Uniport Journal of Engineering and Scientific Research (UJESR)

Vol. 6, Special Issue, 2022, Page 63-72
ISSN: 2616-1192

(www.ujesr.org)

Implementation of a Shunt Compensator to Mitigate Power Quality in the Choba-RSU Distribution Network

Big-Alabo, A* and Ifezue, I
Department of Electrical / Electronic Engineering, Faculty of Engineering, University of Port Harcourt
*Corresponding author's email: amezeodia@yahoo.com

Abstract

This study presents the design of a discrete time domain shunt compensator controller that can be applied in a distribution network. This controller comprised a Phase Locked Loop (PLL), a Voltage and Current Measurement Unit, DC voltage Regulator, AC Voltage Regulator, a Current Regulator, Pulse Width Modulated (PWM), Insulated Gate Bipolar Transistor (IGBT) switch, DC voltage source and coupling transformer. The proposed controller was tested with samples of daily voltage readings obtained from Choba and Rivers State University (RSU) injection substation for the analyses on the quality of power being distributed. The result obtained showed that the proposed control system is an effective integral part of the shunt compensator which generates a feedback signal for the pulse width modulation (PWM) controlled IGBT electronic switching voltage source converter (VSC), injecting the appropriate amount of reactive current for the mitigation of under-voltage challenges in the distribution system. The main advantage of the use of a PWM to control the IGBT switch is that power loss in the switching device is minimal. The proposed model is a closed loop control strategy which guarantees injection of reactive current in quadrature with the line voltage of the distribution network. This approach will help to maintain the system voltage stability and also improve the power quality of these networks.

Keywords: *Power quality, Voltage stability, Pulse width modulation, Shunt compensator*

Received: 1st July, 2022 *Accepted: 14th July, 2022*

1. Introduction

There are several benefits for reactive power compensation, some of which are voltage regulation, increase in system stability, reduced losses in the system, optimized usage of machines connected in the power (Tembhurnikar et al., 2014). Voltages are regulated by predicting and correcting reactive power demand from loads. A decrease in reactive power will result to voltage sag and under voltage in the system while an increase in reactive power will result to voltage swell and over voltage. Under voltage and over voltage are harmful to certain loads and can lead to damage of both sensitive and non-sensitive loads if not mitigated. An increase or decrease of the voltage in power network requires a desired amount of injected or absorbed reactive power to counteract the disturbance. It is therefore necessary to control network parameters of a distribution network in order to ensure stable operation of the power system and operate the lines within their safe loading limits, (Hingorani, 1994). This paper proposes a control system for a shunt compensator to mitigate the effect of power quality problems on a distribution power system. The proposed controller offers compensation of dynamically varying voltage and mitigation of voltage imbalance.

The motivation for this study is that the designed control system will help to enhance the operation of shunt compensator and hence maintain a stable distribution voltage during time of supply to the consumers. Samples of daily voltage and power readings were obtained from Choba and Rivers State University (RSU) injection substation for analyses of the quality of power being distributed. The proposed controller is then tested with samples of daily voltage readings obtained to see how well the controller would effectively perform voltage stability.

2. Related reviews

Voltage sags are the most common and harmful power quality problem which frequently occurs on distribution networks (Sujata and Himabindu, 2013). Voltage sags can be defined as an abrupt decline in the magnitude of RMS AC voltage, at a power frequency below the nominal RMS voltage by 10-90% for duration of 0.5 cycle to 60 seconds (Dan, 2013). Voltage sags result in tripping of electro-magnetic relays, loss in efficiency of electric drives and programmable logic control system, malfunction of electrical appliances (Kaur and Nijhawan, 2016). Electrical network compensation can be achieved using a few techniques such as shunt compensation, series compensation and hybrid compensation (A combination of shunt and series compensation). Compensation techniques can be used to improve the total efficiency of the network and improve controllability (Irinjila and Jaya, 2010). Traditionally, shunt compensation is done by using fixed capacitors. However, this method has certain drawbacks such as problems of resonance with supply system, fixed compensation and limited flexibility (Bhattacharya and Zhong 2001). Shunt compensation can now be effectively accomplished using static switches or power electronic based devices. Examples are distributed static compensator (DSTATCOM) and static VAR compensator (SVC) Vijaysimha and Suman, 2013)

2.1 Review on the control scheme

The control system used in any compensating device or FACTs/Custom power device is the most vital part of the compensating device. It is accountable for the quick response in the dynamic change of loads in the power system. It enhances the operation and controllability of the shunt compensating device. Generally, there are two most common control methodologies of generating compensating commands, Time domain and frequency domain techniques. Application of frequency domain technique involves Fourier analysis of the distorted voltage or current to extract compensating command. The online application of Fourier analysis is complex, involves cumbersome computation and results in large response time, which makes compensation of dynamically varying load difficult (Ambarnath et al., 2012).

Operation of DSTATCOM in time domain control methodology is done in three stages. The first stage involves gathering of accurate power system information by sensing of the power systems voltage and current signal. The second stage involves generating a compensating command based on voltage/current level and the control method used. The third stage involves generation of gate signals for the solid-state power electronic device such as IGBT or GTO, etc. using PWM, sliding mode, hysteresis or fuzzy logic-based control techniques. There exist several control methods in time domain technique which are based on Instantaneous p - q theory, synchronous d – q reference frame method, flux-based controller, notch filter method, synchronous detection method, slide mode controller and PI controller (Alassouola, 2018). The most commonly used control method is the Instantaneous p – q theory using clarks transformation principle and it is based on α-β transformation of voltage and current signal to generate compensating command (Singh and Solanki, 2009).

The Synchronous reference-based method and flux-based controller involves transformation of voltage and current into a Direct - quadrature dq rotating frame using parks transformation theory. Fundamental quantities become DC quantities and then compensating commands are derived. DC bus voltage feedback is generally used to achieve a self-supported DC bus voltage (Elby and Jayaprakash, 2016). In the PI controller and slide mode controller a Voltage Source Converter (VSC) or Current Source Inverter (CSI) is used and their DC bus voltage is maintained at a constant value using a DC bus feedback system. A reference value for supply voltage is obtained and computed with load voltage to generate the compensating signal that eliminates the offset in load voltage (Akil et al., 2015).

3. Materials and methods

All data used in this paper were collected from Choba distribution station in Choba, Rivers State University Injection Substation and head office Port Harcourt distribution company Trans Amadi, Rivers State, all in Nigeria. These data include hourly secondary voltage readings from 15MVA transformers feeding Choba, Aluu, Rumuekini, Federal, Wokoma, Ojoto, and Rivers State University, feeder length, nominal voltage and average loads. Daily average secondary voltage and power data obtained were properly scrutinized and compared with the various power quality problems definitions as stipulated in IEEE 1159 documents. Samples of these data were simulated on Matlab/Simulink environment to obtain the voltage and power readings.

3.1. Choba Substation

Choba distribution sub-station is a part of Port Harcourt distribution network which is been fed from Port Harcourt transmission station via 132/33KV transformer rated at 60MVA. Choba distribution sub-station has two Transformers rated at 15MVA, 33/11kV and 3 outgoing load feeders (Choba, Rumuekini, Aluu) and total power of 5.5MW. Fig. 1 shows a one-line diagram of Choba distribution substation.

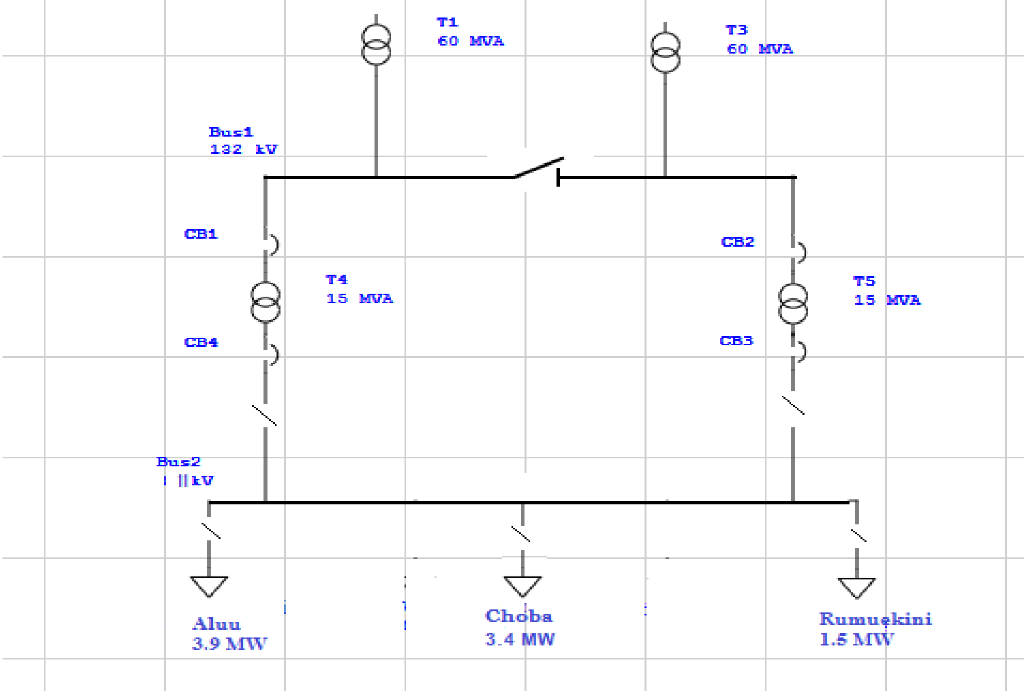

Fig. 1: Single line diagram of Choba distribution substation.

The substation operates load shedding owing to the fact known from observation that the entire power supplied to the substation is insufficient to meet up with demand. Data collected for duration of 5 months from the substation indicates that under-voltage are the most predominant challenge in the quality of power supplied from Choba distribution line according to the definitions of power quality problems on IEEE 1159 document. Table 1 shows samples of feeder voltage. The aim of this study is to mitigate voltage sags and under-voltage observed on the line and to improve the quality of power distributed from the station through the integration of a shunt compensator.

Table 1: Sample voltages for Choba distribution substation

Feeder	Phase	Min V (kV)	Avg V (kV)	Max V (kV)	Nom V (kV)
Choba	Phase A	9.5	10.2	10.7	11
	Phase B	9.5	10.2	10.7	11
	Phase C	9.5	10.2	10.7	11
Aluu	Phase A	9.5	10.2	10.7	11
	Phase B	9.5	10.2	10.7	11
	Phase C	9.5	10.2	10.7	11
Rumuekini	Phase A	9.5	10.2	10.7	11
	Phase B	9.5	10.2	10.7	11
	Phase C	9.5	10.2	10.7	11

3.2. Rivers State University Distribution System

Rivers State University distribution substation is also a part of Port Harcourt distribution network which is fed from Port Harcourt transmission substation via 132/33kV transformer rated 60MVA. The substation is been fed by two incomer cables rated at 33kV. These incomers are terminated to two step-down transformers rated at 15MVA and four up-riser cable (outgoing load feeder) which includes RSU (or UST), Ojoto, Federal and Wokoma. Fig. 2 shows a one-line diagram of the substation. Due to insufficient supply of power, the substation is forced to operate a load shedding scheme for effective maximization of power allocated to the substation. Data collected as shown in Table 2 shows more than -5% decrease in nominal voltage which is below the standard of allowable voltage drop according to IEEE 1159 document.

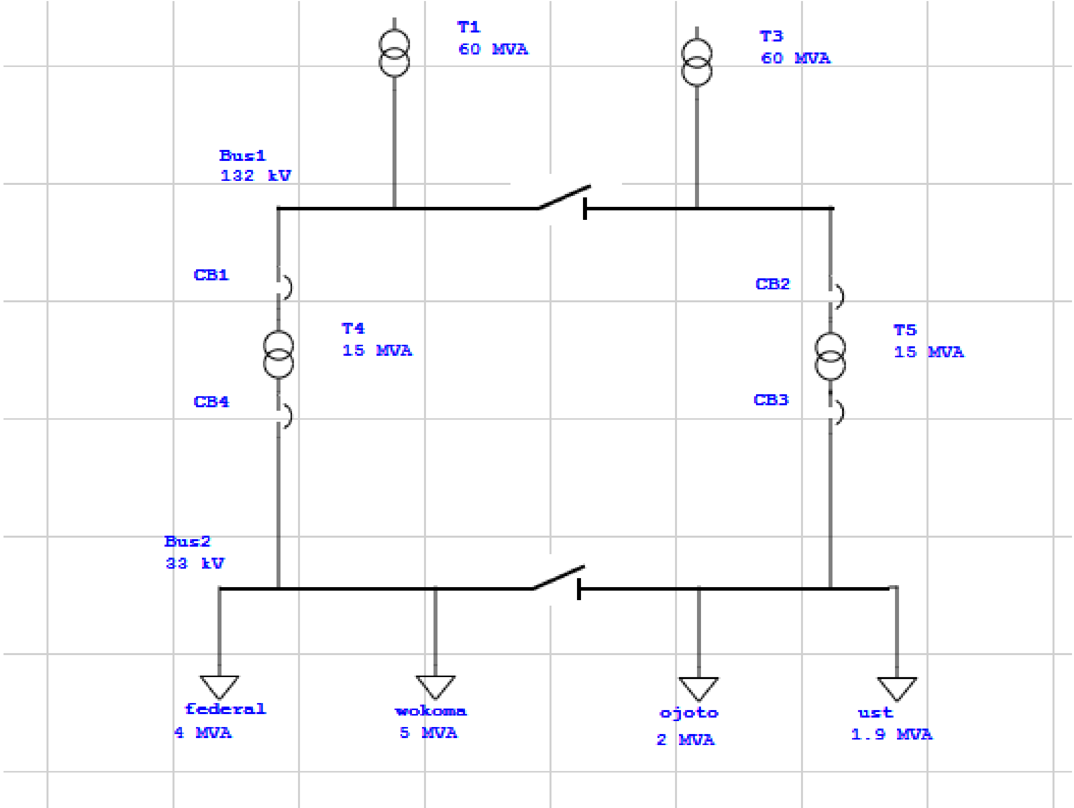

Fig. 2. Single line diagram of Rivers State University distribution substation.

Table 2: Sample voltages for Rivers State University distribution substation.

Feeder	Phase	Min V (kV)	Avg V (kV)	Max V (kV)	Nom V (kV)
Federal	Phase A	9.2	10.0	10.6	11
	Phase B	9.2	10.0	10.6	11
	Phase C	9.2	10.0	10.6	11
Wokoma	Phase A	9.2	10.0	10.6	11
	Phase B	9.2	10.0	10.6	11
	Phase C	9.2	10.0	10.6	11
Ojoto	Phase A	9.2	10.0	10.6	11
	Phase B	9.2	10.0	10.6	11
	Phase C	9.2	10.0	10.6	11
RSU	Phase A	9.2	10.0	10.6	11
	Phase B	9.2	10.0	10.6	11
	Phase C	9.2	10.0	10.6	11

3.3. Control scheme

Keeping voltage at a constant magnitude can be achieved by introducing a shunt compensating device. The control scheme utilizes a discrete time domain control methodology. It comprises of a Phase Locked Loop (PLL), a Voltage and Current Measurement Unit, DC voltage Regulator, AC Voltage Regulator, a Current Regulator, PWM, IGBT switch, DC voltage source and coupling transformer working in unison for the easing of glitches associated with power quality. Figs. 3 and 4 show the control technique adopted in this study. The priority of this controller is to maintain both the DC voltage of the shunt connected compensating device and the AC voltage of the distribution network at a specific value. Fig. 5 presents the modelled distribution network with the shunt compensating device.

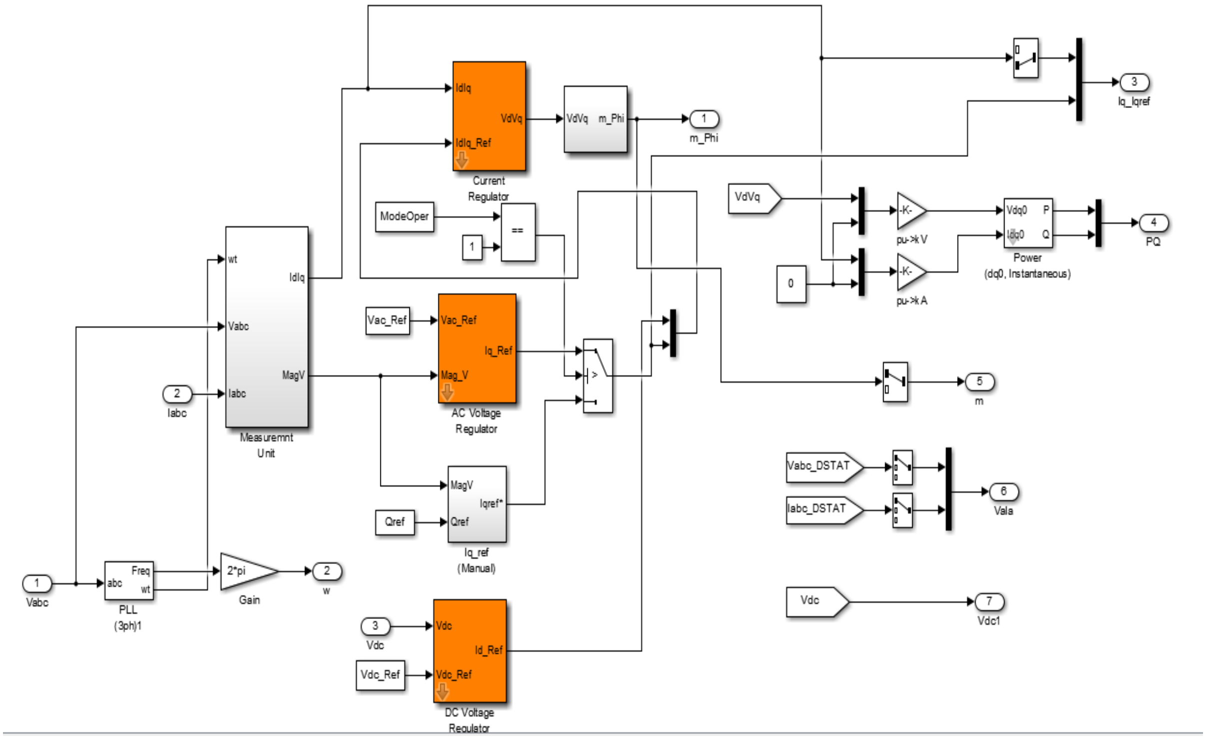

Fig 3: Control Scheme for shunt compensator

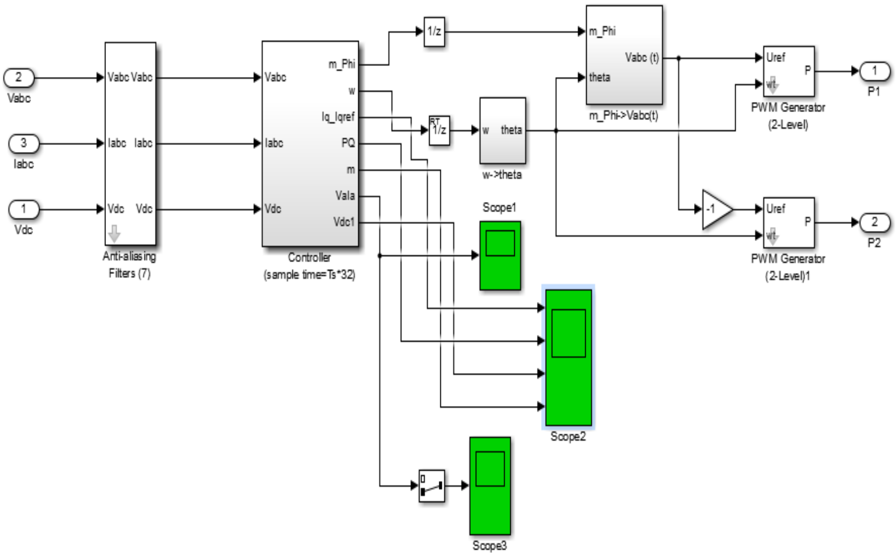

Fig 4: Control to PWM

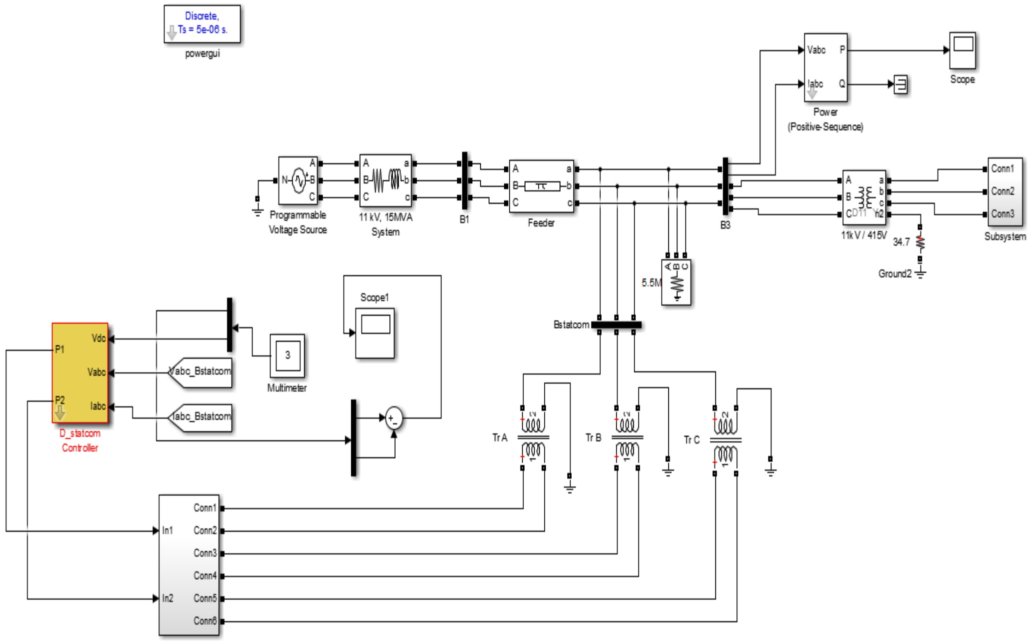

Fig 5: A model of the adopted shunt compensator

3.4 AC voltage regulation

Shunt compensators performs its compensating activities through the following stages: The first stage is measurement of the distribution voltage and current, acquiring information about its dynamic condition using a measurement unit and phase lock loop. The measurement unit converts voltage and current to synchronous reference frame (i_d and i_q) using parks transformation theory. The measurement unit also computes the magnitude of the measured voltage as shown in Equation (1).

$$V_{tm} = [\ (2/3)(V_{tan}^2 + V_{tbn}^2 + V_{tcn}^2)\ ]^{1/2} \qquad (1)$$

V_{tm} = Mag_V = Voltage magnitude

The computed voltage magnitude (Mag_V) from the measurement unit is compared with the desired magnitude of reference voltage (V_{ref}) to determine the error in voltage ($V_{er(n)}$) at the nth sample instance as shown in Equation (2).

$$V_{er(n)} = V_{ref} - V_{ac(n)} \qquad (2)$$

where $V_{er(n)}$ = Error derived from comparison, V_{tm} = (mag_V) = Magnitude of supply voltage, and V_{ref} = Reference voltage. The voltage error is processed through a discrete time integrating PI controller to generate I_{qref}.

$$I_{qref(n)} = I_{qref(n-1)} + K_{pq}\{V_{er(n)} - V_{er(n-1)}\} + K_{iq} V_{er(n)} \qquad (3)$$

K_{pq} and K_{iq} = proportional and integral gain of the PI controller. I_q generated from the transformation of the distribution line terminal voltage using parks transformation theory is compared with I_{qref} using a current regulator. The error generated is processed through a discrete time PI controller to generate V_q.

$$V_{q(n)} = V_{q(n-1)} + K_p\{I_{qer(n)} - I_{qer(n-1)}\} + K_i I_{qer(n)} \qquad (4)$$

K_p and K_i = proportional and integral gain of the PI controller.

3.5. DC voltage regulation

A major priority of the employed control scheme is to control the voltage at the DC terminal of the shunt compensator using a DC voltage regulator. This is achieved by the PI regulation of the DC voltage error generated when the measured DC terminal voltage is compared with a reference DC voltage at an nth sampling instant. PI regulation of the error signal generates $I_{dref(n)}$

$$V_{dc(n)} = V_{dcr} - V_{dc(n)} \qquad (5)$$

$V_{dc(n)}$ = Error in DC voltage
V_{dcr} = Reference DC voltage
$V_{dc(n)}$ = Measured DC terminal voltage

$I_{dref(n)} = I_{dref(n-1)} + K_{pd} \{ V_{dc(n)} - V_{dc(n-1)} \} + K_{id} V_{dc(n)}$
I_d generated from the measuring unit is computed with I_{dref} using a current regulator and the error generated is processed using a PI controller to generate V_d at the n_{th} instant.

$$I_{der(n)} = I_{dref(n)} - I_{d(n)} \qquad (6)$$

where I_{der} = Error generated

$$V_{d(n)} = V_{d(n-1)} + K_p\{I_{der(n)} - I_{der(n-1)}\} + K_i I_{der(n)} \qquad (7)$$

The V_d and V_q signals generated from the AC and DC terminal voltage control gives rise to modulation index 'm' and phase 'Φ' which is then used by the pulse width modulator to generate switching signals for the solid state IGBTs of the Voltage Source Converter. This causes the VSC to maintain the terminal voltage of the distribution network by generating / absorbing the required reactive current. Secondly, it also helps to maintain a constant DC bus voltage of the Voltage Source Converter. The main advantage of the use of a PWM to control the IGBT switch is that power loss in the switching device is very low. Table 3 below presents the parameters used for the controller

Table 3: Controller parameters

Coupling Transformer	**11kV/1.25 kV**
DC Capacitor	10000 mF
Modulation Frequency of VSC	1.4 kHz
PI Ac Voltage Regulator Gain [Kp Ki]	[0.55 2500]
PI Dc Voltage Regulator Gain [kp Ki]	[0.001 0.15]
PI Current Regulator Gain [kp ki]	[0.8 200]
Distribution Voltage	11kV (1pu)

4. Results and discussion

Study was done on the hourly voltage logs collected from Choba and Rivers State University injection substation documented over a period of five months. These voltages were grouped into three categories, namely minimum, average and maximum voltages as shown in Table 1 and Table 2 for simulation purpose. As seen on both tables, Average voltage readings are 10kV and 10.2kV respectively for both substations, which is more than -5% decrease of its nominal voltage. This is below the standard of allowable voltage drop according to IEEE 1159 document. Hence the need for compensation of supply voltage to ensure operation within its nominal supply voltage. The proposed model is a closed loop control strategy which guarantees injection of reactive current in quadrature with the line voltage of the distribution network mentioned above. A DC voltage controller is also an integral part of the control system adopted in this paper which keeps the DC link voltage at the reference value before and after compensation (V_{dc} = 2.4KV). This is one of the major priorities of this control system.

4.1. Without compensator

Four steps are programmed at 0, 0.2, 0.3, and 0.4-time value to successively reduce the amplitude value of the source voltage from 1pu to 0.6pu and 0.8pu then back to 1pu. Figure 6 shows the impact of varied supply voltage on the output power displayed in Figure 7. Without the use of shunt compensator, it is observed that there is a drop in power supply as a result of the varied supply voltage.

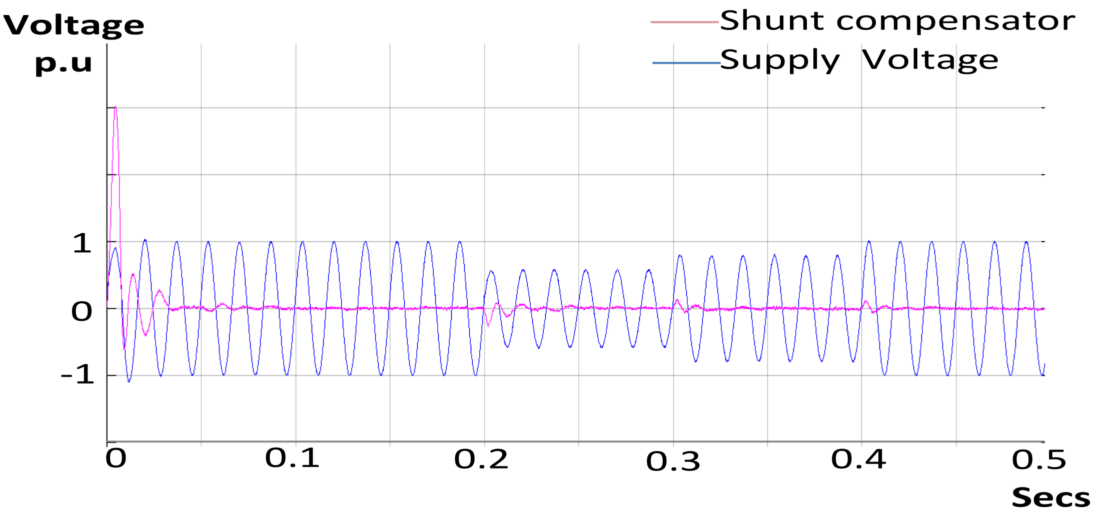

Fig 6: Voltage supply with zero compensation

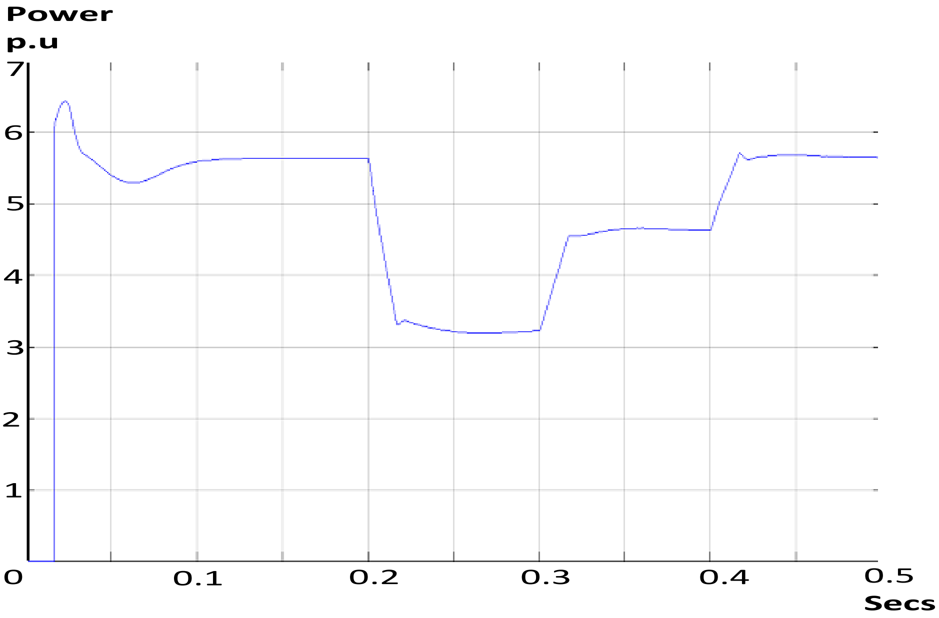

Fig.7: Power supply without compensation

4.2. With compensator

The controller gives a dynamic response towards the varied voltage amplitude level. Fig.8 shows the effect of the swift response of the control system integrated in the shunt compensator as it injects a capacitive current to compensate the drop-in voltage amplitude within 0.2 – 0.4 seconds. This helps to keep the voltage at a stable value (1pu) which is equivalent to the control system reference voltage of 1pu. Stability in voltage translates to a stable power supply as shown in Fig 9.

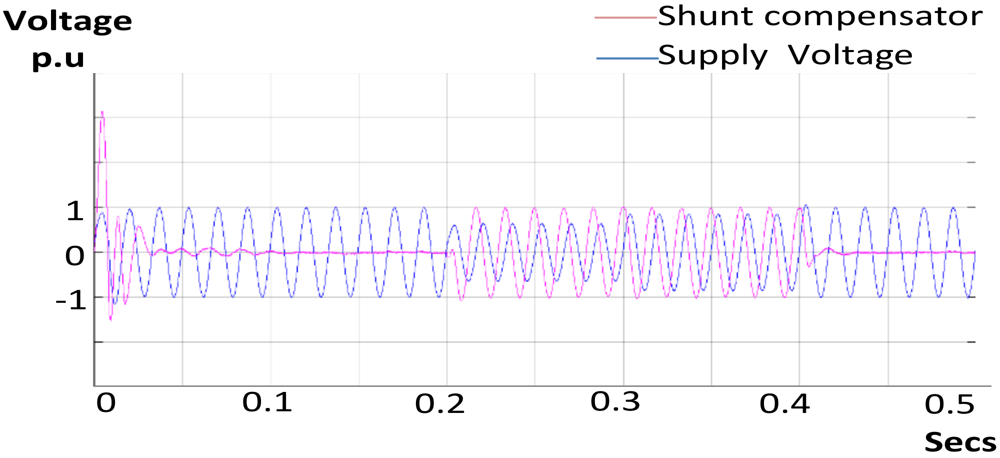

Fig. 8: Voltage supply with compensation

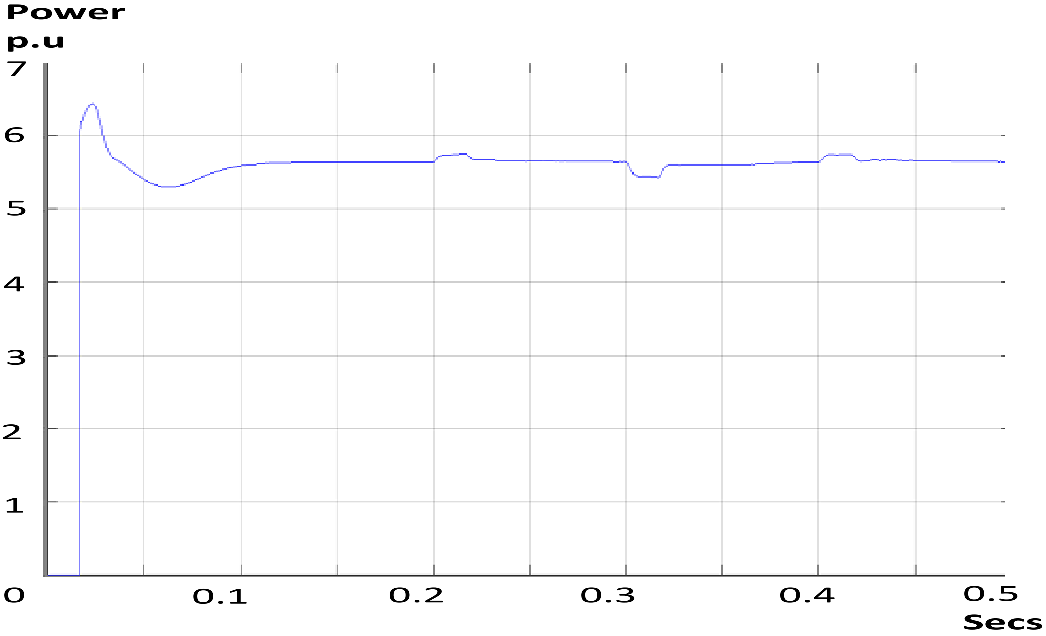

Fig. 9: Power supply with compensation

4. Conclusion

This study considered the design and simulation of a control system for a shunt compensator that will maintain a constant voltage magnitude and mitigate the dynamic imbalance in the system. The proposed control system makes use of a feedback control system, PI controllers, a phase lock loop (PLL), AC current and voltage controller, a DC voltage controller acting as both a rectifier and an inverter. All these features put together makes the shunt compensator respond to power quality issues swiftly and precisely. Results from simulations using daily voltage logs obtained from Choba substation and Rivers State University substation shows that the proposed control system is an effective integral part of the shunt compensator which generates a feedback signal for the pulse width modulation controlled IGBT electronics switching voltage source converter (VSC), injecting the appropriate amount of capacitive reactive current for the mitigation of under-voltage challenges in the distribution system. The results also indicate that the use of the shunt compensator for Choba and Rivers State University distribution network would help to a large extent maintain the voltage stability as well as improve the power quality of these networks.

References

Akil, A., Pramod, G. and Mohammad, S. (2015) Performance of DVR and Distribution STATCOM in Power Systems. International

Journal on Recent and Innovation Trends in Computing and Communication: 2321-8169.

Alassouola, H.M. (2018) Methods of Increasing the Quality and Reliability of Power FACTS System Using Devices: PhD Thesis. Create space Independent Publishing Platform.

Ambarnath, B., Sujit, K.B. and Bhim, S. (2012) Review of Static Compensation of Autonomous Systems. International Journal of Power Electronics and Drive System (IJPEDS), 2(1): 51-56.

Bhattacharya, K. and Zhong, J. (2001) Reactive power as an ancillary service. IEEE Transactions on Power systems, 16(2): 294-300.

Elby-Varghese, K.V. and Jayaprakash, P. (2016) Design and Analysis of DSTATCOM and Comparison of Various Control Algorithms. International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering, 3(1): 163-171

Hingorani, N.G. (1991) FACTS-flexible AC transmission system. In International Conference on AC and DC Power Transmission (pp. 1-7). IET.

Irinjila, K.K. and Jaya-Laxmi, A. (2010) Shunt versus Series compensation in the improvement of Power system Performance. International Journal of Applied Engineering Research, Dindigul, 1(3): 10 pages.

Kaur, S. and Nijhawan, P. (2016) Role of DSTATCOM in distribution network with non-linear and active loads, 7th India International Conference on Power Electronics (IICPE), Patiala, pp. 1-4.

Maxcy, D. (2013) What exactly is Power Quality. Power Protection Product, Inc. 877-393-1223, www.p3-inc.com.

Singh, B. and Solanki, J.A. (2009) Comparison of control algorithms for DSTATCOM. IEEE transactions on Industrial Electronics, 56(7): 2738-2745.

Sujata, D. and Himabindu, E. (2013) Voltage Sag Mitigation Analysis Using DSTATCOM Under Different Faults in Distribution System. International Journal of Emerging Trends in Electrical and Electronics, 9(1): 52-56.

Tembhurnikar, G., Chaudhari, A., Wani, N., Gajare, A. and Gajare, P. (2014) A review on reactive power compensation techniques using facts devices. International Journal of Engineering and Management Research, 4(1): 76-80.

Vijaysimha, N. and Suman, P.K.P. (2013) Shunt compensation on ehv transmission line. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, 2(6): 2452-2460.