Journal of Engineering Science and Technology
Special Issue on ICIT2022 Vol. 18, No. 6 (2023) 48 - 57

CASCADED H-BRIDGE MULTILEVEL INVERTER BASED D-STATCOM USING GOERTZEL ALGORITHM

A. SURESH[1,*], M. R. RASHMI[1], T. SASILATHA[1],
R. RAJAVEL[1], S. PRIYA[1], S. SATISH KUMAR[1], HOONG-PIN LEE[2]

[1]AMET Deemed to be University, Chennai, India
Amrita School of Engineering, Bengaluru, Amrita Vishwa Vidyapeetham, India
[2]Faculty of Engineering and Quantity Surveying, INTI International University, Persiaran Perdana BBN, Putra Nilai, Negeri Sembilan, Malaysia
Corresponding Author: asuresh@ametuniv.ac.in

Abstract

Voltage sag is the major power quality issue in modern power systems. The presence of power converters for various industrial and domestic power control applications introduces voltage sag, which adversely affects the performance of all the equipment connected to the power system. Distributed Static Compensator (D-STATCOM) is an efficient custom power device to overcome this issue. Its advantages include fast dynamic response and power factor correction. D-STATCOMS can mitigate the load harmonics and also, they can prevent the load harmonics flowing into the source. This will also prevent from point of common coupling voltage degrading. The performance of D-STATCOM depends on the accuracy of sag detection. This paper presents a two-level inverter and seven-level Cascaded H-Bridge Multilevel Inverter (CHBMLI) based D-STATCOM with Goertzel Algorithm for accurate sag detection. Application of the Goertzel algorithm helps in finding the fundamental voltage component in such a way that the compensation happens during sag alone. The simulation results, showing the extraction of the fundamental component using the Goertzel algorithm are presented in this paper.

Keywords: Cascaded H-bridge, Distributed static compensator (D-STATCOM), Fundamental component detection, Goertzel algorithm, Multilevel inverter, Power efficiency, Power quality, Voltage sag.

1. Introduction

The Power system operation and control need more attention because of voltage instability. Power quality problems are becoming a serious concern with the ever-increasing utilization and higher loading of existing transmission systems, particularly with increasing energy demands, and competitive generation and supply requirements. Under heavy load conditions, a significant voltage drop may occur in the system. Voltage sags can occur at any instant of time, with amplitudes ranging from 10-90% and duration lasting for half a cycle to one minute [1]. There are several ways to mitigate voltage dips, swell, and interruptions in transmission and distribution systems. At present, a wide range of very flexible controllers which capitalize on newly available power electronics components are emerging for custom power applications [2]. Among these STATCOM is the most effective device. DSTATCOM have the ability to generate the rated current at virtually any network voltage, therefore they have a better dynamic response.

An effective control method is essential for the good dynamic performance of STATCOMs. The voltage or current feedback is taken to generate the pulses for the inverter switches. The inverters can be voltage controlled or current-controlled. Voltage-controlled voltage source inverters are very widely used. The voltage source inverter controls the output voltage as set by the reference. The control loop is based on the dc quantities whereas, the ac voltage of the inverter is a time-varying value, Therefore, this control mode requires a conversion of the time-varying values to fixed values.

There are several methods for conversion, depending on the required parameters to be controlled. The PQ or d-q method will provide active-reactive power and direct-quadratic voltage components. The voltage control mode requires a complex control for gate drive and switching. These gate drive control methods are generally divided into two main categories; which are carrier-based and Space Vector Modulation (SVM) techniques. The other control approach is the current control method which does not require complex gate control. This method is utilized in the cases where the converter current is of great importance. This method suits D-STATCOM applications since it is also based on controlling the current that is injected into the grid [3].

Voltage sag detection plays an important part in measuring and improving power quality. It is necessary for the control system to not only detect the start and end of a voltage sag but also to determine the sag depth and any associated phase shift. Many methods have been proposed to determine the voltage amplitude. The three main considerations when selecting the suitable method are the response time, implementation complexity, and accuracy. Peak value detection is one of the latest approaches to detect voltage amplitude. There are two approaches to find the peak value. One is to find the voltage gradient for each sample and the peak voltage is the voltage level when the gradient is zero [4].

The other method is by finding the maximum absolute voltage. In this method, the maximum of the absolute value of the voltage over the preceding half cycle is calculated [5]. The drawback of this method is that it takes up to half cycle for the sag depth information before the value is calculated. It may also be affected by noise and harmonics. To improve peak value detection, a new approach was proposed in [6], based on peak value detection by 900 shifting of the instantaneous voltage value. Voltage sag detection based on synchronously rotating reference frame was proposed in [7] for a 1φ system.

In this approach, a differentiator was used orthogonal phase shifter to generate orthogonal ac voltage from grid voltage information. These two voltages are passed through Park's transformation to get dc voltages. The dc voltages were used for generating the sag signals. The voltage sag can be recognized by this approach in a very short time in every condition of voltage sags.

Another recent approach is the Least Squares Method. In this method, the main harmonic of the grid is determined by finding the coefficients of Fourier transform which makes the error between the Fourier series and the actual data minimum. The least-square technique possesses simplicity and robustness. Owing to these features the power system harmonic estimation can be improved by this method [8] and it is used in power quality monitoring. This process is usually done by matrix manipulation, and it requires extensive calculations. So, it is not suitable for practical online applications. In order to overcome this drawback an efficient least square method is proposed in [9].

This approach extracts the active and reactive parts of the positive- and negative-sequence components for generating reference values of current that need to be injected into the point of connection D-STATCOM in order to compensate for the voltage errors. Model predictive control with finite control set for D-STATCOM was proposed in [10]. Using this algorithm, it was possible to improve voltage stability and was also possible to track the current simultaneously.

In [11-13], fixed frequency current controllers were used to mitigate voltage sag and reduce the harmonic contents in the output current. A sag detection method based on Goertzel algorithm was introduced.

This paper presents the implementation of D-STATCOM using two level inverter and seven level cascaded H-bridge inverter. Differently Evolution with space vector pulse width modulation was proposed in [14-16] in order to reduce the harmonics in STATCOM. Goertzel algorithm-based implementation is presented in this paper.

2. Goertzel Algorithm

The Goertzel algorithm is a digital signal processing technique that provides a mean for efficient evaluation of individual terms of the discrete Fourier transform. Goertzel algorithm is suitable for applications where only a few points in the frequency spectrum are required. Compared to a direct N-point DFT calculation. This algorithm uses half the number of real multiplications, the same number of real additions, and requires approximately 1/N the number of trigonometric evaluations. Since the algorithm processes samples in time domain, it allows the application to begin when the first sample arrives. In contrast, the DFT must have the entire frame in order to start the calculation. This algorithm requires N real multiplication and 2N real addition and 2 trigonometric evaluations. The transfer function for Goertzel algorithm is given by equation (1) and the state flow diagram is shown in Fig. 1.

$$H_k(z) = \frac{1-W^k{}_N z^{-1}}{1-2cos\left(\frac{2\pi k}{N}\right)z^{-1}+z^{-2}} \quad (1)$$

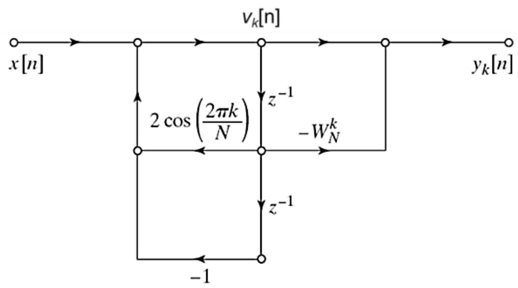


Fig. 1. Goertzel algorithm state flow diagram.

It only needed to bring the system to a state from which $y_k[n]$ can be computed, the complex multiplication by $-W_n^k$ required to implement the zero of the system need not be performed at every iteration but only after the Nth iteration by the difference equation (2).

$$v_k[n] = x[n] + 2\,cos\left(\frac{2\pi k}{N}\right) v_k[n-1] - v_k[n-2] \quad (2)$$

where $0 \le k \le N$.

It requires two real multiplications and four real additions to compute $v_k[n]$. The multiplication by is performed only when n=N, which requires four real multiplication and four real addition. Finally, a total of 2N+4 real multiplication and 4N+4 real additions are required. To compute all the X[k], k = 0….., N-1, it needed 2N(N+2) real multiplication and 4N(N+1) real addition where the number of multiplications are reduced almost half.

Goertzel algorithm is usually used to compute X[k] for which only a single k or a small number of k values are needed. Like DFT, the Goertzel algorithm analyses one selectable frequency component from a discrete signal. Unlike direct DFT calculation the Goertzel algorithm applies a single real valued arithmetic for real valued input sequences. The simple structure of the Goertzel algorithm makes it well suited to small processor and embedded applications.

3. D-STATCOM Description

The block diagram of D-STATCOM is shown in Fig. 2. The load is connected to grid. To visualize the effect of nonlinear load on voltage, a transformer is connected. This coupling transformer connects the Inverter to the grid when there is a dip in supply voltage. The inverter may be a conventional two-level inverter or seven level CHBMLI.

Control scheme is shown in Fig. 3. The instantaneous load voltage is sensed using voltage sensor and this voltage is converters to discrete signal and Goertzel algorithm is applied to get the magnitude of fundamental component. This fundamental component of voltage is compared with the supply voltage peak. A Phase locked loop is used to extract the peak of the supply. These two voltages are fed to a comparator. The error voltage is used to produce the pulses for the inverter. At this instant a relay is energized to connect the inverter to the grid. A zero-crossing detector is used to synchronize the inverter voltage with the grid supply.

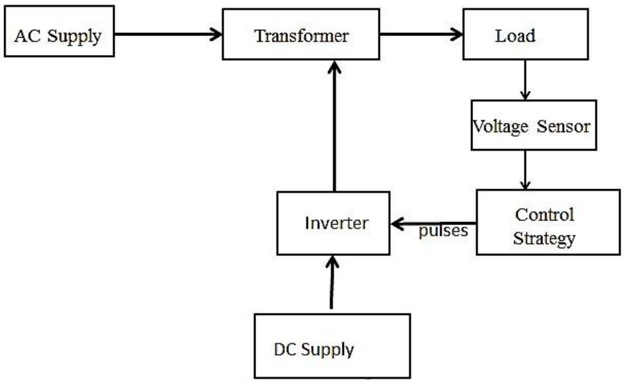


Fig. 2. Block diagram of D-STATCOM.

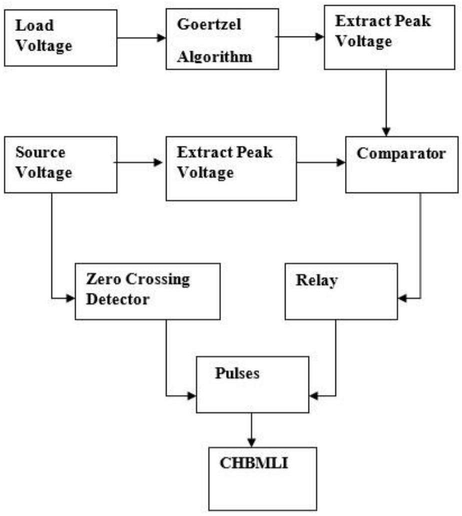


Fig. 3. Block diagram of control scheme.

4. Simulation Analysis and Results

The simulation is carried out in MATLAB/Simulink platform. The specifications are listed in Table 1. Rectifier fed R load is considered. The voltage sag is created by connecting additional RL load along with the existing load. The supply voltage before introducing additional load is shown in Fig. 4. RL load is introduced from 0.3 to 0.8 sec. The transformer secondary voltage is shown in Fig. 5.

Table 1. Specifications.

Parameter	Values
Supply Voltage	230 V
Supply Frequency	50 Hz
Coupling Transformer	Turns Ratio 1:1
DC Link Voltage	230 V
R Load	200 Ω
Additional RL Load	100 Ω and 3μH

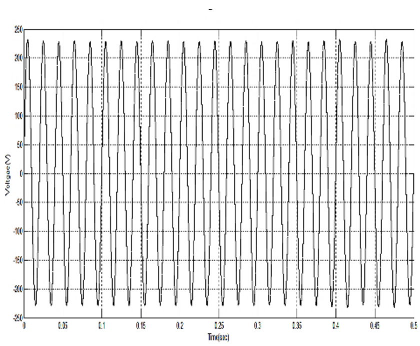


Fig. 4. Input voltage.

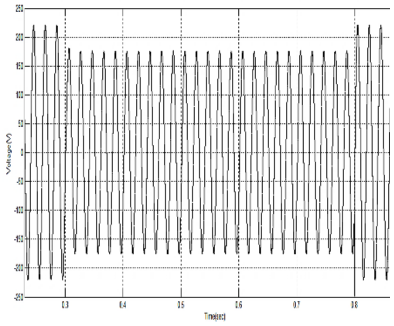


Fig. 5. Transformer secondary voltage.

As observed from Fig. 5, from 0.3 secs to 0.8 secs, there is a dip in the transformer secondary voltage. The rectifier bridge is connected across the transformer secondary. Therefore, the load voltage is also reduced. To compensate for this voltage sag, an inverter is connected to the grid through coupling transformer. This inverter is supplied from a battery.

Goertzel algorithm is applied to extract the fundamental voltage. The Simulink model for this algorithm is shown in Fig. 6. Figure 7 indicates the output extracted after applying this algorithm. The algorithm extracts the fundamental component from the load voltage.

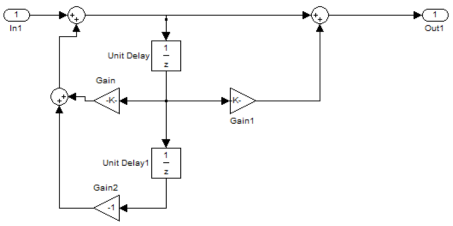


Fig. 6. Simulink model for Goertzel algorithm

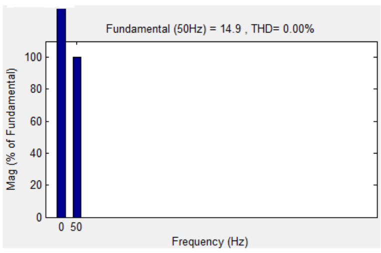


Fig. 7. FFT spectra extracted from the algorithm

4.1. Two level inverter based D-STATCOM

The Simulink model of the two level inverter D-STATCOM is shown in Fig. 8. Figure 9 shows the inverter output. From Fig. 9, it is observed that, inverter gives the output voltage only during voltage sag. Figure 10 shows the transformer secondary side voltage after compensation by using two level inverter. From Fig. 10, it is observed that the voltage sag (0.3 sec.-0.8 sec) is compensated using D-STATCOM. The FFT analysis of the transformer secondary voltage was carried out and the FFT spectrum is shown in Fig. 11. It is observed that the total harmonic distortion in the transformer secondary voltage is 36.7%.

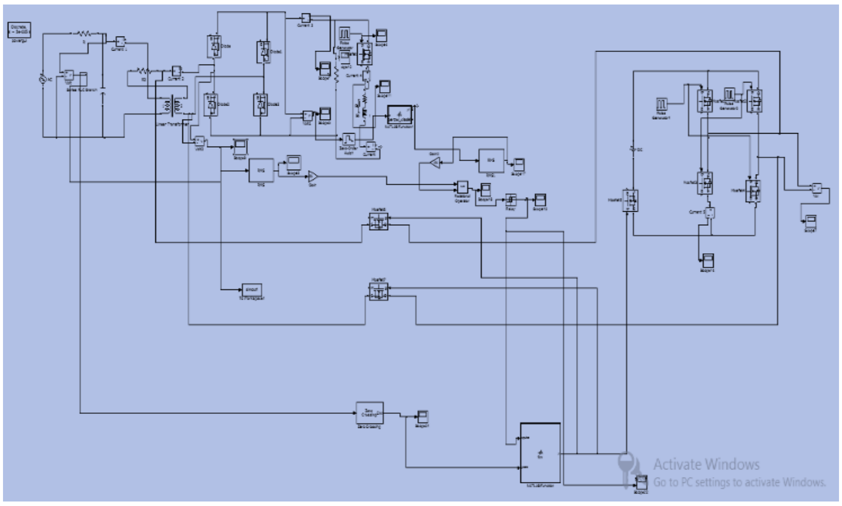


Fig. 8. Simulink model for two level inverter based DSTATCOM.

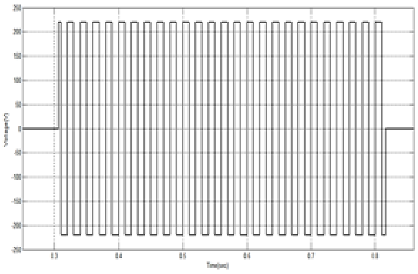


Fig. 9. Inverter output voltage (0.3-0.8 s).

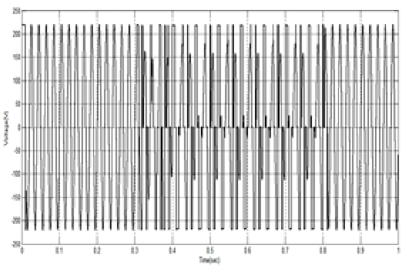


Fig. 10. Transformer secondary voltage.

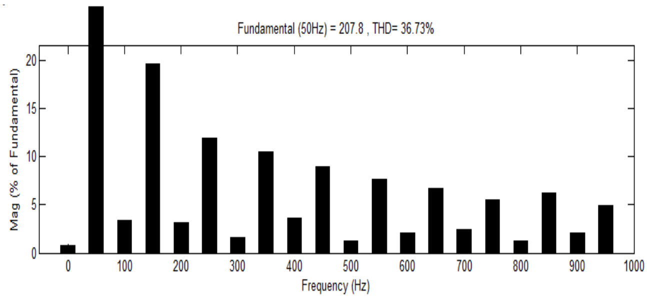


Fig. 11. FFT spectra of transformer secondary voltage after compensation.

4.2. Seven level cascaded multilevel inverter based D-STATCOM

The proposed seven level CHBMLI with minimum number of switches is shown in Fig. 12. This topology consists of six power switches: Sa, Sb, SL1, SL2, SR1, SR2 and two DC voltage sources. Asymmetric cascaded H-bridge inverter is considered because a greater number of levels in output voltage can be obtained with reduced number of switches and few voltage sources. This helps in reducing the switching complexities as well.

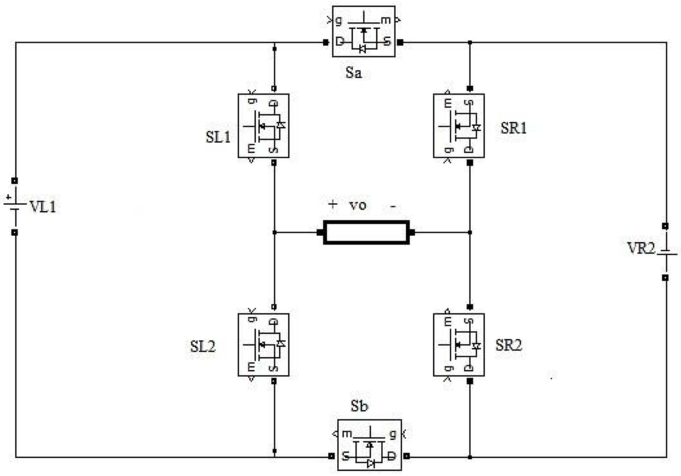


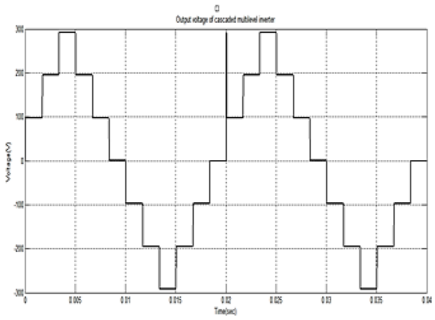
Fig. 12. Cascaded H-bridge multilevel inverter topology.

Unequal DC source voltages are considered to generate more levels with a smaller number of voltage sources. The magnitudes of dc voltage source are: $V_{L1} = V_{dc}$, $V_{R2} = 2V_{dc}$. Table 2 shows the switching state for seven level cascaded multilevel inverter.

The multilevel was simulated for 7 levels of output voltage with a 300 V dc source. The output voltage of CHBMLI is shown in Fig. 13. The inverter output voltage which appears only during sag is shown in Fig. 14. The transformer secondary voltage is shown in Fig. 15. The FFT spectrum of the secondary voltage is shown in Fig. 16. The THD is found to be 22.46%. This THD can be further brought down using LC filter or LCL filters or harmonic filter.

Table 2. Switching pattern for seven level cascaded multilevel inverter.

S_{L1}	S_{L2}	S_{R1}	S_{R2}	S_a	S_b	v_o
1	0	0	1	0	1	V_{L1}
1	0	0	1	1	0	-V_{R2}
1	0	1	0	0	1	V_{L1}+V_{R2}
0	1	0	1	0	1	0
0	1	1	0	1	0	-V_{L1}
0	1	1	0	0	1	V_{R2}
0	1	0	1	1	0	-(V_{L1}+V_{R2})



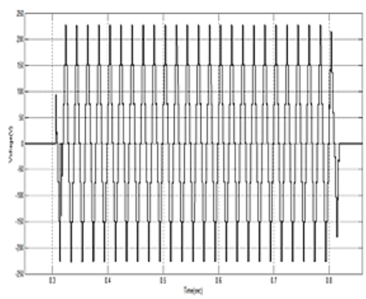


Fig. 13. Output voltage of CHBMLI. **Fig. 14. MLI output voltage.**

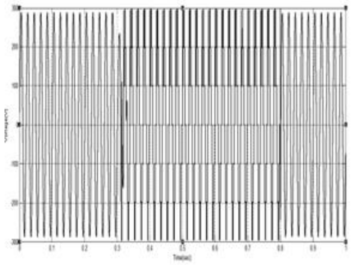


Fig. 15. Transformer Secondary voltage with CHBMLI D-STATCOM

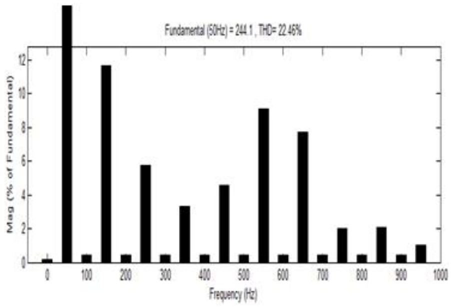


Fig. 16. FFT spectra after compensation

5. Conclusion

A simple control algorithm using Goertzel algorithm was presented to compensate for the voltage dip due to non-linear loads. Two level inverter and seven level CHBMLI based D-STATCOMs were analysed. An improved performance is obtained by using CHBMLI. Further the work can be extended to investigate on voltage sag during transformer faults such as interturn short circuit fault and during starting of induction motors.

Abbreviations	
CHBMLI	Cascaded H-Bridge Multilevel Inverter
D-STATCOM	Distributed Static Compensator
MLI	Multilevel Inverter

References

1. Padiyar, K.R. (2007). *FACTs controllers in power transmission and distribution*. New age international (P) Ltd publishers.
2. Hingorani, N.G.; and Gyugyi, L. (1999).*Understanding FACTS: Concepts and technology of flexible AC Transmission systems*. John Wiley& Sons Inc.
3. Chiang, H.-K.; Lin, B.-R.; Yang, K.-T.; and Yang, C.-C. (2005). Analysis and implementation of a NPC-based DSTATCOM under the abnormal voltage conditions. *Proceedings of the 2005 IEEE International Conference on Industrial Technology*. Hong Kong, China, 665-670.
4. Fitzer, C.; Barnes; M.; and Green, P. (2004). Voltage sag detection technique for a dynamic voltage restorer. *IEEE Transactions on Industry Applications,* 40(1), 203-212.
5. Naidoo; and Pillay, P. (2007). A new method of voltage sag and swell detection. *IEEE Transactions on Power Delivery,* 22(2), 1056-1063.
6. Ding, K.; Cheng, K.W.E.; Xue X.D.; Che, Y.B.; Wang, D.H.; and Dong, P. (2006). A novel detection method for voltage sags. *Proceedings of the 2006*

2nd International Conference on Power Electronics Systems and Applications, Hong Kong, China, 250-255.

7. Sillapawicharn, Y. (2014). A fast single-phase voltage sag detection for voltage sag compensation system. *Proceedings of the TENCON 2014 - 2014 IEEE Region 10 Conference*. Bangkok, Thailand, 1-6.
8. Li, C.; Tayjasanant, T.; Xu, W.; and Liu, X. (2003). Method for voltage-sag-source detection by investigating slope of the system trajectory. *IEE Proceedings - Generation Transmission and Distribution,* 150(3), 367-372.
9. Manmek, T.; Mudannayake, C.P.; and Grantham C. (2006). Voltage dip detection based on an efficient least squares algorithm for DSTATCOM application. *Proceedings of the 2006 CES/IEEE 5th International Power Electronics and Motion Control Conference*. Shanghai, China, 1-6.
10. Chakrabarty, R.; and Adda, R. (2018). Model predictive control of DSTATCOM employing a single DC source cascaded H-bridge multilevel inverter in a weak distribution system. *Proceedings of the 2018 20th National Power Systems Conference (NPSC).* Tiruchirappalli, India, 1-6.
11. Suresh A.; and Rashmi M.R. (2022). Analysis of inverter side voltage issues in HVDC transmission systems. *Proceedings of the 2022 International Mobile and Embedded Technology Conference (MECON),* Noida, India, 124-129.
12. Najafi, E.; and Yatim A.H.M. (2010). A D-STATCOM based on Goertzel algorithm for sag detection and a novel current mode controller. *Proceedings of the 2010 5th IEEE Conference on Industrial Electronics and Applications*. Taichung, Taiwan, 1006-1011.
13. Mahalakshmi, R.; and Sasilatha, T. (2018). An improved digital FIR filter design using fast FIR algorithm and modified carry save addition. *National Academy Science Letters,* 41, 147-150.
14. Rashmi M.R.; and Anu, B. (2013). Cascading of diode clamped multilevel inverter boosters for high voltage applications. *Applied Mechanics and Materials* Volume 313-314, 876-881.
15. Rajendran S.; Muthu Kumar A.; Hari Prasath T.; and Rajesh K. (2021). WITHDRAWN. Efficient control techniques to enhance STATCOM performance with DE algorithm. *Materials Today: Proceedings.*
16. Gnanavel C.; Rajavelan M.; Muthukumar P.; and Baldwin Immanuel T. (2018). A performance investigation of a single phase multilevel inverter fed nonlinear loads for solar PV applications. *International Journal of Engineering and Technology,* 7(3.24), 388-391.