D-STATCOM Model for Restoration of Distribution System Stability

Rajib Baran Roy *, Md. Habibur Rahman

Department of Electrical and Electronics Engineering, Sonargaon University (SU)

*Corresponding Author: Assistant Professor, Sonargaon University (SU) Dhaka, Bangladesh.

Email: rbroy_eee@su.edu.bd

Abstract

Due to complexity of electrical power system network, the assurance of uninterrupted supply of electricity and quality power has become the main challenge for the distribution system. The fluctuation of system voltage, frequency as well as real and reactive power hampers the system stability which jeopardizes uninterrupted supply of electricity to the consumers. Utility distribution networks, sensitivity industrial loads and critical commercial operations suffer from various types of outages and service interruptions which can cost significant financial losses. The voltage sag and swell are the most important power quality problems which are seen in industrial and commercial installations. For improving power quality at the distribution network, various FACTS (flexible AC transmission system) devices like D-STATCOM (dynamic static synchronous compensator), DVR (dynamic voltage restorer), SVC (static VAR compensator) and others are used. The D-STATCOM (distribution static compensator) is now replacing other FACTS devices in the distribution system for its better performance than others. The D-STATCOM has the capability of instantaneous system voltage improvement in case of voltage sag and flicker within the distribution system. The design of the control system is the main aspect of the D-STATCOM. In this paper, a 6 pulse D-STATCOM model is designed and simulated by using PSCAD/EMTDC for improving of distribution system stability by mitigation of voltage dips. The PI controller is used for controlling the voltage and reactive power flow to and from the DC capacitor of the D-STATCOM. The PLL (phase locked loop) is used for controlling the gate triggering pulses of IGBT based VSC (voltage source converter) of the D-STATCOM by using PWM (pulse width modulation)

Keywords: Voltage dip; Power quality; FACTS; D-STATCOM; PSCAD/EMTDC.

1.0. Introduction

The power quality is the main concern of the modern power system network. In order to supply quality power to the consumers, it is required to keep the system voltage and frequency within the permissible limit. Even minor lapses in quality power causes instability and interruption in the system which leads to large financial losses in industries and manufacturing units (Zhang et al., 2006). One of the most common power quality problems of today is voltage dips. A voltage dip is caused by a fault in the utility system, a fault within the customer's facility or a large increase of the load current, like starting a motor or energizing a transformer (Dugan et al., 2006). The voltage dip is the reduction of voltage caused by short circuits, overloads, and starting of large motors and inducing direct lightning strokes within short time (Dugan et al., 2006). The voltage dip mainly causes problems in adjustable-speed drives, process control equipment and other devices at consumer premises. According to the IEEE standard 1159, the voltage dip is a reduction in the rms value in the range of 0.1 and 0.9 per unit for the rated voltage and its duration from 0.5 cycles to 1 minute (Dugan et al., 2006, Padiyar et al., 2007). The voltage swell is much less common than voltage dips and its effect in power system is usually not severe. The most common fault in power system is the single line-to-ground. During a single line-to-ground fault, the voltages on the un-faulted phases increase due to the zero-sequence impedance (Zhang et al., 2006). In an ungrounded system, the voltage on the un-faulted phase can be as high as 173% of the rated system voltage (Munoz et al., 2007). In case of single line to ground fault, high current causes voltage drop in the network impedance (Zhang et al., 2006, Dugan et al., 2006).

Utilities often focus on disturbances from end-user equipment as the main power quality problems. If the economic losses due to voltage dips are significant, mitigation actions can be profitable for the customer and even in some cases for the utility (Singh et al., 2008). Since there is no standard solution which will work for every site, each mitigation action must be carefully planned and evaluated. There are different ways to mitigate voltage dips, swell and interruptions in transmission and distribution systems. Various FACTS (flexible AC transmission system) devices which use power electronics components can be utilized power quality improvement (Dinavahi et al., 2004). Among these, D-STATCOM (distribution static compensator) and DVR (dynamic voltage restorer) are most effective devices, both of them based on the VSC (voltage source converter) principle (Singh et al., 2008, Dinavahi et al., 2004). A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage dips. The converter comprises of solid state electronic devices and DC voltage source generally capacitor. The VSC is not only used for voltage dip mitigation, but also for other power quality issues like flicker and harmonics (Dinavahi et al., 2004).

1.1. D-STATCOM and DVR in Distribution System

The component of an electrical power system connecting all the consumers in an area to the bulk power sources is called a distribution system (Mitra et al., 2008). The electricity distribution system is the final stage in the delivery of electricity to end users. A distribution system network generally, carries electricity from the transmission system and delivers it to consumers. Typically, the network would include medium voltage power lines, substations and pole-mounted transformers, low-voltage distribution wiring, meters and protection equipment (Singh et al., 2006). The diagram of a simple distribution network is shown in Fig. 1. The variation in system load causes voltage dip and voltage flicker in the distribution system which also changes system frequency and power (Mitra et al., 2008). These create unbalance in the overall distribution system which hampers the uninterrupted supply of electricity to the consumer premises. The feeding of green electricity to the national grid also hampers the power quality and system reliability due to intermittent nature of renewable energy sources (Singh et al., 2008). The reactive power compensation is the most effective way for restoring system stability. The static var compensator and capacitor bank are two commonly used techniques for ensuring power quality in distribution system. The D-STATCOM and DVR are now replacing the conventional FACTS compensator due to their better performance in system stability (Han et al., 2008).

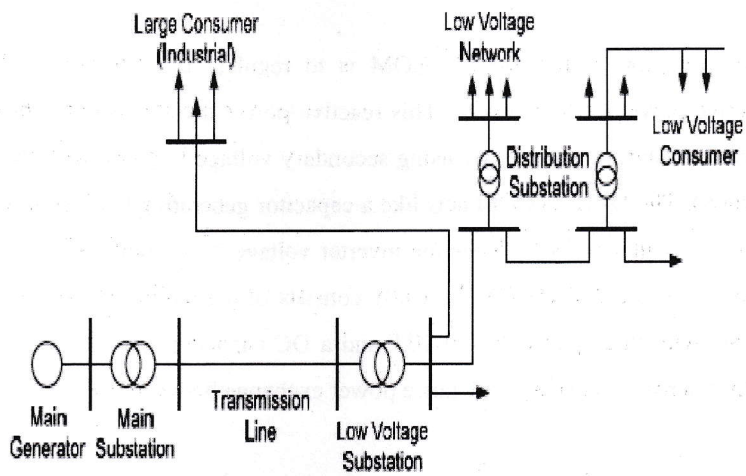


Fig. 1. Distribution Network.

1.2. D-STATCOM

The D-STATCOM is a three phase and shunt connected power electronics based reactive power compensation equipment, which generates and absorbs the reactive power according to the system's requirement in order to maintain control of specific parameters of the electric power system (Dinavahi et al., 2004). In its most basic form, the D-STATCOM configuration consists of a VSC, a dc energy storage device, a coupling transformer connected in shunt with the ac system and associated control circuits. The Fig. 2 shows the basic configuration of D-STATCOM. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system (Han et al., 2008)

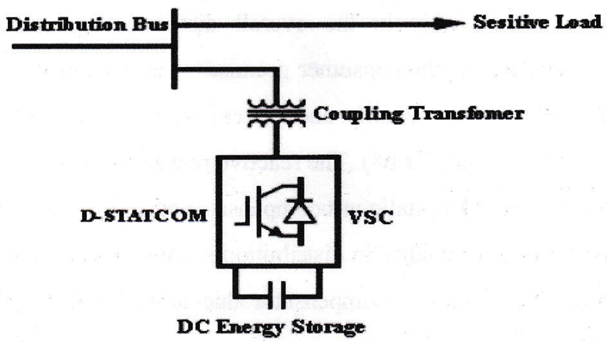


Fig. 2. Basic Configuration of D-STATCOM.

The main function of the D-STATCOM is to regulate the bus voltage by absorbing or generating reactive power to the network. This reactive power transfer is done through the leakage reactance of the coupling transformer by using secondary voltage in phase with the primary voltage (Singh et al., 2006). The D-STATCOM acts like a capacitor generating reactive power to the bus. In steady state, the bus voltage always leads the inverter voltage by a small angle in order to supply a small active power. The D-STATCOM basically consists of a coupling transformer with a leakage reactance, a VSC with three phase GTO/IGBT and a DC capacitor (Padiyar et al., 2007). The AC voltage difference across the leakage reactance power exchange between the D-STATCOM and the

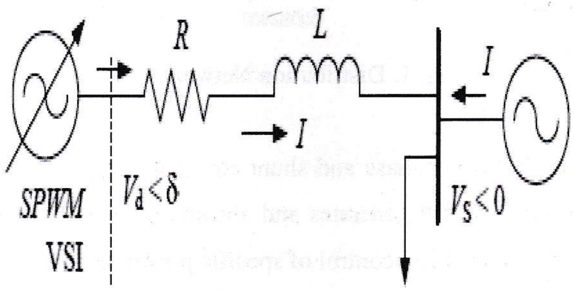


Fig. 3. Equivalent Circuit of D-STATCOM.

power system, such that the ac voltages at the bus bar can be regulated to improve the voltage profile of the power system, which is primary duty of the D-STATCOM (Hossain et al., 2007).

The D-STATCOM not only mitigates voltage dips but also improves system power factor and voltage regulation. Other power quality issues like voltage flicker and harmonics can also be eliminated by using D-STATCOM (Munoz et al., 2007).The equivalent circuit of D-STATCOM is shown in Fig. 3. From the figure above, the active and reactive power can be calculated by following equations (Singh et al., 2008, Hosssain et al., 2007):

$$P = \left(\frac{V_{bus} V_1}{X_L}\right) \sin \alpha \qquad (1)$$

$$Q = \left(\frac{V_{bus}^2}{X_L}\right) - \left(\frac{V_{bus} V_1}{X_L}\right) \cos \alpha \qquad (2)$$

1.3. DVR

The DVR is a FACTS controller that is commonly used voltage sag mitigation at the point of connection of the distribution system (Padiyar et al., 2007). The main concept of the DVR consists of an injection transformer, harmonic filter, VSC and an emergency storage and control system. In case of DVR, the coupling transformer is connected in series with the ac system (Han et al., 2008). The Fig. 4 shows the basic configuration of the DVR. The VSC generates a three phase AC output voltage which is controllable in phase and magnitude. These voltages are injected into the ac distribution system in order to maintain the load voltage at the desired voltage reference. The main function of the DVR is to mitigate the voltage sag but it can be used for harmonics and reactive power compensation (Bhattacharya et al., 2008).

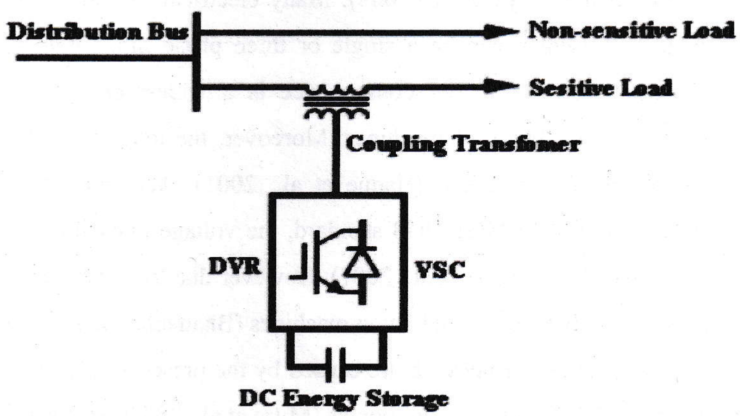


Fig. 4. Basic Configuration of the DVR.

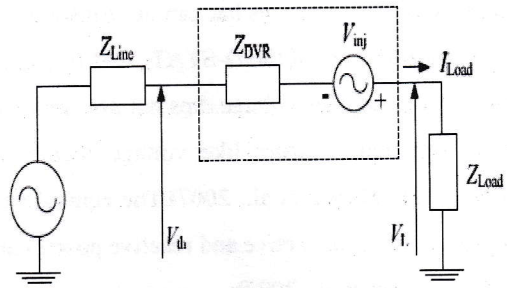


Fig. 5. Equivalent circuit of DVR.

The Thevenin's equivalent circuit of the DVR is shown in the Fig. 5 with system impedance Z_{th}depends on the fault level of the load bus. When the system voltage (V_{th}) drops, the DVR injects a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be maintained. The series injected voltage of the DVR can be written as (Dugam et al., 2006, Shukla et al., 2006),

$$V_{DVR} = V_L + Z_{th} I_L + V_{th} \quad (3)$$

$$S_{DVR} = V_{DVR} * I_L \quad (4)$$

2.0. D-STATCOM and Power Quality

The change in system voltage, frequency and power factor occur due to change in load in distribution system. The change in system voltage also causes change in real and reactive power factor of the overall distribution network which hampers the operation of load at the consumer premises. The voltage dips is one of the most common problem of variation of system load in distribution system (Bhattacharya et al., 2008). Many electrical machines can easily ride through short term voltage dips (which can be a single or three phase dip, single phase being the most common) (Hossain et al., 2007). The consequence is a widespread failure of many types of equipment with shortened lifetime of machines. Moreover, the long-term voltage dips may trip or shutdown generators in power station (Haque et al., 2001). According to the National Electric Machines Association (NEMA) MG1-1993 standard, the voltage imbalance for induction machines should be kept less than 1% (Munoz et al., 2007). However due to voltage variation in the electrical network may cause 3% unbalance for induction machines (Bhattacharya et al., 2008).

Harmonics in the power network are caused by the presence of non-linear loads which can produce significant 3rd, 5th, 7th, and 11th harmonics (Mitra et al., 2008; Haque et al., 2001). Harmonics have a number of deleterious effects on the power system are capacitors on the network draw excessive currents that can lead to damage, system resonance may occur which can result in over-voltages and disrupt distribution and transmission equipment, excessive losses occur in transformers, commutation failure of converters and low system power factor (Singh et al., 2006). The variation of system load causes change in power factor which results in variation of system voltage at the consumer end (Han et al., 2008). The poor power factor means very poor utilization of the power network infrastructure (Shukla et al., 2006). However, by using suitable FACTS devices for reactive power compensation can control the variation of system voltage within the permissible limit (Haque et al., 2001). This will also eliminate the effect of harmonics due to rapid switching of connected load and generators (Dugam et al., 2006, Singh et al., 2006).

Utility and customer-side disturbances result in terminal voltage fluctuations, transients, and waveform distortions on the electric grid. Power electronic controllers for distribution systems, namely custom power devices, are able to enhance the reliability and quality of power that is delivered to customers (Zhang et al., 2006). During the transient conditions the D-STATCOM provides leading or lagging reactive power to active system stability, power factor correction, load balancing and harmonic compensation of a particular load (Padiyar et al. 2007; Munaz et al., 2007). The D-STATCOM has emerged as a promising device to provide not only for voltage dip mitigation but also for power quality solutions such as voltage stabilization, flicker suppression, power factor correction and harmonic control (Singh et al., 2008). The D-STATCOM has additional capability to sustain reactive current at low voltage, reduce end use and can be developed as a voltage and frequency support by replacing capacitors with batteries as energy storage (Dinavahi et al., 2004).

3.0. D-STATCOM Model and Simulation Results

A simple 6 pulse D-STATCOM model is created by using PSCAD/EMTDC which is shown in the Fig. 6. The model comprises of a capacitor as dc source and a 6-pulse thyristor based bi directional converter which is connected to a distribution bus of 415 V having an ac source of generating voltage of 415 V and a load of 88 MVA. The bus is grounded through a reactance where short circuit fault is considered to be occurred. The PLL (phase locked loop) and comparator are used for generation of triggering pulses by synchronizing triangular waveform with system ac voltage. The PI controller based control loop is used for controlling system voltage error by means of angle and phase matching. The voltage control loop is shown in Fig. 7. The pulse width modulation technique is used for generating gate pulses of thyristors by comparing triangular waveform with system ac voltage. The Fig. 8 shows the pulse width modulation technique for generation of gate pulses (Lara et al., 2002). The overall simulation can be divided into following operating conditions:

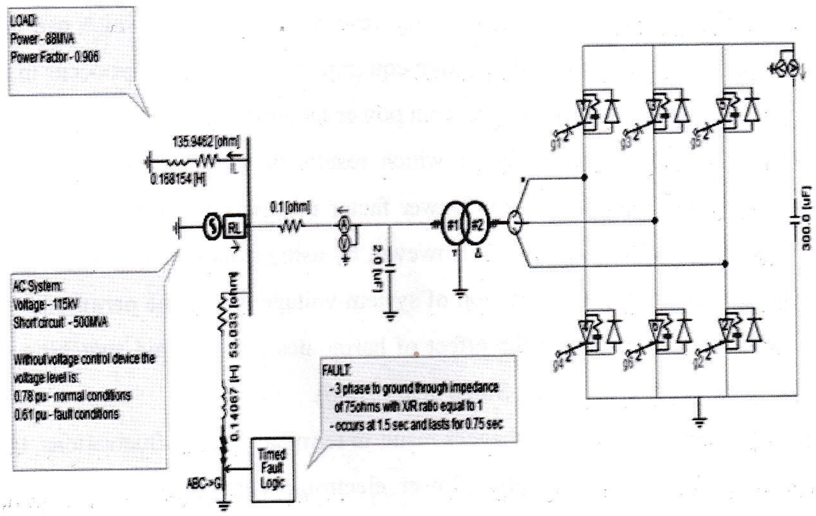


Fig. 6. 6 Pulse D-STATCOM Model.

i. In the simulation period 300–600 ms, the load is increased and thereby the system voltage drops by almost 20% with respect to the reference value. At 600 ms, the load voltage is very close to the reference value, i.e., 1 pu.

ii. In the simulation period 900–1200 ms when the D-STATCOM is connected with the system then the load rms voltage increases 20% with respect to the reference voltage.

iii. A three phase to ground fault occurs at the bus end in between 300 - 600 ms which causes change in

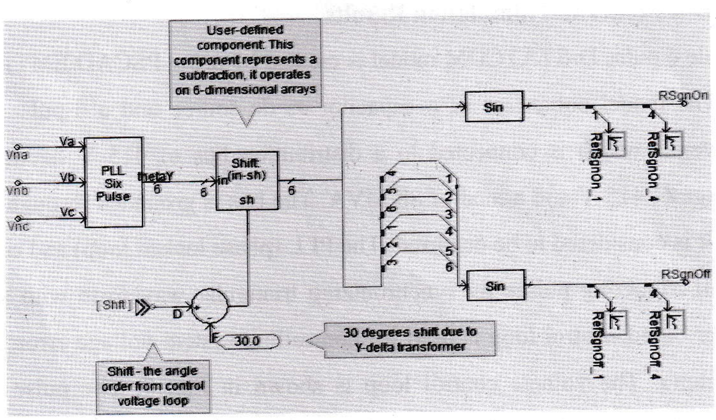
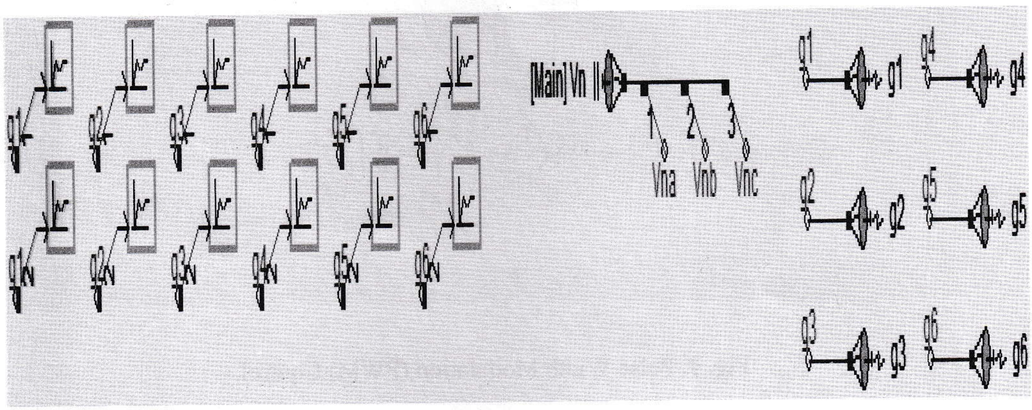


Fig. 7. Voltage Control Loop.

voltage, active and reactive power of the overall distribution system. The graph 1 shows the rms voltage, phase angle and voltage error of the load. Whereas the graph 2 shows dc voltage, active and reactive powers of the bus after occurrence of three phases to ground fault at the bus end. It can be observed from the waveforms of Fig. 9 and 10 that the D-STATCOM restores the system parameters like system voltage, active and reactive power after increment of load and clearance of three phase to ground fault. The sudden voltage dip and flicker can be restored by D-STATCOM.



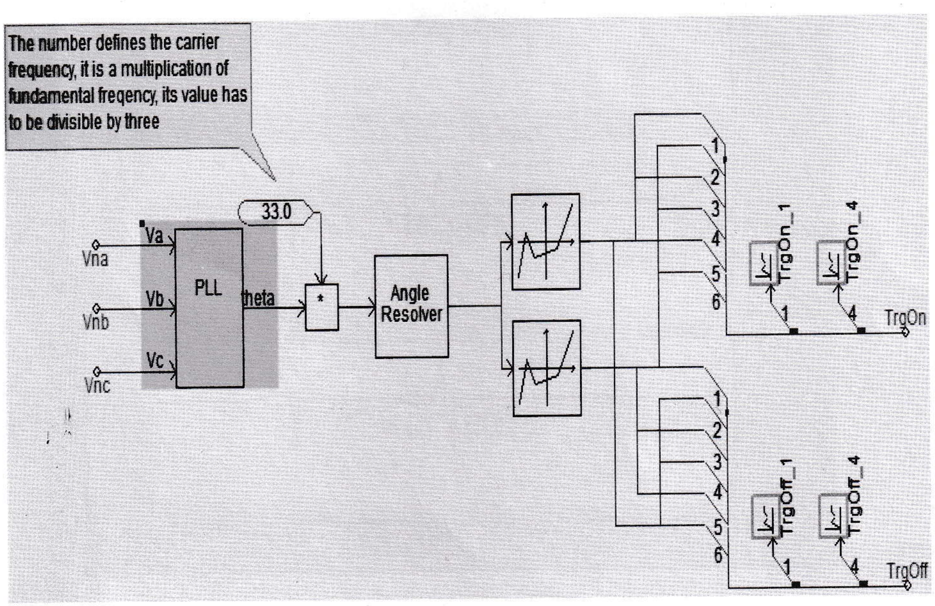


Fig. 8. Voltage Control Loop.

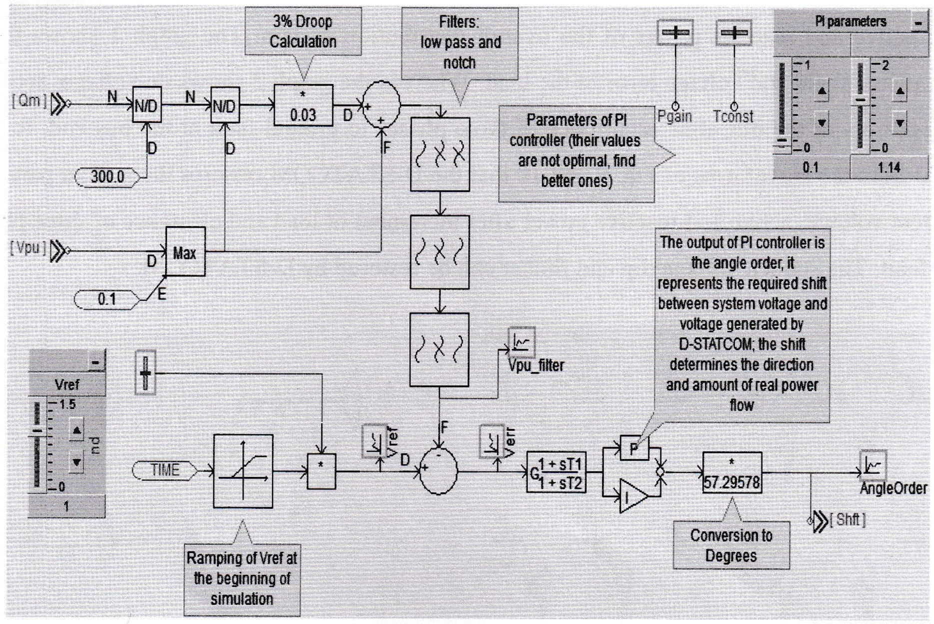


Fig. 9. Pulse Width Modulation (PWM) Control.

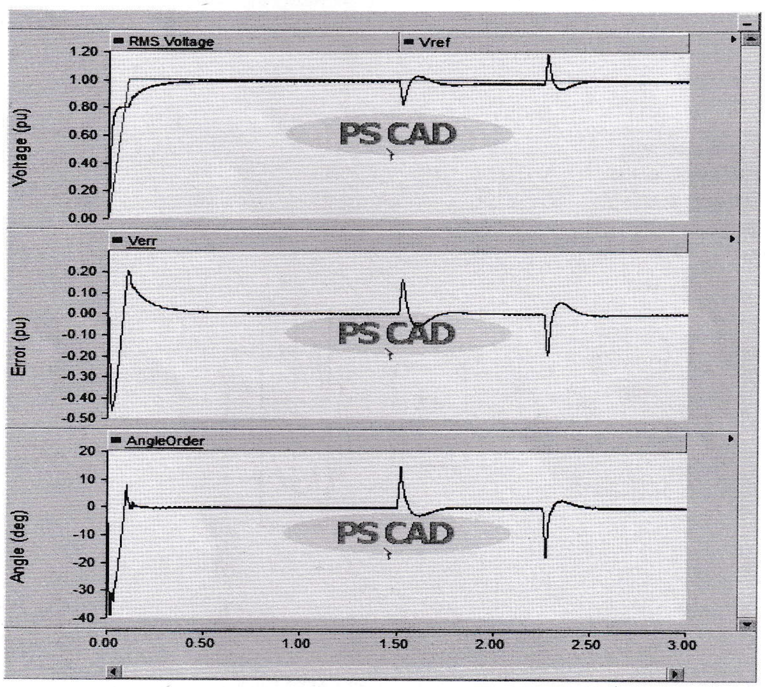


Fig. 10. Rms and reference voltage and angle order of load.

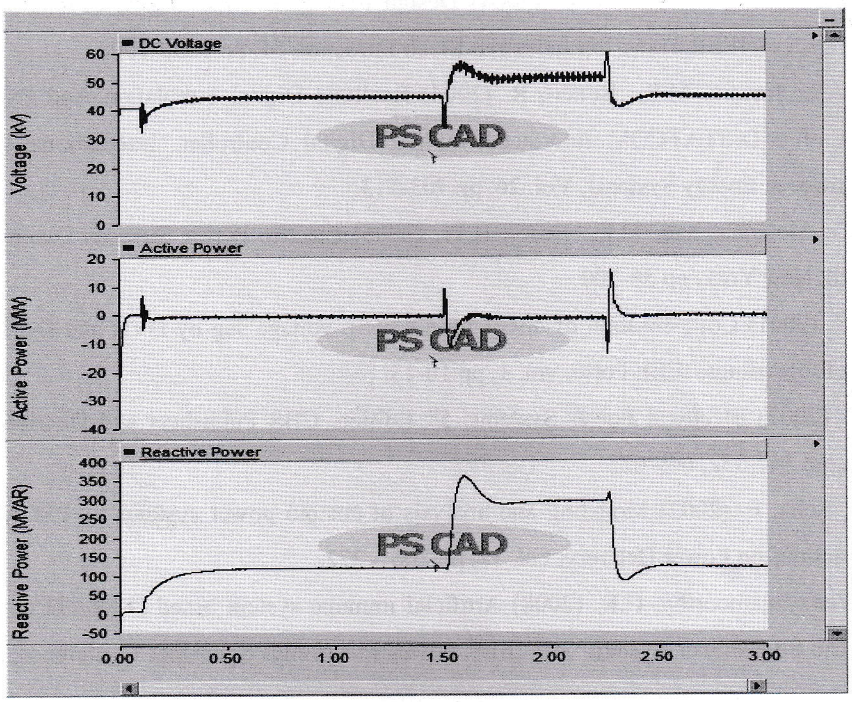


Fig. 11. DC Voltage, Active and Reactive Power of System Bus.

4.0. Conclusion

The system stability is the prime factor for providing quality power to consumers. The FACTS devices like the D-STATCOM restore the system stability by retaining the system parameters to its rated value during the variation of load in the distribution network. It can be inferred from the simulated results that there is less deviation of system parameters from the rated values due to have D-STATCOM. The D-STATCOM retains the system voltage stability by preventing the voltage dip and swell as well as flickering by managing real and reactive power of the simulated model of power system.

References

C. Han, A.Q. et al., (2008) STATCOM impact studyon the integration of a large wind farm into aweak loop power system, IEEE Trans. on Energy Conv.,Vol. 23, pp 226–232.

Dinavahi, V.; Iravani, R.; Bonert, R. (2004) Design of a Real-Time Digital Simulator for a D-STATCOM system, IEEE Trans. On Industrial Electronics, vol. 51, pp 1000-1008.

Dinavahi, V.R.; Iravani. M.R.; Bonert, R. (2004) Realtime Digital Simulation And Experimental Verification of a D-STATCOM Interfaced With a Digital Controller, International Journal of Electrical Power & Energy Systems, Vol. 26, pp 703-713.

Dugan, R.C.; McGranaghan, M.F. Beaty, H.W. (2006) Electric Power Systems Quality. 2nd ed. McGraw Hill, New York, pp 58-100.

Haque, M.H. (2001) Compensation of distribution system voltage sag by DVR and D-STATCOM, Power Tech Proceedings, IEEE Porto, vol. 1, pp 10-13.

Hossain, A. (2007) Electrical Power Systems, 5th Edition, CBS Publishers and Distributors, New Delhi, India, pp 347-352, 609-625.

Lara, O.A.; Acha, E. (2002) Modeling and analysis of custom power systems by PSCAD/EMTD, IEEE Transactions on Power Delivery, vol. 17, pp 266 – 272.

Mitra, P.; Venayagamoorthy, G.K. (2008) Artificial immune system based D-STATCOM. Control for an Electric Ship Power System, 39th IEEE Power Electronics Specialist Conference, PESC, pp 718-723.

Munoz, A.M. (2007) Power Quality: Mitigation Technologies in a Distributed Environment, 2nd ed.Springer-Verlag London limited, London, pp 35-50.

Padiyar, K.R. (2007) FACTS Controllers in Power Transmission and Distribution, 1sted., vol.1.New Age International Limited Publishers, New Delhi, pp 96-120.

S. Bhattacharya, (2008) Improving distribution system performance with integrated statcom and super capacitor energy storage system, IEEE Power Electronics Specialists Conference, PESC, pp 65-71.

Shukla, A.; Ghosh, A.; Joshi, A. (2006) State feedback control of multilevel inverters for D-STATCOM Applications, IEEE Transactions on Power Delivery, pp 19-21.

Singh, B.; Adya, A.; Mittal, A.P.; Gupta, J.P.R.; Singh, B.N. (2006) Application of DSTATCOM for Mitigation of Voltage Sag for Motor Loads in Isolated Distribution Systems Industrial Electronics, IEEE International Symposium on Digital Object Identifier, pp 25-31.

Singh, B.; Jayaprakash, P.; Somayajulu, T.R.; Kothari, D.P.; Chandra, A.; Al-Haddad, K. (2008) Integrated three-leg VSC with a zig-zag transformer based three-phase four-wire DSTATCOM for power quality improvement, Proc. of IECON 2008, Nov. pp 796 -800.

Zhang, X.P.; Rehtanz, C.; Pal, B. (2006) Flexible AC Transmission Systems: Modelling and Control (Power Systems), 3rd ed. Springer, pp 123-200.