ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 4, Special Issue 6, April 2017

Design and Modeling of Synchronverter Based HVDC Transmission System

Akshara Mohan
PG Scholar,
MCET,Thriruvananthapuram
aksharamohan379@gmail.com

Prameeda Mohan
Asst.Professor,
MCET,Thiruvananthapuram
prameedamohan@gmail.com

Abstract—**Moreattention has been paid to the energy crisis due to the increasing energy demand from industrial and commercial applications. The utilization of renewable energy such as solar,wind etc are considered as one of the most promising electrical energy sources, which has grown rapidly in the last three decades. Many power converter techniques have been developed to integrate renewable energy with the electrical grid. HVDC systems use dc for huge amount of electric transmission power based on large power electronics which provide the opportunity to enhance controllability, stability and power transmission capability of AC transmission systems. Conversion of power between AC and DC became possible with the development of power electronics devices such as thyristors and voltage source converters (VSC). The VSC technology offers new capabilities for dynamic voltage support, more flexibility and independent controls of active and reactive power. A new control strategy of HVDC transmission based on the synchronverter concept. In this work, there is a new controlstrategy is known as synchronverter control which is using the synchronous generator mathematical equations as a reference. For a complete DC system, a rectifier and inverter are bound by a DC link. Therefore, another synchronverter working as a synchronous motor (SM) based on the same mathematical derivation is necessary for rectifier control. So, the DC power is sent from the SM to the SG. The main idea is a conceptual control strategy of the DC line, where the sending-end rectifier controls emulate a synchronous motor (SM) and the receiving end inverter emulates an synchronous generator (SG), both along with their controls. So the resulting synchronverter-based HVDC will be called SHVDC. Better results than with the conventional VSC control were obtained with better dynamic performances and stability margin is obtained. Analysis, simulations are presented to demonstrate the proposed concept.**

Index Terms—**High voltage direct current (HVDC), synchronous generator/motor, synchronverter, Voltage source converter(VSC).**

I. INTRODUCTION

High voltage direct current (HVDC) systems use direct current for bulk electric transmission power basedon high power electronics which provide the opportunity to enhance controllability, stability and power transmission capability of AC transmission systems [1]. Practical conversion of power between AC and DC became possible with the development of power electronics devices such as thyristors and voltage source converters (VSC). The VSC technology offers even more flexibility, new capabilities for dynamic voltage support, independent controls of active/reactive power and easier integration of wind farms [2]. These HVDC transmission systems are specifically used to connect asynchronous grids, as for example the England-France interconnection [3]. Nonetheless, other equally important HVDC applications concern complex AC interconnected systems in order to enhance the power transmission capacity and meet the growing demand. The planned Spain-France interconnection [4], which will use the VSC technology scaled up to 2000 MW, is such an example. These emerging applications gave rise to the co-existence of parallel HVDC/HVAC, and consequently, an increased level of AC/DC/AC converted power injected into AC networks. Many studies have shown that the methods of controlling HVDC converters have an impact on stability of the system in which the link is inserted. The main trend in control techniques for HVDC-VSC links are based on the well-established vector control scheme. For example, in [5] the standard vector control has been modified to improve the dynamic performance of a parallel AC/DC interconnection. In [6], the VSC-HVDC operating characteristics are determined by a decoupled PI controller to provide decoupled and independent control of the active and reactive powers for each converter. Generally, and due to their simple

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 4, Special Issue 6, April 2017

structure and robustness, PI controllers have been adjusted to meet HVDC specifications. For example, the authors in [8] proposed a robust control scheme for a parallel AC/DC system. In [8], an adaptive optimal control was developed for an HVDC system. Recently, in [9]–[14], the authors have proposed a different control method for which an inverter can be operated to mimic the behavior of a synchronous generator (SG) and the resulting closed-loop has been called a *synchronverter*[9]. Since the operation of AC systems via SGs voltage/frequency regulation is rather well known [15], the synchronverter concept led to new applications. For example, in [16]-[20], a STATCOM controller was synthesized from the mathematical model of synchronous generators operated in a compensator mode. In this work, the synchronverter concept is adapted toconverters of an HVDC transmission. The idea is a conceptual control strategy of the DC line, where the sending-end rectifier controls emulate a synchronous motor (SM), and the receiving end inverter emulates an SG, both along with their controls. This resulting synchronverter-based HVDC will be called SHVDC in the paper.[21]-[23].The rest of the paper is organized as follows: in Section II, Modeling and control of an HVDC-VSC transmission system is briefly overviewed. HVDC system basedsynchronverter concept is extended in Section III and also the SHVDC structure proposed for the HVDC link is analyzed from a structural point of view. Simulation results is given in Section IV, conclusions are presented in Section V.

II. MODELING AND CONTROL OF AN HVDC-VSC TRANSMISSION SYSTEM

An HVDC system consists of three parts: a rectifier station, an inverter station and a high-voltage DC transmission line as shown in Fig. 1.

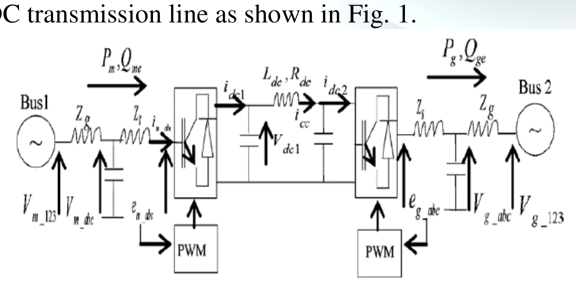


Fig. 1. Two terminal HVDC-VSC link.

Each converter is connected to the AC network via a grid impedance representing the short-circuit power at the connection point. For its advantages on control capability, the VSC technology is assumed. Each converter holds two degrees of freedom for the control. Usually, these degrees are used for the control of the reactive power at each side, of the active power and for the DC voltage [6]. Each station controls its reactive power independently of the other station. The flow of active power in the DC transmission system must be balanced, which means that the active power entering the HVDC system must match the active power leaving it, plus the losses in the DC transmission system. To achieve this power balance, one of the stations has to control the active power, while the other station should be designed for the DC voltage control. Usually, the two converters of an HVDC are controlled by two independent loops and each of these controls is based on the vector control approach in thed-q frame, using cascaded PI controllers [2]: the outer control loop generates the respective d-q current references to the inner current control loop.

III. HVDC SYSTEM BASED SYNCHRONVERTER

In this part, a new control strategy based on synchronverter technology is introduced for HVDC-VSC converters.The HVDC converters are run as synchronous machines. The synchronverter proposed in [9] is an inverter that mimics the structure and the regulations of a synchronous generator (SG). The usual control strategies used for conventional SG can thus be used for the inverter. But for a complete DC system, a rectifier and an inverter are bound by a DC link. So, to provide an HVDC structure, another synchronverter working as a synchronous motor (SM) based on the same mathematical derivation is required. As a result, the DC power is sent from the SM to the SG. Firstly, an overview of the synchronverter concept is presented, where the inverter is modeled according the mathematical model of an SG. Next, the synchronverter concept is extended to a rectifier that mimics an SM.

Most of the references make variousassumptions, such as steady state and/or balanced sinusoidalvoltages/currents, to simplify the analysis. Here, we brieflyoutline a model that is a (nonlinear) passive dynamic systemwithout any assumptions on the signals from the perspectiveof system analysis and controller design. We consider a roundrotor machine so that all stator inductances are constant. Ourmodel assumes that there are no damper windings in the rotor,that there is one pair of poles per phase (and one pair of poleson the rotor) and that there are

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 4, Special Issue 6, April 2017

no magnetic-saturation effectsin the iron core and no eddy currents. As is well known, thedamper windings help to suppress hunting and also help tobring the machine into synchronism with the grid.

A. Modeling of synchronous generator(Inverter station) based on synchronverter concept

A synchronverter is an inverter which regulations are chosen such that the resulting closed-loop mimics the behavior of a conventional SG. For the purpose of the development, the structure of a three-phase round rotor synchronous machine [15] as shown in Fig. 2.

The stator windings can be seen as concentrated coils having self-inductance(L) and mutual inductance (-M).The field winding can be seen as a concentrated coil having a self-inductance(L_f).

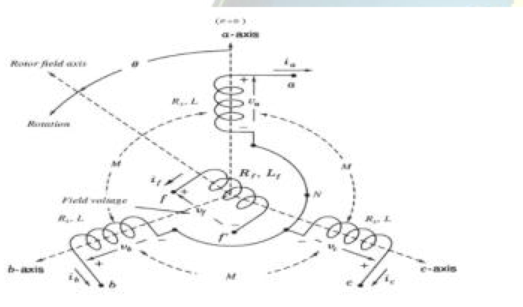


Fig. 2. Structure of an idealized three-phase round-rotor SG

The phase terminal voltage vector, V_{g-abc} = [Vga Vgb Vgc]^T may be expressed by

V_{g-abc} = -$R_S i_{g-abc}$ - $L_S \frac{d_{i_{g-abc}}}{dt}$ + e_{g-abc} (1)

Where i_{g-abc} is the stator phase currents vector,and $L_s = L + M$ and $R_S$are the inductance and resistance of the stator windings.

The back emf vector e_{g-abc} = $[e_{ga} e_{gb} e_{gc}]^T$ is the back emf given by

e_{g-abc} = $M_g s\theta_g \sin\theta_g$(2)

Where$M_g$is the flux field,θ_g is the electric rotor angle, and

$\widetilde{Sin\theta}_g$= $[sin\theta g \;\; sin\,(\theta g - 2\pi/3) \;\; sin\,(\theta g + 2\pi/3)]^T$(3)

The mechanical equation of the machine is given by

$J_g \theta_g = T_{gm} - T_{ge}$- D_{gp}s θ_g (4)

Where J_g the combined moment of inertia of generator and turbine is, $T_{gm}$is the mechanical torque,T_{ge} is the electromagnetic torque, and $D_{gp}$is a damping factor. The torqueT_{ge} is given by

T_{ge}= $M_g < i_{g-abc}, \sin\theta_g >$(5)

The real and reactive powers generated by the SG are, respectively

$P_g = M_g s\theta_g < i_{g-abc}, \sin\theta_g >$ (6)

Q_{ge}= $M_g s\theta_g < i_{g-abc}, \cos\theta_g >$(7)

Based on the SG model above (1)–(7), the concept of synchronverteris developed. The latter consists of an inverter on which specific controls are built and structured, as shown in Fig. 3. On the figure, we depict 1) the power part consisting of the inverterplus the LC filter and 2) the controls assured by the electronic part. The inverter switches are operated so that the average values of e_{ga}, e_{gb} and e_{gc} over aswitching period are to be equal to e_{g-abc}given in (2).This can be achieved by the usual PWM technique. It's worth noting that the VSC technology used in this work is not exclusive. However, it is suited for generating pulse control signals. The electronic part controls the switchesin the power part. These two parts interact via the signals $e_{g-abc}$and i_{g-abc}.

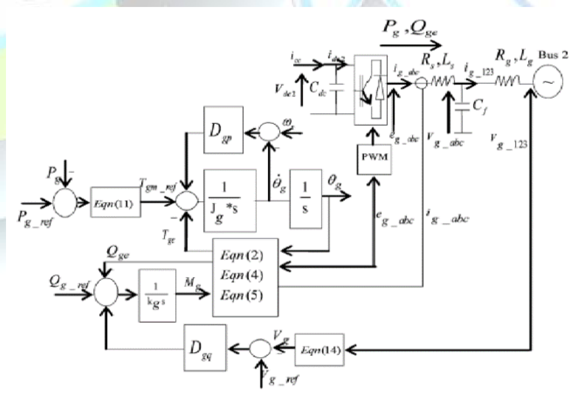


Fig. 3. Model of the synchronverter: power and electronic parts

The synchronverter given in Fig. 3 is connected to the grid via the impedance thus, its output current and voltage may be given by

$V_{g-abc} = \frac{1}{C_f s}$($i_{g-123}$-$i_{g-abc}$) (8)

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 4, Special Issue 6, April 2017

$i_{g-123} = \frac{1}{R_g+L_g s}(V_{g-123} - V_{g-abc})$ (9)

Swing equation for the synchronverter,

$\ddot{\theta_g} = \frac{1}{J_g}(T_{gm} - T_{ge} - D_{gp} s\theta_g)$ (10)

Where the mechanical torque T_{gm} is a control input, and θ_g is the angle position of the synchronverter.The electromagnetic torque T_{ge} depends on i_{g-abc} and θ_g.

To mimic the droop of the SG, the following frequency droop control loop is proposed

$T_{gm} = T_{gm-ref} + D_{gp}(w_n$-s $\theta_g)$ (11)

The synchronverter thus shares load with the other generators of the AC grid to which it is connected in proportion with the static droop coefficient . In (10),T_{gm-ref} is the mechanical torque applied to the rotor and it is generated by a PI controller as shown in Fig. 3 to regulate the real power output P_g

$T_{gm-ref} = (K_{P-P_g} + \frac{K_{i-P_g}}{s})(P_g - P_{g-ref})$ (12)

The reactive power Q_g is controlled by a voltage droop control loop using a voltage droop coefficient D_{gq} , in order to regulate the field excitation M_g which is proportional to the voltage generated following (12) and (13)

$M_g = \frac{-1}{k_g s}(Q_{gm} - Q_{ge})$ (13)

$Q_{gm} = Q_{g-ref} + D_{gq}(V_{g-ref} - V_g)$ (14)

Where V_g is the output voltage amplitude computed by,

$V_g = \frac{2}{\sqrt{3(V_{ga}V_{gb} + V_{ga}V_{gc} + V_{gb}V_{gc}}}$(15)

B. Modeling of synchronous motor(Rectifier station) based on synchronverter concept

To obtain an HVDC transmission system, in addition to an SG emulated by a synchronverter as in thesection above, a rectifierthat mimics an SM and a DC line are needed. The resultingsystem, an SM/SG and a DC line are called synchronverter highvoltage direct current (SHVDC).

The synchronvertermodel of an SM consists of an LC filter and mainly controls shown in the same Fig. 3.

The phase terminal voltage vector is given by,

$V_{m-abc} = [\text{Vma Vmb Vmc}]^T$(16)

$V_{m-abc} = -R_S i_{m-abc} - L_S \frac{d i_{m-abc}}{dt} + e_{m-abc}$(17)

The back emf vector , $e_{m-abc} = [e_{ma} e_{mb} e_{mc}]^T$

$e_{m-abc} = M_m s\theta_m \sin\theta_m$(18)

The mechanical equation of the machine is

$J_m\theta_m = T_{mm} - T_{me} - D_{mp} s\ \theta_m$(19) Where torque T_{me} is given by,

$T_{me} = M_m < i_{m-abc}, \sin\theta_m >$(20)

The real and reactive powers generated by the SM,

$P_m = M_m s\theta_m < i_{m-abc}, \sin\theta_m >$ (21)$Q_{me} = M_m s\theta_m < i_{m-abc}, \cos\theta_m >$(22)

Based on the SM model above (16)–(22), the concept of synchronverter is developed. The synchronverter given in Fig. 3 is connected to the grid via the impedance thus, its output current and voltage may be given by

$V_{m-abc} = \frac{1}{C_f s}(i_{m-123} - i_{m-abc})$ (23)

$i_{m-123} = \frac{1}{R_g+L_g s}(V_{m-123} - V_{m-abc})$ (24)

To mimic the droop of the SM, the following frequency droop control loop is proposed

$T_{mm} = T_{mm-ref} + D_{mp}(w_n$-s $\theta_m)$ (25)

where, T_{mm-ref} is the mechanical torque applied to the rotor. It is generated by a PI controller to regulate the real power output, P_M

$T_{mm-ref} = (K_{P-vdc} + \frac{K_{i-vdc}}{s})(V_{dc-ref} - V_{dc1})$ (26)

The reactive power Q_m is controlled by a voltage droop control loop using a voltage droop coefficient D_{mq}.

$M_m = \frac{-1}{k_m s}(Q_{mm} - Q_{me})$ (27)

$Q_{mm} = Q_{m-ref} + D_{mq}(V_{m-ref} - V_m)$ (28)

Where V_m is the output voltage amplitude computed by

$V_m = \frac{2}{\sqrt{3(V_{ma}V_{mb} + V_{ma}V_{mc} + V_{mb}V_{mc}}}$(29)

C. Coupling Equations: The circuit equations of the DC line (Figs. 1 and 3) are

$V_{dc1} = \frac{1}{C_{dc} s}(i_{dc1} - i_{dc2})$ (30)

$V_{dc2} = \frac{1}{C_{dc} s}(i_{cc} - i_{dc2})$ (31)

$i_{cc} = \frac{1}{L_{dc} s}(V_{dc1} - V_{dc2} - R_{dc} i_{cc})$(32)

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 4, Special Issue 6, April 2017

D. Frequency drooping

The speed regulation system of the prime mover for a conventional synchronous generator can be implemented in a synchronverter by comparing the virtual angular speed with the angular frequency reference before feeding it into the damping block. As a result, the damping factor actually behaves as the frequency drooping coefficient, which is defined as the ratio of the required change of torqueto the change of speed (frequency):

$$D_p = \frac{\Delta T}{\Delta \theta} \quad (33)$$

Because of the built-in frequency drooping mechanism, a synchronverter automatically shares the load with other inverters of the same type and with SGs connected on the same bus.

E. Voltage drooping

The regulation of reactive power Q flowing out of the synchronverter can be realised similarly. Define the voltage drooping coefficient Dq as the ratio of the required change of reactive power to the change of voltage:

$$D_q = \frac{\Delta Q}{\Delta V} \quad (34)$$

The difference between the reference voltage and the amplitude of the feedback voltage is amplified with the voltage drooping coefficient Dqbefore adding to the difference between the set point and the reactive power. The resulting signal is then fed into an integrator with a gain to generate $Mf\ if$. Christo Ananth et al.[7] presented a brief outline on Electronic Devices and Circuits which forms the basis of the Clampers and Diodes.

IV. SIMULATION RESULTS

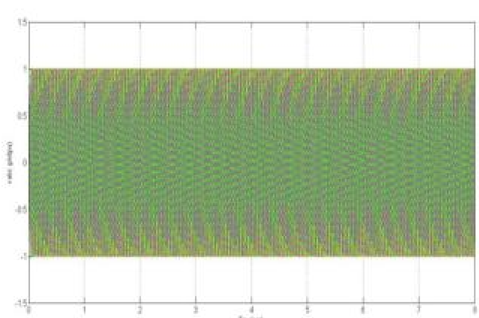
The ideasbased on synchronverter described earlier have been verified with simulations. The simulations were carriedout in MATLAB Simulink.The parameters of the proposed system used in the simulations are given in Table I.

TABLE I
PARAMETERS OF SHVDC

Parameter	Values		Parameter	Values
Line Voltage	100kV		R(parallel to C)	1000Ω
Frequency	50Hz		Rated power	100W
L_s	$0.45mH$		L_s	0.45mH
R_s	0.135Ω		R_s	0.135Ω
C	22µF		DC link voltage	42V

The proposed control strategy should work for high voltage and high power as well. We have chosen Dp= 0.2026, which means that a frequency drop of 0.5% causes the torque (hence, the power) to increase by 100% (from nominal power). The voltage-drooping coefficient is chosen as Dq= 117.88. The time constants of the droop loops are chosen as τf= 0.002 s and τv= 0.002 s.

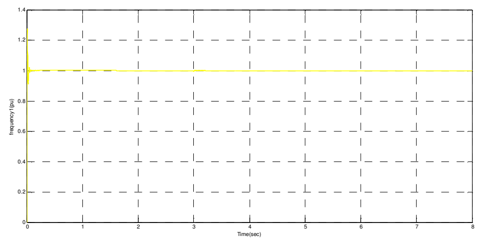
The simulation was started at t = 0. A PLL was used for the initial synchronization. The initial settings for Pset and Qset were zero. The circuit breaker was turned on at t = 1 s; the real power Pset= 80 W was applied at t = 2 s, and the reactive power Qset= 60 Varwas applied at t = 3 s. The drooping feedbacks were enabled at t = 4 s, and then the grid voltagewas decreased by 5% at t = 5 s.



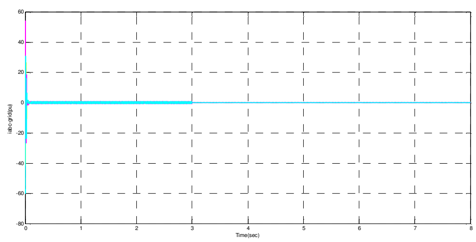
(a)

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

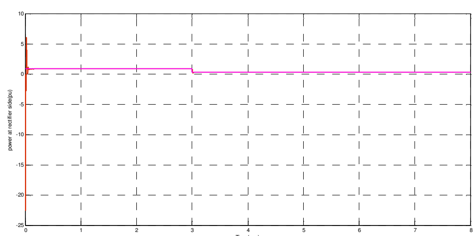
International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 4, Special Issue 6, April 2017



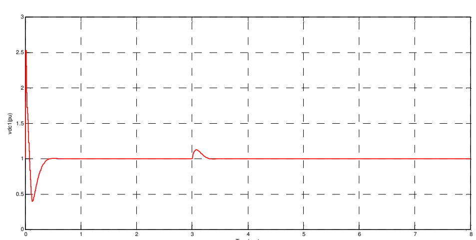
(b)



(c)

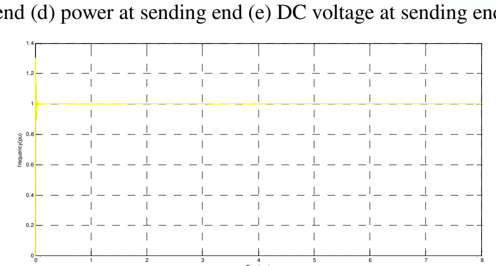


(d)

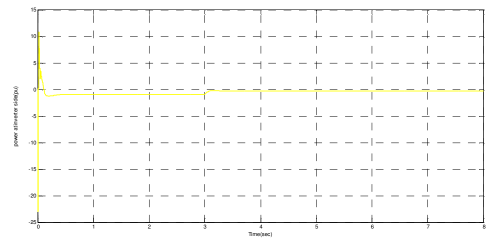


(e)

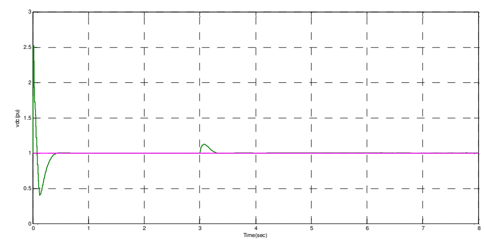
Fig.4. Simulation results (a) grid voltage at sending end (b) nominal grid frequency at sending end (c) grid current at sending end (d) power at sending end (e) DC voltage at sending end



(a)



(b)



(c)

Fig.5. simulation results (a) frequency at receiving end (b) power at receiving end (c) DC voltage at receiving end

The simulation results on the sending end station are shown in Fig.4(a)-(e). The frequencytracked the grid frequency very well all the time. The voltage difference between *v* and *vg* before any power demand was applied was very small, and the synchronization was very quick. There was no problem turning the circuit breaker on at *t* = 1 s; there was not much transient response caused by this event. The synchronverter responded quickly both to the step change in real-power demand at *t* = 2 s and to the step change in reactive power demand at *t* = 3s, and it settled down in less than ten cycles without any error. The coupling effect between the real power and the reactive power is reasonably small, and the decoupling control of the real power and reactive power is left for future research. When the drooping mechanism was enabled at *t* = 4 s, there was not much change to the realpower output as the frequency was not changed, but the reactive power dropped by about 53 Var, about 50% of the power rating, because the local terminal voltage *v* was about 2.5% higher than the nominal value. When the grid voltage dropped by 5% at *t* = 4 s, the local terminal voltage dropped to just below the nominal value. The reactive-power output then increased to just above the setpoint of 60 Var.The simulation results on the receiving end station are shown in Fig.5(a)-(c).

V. CONCLUSION

In this paper, the idea of operating the converters as a Synchronous machine has been developed for HVDC system. Modeling of rectifier station (synchronous motor) and inverter station (synchronous generator) has been done using VSC. The control for VSC is modeled using synchronverter concept. The mathematical model developed here can be used to investigate the stability of power systems dominated by parallel-operated inverters in distributed generation. Output of the proposed system has been obtained. The operation and control techniques of this topology are explained in detail. The efficacy of the proposed topology is validated through simulation.

REFERENCES

[1] RaouiaAouini, Bogdan Marinescu, Khadija Ben Kilani,MohamedElleuch, "Synchronverter-Based Emulation and Control of HVDC Transmission", IEEE Trans On Power Sys, Vol. 31, No. 1, Jan 2016

[2] D. Murali, M. Rajaram, and N. Reka, "Comparison of FACTS devices for power system stability enhancement," *Int. J. Comput. Applicat.*,vol. 8, no. 4, 2010, 0975–8887.

[3] F. Wang, L. Bertling, and T. Le, "An overview introduction of VSCHVDC: State-of-art and potential applications in electric power systems," Cigré 2011.

[4] F. Goodrich and B. Andersen, "The 2000 MW HVDC link between England and France," *Power Eng. J.*, vol. 1, no. 2, pp. 69–74, 1987.

[5] Y. Decoeur, "France-Spain interconnections, first step for smart grids," Inelfe. Madrid, Spain, Mar. 26th, 2012.

[6] A. E. Hammad, J. Gagnon, and D. McCallum, "Improving the dynamic performance of a complex AC/DC system by HVDC control modifications," *IEEE Trans. Power Del.*, vol. 5, no. 4, pp. 1934–1943, Oct. 1990.

[7] Christo Ananth, W.Stalin Jacob, P.Jenifer Darling Rosita. "A Brief Outline On ELECTRONIC DEVICES & CIRCUITS.", ACES Publishers, Tirunelveli, India, ISBN: 978-81-910-747-7-2, Volume 3,April 2016, pp:1-300.

[8] H. Latorre and M. Ghandhari, "Improvement of power system stability by using a VSC-HVDC," *Int. J. Electr. Power Energy Syst.*, vol. 33, no. 2, pp. 332–339, 2011.

[9] N. Rostamkolai, A. G. Phadke, W. F. Long, and J. S. Thorp, "An adaptive optimal control strategy for dynamic stability enhancement of AC/DC power systems," *IEEE Trans. Power Syst.*, vol. 3, no. 3, pp. 1139–1145, Aug. 1988.

[10] Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011.

[11] L. Zhang, L. Harnefors, and H.-P. Nee, "Power synchronization control of grid-connected voltage-source converters," *IEEE Trans. PowerSyst.*, vol. 25, no. 2, pp. 809–820, May 2010.

[12] H.-P. Beck and R. Hesse, "Virtual synchronous machine," in *Proc. 9thInt. Conf. Electrical Power Quality and Utilisation (EPQU)*, 2007, pp.1–6.

[13] J. Driesen and K. Visscher, "Virtual synchronous generators," in *Proc. IEEE Power and Energy Soc. General Meeting*, 2008, pp. 1–3.

[14] Y. Chen, R. Hesse, D. Turschner, and H.-P. Beck, "Improving the grid power quality using virtual synchronous machines," in *Proc. 2011 Int. Conf. Power Engineering, Energy and Electrical Drives (POWERENG)*, 2011, pp. 1–6.

[15] P. Kundur*, Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1994.

[16] P.-L. Nguyen, Q.-C. Zhong, F. Blaabjerg, and J.-M. Guerrero, "Synchronverter- based operation of STATCOM to Mimic synchronous condensers," in *Proc. 2012 7th IEEE Conf. Industrial Electronics and Applications(ICIEA)*.

[17] H. Bourlés and B. Marinescu, *Linear-Time Varying Systems, Algebraic- Analytic Approach*. New York, NY, USA: Springer-Verlag,2011, LNCIES 410.

[18] "IEEE recommended practice for excitation system models for power system stability studies," *IEEE Power Engineering Soc.,* Apr. 21, 2006.

[19] S. Li, T. A. Haskew, and L. Xu, "Control of HVDC light system using conventional and direct current vector control approaches," *IEEETrans. Power Electron.*, vol. 25, no. 12, pp. 3106–3118, Dec. 2010.

[20] M.-K.-S. Sangathan and J.- Nehru, "Performance of high-voltage direct current (HVDC) systems with line-commutated converters," Apr. 2013, Bureau of Find Indian Standard ManakBhavan, 9 Bahadur Shah Zafar Marg New Delhi 110002.

[21] G. Rogers*, Power System Oscillations*. Norwell, MA, USA: Kluwer, 2000.