EMPIRICAL
RESEARCH
PRESS

International Journal of
Engineering and Applied Computer Science

Volume: 04, Issue: 04, May 2022 ISBN: 9780995707545

Reactive Power Compensation and Harmonic Mitigation in Single-Phase Distribution System using Multilevel Converter Based D-STATCOM

Adeyemo I. A.[1], *Adegbola O. A.*[2], *Adebiyi O. W.*[3]
[1, 2, 3] Department of Electronic & Electrical Engineering, Ladoke Akintola University of Technology,
Oyo State, Nigeria.

doi 10.24032/IJEACS/0404/011

Empirical Research Press Ltd.
London, United Kingdom
www.ijeacs.com

International Journal of Engineering and Applied Computer Science (IJEACS)
Volume: 04, Issue: 04, ISBN: 9780995707545, May 2022

Reactive Power Compensation and Harmonic Mitigation in Single-Phase Distribution System using Multilevel Converter Based D-STATCOM

Abstract— **This paper presents a study of a single-phase cascaded H-bridge multilevel converter-based Distribution Static Synchronous Compensator (D-STATCOM) with active harmonic filtering capability. For the proper operation of the proposed D-STATCOM, a constant voltage is maintained at its DC bus link using a proportional and integral (PI) controller. Based on instantaneous current errors, gate pulses for controlling duty cycles of the D-STATCOM operation are generated using the hysteresis current control (HCC) technique. The proposed D-STATCOM was modeled and simulated in MATLAB. Simulation results show that the proposed method effectively compensates for reactive power and mitigates current harmonics. The proposed method offers structural simplicity and efficiency without complex calculations.**

Keywords- ***D-STATCOM, Active Harmonic Filter, PI controller, Hysteresis band current controller.***

I. INTRODUCTION

In traditional power systems, generation plants sited at remote locations due to proximity to energy sources are connected to load centres with long transmission lines. Power transmission over a long distance degrades the generated power resulting in power quality (PQ) problems such as harmonic distortion, power loss, and voltage fluctuations. The inclusion of distributed generation (DG) in the modern grid has also exacerbated the PQ problems. Sequel to the advances made in power electronic conversion and control systems over years, there is a widespread use of high-power switching devices in grid-connected power conditioning systems. These devices act like nonlinear loads that draw non-sinusoidal currents with the attendant power quality problems, which have deteriorating effects on electric power equipment [1]. The proliferation of inductive loads in homes and industries coupled with the large number of transformers used in transmission and distribution systems have also resulted in a tremendous burden on the power system. These inductive loads are nonlinear and the current drawn by them is lagging with respect to the voltage, which results in further degradation of the power quality of the grid [2].

Significant efforts are continually made to proffer solutions to the PQ problems in order to ensure power system improvement and stability. Presently, there are two ways of mitigating the PQ problems. The first approach to the mitigation of PQ problems is called the load conditioning technique and it is based on making the equipment more resistant to the power system disturbances. This approach facilitates the safe operation of equipment even when exposed to significant power disturbances. The second approach is based on the installation of line-conditioning systems that are capable of suppressing or counteracting the PQ problems [3]. The advent of high-speed solid-state electronic devices with high power handling capability has enabled the power industry to mitigate PQ problems using line-conditioning systems that incorporate Flexible AC Transmission Systems (FACTS) devices. These are power conditioning devices that are deployed in the AC transmission network for harmonic mitigation, power loss reduction, enhancement of the power transfer capability of the existing AC transmission lines, and active and reactive power control of the network [4].

Depending on how they are connected to the network, FACTS devices can be classified into two main types: series-connected compensators and shunt connected compensators [5, 6]. For reactive power compensation and harmonic mitigation in power systems, high-power thyristor-based controller called Static Var Compensator (SVC) and power electronic controller called Static synchronous Compensator (STATCOM) are presently the leading shunt compensation devices used for rapid injection of reactive power. In SVC, reactive power compensation is provided by controlling the reactance connected in parallel to the system using the thyristor's firing angle. STATCOM on the other hand uses an inverter for the conversion of DC voltage at its input to a controllable AC voltage at its output. However, STATCOM is preferred to SVC due to its faster response, low harmonic distortion, and ability to provide better reactive power under the same condition and compensation capacity [7].

Although STATCOM is a shunt-connected controller originally designed for reactive power compensation on the transmission grid, this compensator is increasingly used in distribution networks for power factor correction, voltage regulation, and active harmonic filtering. In contrast to transmission systems, distribution networks suffer from harmonic distortion due to the connection of nonlinear loads, voltage imbalances resulting from the unbalanced load connection, transformer overloading, and failure, short circuits in the coils of inductive loads, etc. The STATCOM used in distribution systems is called Distribution-Static Synchronous Compensator (D-STATCOM) [4, 8]. D-STATCOM is a voltage source inverter (VSI) based custom power device that is shunt-connected at its point of common coupling (PCC). D-STATCOM ensures power quality improvement by mitigating harmonics, balancing source currents for unbalanced load, and providing compensation for reactive power loss.

Low voltage single-phase inductive loads such as adjustable speed drive-fed motors, conveyors, pumping machines, air conditioners, welding equipment, etc. are widely used in distribution systems. Such loads draw non-sinusoidal current with the attendant problems of reactive power loss and harmonic distortion. To mitigate harmonic distortion, active harmonic filtering technology is widely used in industrial and commercial applications where high-power quality is desired. When deployed for active harmonic filtering, D-STATCOM acts as a shunt connected current source that provides a compensating current with harmonics of equal magnitude but opposite phase angle to the existing load harmonics, thus canceling them out. By injecting a compensating current with nonlinearities opposite to the load nonlinearities at the PCC, the harmonics contained in the injected compensating current cancel out the load current harmonics such that a purely sinusoidal current is drawn from the source. D-STATCOM operated as an active harmonic filter (AHFs) are very fast, and are thus reliable for rapidly varying or unbalanced loads and also for systems with high harmonics.

II. MULTILEVEL CONVERTER BASED D-STATCOM

The multilevel voltage source converter (VSC) contained in D-STATCOM is a bidirectional converter that operates as an inverter when supplying the compensating voltage to load, and as a rectifier when charging the DC capacitor. For the inverter operation, a DC capacitor maintains a constant DC voltage at the input of the VSC while an interfacing inductor connects the synthesized output AC voltage of the VSC to the power system at the PCC [2, 8, 9]. The DC capacitor voltage is kept constant at the required value by proper monitoring and adjustment of the active component of the compensating current injected by the D-STATCOM. The average active power in the system is controlled to be zero. However, in some applications where active power compensation is required for a short time, the DC capacitor can be replaced by an energy storage system such as a superconducting magnetic energy system (SMES), ultra-capacitor, battery, etc. [4]. The block diagram of the proposed single-phase D-STATCOM is shown in Figure 1, where V_s is the system voltage, R_s and L_s are the source resistance and inductance, respectively, are L_f is the interfacing inductor, and C_{dc} is the storage capacitor.

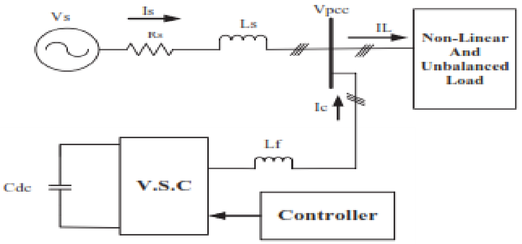


Figure 1. Single-phase D-STATCOM system

In accordance with Kirchhoff's current law, the algebraic sum of the compensating current injected by the D-STATCOM (i_C), the source current (i_S), and the load current (i_L) at PCC is zero, and the expression can be written as:

$$i_S = i_L - i_C \tag{1}$$

Nonlinear load current (i_L) can be resolved into its fundamental component, $i_{L,1}$ and harmonic component, $i_{L,h}$ as follows:

$$i_L = i_{L,1} + i_{L,h} \tag{2}$$

Thus, the compensating current that will be injected by the D-STATCOM is only the harmonic component of the load current which can be expressed as:

$$i_C = i_{L,h} \tag{3}$$

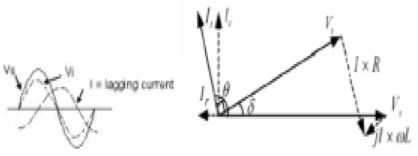
After connecting D-STATCOM, the compensated current that will be drawn from the power supply by the nonlinear load is given by:

$$i_S = i_L - i_C = i_{L,1} + i_{L,h} - i_{L,h} = i_{L,1} \tag{4}$$

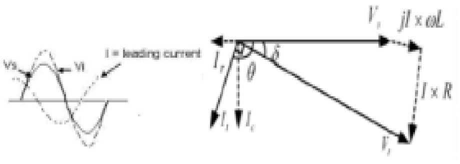
Consequently, the load current that is drawn from the source contains only the fundamental component while the harmonic component is filtered out.

A. *D-STATCOM Operation*

The operation of D-STATCOM is based on the comparison of a controllable output voltage (V_i) of the VSC with the system voltage (V_s), and there are two modes of operation: inductive mode and capacitive mode. The operating modes of D-STATCOM and their respective voltage phasor diagram at the PCC are shown in Figure 2. The phase angle between V_i and V_s is denoted by δ.



(a) Inductive mode



(b) Capacitive mode

Figure 2. Operating modes of D-STATCOM

When both V_i and V_s are equal in magnitude and phase, the D-STATCOM remains inactive as it neither generates nor absorbs reactive power. When V_i is less than V_s, D-STATCOM operates in the inductive mode by acting as a variable inductive load that draws a current (I_C) lagging the system voltage such that reactive power is absorbed. However, when V_i is higher than V_s, D-STACOM operates in the capacitive mode by behaving like a capacitive load with current (I_C) leading the system voltage, and reactive power is generated [4, 8]. It is noteworthy that the use of D-STATCOM for voltage regulation and power factor correction are mutually exclusive. When a D-STATCOM is used for power factor correction, the supply currents and supply voltages are required to be in phase while the supply currents are required to lead the supply voltages when it is deployed for voltage regulation [8]. In this work, the adopted control strategies are geared towards voltage regulation and active harmonic filtering operation of D-STATCOM.

B. Cascaded H-Bridge Multilevel Inverter

Several multilevel converter topologies and modulation techniques have been developed to overcome the limits of semiconductor switches. The most commonly used multilevel inverter (MLI) topology in industries is cascaded H-bridge (CHB) due to its circuit layout flexibility, modularity, and fewer components requirements that make it suitable for many applications [10, 11]. Another advantage is that the number of output voltage levels in CHB multilevel inverter can easily be increased by having more H- bridges connected in cascade.

In CHB multilevel inverter, an almost sinusoidal output voltage is synthesized from several dc input voltages. Each H-bridge of the CHB multilevel inverter comprises of a separate DC source (SDCS) and four unidirectional switches with only two switches in the on-state at a time. The possible switching states of the H-bridge and corresponding output voltage are shown in Table I.

TABLE I. H-BRIDGE SWITCHING STATES AND OUTPUT VOLTAGE

On-state	Off-state	Output voltage
S_1 and S_4	S_2 and S_3	$+V_{dc}$
S_2 and S_3	S_1 and S_4	$-V_{dc}$
S_1 and S_2	S_3 and S_4	0
S_3 and S_4	S_1 and S_2	0

The synthesized output voltage of the CHB multilevel inverter is the summation of square wave voltages from the H-bridge cells with each cell having a different duty cycle [12, 13]. For an n-level inverter, the number of H-bridges that are required to be connected in cascade per phase is given by:

$$s = \frac{n-1}{2} \qquad (5)$$

Thus, for the proposed CHB 5-level converter-based STATCOM, S = 2.

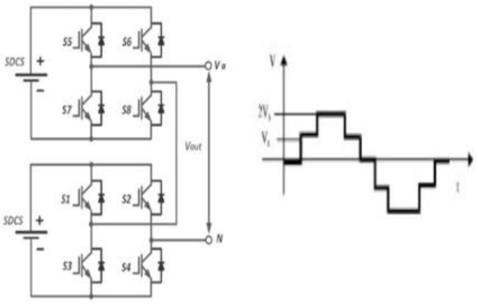


Figure 3. Cascaded H-bridge 5-level converter and its waveform

III. CONTROL STRATEGY

The quality of synthesized output voltage of a multilevel converter system is largely dependent on the choice of the control strategy. Several pulse width modulation (PWM) techniques previously used for the control of two-level inverters are increasingly modified and used for the control of multilevel inverters. For the voltage regulation and active harmonic filtering operation of D-STATCOM, current-mode control PWM is preferred to the conventional voltage-mode control PWM techniques due to its several advantages such as simple implementation, fast response, and excellent dynamic characteristics and robustness against parameter variations and nonlinearities of an unbalanced load.

A. DC Link Voltage Regulation

For a proper operation of D-STATCOM, the capacitor voltage at the DC-link must be kept constant. This is achieved with a proportional and integral (PI) feedback controller, which generates the reference compensating current that is required to keep the DC-link voltage constant. The proportional component of the PI controller maintains the desired set point and adjusts the controller whenever there is deviation while the integral component removes the steady-state error and improves the steady-state response. The input signal to the PI controller is an error signal obtained from the comparison of the DC capacitor voltage V_{dc} with a reference DC-link voltage V_{dc_ref}. The error signal is processed by the PI controller to determine the inverter losses as well as the compensating current required to maintain V_{dc} at a constant value, which invariably compensates for the VSC losses [4, 14]. The rule of thumb for choosing the reference DC-link voltage value is that it should be higher than the system voltage V_s in magnitude [14]. A general block diagram depicting the operating principle of the PI controller is shown in Figure 4, where k_p is the proportional gain and k_i is the integral gain of the PI controller.

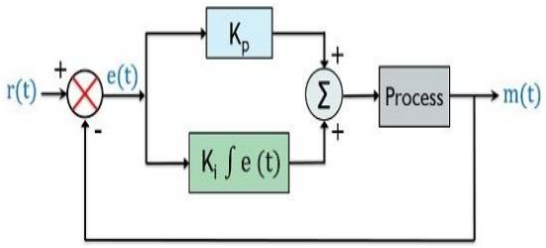


Figure 4. PI controller

B. Hysteresis Band Current Controller

It deals with the control of the compensating current at the PCC in such a way that the compensating current injected by the D-STATCOM is the same as the generated reference value. Hysteresis band current controller is a closed-loop control system in which an error signal, e(t) obtained from the comparison of the estimated reference compensating current $I_{ref}(t)$ and the compensating current injected by the inverter $I_c(t)$ is used to generate the gate pulses that control the switching operation of the inverter [15]. By controlling the inverter output voltage, compensating current of desired amplitude and phase is dynamically injected at the PCC resulting in reactive power compensation and active harmonic filtering. As shown in Figure 5, the error signal is confined within the specified limits and the inverter IGBT switches are controlled to vary the current according to the variation in the signal error [14].

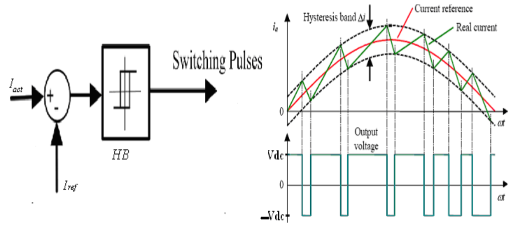


Figure 5. **Hysteresis Band Current Control and Switching Logic**

IV. SIMULATION RESULTS AND DISCUSSION

As shown in Figure 6, the proposed single-phase D-STATCOM was designed, modeled, and simulated in MATLAB/Simulink environment using the adopted control strategy:

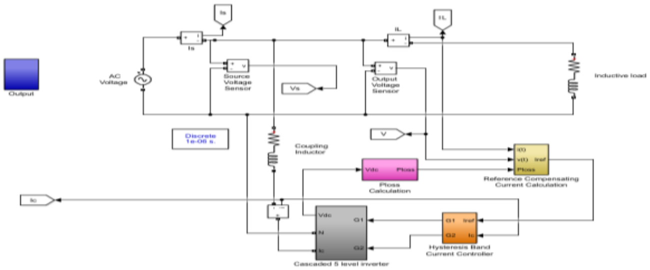


Figure 6. **Model structure of the proposed D-STATCOM**

The system parameters used for performing the simulations are as follows: System voltage $V_s = 220\ V$, frequency = $50Hz$, dc capacitor voltage $V_{c1} = V_{c2} = 400V$, capacitance $C_1 = C_2 = 4700\mu$F, coupling Inductor and its internal resistance: R = 1Ω, L = 60mH, inductive load: R=50 Ω , L= 800mH. The proportional gain k_p and integral gain k_i of the PI controller are chosen as 0.5 and 1.3, respectively.

A. Results Before Compensation

When the D-STATCOM is unconnected in the circuit, the source current shown in Figure 7 is the same as the distorted and non-sinusoidal load current.

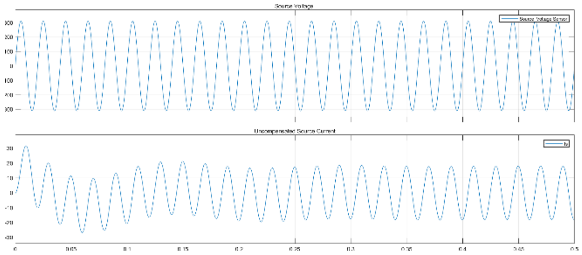


Figure 7. **Source voltage and uncompensated current waveforms**

Shown in Figure 8 is the harmonic spectrum of the distorted source current obtained with the Fast Fourier Transform (FFT) block in MATLAB/Simulink. The source current has a Total Harmonic Distortion (THD) value of 13.67%, which is more than the maximum current distortion limit specified by IEEE-519-2014 and IEC 61000-4-7 standards.

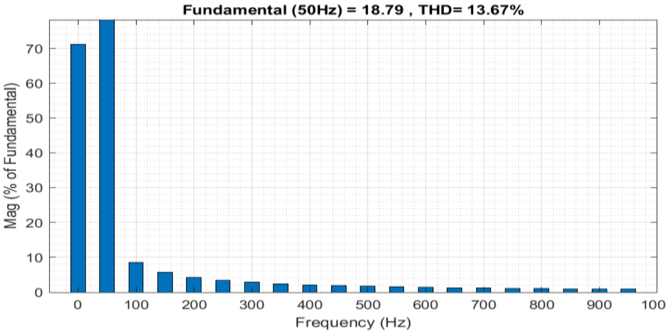


Figure 8. **Harmonic spectrum of the distorted and non-sinusoidal source current**

Figure 9 shows the real and reactive power waveforms prior to compensation.

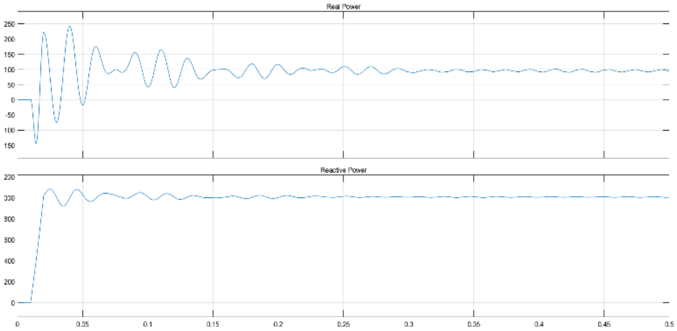


Figure 9. **Real and reactive power waveforms prior to compensation**

With the connection of the D-STATCOM, a compensating current with nonlinearities opposite to the load nonlinearities is injected at the PCC as shown in Figure 10. The harmonics contained in the injected compensating current cancel out the load current harmonics such that a compensated and purely sinusoidal current is drawn from the source as shown in Figure 11.

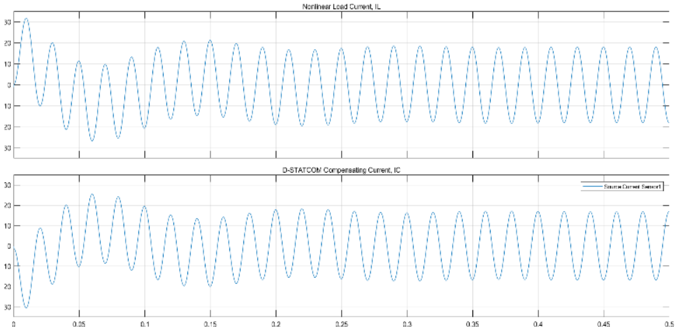


Figure 10. **Waveforms of the load current and D-STATCOM compensating current**

B. Results After Compensation

As shown in Figure 11, both the source voltage and compensated current drawn from the source are undistorted and sinusoidal.

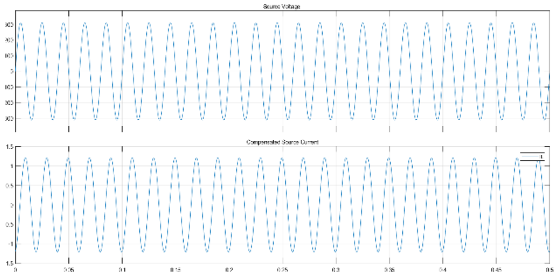


Figure 11. Waveforms of the source voltage and compensated source current

Sequel to the active harmonic filtering operation of the D-STACOM, Figure 12 shows that the current drawn from the source is undistorted and sinusoidal with a well attenuated harmonic content.

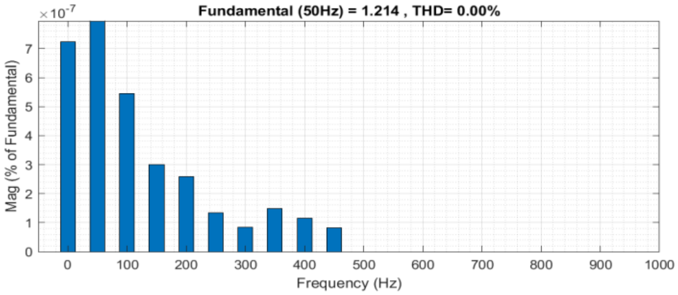


Figure 12. Harmonic spectrum of the compensated current

Figure 13 shows the waveforms of the real and reactive power after compensation.

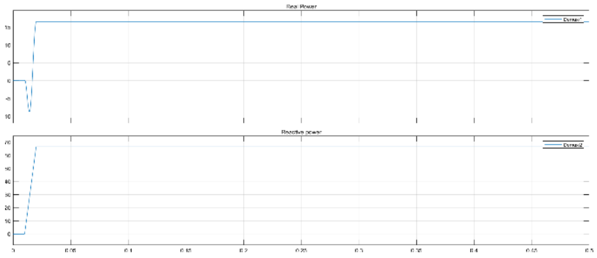


Figure 13. Waveforms of the real and reactive power after compensation

V. CONCLUSION

A multilevel VSC-based D-STATCOM proposed as an active harmonic filter in a single-phase distribution system is presented in this study. The reactive power compensation and harmonic mitigation capabilities of the proposed D-STATCOM have been successfully demonstrated by simulating a single-phase distribution system under distorted supply conditions in the MATLAB/Simulink environment. Simulation results show that the proposed D-STATCOM effectively improves power quality and completely eliminates current harmonics.

REFERENCES

[1] S. S. Babu, R. Elangovan and S. Ezhilarasan, “Multilevel Inverter Based Statcom for Reactive Power Compensation and Harmonic Mitigation by using SRF/MCPWM in Distribution Network,” International Journal of Pure and Applied Mathematics, volume 119 no. 12, pp. 2061-2071, 2018.

[2] S. S. Pawar, A. P. Deshpande and M. Murali, “Modelling and Simulation of DSTATCOM for Power Quality Improvement in Distribution System using MATLAB Simulink Tool,” International Conference on Energy Systems and Applications, pp. 224 -227, Nov, 2015.

[3] V. Ramesh1, B. Haritha, P. R. Sulthanav and M. D. Reddy, “An Adaptive Hysteresis Band Current Controlled Shunt Active Power Filter,” International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 3, Issue 3, pp. 8031-8040, March 2014.

[4] J. Ekanayake, k. Liyanage, J. Wu, A. Yokohama andN. Jenkins, Smart Grid: Technology and Applications, First Edition 2012 Published by John Wiley and Sons Ltd.

[5] M. Patel, D. S. Patel, M. J. Chapadiya; K. K. Naik and; B. K. Patel, “Reactive Power Compensation using STATCOM,” International Research Journal of Engineering and Technology (IRJET), Vol. 04, Issue 04, pp. 564 – 567, Apr. 2017

[6] R. Nedumaran and P. S. Kumar, “A Control Scheme of Cascaded Multilevel Inverter Based D-STATCOM for Improving the Voltage Control and Reduce Total Harmonics Distortion,” International Journal of Science and Research (IJSR), Vol. 4, Issue 3, pp. 1260 - 1266, March 2015

[7] M. Ayala-Chauvin, B. S. Kavrakov, J. Buele and J. Varela-Aldás, “Static Reactive Power Compensator Design, Based on Three-Phase Voltage Converter”, Energies, 14, 2198. https:// doi.org/10.3390/en14082198, 2021.

[8] B. Sunil and M. Rosaiah, “Power Quality Improvement using Single Phase D-STATCOM in Wind,” International Journal of Advanced Technology and Innovative Research, Vol. 7, Issue 8, pp. 1452 – 1456, July 2015.

[9] D. Uma, K. Vijayarekha and S. Manikandan, “Implementation of Cascaded Multilevel Inverter with Bidirectional Switches for STATCOM,” Journal of Applied Sciences, vol.14, Issue 14, pp. 1582-1587, 2014.

[10] J. Rodríguez, J. Lai, F. Peng, “Multilevel inverters: a survey of topologies, controls and applications,” IEEE Transactions on Industry Applications, vol. 49, no. 4, pp. 724-738, Aug. 2002.

[11] S. Khomfoi, L. M Tolbert, Chapter31. Multilevel Power Converters. The University of Tennessee. pp.31-1 to 31-50.

[12] J. Kumar, B. Das, and P. Agarwal, “Selective Harmonic Elimination Technique for Inverter,’’ 15th National Power System Conference (NPSC), IIT Bombay, Multilevel pp. 608-613, 2008.

[13] J. Chiasson, L. M. Tolbert, K. McKenzie, and Z. Du, “Elimination of Harmonics in a Multilevel Converter using the Theory of Symmetric Polynomial and Resultant,’’ Proceedings of the 42nd IEEE Conference on Decision and Control, pp. 216-223, Dec. 2005.

[14] M. K. Rathi, “A Hysteresis Current Controller based DSTATCOM for Power-Quality Improvement,’’ International Journal of Pure and Applied Mathematics, Vol. 120, No. 6, pp. 1257-1271, Nov. 2018.

[15] V. Ramesh, B. Haritha, P. R. Sulthana and M. D. Reddy, “An Adaptive Hysteresis Band Current Controlled Shunt Active Power Filter,” International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 3, Issue 3, pp. 8031 – 8040, March 2014. K. Elissa, “Title of paper if known,” unpublished.