9] Hypersim, Software Realize3.0, Reference Guide Manual 9.2, *Hydro-Quebec Group, August 2007*.

[10] J. Bélanger, J. N. Paquin and P. Vene, the What, Where and Why of Real-Time Simulation, *IEEE PES General Meeting, Minneapolis. USA, July 2010*.

[11] W. Zhinong, Y. Yang, L. Xiao, W. Huawei, S. Guoqiang, and S. Yonghui, Direct-current redictive control strategy for inhibiting commutation failure in HVDC converter, *IEEE Trans. Power Syst., vol. 29, pp. 2409–2417, 2014*.

[12] D .H. Kwon, H. Moon, R. Kim, G. K. Chan, S. Moon, Modeling of CIGRE Benchmark HVDC System Using PSS/E Compared with PSCAD, *IEEE, 5th International Youth Conference on Energy (IYCE),Italy, May 2015*

[13] Z. Lidong and L. Dofnas, A novel method to mitigate commutation failures in HVDC systems, *in Proc. Int. Conf. Power System Technology, 2002, vol. 1, pp. 51–56*.

[14] D. Jovcic, Thyristor-based HVDC with forced commutation, *IEEE, Trans. Power Del., vol. 22, pp. 557–564, 2007*.

[15] F. Guay, J. Cardinal, E. Lemiex, and S. Guerette, Digital real-time simulator using IEC 61850 communication for testing devices, *in Proc. CIGRE Canada Conf., Montreal, QC, Canada, Sep. 2012*.

[16] H. W. Dommel, EMTP Theory Book, *Bonneville Power Administration, Portland, Oregon, USA, Aug. 1986*.

[17] M. Szechtman, T. Wess, and C. V. Thio, First benchmark model for HVDC control studies, *Electra, no. 135, pp. 54–67, Apr. 1991*.

[18] D. Van Que, J.C. Soumagne, G. Sybille, G. Turmel, P. Giroux, G.Cloutier, S. Poulin, "Hypersim--an integrated real-time simulator for power networks and control systems,"*Proc. Int. Conf. Digital Power System Simulators, Vasteras, Sweden, May 1999*.

[19] C. Kim, V. K. Sood, G. Jang, S. J Lim, S. J. Lee, HVDC Transmission: Power Conversion Applications in Power Systems, *John Wiley & Son (Asia), 2009*.