
# Power Quality Enhancement in Distribution System using D-STATCOM

[1]Atta Ullah, [2]Abdul Basit, [1]Muhammad Aslam and [2]Naeem Khan
*[1]Department of Electrical Energy System Engineering, US-Pakistan Center for Advanced Studies in Energy, UET Peshawar, Pakistan*
*[4]Department of Electrical Engineering, UET Peshawar, Pakistan*

**Key words:** Power quality, D-STATCOM, VSC, PWM, FACTS

**Abstract:** Power quality and the dynamic performance of the distribution system in Pakistan is poor because of weak and out-of-date system. It is unable to deliver the required reactive power in case of various system disturbances. Distribution Static compensator (D-STATCOM) is an important compensator which is able to enhance the power quality and dynamic performance of the distribution system. In order to improve power quality and dynamics performance of the distribution system effectively a more robust and optimal control algorithm is required for D-STATCOM. Hence, in this research work an improved and optimal control algorithm have been designed for D-STATCOM. In improved control scheme SRF theory control is used for the reference current generation. For the generation of gat pulses for VSC of D-STATCOM level shifted PWM scheme have been used because it offers very good performance for reduction of harmonics distortion. The designed device is implemented in MATLAB-Simulink and is capable to deliver good reactive power compensation under various loading environments such as inductive load, capacitive load and under abnormal faults conditions.

**Corresponding Author:**
Atta Ullah
*Department of Electrical Energy System Engineering, US-Pakistan Center for Advanced Studies in Energy, UET Peshawar, Pakistan*

Page No.: 23-31
Volume: 14, Issue 3, 2020
ISSN: 1990-7958
International Journal of Electrical and Power Engineering


## INTRODUCTION

The dynamic performance and power quality of the distribution system in Pakistan is poor because of weak and out-of-date system. It is unable to deliver the required reactive power in case of various system disturbances. Due to large number of nonlinear loads, occasions such as induction motor starting, switching of capacitor banks and abnormal faults, power quality on the distribution side is adversely effected. The use of large number of personal computer and power electronics based electric loads draw sever harmonic currents from the distribution system which results in poor power quality. These harmonic currents can cause the distribution lines and transformers to be overheated, malfunction of electronic equipment, damaging of capacitor banks; resonance, non-sinusoidal supply voltage, etc.[1, 2].

Most of the AC loads such as air conditioning and refrigerating loads are consuming reactive power (Q) because of inductive nature which results in poor power quality problems. Domestic and industrial consumer's uses Automatic Voltage Stabilizers (AVS) and capacitor banks for voltage sags and poor power quality problems, respectively. AVS regulate the output voltage but at the same time it draws high current from the distribution system which may cause the distribution system to be overload. In summers, demand for reactive power increases due to inductive nature of the loads and if not delivered effectively may cause voltage sag. AVS, helps in maintaining the terminal voltage within acceptable range. But because of tap changing action AVS draw high current from the line as a result of which reactive power losses increases[3, 4]. On the other hand capacitor banks have also good capability to maintain the required steady state voltage but is not suitable for rapidly changing loads such as industrial loads which changes rapidly. They need a good dynamic and more reliable compensation device.

Today power quality problems have adversely effected the reliability and security of power system especially on the distribution side. The new developments in power electronics (G.T.O and I.G.B.T) based devices provides fast and reliable control of power flow over transmission and distribution system. Among these FACTS (Flexible Alternating Current Transmission System) controllers are the best choice for reliable and fast control over the transmission and distribution system parameters, i.e., Voltage (V), impedance of the line (Z) and phase angle difference (δ) between the sending ($V_S$) and receiving ($V_R$) end voltages[5].

FACTS controllers are used to correct power quality problems at transmission level while Custom Power Devices (CPD) are employed to correct power quality problems on distribution side[6,7]. Amongst the CPDs, Distribution Static Compensator (D-STATCOM) is better shunt compensator which offer economic solution toward quality problems such as low voltages, voltage swells, harmonics and unbalancing loads[8]. The beauty of D-STATCOM is that it has the ability to inject both active and reactive power in the distribution system. For this purpose D-STATCOM change the amplitude and phase angle (δ) of the Voltage Source Converter (VSC) output voltage with respect to the terminal voltage of the distribution network[9].

The performance of the DSTATCOM mainly governed by its control algorithm which is responsible for the generation of reference currents. For reference current generation various control schemes have been given in literature survey such as Instantaneous Reactive Power (IRP) theory, instantaneous symmetrical components based control scheme, Synchronous Reference Frame (SRF) theory control, Neural network based control algorithm and scheme based on hysteresis control. But Amongst all of the control algorithms for generation of reference currents IRP theory and SRF theory based control algorithms are the utmost effective control schemes[10].

The main focus in this work is to design an improved control algorithm for the generation of reference of reference currents for D-STATCOM which will help in compensation for low voltages, voltage swells and abnormal faults conditions in the distribution network in order to ensure high quality of power.

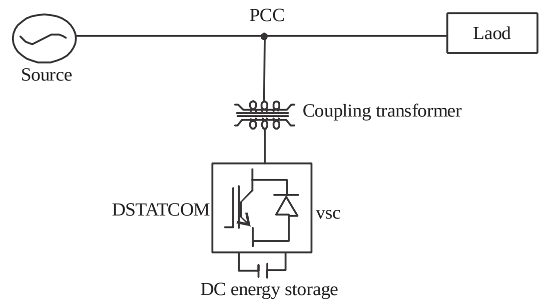


Fig. 1: Basic configuration of D-STATCOM

**D-STATCOM:** D-STATCOM is considered as the most effective and widespread conditioners amongst the CPD family because of its ability to hand over power quality problems. The basic and fundamental unit of D-STACOM is VSC with which a capacitance is connected on the DC-side. It is connected in shunt connection with the distribution network with the help of a transformer and a Low Pass Filter (LPF). The LPF is used to minimize ripples and compensate for harmonics. A lot number of research papers exist which deals with D-STATCOM. In these works D-STATCOM has been implemented using different control techniques (for the generating reference current components) such as IRP theory, active and reactive power theory, instantaneous symmetrical components theory, indirect control scheme, SRF theory, hysterics control and so on[11-14]. For any compensation technique such as D-STATCOM the main goal and objective is to have a fast response, easy control, less complexity and easy implementation. For this reason an improved control algorithm for D-STATCOM will be designed in order to respond towards power quality problems in a most effective way.

**Basic configuration of D-STATCOM:** D-STATCOM's basic configuration is such that it contains a VSC which is the basic unit, a DC-link capacitor or DC energy source, a set of coupling reactors or a coupling transformer (leakage reactances of the transformer) and a controller circuit. It is connected in parallel connection with the distribution network. Figure 1, illustrates the basic configuration of shunt connected D-STATCOM in a distribution system. D-STATCOM is linked to the distribution network at the Point of Common Coupling (PCC). The main function VSC is to transmit the DC-link voltage across the capacitor or DC energy source into a three phase AC output voltages which are in phase with the main supply voltage[15]. Behind the reactance of coupling reactor or transformer AC voltage is produced.

The difference between D-STATCOM output voltage and voltage at PCC is responsible for the transfer of active and reactive power between the D-STATCOM and the distribution network according to the requirements.

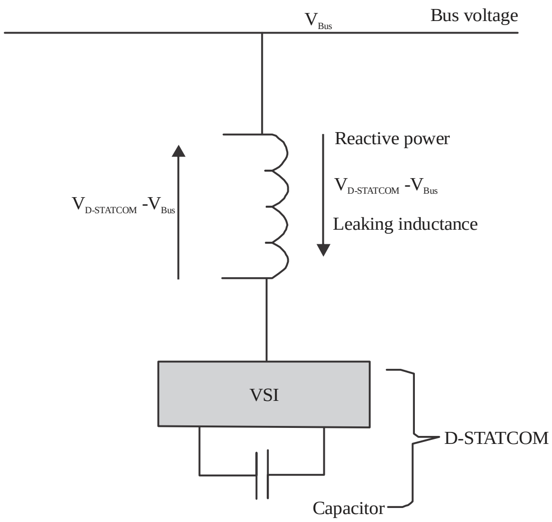


Fig. 2: Principal of operation of D-STATCOM

**Principal of operation of D-STATCOM:** The basic working principal of D-STATCOM is just like a synchronous machine. The synchronous machine working principal is such that it generates reactive power when it is overexcited and absorb reactive power when under excited. D-STATCOM also has the beauty that it can inject active power to the AC network when an external DC voltage source is provided[16].

**Exchange of reactive power:** If the D-STATCOM output voltage is greater than the AC bus voltage at PCC then D-STATCOM deliver reactive to the system (inject leading current to the AC system) and will behave as capacitor as shown in Fig. 2.

On the other hand if the D-STATCOM output is less than the AC bus voltage at PCC then it will absorb reactive power from the line (inject lagging current to the AC bus) will behave as a inductor and in order to maintain 1 p.u bus voltage at PCC as show in Fig. 2:

$$Q=\left(\frac{V_{DS}*V_{BUS}}{X_l}\right)\left(\left(\frac{V_{DS}}{V_{BUS}}\right)-\cos\left(\delta_{DS}-\delta_{BUS}\right)\right) \tag{1}$$

**Exchange of real power:** Sometimes there is also a need for the exchange of active power in AC system. As the switching devices on completely lossless therefore a storage device is required to deliver real power to the switching components. For the exchange of active power with the distribution network in case of voltage sags due to abnormal faults or heavy loaded conditions then a DC energy source is need to be connected on the DC side of D-STATCOM’s VSC.

$$P=\left(\frac{\left(V_{DS}\right)\left(V_{BUS}\right)}{X_l}\right)\left(\sin\left(\delta_{DS}-\delta_{BUS}\right)\right) \tag{2}$$

Hence, the injection and absorption of active and reactive power by D-STATCOM with power system is the major requirement, so as to retain the bus voltage at 1 p.u and enhance the quality of power supplied to customers.

## MATERIALS AND METHODS

**Proposed solution:** Amongst all control schemes the most widely used and efficient control scheme is SRF theory. In this control scheme it is first required to measure DC bus voltage, AC source voltage and current and load current which are then used for controlling purpose. SRF theory based control scheme mainly consists of three regulators, i.e., DC bus voltage regulator, AC bus voltage regulator and current regulators as shown in Fig. 3. The main responsibility of AC voltage regulator is to control the voltage regulation of the AC bus where the D-STATCOM is shunt connected either by injecting or absorbing reactive power. The main function of DC voltage regulator is to control the DC-voltage across the DC-link capacitor of the controller. In this research work AC as well as DC voltage regulators have been intended with proportional integral type controllers also known as PI controllers. Current regulator is responsible for controlling the real $i_d$ and reactive $i_q$ components of the D-STATCOM injected current for load compensation (Fig. 3).

The current drawn by three phase load ($I_{La}$, $I_{Lb}$, $I_{lc}$) are measured using CT which is then transformed from abc into dq0 reference frame using the following Parks transformation matrix:

$$\begin{bmatrix} I^*_{sa} \\ I^*_{sb} \\ I*_{sc} \end{bmatrix}=\frac{2}{3}*\begin{bmatrix} \cos(\theta) & \cos\left(0-\left(\frac{2}{3}\right)\pi\right) & \cos\left(0+\left(\frac{2}{3}\right)\pi\right) \\ \sin(\theta) & \sin\left(\theta-\left(\frac{2}{3}\right)\pi\right) & \sin\left(\theta+\left(\frac{2}{3}\right)\pi\right) \\ \left(\frac{1}{2}\right) & \left(\frac{1}{2}\right) & \left(\frac{1}{2}\right) \end{bmatrix}\begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \tag{3}$$

Three phase PLL function block is employed to measure source voltage phase difference for synchronizing purpose. By using inverse dq0 transformation matrix we can get the mathematical equations for source reference currents as follows:

$$\begin{bmatrix} I^*_{sa} \\ I^*_{sb} \\ I*_{sc} \end{bmatrix}=\frac{2}{3}*\begin{bmatrix} \cos(\theta) & \sin(\theta) & 1.0 \\ \cos\left(\theta-\left(\frac{2}{3}\right)\pi\right) & \sin\left(\theta-\left(\frac{2}{3}\right)\pi\right) & 1.0 \\ \cos\left(\theta+\left(\frac{2}{3}\right)\pi\right) & \sin\left(\theta+\left(\frac{2}{3}\right)\pi\right) & 1.0 \end{bmatrix}\begin{bmatrix} I^*_{d} \\ I^*_{q} \\ I^*_{0} \end{bmatrix} \tag{4}$$

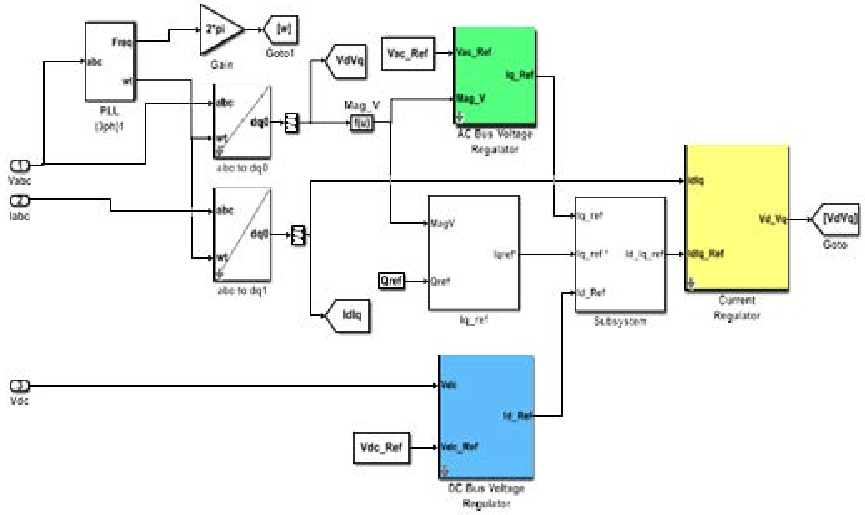


Fig. 3: Simulink model of SRF theory based control scheme

Due to harmonic distortion the q-axis ($I_{Lq}$) and d-axis ($I_{Ld}$) load current components contain AC as well as DC components from which AC component can removed either using mean block or Low Pass Filter (LPF) in case of MATLAB simulation. Here we have used LPF for the removal of AC component. ($I^*_d$) and ($I^*_q$) are the d-axis and q-axis reference current components. The addition of $I_{ddc}$ and $I_{loss}$ components will results d-axis reference current as give:

- $I_{ld} = (I_{ddc})+(I_{dac})$
- $I_{lq} = (I_{qdc})+(I_{qac})$
- $I^*_d = (I_{ddc})+(I_{loss})$

where, $I_{loss}$ is the of DC-link volatge regulator. D-STATCOM mainly operates in two modes, one is Unity Power Factor (UPF) mode and other is Zero Voltage Regulation (ZVR) mode. The value of q-axis load reference current component $I^*_q$ depends upon the operating mode of the D-STATCOM. For UPF mode where the whole reactive power is supplied by D-STATCOM and the contribution from source side is (0), i.e.

$$I^*_q = 0(\text{for UPF operating mode})$$

On the other hand in ZVR mode both D-STATCOM and source will supply reactive power so as to compensate for the reactive power and preserve PCC voltage at 1 p.u while keeping zero voltage regulation:

$$I^*_q = I_{qdc} + I_{qloss}(\text{for ZVR operating mode})$$

In case of PWM switching techniques the required PWM switching pulses for controlling the operations of VSC based D-STATCOM can bbe achieved by comparing the calculated reference signals with high frequency traingular wave form. By adjusting the active $I^*_d$ and reactive $I^*_q$ reference current components of the performance of D-STATCOM for reactive power compensation and harmonies elimination of D-STATCOM mainly depends upon current regulation.

SRF theory based control scheme mainly consists of three regulations, i.e., DC bus voltage regulator (blue block), AC bus voltage regulator (green block) and current regulations (yellow block) as shown in Fig. 3.

**AC bus voltage regulator:** AC voltage regulator is accountable for controlling and regulating the AC-bus voltage where the D-STATCOM is shunt connected. Here the magnitude of measured AC-bus voltage is subtracted from the reference Voltage signal ($V_{ac}$-$_{Ref}$) and the resultant error is then provided as input to the PI controller to generate q-axis reference current as presented in Fig. 4 and 5.

**DC bus voltage regulator:** DC voltage regulator is accountable for controlling and regulating the DC-link capacitor voltage. In this research, we have used PI controllers in the designing of both voltage regulators. DC-link measured voltage is $V_{dc}$ which is subtracted from the reference value $V_{dc\_ref}$. Rate limiter is responsible for the rising and falling rate of the signal. The error signal of $V_{dc}$ and $V_{dc\_ref}$ is provided as input signal to the PI controller which produce d-axis reference current $I_{d\_ref}$ as shown in Fig. 6. The main function

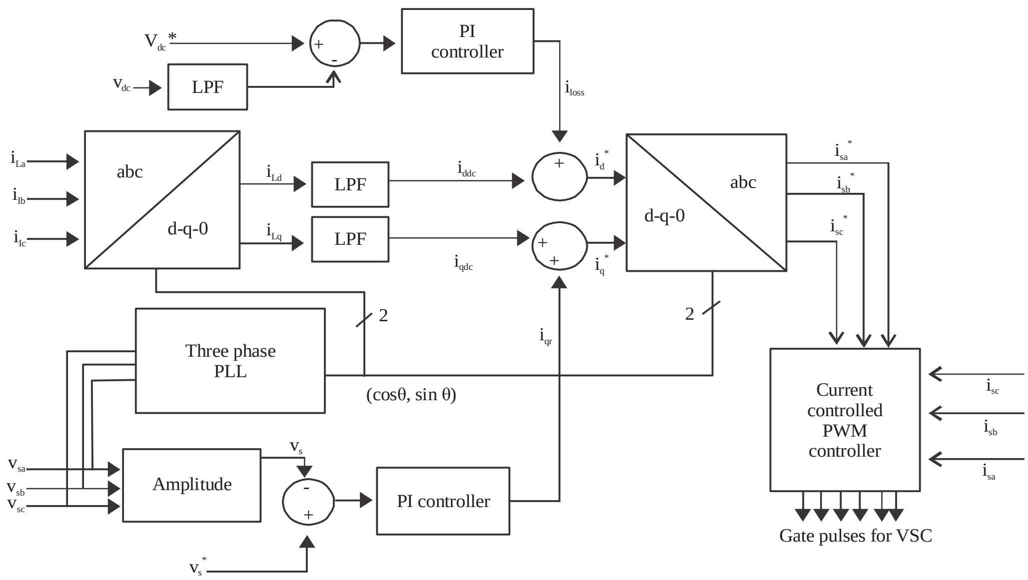


Fig. 4: SRF theory based D-STATCOM control scheme

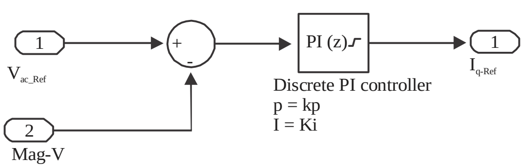


Fig. 5: AC bus voltage regulator

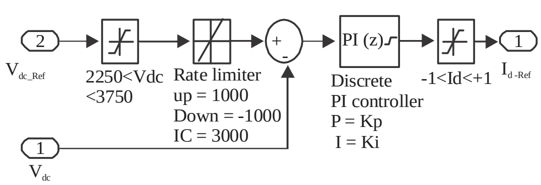


Fig. 6: DC bus voltage regulator

saturation block is to limit input error signal ($I_d$) to the required higher and lower restraining values which are 1 and -1, respectively.

**Current regulator:** There are two discrete PI controllers in the current regulator as presented in Fig. 7. The difference of $I_d$ and $I_{d\_Ref}$ is given as input to one PI-controller whose output is d-axis Voltage $V_d$. The difference of $I_q$ and $I_{q\_Ref}$ is given as input to the second PI controller whose output is q-axis Voltage $V_q$. Current regulator is accountable for controlling real $i_d$ and reactive $i_q$ components of the D-STATCOM injected current for load compensation.

By using inverse dq0 or Clarks transformation matrix of Eq. 4 we get the reference signals. When the reference signals are achieved they are given to the PWM generator where its comparison is taken place with high frequency carrier signal and finally PWM pulses are obtained for operating switching devices (IGBTs) of the VSI.

## RESULTS AND DISCUSSION

This stduy is about to expound the simulation results based on MATLAB-Simulink modeling discoursed in the preceding chapter. It gives detail about the operation of D-TATCOM under various loading conditions and abnormal faults conditions (Fig. 7).

**Voltage sag analysis:** Voltage sags due to large inductive load and various faults conditions have been implemented in MATLAB Simulink and an improved control algorithm based D-STATCOM was used to compensate for these abnormal conditions (Fig. 8-11).

**Case-I: inductive load:** Figure 8 demonstrates the MATLAB Simulink results of the load bus voltages in p.u. The large inductive load is linked to the load bus at time 0.05 sec while D-STATCOM is activated at time 0.1 sec. From the figure we see that the level of system voltage goes down due to heavy consumption of reactive power when inductive load is connected. When D-STATCOM is connected after 0.05 sec, i.e. at 0.1 sec the voltage level is brought back to nominal value (1 p.u).

**Case-II: three phase fault (3-φ) on load side:** In an electric distribution system apart from inductive loads,

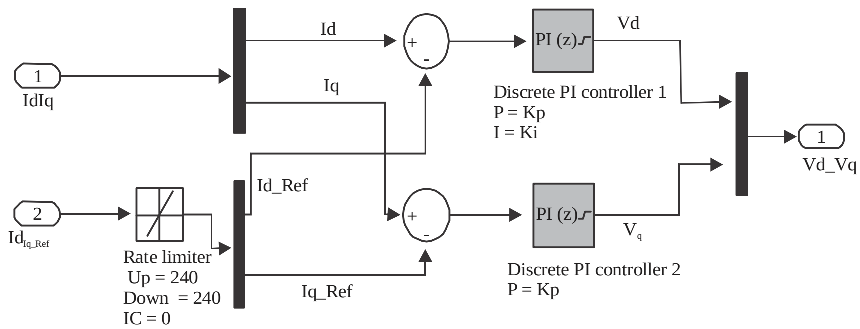


Fig. 7: Current regulator

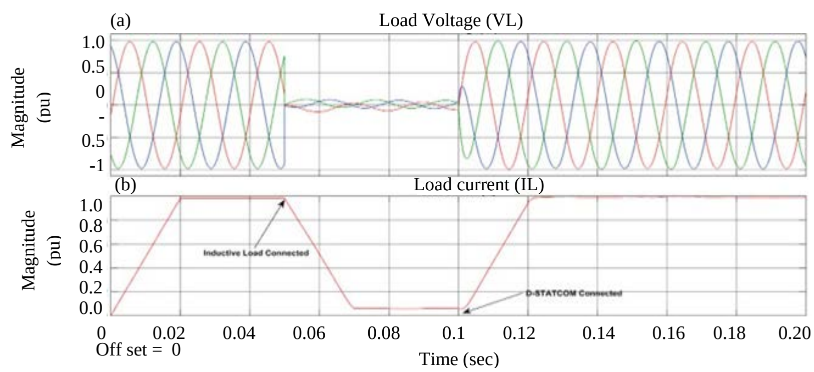


Fig. 8(a, b): Load bus voltage sag due to inductive load with

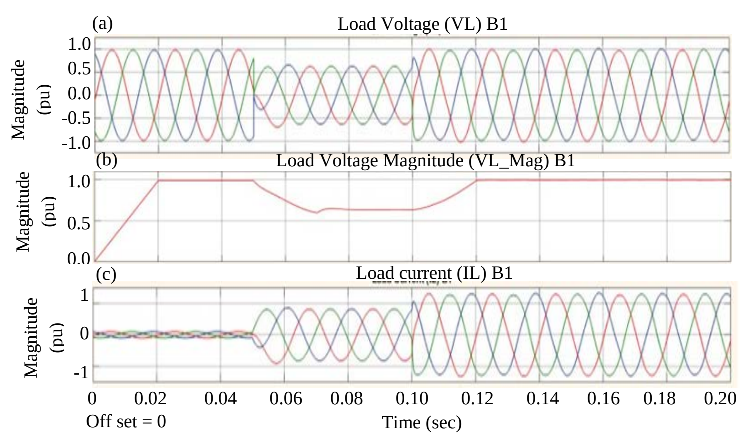


Fig. 9 (a-c): Load bus voltage sag due to 3-φ fault with

voltage sags may also occur because of abnormal faults. In this research work on 3-φ to ground fault (L.L.L-G) on load side as well as on source is implemented in MATLAB Simulink. First of all L.L.L-G is on load side is implemented. The fault Resistance is ($R_{on}$) is 0.1 Ω and ground Resistance ($R_g$) is 0.1 Ω. Figure 9 demonstrate the Simulink simulation results of load bus when a 3-φ to ground fault occur at time 0.0 5 sec. Figure 9 shows that when fault occurs at 0.05 sec the load bus 1 current increase and the voltage at this bus goes down. At time 0.1 sec when D-STATCOM is activated the load bus 1 current increases further increases.

**CASE-III: Three phase fault (3-φ) on source side:** Figures 10 depicts simulation results when the same three phase fault (fault resistance ($R_{on}$) 1 Ω and ground resistance ($R_g$) 0.1 Ω) occurs on the source side. Figure 10 represents that the load bus voltage and current

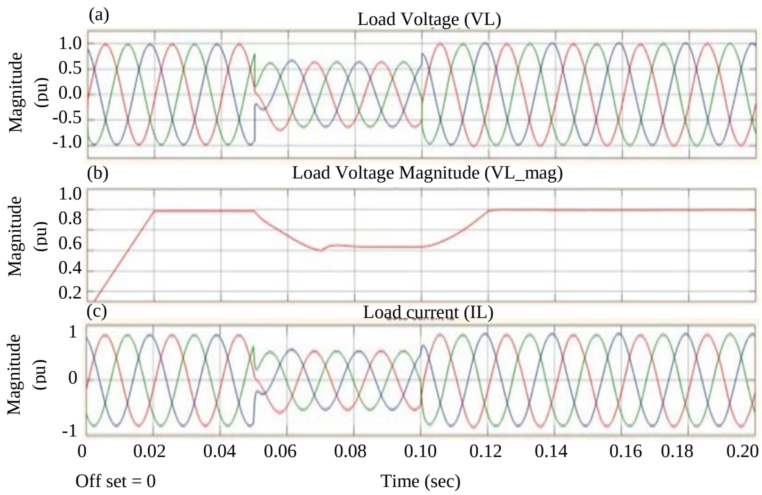


Fig. 10(a-c): Load bus voltage Sag and current under 3-φ Fault with D-STATCOM

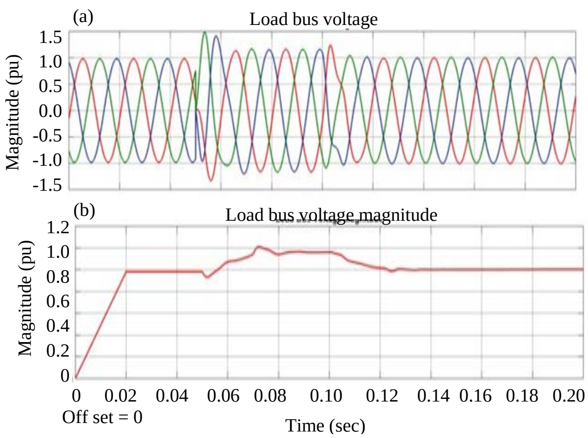


Fig. 11(a, b): Load bus voltage swell due to capacitive load with D-STATCOM

both decreases when the fault occurs on the source bus because the follow the direct short circuit/low resistance path. Now when at time 0.1 sec D-STATCOM is activated, the load bus voltage and current goes to the normal value.

**Voltage swell analysis:** Usually over voltages/swells are generated because of load switching process for example when a large inductive load is suddenly dis-connected or a capacitor bank is activated quickly.

Here, we analyzed the voltage swell process by energizing a large capacitive load (10 W, 100 kVAR) in MATLAB Simulink.

**Capacitive load:** Figure 11 represents the simulation results (voltage of the source bus and its magnitude) when a large capacitive load is connected at time 0.05 sec. When the large capacitive load (10 W, 100 kVAR) is connected ta time t = 0.05 sec the voltage level goes up (voltage swell) form the nominal value. Now when at time 0.1 sec D-STATCOM is activated the source bus voltage is brought back to nominal value (1 p.u). It is depicted that when capacitive load (10 W, 100 kVAR) is activated at time 0.05 sec, the load bus voltage rises (voltage swell) but when D-STATCOM is energized at time 0.1 sec voltage of the load bus is brought back to its nominal value (1 p.u).

## CONCLUSION

The dynamic performance and power quality of the distribution system in Pakistan is poor because of weak and out-of-date system. It is unable to deliver the required reactive power in case of various system disturbances. Domestic and industrial consumers use AVS and capacitor banks respectively for voltage sags and poor power quality problems. Both AVS and capacitor banks can regulate the output voltage but AVS draws an increased line current system which may cause the distribution system to be overload while capacitor banks perform poorly when the load variation occur frequently such as in industries. D-STATCOM is an important compensator which is able to enhance the power quality and dynamic performance of the distribution system.

In order to improve power quality and dynamics performance of the distribution system effectively a more robust and optimal control algorithm is required for D-STATCOM. For this purpose in this research control scheme SRF theory for D-STATCOM have been designed and implemented in MATLAB-Simulink. Therefore, an improved control algorithm based on SRF theory and PI-controllers for D-STATCOM have been developed which control reactive power in real time and handle poor power quality problems in a better way.

## ACKNOWLEDGEMENTS

First and foremost, i prolong my sincere appreciation to my supervisor, Assistant Professor Dr. Abdul Basit for his immense acquaintance and capability who has supported me throughout my thesis. I am very grateful to USPCAS-E at UET Peshawar and USAID Pakistan for giving me this precious chance of fully funded scholarship to endure the bright career by doing MSc in EESE.

## APPENDIX

Appendix 1: Parameters

| 3-φ source voltage and frequency | 220 kV, 50 Hz |
|---|---|
| 3-φ source impedance (R, L) | 100 mΩ, 758 mH |
| Source side Transformer (100MVA) | 220/11 kV |
| Line Impedance ( R, L) | 10 mΩ , 1.2 mH |
| RL Load 1 (R, L) (always connected) | 10 kW, 130 kVAR |
| RL Load 2 (R, L) (Inductive Load) | 10 MW, 1 MVAR |
| RC Load 3 (R, C) (Capacitive Load) | 10 W, 100 kVAR |
| DC Link Capacitor | 750 μF |
| LCL filter 1.33 mH | 35 μH, 11.5 mF, |
| Three Phase Fault Resistance ($R_{on}$ , $R_g$) | 1 Ω, 0.1 Ω |

## REFERENCES

01. Sharma, A. and A.S. Thosar, 2018. Distribution system power quality improvement using D-STATCOM. J. Adv. Res. Power Electron. Power Syst., 5: 14-20.
02. Deepak, S.C., S.G. Dharmesh, K.M. Sameer, S.N. Rakesh and J.A. Tailor, 2018. Minimizing penalty in industries by engaging automatic power factor correction unit. Int. J. Innovative Res. Sci. Eng. Technol., 7: 3029-3036.
03. Bollen, M.H.J., 2000. Understanding Power Quality Problems: Voltage Sags and Interruptions. 1 Edn., IEEE Press, New York, ISBN: 0-7803-4713-7.
04. Johnson, D.O. and K.A. Hassan, 2016. Issues of power quality in electrical systems. Int. J. Energy Power Eng., 5: 148-154.
05. Mahela, O.P. and A.G. Shaik, 2016. Topological aspects of power quality improvement techniques: A comprehensive overview. Renewable Sustainable Energy Rev., 58: 1129-1142.
06. Sen, K.K. and M.L. Sen, 2009. Introduction to FACTS Controllers: Theory, Modeling and Applications. Vol. 54, John Wiley & Sons, Hoboken, New Jersey, Pages: 522.
07. Hingorani, N.G., L. Gyugyi and M. El-Hawary, 2000. Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. Vol. 1, Wiley, Hoboken, New Jersey, USA., ISBN:9780780334557, Pages: 432.
08. Kasari, P.R., M. Paul, B. Das and A. Chakraborti, 2017. Analysis of D-STATCOM for power quality enhancement in distribution network. Proceedings of the TENCON 2017-2017 IEEE Region 10 Conference, November 5-8, 2017, IEEE, Penang, Malaysia, pp: 1421-1426.
09. Das, E., A. Banerji and S.K. Biswas, 2017. State of art control techniques for DSTATCOM. Proceedings of the 2017 IEEE Calcutta Conference (CALCON), December 2-3, 2017, IEEE, Kolkata, India, pp: 268-273.
10. Varshney, G., D.S. Chauhan and M.P. Dave, 2015. Performance analysis of photovoltaic based DSTATCOM using SRF and IRP control theory1. Proceedings of the 2015 1st International Conference on Next Generation Computing Technologies (NGCT), September 4-5, 2015, IEEE, Dehradun, India, pp: 779-783.

11. Singh, B. and J. Solanki, 2006. A comparative study of control algorithms for DSTATCOM for load compensation. Proceedings of the 2006 IEEE International Conference on Industrial Technology, December 15-17, 2006, IEEE, Mumbai, India, pp: 1492-1497.
12. Akagi, H., E.H. Watanabe and M. Aredes, 2017. Instantaneous Power Theory and Applications to Power Conditioning. John Wiley & Sons, Hoboken, New Jersey, USA., Pages: 454.
13. Meeravali, S.K. and K. Chandrasekhar, 2015. Power quality enhancement using multi-level cascaded H-bridge based D-STATCOM with IRP theory. Int. Electr. Eng. J. (IEEJ.), 6: 1756-1764.
14. Bhattacharya, S. and B.A. Shimray, 2017. Power quality improvement and mitigation of harmonic distortion using DSTATCOM with PI and fuzzy logic controller. Proceedings of the 2017 International Conference on Smart Grids, Power and Advanced Control Engineering (ICSPACE), August 17-19, 2017, IEEE, Bangalore, India, pp: 183-189.
15. Swetha, K. and V. Sivachidambaranathan, 2019. A review on different control techniques using DSTATCOM for distribution system studies. Int. J. Power Electron. Drive Syst., 10: 813-821.
16. Jovitha, J. and R. Subha, 2014. Power quality enhancement in distribution system (DSTATCOM). Proceedings of 13th National Power Systems Conference (NPSC), December 18-20, 2014, Indian Institute of Technology (IIT), Chennai, India, pp: 27-30.