DIRECT CONTROL OF D-STATCOM BASED ON 23-LEVEL CASCADED MULTILEVEL INVERTER USING HARMONICS ELIMINATION PULSE WIDTH MODULATION

AHMED MAJED AHMED SAIF

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

FEBRUARY 2017

This thesis is first dedicated to my beloved, patient and struggling mother, **Huda Abdul-Raheem***. She has always been in the forefront of love, concern, Dua'a, advice and guidance to make sure we achieve the best of both worlds. May Allah preserve her in goodness and grant her happiness in both worlds. It is also dedicated to my wise and patient father,* **Dr. Majed Ahmed***. This thesis is a testimony to his effort of how he advised, prayed and struggled for us to get the best things of both worlds. May Allah grant him happiness in both worlds. Also dedicated to my only sister,* **Shaima'a***, the new baby gifted and bestowed to us by Allah while I was in the second semester of my Master-degree. Also dedicated to my 'treasure' beloved future wıfe,* **Bushra***, for here patience and understanding. May Allah preserve her in goodness. To my lovely brothers,* **Muhammad** *and* **Ehap***. I will never forget their support, encouragement, and understanding. They have released me from all family responsibilities just to come up with this thesis. Finally, to the brother from another mother,* **Dr. Suleiman Zubair***. He has been a supporting pillar of encouragement and motivation throughout the work of this thesis. May Allah preserve them in goodness and give all, the best of this world and in the hereafter.*

2.12	The 15-level cascaded MVSI output voltage based HEPWM method for M_I = 5.40 (a) voltage waveforms (b) harmonics spectra.	37
3.1	A 3-phase cascaded MVSI based D-STATCOM.	41
3.2	The tree diagram for HEPWM computational methods.	42
3.3	A generalized quarter wave HEPWM switching.	47
3.4	The flowchart (a) to compute HEPWM solution sets using DE (b) to select the solution sets to form the HEPWM angles trajectories.	50
3.5	HEPWM angles trajectories plot for 23-level MVSI.	51
3.6	The 23-level MVSI output voltage for MI = 5.40, 6.30 and 7.70 (a) 23-level simulation model (b) the phase voltage waveforms (c) the harmonics spectra of the phase voltage (d) the line-to-line voltage waveforms (e) the harmonics spectra of the line-to-line voltage.	52
3.7	Overall direct-control approach of D-STATCOM.	56
3.8	Variables in *abc* stationary frame and *dq* synchronous frame.	58
3.9	Generation of dc capacitor reference voltage.	60
3.10	Schematic diagram of inner current control.	64
3.11	Internal diagram of PLL.	65
3.12	Generation of the triggering pulses based on (a) HEPWM method (b) PS-PWM method.	66
3.13	Reference triangular signals generation (a) the Simulink model (b) output signals at point A (c) output signals at point B (d) output signals at point C.	67

3.14	Driving pulses and output voltage for one H-bridge.	69
3.15	A 23-level MVSI based on HEPWM (a) switching pulses generation for phase-a (b) line-to-neutral output voltages.	70
3.16	Generation of (a) switching pulses for single-phase 23-level MVSI based on PS-PWM method (b) sinusoidal modulating signals.	72
4.1	Direct control response for i_{Cq}* step test for (a) HEPWM (b) PS-PWM.	80
4.2	The HEPWM based D-STATCOM's steady-state performance under ± 300 step test: (a) line-to-line voltage in capacitive mode, (b) line-to-line voltage in inductive mode, (c) line current in capacitive mode, (d) line current in inductive mode.	82
4.3	The PS-PWM based D-STATCOM's steady-state performance under ± 300 step test: (a) line-to-line voltage in capacitive mode, (b) line-to-line voltage in inductive mode, (c) line current in capacitive mode (d) line current in inductive mode.	83
4.4	The THD% of the line-to-line output voltage at the same switching frequency.	84
4.5	Harmonics spectra of the line-to-line voltage of HEPWM and PS-PWM based D-STATCOM in (a) capacitive mode (b) inductive mode.	85
4.6	Harmonics spectra of the line-to-line voltage of PS-PWM based D-STATCOM for switching frequency of (a) 4.4 kHz (b) 6.6 kHz (c) 9.9 kHz.	86
4.7	THD% for D-STATCOM line current at (a) capacitive mode (b) inductive mode.	88

4.8	Losses analysis at capacitive operation (a) switching loss (b) power loss.	89
4.9	The THD of the line current for different L_{AC} values in (a) capacitive mode (i_{Cq} = 500 A) (b) inductive mode (i_{Cq} = −500 A).	90
4.10	Dynamic performance of HEPWM based direct control; response of (a) reactive current I_{Cq} (b) M_I (c) line-to-line v_C (d) line-to-line i_C.	91
4.11	Performance of the proposed D-STATCOM for sag mitigation.	94
4.12	Performance of the proposed D-STATCOM for swell mitigation.	95

$\alpha_1, \alpha_2 \ldots \alpha_N$	–	HEPWM switching angles
ε	–	Voltage drop coefficient
η	–	Ripple current coefficient
I_{RMS}	–	Rated RMS current
f_{sw}	–	Switching frequency
f	–	Fundamental frequency in Hz
ω	–	System frequency in rad/s
C_{dc}	–	dc capacitance for each H-bridge unit
V_{DC}	–	dc voltage across capacitors in each H-bridge unit
U_{DC}	–	Input dc voltage per phase
V_I	–	Voltage magnitude of the fundamental component
$i_{Cq}*$	–	Reference reactive current
$i_{C\,L\text{-}L}$	–	Line-to-line D-STATCOM current
$V_{C\,L\text{-}L}$	–	Line-to-line output voltage of D-STATCOM
R_S	–	Source resistance
X_S	–	Source inductance
Z_S	–	Source impedance

CHAPTER 1

INTRODUCTION

1.1 Overview

Due to the depletion of fossil fuel resources and the environmental contamination by green-house gases, the utilization of renewable energy (RE) has been on a constant rise. It is envisaged that RE will play an important role in the future energy mix [1]. For instance, by 2020, it is expected that 12% of the world's electricity will be produced by RE [2]. Furthermore, the global awareness is increasing in many countries, while international communities are promoting the climate-friendly and clean energy sources. These concerns are reflected in the recent 21st Conference of Parties (COP21) on climate change which was held in Paris [3]. However, RE resources are naturally unstable and highly intermittent. The inter-connection of RE sources with various kinds of loads have imposed serious power quality (P-Q) issues to the electrical grid. The most common P-Q problems are the voltage sag, swell and harmonics [4]. This is more severe with the proliferation of loads that draw non-sinusoidal current.

Rapid development in power electronics and control offers P-Q improvement using flexible AC transmission system (FACTS) controllers [5]. At the electrical distribution level, the D-STATCOM, which is in the family of FACTS devices, has been frequently used for power factor correction, load balancing, voltage regulation and stabilization. These functions are achieved by means of the reactive power compensation [6-8]. Traditionally, the low cost, two-level voltage source inverter (VSI) with a series coupling inductor, is used as the main building block of the D-STATCOM [9, 10]. However, the output voltage of the VSI is characterized by high harmonics that require bulky and costly filtering. Furthermore, for high and medium voltage interconnections, it is mandatory to use the line frequency (50 Hz) step-up transformer to match the output voltage of the VSI to the utility grid. This increases the cost, size, weight and power losses of the overall D-STATCOM. Thus, the multilevel VSI (MVSI) is being exploited to replace the two-level VSI [11-13].

Since the MVSI is sufficiently capable of providing high voltage, the use of step-up transformer can be avoided [14-16]. As a result, the weight and cost of the hardware are reduced significantly. For example, with the absence of the transformer, the weight of 3-phase cascaded MVSI, rated at 6.6 kV/1 MVA can be reduced three to four times compared to its transformer counterpart [14, 17]. In [17], it is reported that the transformer and its ac inductor is about half of a 360 kVA D-STATCOM weight. Additionally, the efficiency of the system can be increased; in a typical D-STATCOM system, approximately 70% of overall power loss per MVA rating is attributed to the transformer [16].

For a proper exchange of reactive power with the electrical grid, an efficient control of the D-STATCOM is crucial [8]. Two approaches, namely the direct and indirect control are widely used [18-21]. For the former, the phase angle of the VSI output voltage (δ) is the control variable, while the modulation index (M_I) is held constant at maximum value. Thus, the output voltage distortion (reflected by the THD value) can be kept minimum by imposing the maximum value of M_I. However, a rapid adjustment of reactive power is unachievable since the output voltage control using δ is restricted by the time constants of the capacitor charging and discharging within the VSI.

This speed limitation is addressed by the direct control approach [15, 20, 22]. In this scheme, the capacitor voltages are fixed, while the control of reactive power is obtained by varying the amplitude of the VSI output voltage. The rapid response to the reactive power demand is achieved by changing the M_I of the pulse width modulation (PWM) switching scheme [20]. Despite the improved performance, two problems are inherent for the direct control. First, the THD changes with the variation of M_I. At low

M_I, the harmonics profile of the output voltage is poor. Second, the high switching frequency of the PWM scheme increases the losses of the D-STATCOM [12].

The most popular modulation technique is the phase shifted PWM (PS-PWM) [23-25]. The concept is similar to the conventional sinusoidal PWM, whereby the switching pulses are generated by comparing a modulating and multiple carrier signals [16, 25]. For the MVSI topology, the PS-PWM switching is very complex due to the number of carriers that need to be phase-shifted in the correct sequence. For instance, to trigger the switches of a 3-phase 15-level MVSI, 29 carrier signals are required. In addition, the PS-PWM cannot directly eliminate the harmonics; thus it needs to be operated with high switching frequency to maintain the THD below the IEEE-519 Standard (5%). Another modulation method that is used in the direct control of the D-STATCOM is the space vector modulation (SVM) [26, 27]. The scheme is based on vector calculation and switching states selection to achieve certain desired performance [27]. Despite the comparatively lower switching frequency that can be attained, the process of selecting switching states becomes increasingly complicated as the level of MVSI becomes higher [16].

On the other hand, the harmonic elimination PWM (HEPWM) [22, 28] is known for its superior harmonics profile and lower switching losses. Despite being an off-line technique (i.e. the angles are computed prior to execution and stored in a look-up table), it is becoming a popular choice, particularly for high power applications. The difficulty of storing the angles in look-up table does not arise due to availability of low-cost memories. Therefore, HEPWM is a competitive alternative for the direct control scheme of the D-STATCOM especially when the MVSI topology is utilized. However, to implement HEPWM for high output voltage, a wide range of M_I is necessary which in turn, requires more switching angles to be obtained. This is where the challenge in HEPWM is noted. The problem that arises in solving for the HEPWM angles for a wide M_I range is due to the large number of non-linear transcendental equations that govern them [23, 29]. In spite of this, several works that utilize HEPWM for direct control albeit for a lower number of angles, are reported [16, 21, 22, 30]. For example, a direct control scheme based HEPWM technique was proposed in [22] for 10 MVAr /12 kV, 11-level (five angles) MVSI. In [30], authors presented a HEPWM strategy to minimize the THD of the output voltage of MVSI D-STATCOM. Furthermore, dc-dc converters have been used with HEPWM technique to control output voltage of single-phase five-level cascaded D-STATCOM [16]. However, in these methods [22, 30], the M_I values are calculated for a maximum levels of 11-levels and for limited operation range; and for [16], a dc-dc converter is used for each H-bridge to produce a controllable dc input voltage, resulting in a complex and bulky system especially for high levels MVSI.

Understandably, due to the complexity in solving the equations for the HEPWM angles, no work is reported on the direct control for a MVSI D-STATCOM for more than 15-level. However, even with the 15-level, it is not possible to achieve the desired THD values below 5% over the entire modulation range. Thus, one of the objectives of this work is to increase the MVSI level in order to produce wider M_I range, while keeping the THD below the desired value.

1.2 Motivation

From the above overview, it is clear that the direct control strategy is favored for D-STATCOM due to its ability to compensate for the reactive power rapidly. Commonly, PS-PWM switching is used in the direct control of the MVSI D-STATCOM. However, to obtain a low THD of the output voltage of the D-STATCOM, the PS-PWM needs to be operated at high switching frequency. This results in high switching losses, hence lower efficiency. To overcome these limitations, the direct control scheme based on HEPWM is proposed. The main advantage of using HEPWM is the low THD; using a sufficiently high level MVSI, the THD below 5% over the entire operating range can be achieved. Furthermore, due to the lower switching frequency, HEPWM exhibits much lower switching loss compared to PS-PWM. In addition, for the available rating of power semiconductor switches, it is not difficult to realize D-STATCOM for direct connection to 11 kV distribution network (or higher voltage) using MVSI. This eliminates the bulky and lossy step-up transformer.

1.3 Objectives of the Research

By considering the aforementioned background and motivation, the objectives of this research are formulated as follows:

i) to propose a direct control scheme, which is based on HEPWM switching for 23-level MVSI D-STATCOM.

ii) to evaluate the performance of the proposed control scheme in terms of harmonics and power losses against the PS-PWM methods.

iii) to test the dynamic performance of the HEPWM based D-STATCOM under sag and swell problems.

The HEPWM angles are computed using a soft computing method, known as the differential evolution (DE). It is a powerful search and optimization method used to solve highly correlated and complicated non-linear problems. For validation, a ± 6.5 MVAr/11 kV D-STATCOM system, modelled in Simulink and PLECS software is used.

1.4 Scope of the Research

The scope and limitations of this research are as follows:

i) The angles trajectories are computed offline for wide range of M_I using DE.

To ensure that the THD is kept below 5%, a 23-level MVSI is required, which in turn, requires the number of HEPWM angles to be increased to eleven. The maximum achievable range of M_I is $5.40 \leq M_I \leq 8.15$ (i.e. HEPWM allows over modulation operation), with an incremental step of 0.01. The 0.01 step for M_I can be considered very accurate; it gives a total of 273 values for the given range of M_I.

ii) The voltages across the capacitors are fixed by using floating dc sources.

In a normal STATCOM, a capacitor bank is used to maintain the dc voltage of the VSI. For cascaded multilevel VSI, the number of the capacitors is proportional to the number of the synthesized levels. Due to different losses of H-bridge units, measurement error in the voltage and current sensors and the tolerance of the passive elements, the capacitor voltages may be unbalanced. Improper balancing among the capacitors affects the operation of the HEPWM method. In this work, for simplicity, the capacitor voltages are kept constant using floating dc sources similar to [31].

iii) Simulation using Simulink/Matlab and PLECS software.

To validate the effectiveness of the proposed control scheme, the D-STATCOM is modelled in Simulink/MATLAB. The pre-calculated switching angles are stored in look-up table. In addition, the PLECS software (which is integrated with Simulink) is used for the calculation of the thermal losses.

iv) Performance validation: comparison between HEPWM and PS-PWM

To validate the performance of the proposed HEPWM switching, a comparison is made with PS-PWM for the same 23-level MVSI D-STATCOM was steady state. In addition, the dynamics performance of the HEPWM based direct control is tested under sag and swell problems.

1.5 Significance of the Research

The advantages of the proposed HEPWM D-STATCOM can be summarized as:

i) Fast reactive power compensation.

The utilization of direct control scheme instead of the indirect control scheme allows for fast compensation of the reactive power [9, 18]. The control of reactive power is achieved by using HEPWM switching to vary the amplitude of the VSI output voltage using M_I.

ii) Superior harmonic performance and low switching losses.

The proposed HEPWM switching for 23-level MVSI D-STATCOM allows the elimination of the lower order and the triplens harmonics from the line-to-line output voltage. Thus, very low THD of the output voltage waveform is obtained. In addition, due to the low switching frequency of the HEPWM, lower switching loss results.

iii) Reduction in the size and cost of the D-STATCOM.

This work presents a D-STATCOM based on 23-level cascaded MVSI which allow the elimination of the bulky and costly step up transformer used to connect the D-STATCOM to distribution level. In addition, due to the good harmonics performance of the output voltage of the proposed D-STATCOM, a smaller series-coupling inductor can be used, hence the lower size of the overall system.

1.6 Thesis Outline

The thesis is comprised of five chapters. The remaining chapters are organized as follows:

i) Chapter 2 is a review on the topologies, control and modulation methods used for D-STATCOM. It provides the important background knowledge regarding the research. The chapter starts by comparing the STATCOM to the other types of FACTS devices. Then, the MVSI topologies, control strategies and modulation techniques utilized for STATCOM are presented alongside a comparative analysis between them. The common PWM methods (i.e. PS-PWM and HEPWM) used for the direct control of STATCOM are presented alongside a critical discussion between them. It is shown that HEPWM is a competitive alternative for the direct control scheme of the D-STATCOM.

ii) Chapter 3 begins by introducing the concept of a direct control scheme based on HEPWM switching for a 23-level MVSI D-STATCOM. Then a detailed outline of the design considerations and control of the proposed system is provided. The methods for solving the HEPWM equations, the formulation of HEPWM equations, the concept of DE and its application on solving the eleven switching angles (to achieve 5.40 – 8.15 p.u. M_I range) are discussed and the angles trajectories for 23-level MVSI are shown. In addition, the selection of the passive elements is explained alongside a discussion about its effect on the operation of the STATCOM. The simulation of the direct control based PS-PWM switching for 23-level MVSI D-STATCOM is also presented. For both systems (i.e. HEPWM and PS-PWM), the generation of the switching pulses is described in details.

iii) Chapter 4 examines the performance of the HEPWM based direct control scheme alongside a detailed comparison with the traditional PS-PWM switching in steady state. Their performance is benchmarked using ± 6.5 MVAr/11 kV D-STATCOM modelled in MATLAB-Simulink and PLECS software. Furthermore, dynamic performance of the proposed HEPWM D-STATCOM is tested under voltage sag and swell cases and a comparative discussion is made with the indirect control scheme.

iv) Chapter 5 concludes the work and provides a suggestions and directions for the future work.

REFERENCES

1. Lund, P. D. Clean energy systems as mainstream energy options. *International Journal of Energy Research.* 2015
2. Bozhko, S. V., Blasco-Gimenez, R., Li, R., Clare, J. C., and Asher, G. M. Control of offshore DFIG-based wind farm grid with line-commutated HVDC connection. *IEEE Transactions on Energy Conversion.* 2007. 22(1): 71-78.
3. Wu, J., Thompson, J., Zhang, H., and Kilper, D. C. Green communications and computing networks [Series Editorial]. *IEEE Communications Magazine.* 2015. 53(11): 148-149.
4. Milanovic, J. V. and Zhang, Y. Modeling of FACTS devices for voltage sag mitigation studies in large power systems. *IEEE Transactions on Power Delivery.* 2010. 25(4): 3044-3052.
5. Hingorani, N. G. and Gyugyi, L. *Understanding facts.* IEEE press. 2000
6. Arya, S. R. and Singh, B. Implementation of distribution static compensator for power quality enhancement using learning vector quantisation. *IET Generation, Transmission & Distribution.* 2013. 7(11): 1244-1252.
7. Singh, B., Arya, S. R., Jain, C., and Goel, S. Implementation of four-leg distribution static compensator. *IET Generation, Transmission & Distribution.* 2014. 8(6): 1127-1139.
8. Patel, S. K., Arya, S. R., Maurya, R., and Singh, B. Interior point algorithm for optimal control of distribution static compensator under distorted supply voltage conditions. *IET Generation, Transmission & Distribution.* 2016. 10(8): 1778-1791.
9. Singh, B., Saha, R., Chandra, A., and Al-Haddad, K. Static synchronous compensators (STATCOM): a review. *IET Power Electronics.* 2009. 2(4): 297-324.
10. Singh, B. and Kadagala, V. S. Simulation of three-level 24-pulse voltage source converters-based static synchronous compensator for reactive power control. *IET Power Electronics.* 2014. 7(5): 1148-1161.

11. Gupta, K., Ranjan, A., Bhatnagar, P., Sahu, L. K., and Jain, S. Multilevel Inverter Topologies with Reduced Device Count: A Review. *IEEE Transactions on Power Electronics.* 2016. 31(1): 135-151.

12. Kouro, S., Malinowski, M., Gopakumar, K., Pou, J., Franquelo, L. G., Wu, B., *et al.* Recent advances and industrial applications of multilevel converters. *IEEE Transactions on Industrial Electronics.* 2010. 57(8): 2553-2580.

13. Rodríguez, J., Bernet, S., Wu, B., Pontt, J. O., and Kouro, S. Multilevel voltage-source-converter topologies for industrial medium-voltage drives. *IEEE Transactions on Industrial Electronics.* 2007. 54(6): 2930-2945.

14. Mohammadi, H. and Bina, M. T. A transformerless medium-voltage STATCOM topology based on extended modular multilevel converters. *IEEE Transactions on Power Electronics.* 2011. 26(5): 1534-1545.

15. Song, Q., Liu, W., and Yuan, Z. Multilevel optimal modulation and dynamic control strategies for STATCOMs using cascaded multilevel inverters. *IEEE Transactions on Power Delivery.* 2007. 22(3): 1937-1946.

16. Haw, L. K., Dahidah, M. S., and Almurib, H. A. SHE-PWM cascaded multilevel inverter with adjustable DC voltage levels control for STATCOM applications. *IEEE Transactions on Power Electronics* 2014. 29(12): 6433 - 6444.

17. Sano, K. and Takasaki, M. A Transformerless D-STATCOM Based on a Multivoltage Cascade Converter Requiring No DC Sources. *IEEE Transactions on Power Electronics.* 2012. 27(6): 2783-2795.

18. Chen, B.-S. and Hsu, Y.-Y. A minimal harmonic controller for a STATCOM. *IEEE Transactions on Industrial Electronics.* 2008. 55(2): 655-664.

19. Babaei, S., Parkhideh, B., Chandorkar, M. C., Fardanesh, B., and Bhattacharya, S. Dual Angle Control for Line-Frequency-Switched Static Synchronous Compensators Under System Faults. *IEEE Transactions on Power Electronics.* 2014. 29(6): 2723-2736.

20. Schauder, C. and Mehta, H. Vector analysis and control of advanced static VAR compensators. *IEE Proceedings C (Generation, Transmission and Distribution)*: IET 1993. 299-306.

21. Çetin, A. and Ermis, M. VSC-based D-STATCOM with selective harmonic elimination. *IEEE Transactions on Industry Applications.* 2009. 45(3): 1000-1015.

22. Gultekin, B. and Ermis, M. Cascaded multilevel converter-based transmission STATCOM: System design methodology and development of a 12 kV±12 MVAr power stage. *IEEE Transactions on Power Electronics.* 2013. 28(11): 4930-4950.

23. Townsend, C. D., Summers, T. J., and Betz, R. E. Impact of Practical Issues on the Harmonic Performance of Phase-Shifted Modulation Strategies for a Cascaded H-Bridge StatCom. *IEEE Transactions on Industrial Electronics.* 2014. 61(6): 2655-2664.

24. Ota, J., Shibano, Y., Niimura, N., and Akagi, H. A Phase-Shifted-PWM D-STATCOM Using a Modular Multilevel Cascade Converter (SSBC): Part I. Modeling, Analysis, and Design of Current Control. *IEEE Transactions on Industry Applications* 2015. 51(1): 279 - 288.

25. Townsend, C. D., Summers, T. J., and Betz, R. E. Phase-Shifted Carrier Modulation Techniques for Cascaded H-Bridge Multilevel Converters. *IEEE Transactions on Industrial Electronics.* 2015. 62(11): 6684-6696.

26. Saeedifard, M., Nikkhajoei, H., and Iravani, R. A space vector modulated STATCOM based on a three-level neutral point clamped converter. *IEEE Transactions on Power Delivery.* 2007. 22(2): 1029-1039.

27. Yao, W., Hu, H., and Lu, Z. Comparisons of space-vector modulation and carrier-based modulation of multilevel inverter. *IEEE Transactions on Power Electronics.* 2008. 23(1): 45-51.

28. Dahidah, M. S. A., Konstantinou, G., and Agelidis, V. G. A Review of Multilevel Selective Harmonic Elimination PWM: Formulations, Solving Algorithms, Implementation and Applications. *IEEE Transactions on Power Electronics* 2015. 30(8): 4091-4106.

29. Moeed Amjad, A. and Salam, Z. A review of soft computing methods for harmonics elimination PWM for inverters in renewable energy conversion systems. *Renewable and Sustainable Energy Reviews.* 2014. 33(141-153.

30. Tolbert, L. M., Chiasson, J. N., and Peng, F. Z. Modulation index regulation of a multilevel inverter for static var compensation. *Power Engineering Society General Meeting, 2003, IEEE*: IEEE 2003.

31. Beza, M. *Power System Stability Enhancement Using Shunt-connected Power Electronic Devices with Active Power Injection Capability.* Chalmers University of Technology. 2015

32. Kunya, A. B., Yalcinoz, T., and Shehu, G. S. Voltage sag and swell alleviation in distribution network using custom power devices; D-STATCOM and DVR. *Power Electronics and Motion Control Conference and Exposition (PEMC),* IEEE 2014. 400-405.

33. Dixon, J., Moran, L., Rodriguez, J., and Domke, R. Reactive power compensation technologies: State-of-the-art review. *Proceedings of the IEEE.* 2005. 93(12): 2144-2164.

34. Yang, H. T. and Liao, J. T. Hierarchical reactive power regulation strategies for high-penetration photovoltaic distribution systems. *International Journal of Energy Research.* 2015

35. Adamczyk, A., Teodorescu, R., Mukerjee, R., and Rodriguez, P. Overview of FACTS devices for wind power plants directly connected to the transmission network. *Industrial Electronics (ISIE), 2010 IEEE International Symposium on*: IEEE 2010. 3742-3748.

36. Edris, A., Adapa, R., Baker, M., Bohmann, L., Clark, K., Habashi, K., *et al.* Proposed terms and definitions for flexible AC transmission system (FACTS). *IEEE Power Engineering Review.* 1997. 17(46-46.

37. Faruque, M., Dinavahi, V., Santoso, S., and Adapa, R. Review of electromagnetic transient models for Non-VSC FACTS. *IEEE Transactions on Power Delivery.* 2005. 20(2): 1065-1079.

38. Migliavacca, G. *Advanced Technologies for Future Transmission Grids.* Springer Science & Business Media. 2012

39. Zhang, X.-P., Rehtanz, C., and Pal, B., "FACTS-Devices and Applications," in *Flexible AC Transmission Systems: Modelling and Control*, ed: Springer, 2012, pp. 1-30.

40. Mathur, R. M. and Varma, R. K. *Thyristor-based FACTS controllers for electrical transmission systems.* John Wiley & Sons. 2002

41. Chen, W.-L., Liang, W.-G., and Gau, H.-S. Design of a Mode Decoupling STATCOM for Voltage Control of Wind-Driven Induction Generator Systems. *IEEE Transactions on Power Delivery.* 2010. 25(3): 1758-1767.

42. Sidhu, T. S., Varma, R. K., Gangadharan, P. K., Albasri, F. A., and Ortiz, G. R. Performance of distance relays on shunt-FACTS compensated transmission lines. *Power Delivery, IEEE Transactions on.* 2005. 20(3): 1837-1845.

43. Gerçek, C. O. and Ermis, M. Elimination of Coupling Transformer Core Saturation in Cascaded Multilevel Converter Based T-STATCOM Systems. 2014

44. Schauder, C., Gernhardt, M., Stacey, E., Lemak, T., Gyugyi, L., Cease, T., *et al.* Development of a±100 MVAR static condenser for voltage control of transmission systems. *IEEE Transactions on Power Delivery* 1995. 10(3): 1486-1496.

45. Gultekin, B., Gercek, C. O., Atalik, T., Deniz, M., Biçer, N., Ermis, M., *et al.* Design and Implementation of a 154-kV 50-Mvar Transmission STATCOM Based on 21-Level Cascaded Multilevel Converter. *IEEE Transactions on Industry Applications.* 2012. 48(3): 1030-1045.

46. Reed, G. F., Greaf, J. J., Matsumoto, T. M., Yonehata, Y., Takeda, M., Aritsuka, T., *et al.* Application of a 5 MVA, 4.16 kV D-STATCOM system for voltage flicker compensation at Seattle Iron and Metals. *Power Engineering Society Summer Meeting,* IEEE 2000. 1605-1611.

47. Mori, S., Matsuno, K., Hasegawa, T., Ohnishi, S., Takeda, M., Seto, M., *et al.* Development of a large static var generator using self-commutated inverters for improving power system stability. *Power Systems, IEEE Transactions on.* 1993. 8(1): 371-377.

48. Haw, L. K., Dahidah, M. S. A., and Almurib, H. a. F. A New Reactive Current Reference Algorithm for the STATCOM System Based on Cascaded Multilevel Inverters. *IEEE Transactions on Power Electronics.* 2015. 30(7): 3577-3588.

49. Mahela, O. P. and Shaik, A. G. A review of distribution static compensator. *Renewable and Sustainable Energy Reviews.* 2015. 50(0): 531-546.

50. Kumar, C. and Mishra, M. K. A Voltage-Controlled DSTATCOM for Power-Quality Improvement. 2014

51. Ge, B., Peng, F. Z., and Li, Y. Multilevel Converter/Inverter Topologies and Applications. *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications.* 2014422-462.

52. Lee, C., Leung, J. S., Hui, S. R., and Chung, H. S.-H. Circuit-level comparison of STATCOM technologies. *PESC Record-IEEE Annual Power Electronics Specialists Conference*: IEEE 2003. 1777-1784.

53. Soto, D. and Green, T. C. A comparison of high-power converter topologies for the implementation of FACTS controllers. *IEEE Transactions on Industrial Electronics*. 2002. 49(5): 1072-1080.

54. Lai, J.-S. and Peng, F. Z. Multilevel converters-a new breed of power converters. *IEEE Transactions on Industry Applications*. 1996. 32(3): 509-517.

55. Ayob, S. M. and Salam, Z. A new PWM scheme for cascaded multilevel inverter using multiple trapezoidal modulation signals. *Power Electronics, Machines and Drives, 2004. (PEMD 2004). Second International Conference on (Conf Publ. No. 498)*: 2004. 242-246 Vol.1.

56. Rodriguez, J., Jih-Sheng, L., and Fang Zheng, P. Multilevel inverters: a survey of topologies, controls, and applications. *IEEE Transactions on Industrial Electronics*. 2002. 49(4): 724-738.

57. Gabbar, H. A., Islam, R., Isham, M. U., and Trivedi, V. Risk-based performance analysis of microgrid topology with distributed energy generation. *International Journal of Electrical Power & Energy Systems*. 2012. 43(1): 1363-1375.

58. Franquelo, L. G., Rodriguez, J., Leon, J. I., Kouro, S., Portillo, R., and Prats, M. a. M. The age of multilevel converters arrives. *Industrial Electronics Magazine, IEEE*. 2008. 2(2): 28-39.

59. Elgamal, M. E., Lotfy, A., and Ali, G. E. M. Voltage profile enhancement by fuzzy controlled MLI UPFC. *International Journal of Electrical Power & Energy Systems*. 2012. 34(1): 10-18.

60. Trabelsi, M., Ghazi, K. A., Al-Emadi, N., and Ben-Brahim, L. A weighted real-time predictive controller for a grid connected flying capacitors inverter. *International Journal of Electrical Power & Energy Systems*. 2013. 49(0): 322-332.

61. Marzoughi, A., Imaneini, H., and Moeini, A. An optimal selective harmonic mitigation technique for high power converters. *International Journal of Electrical Power & Energy Systems*. 2013. 49(0): 34-39.

62. Nabae, A., Takahashi, I., and Akagi, H. A new neutral-point-clamped PWM inverter. *IEEE Transactions on Industry Applications*. 19815): 518-523.

63. Yuan, X. and Barbi, I. Fundamentals of a new diode clamping multilevel inverter. *IEEE Transactions on Power Electronics*. 2000. 15(4): 711-718.

64. Meynard, T. and Foch, H. Multi-level conversion: high voltage choppers and voltage-source inverters. *Power Electronics Specialists Conference, 1992. PESC'92 Record., 23rd Annual IEEE*: IEEE 1992. 397-403.

65. Peng, F. Z., Lai, J.-S., Mckeever, J. W., and Vancoevering, J. A multilevel voltage-source inverter with separate DC sources for static var generation. *IEEE Transactions on Industry Applications.* 1996. 32(5): 1130-1138.

66. Rodriguez, J., Lai, J.-S., and Peng, F. Z. Multilevel inverters: a survey of topologies, controls, and applications. *IEEE Transactions on Industrial Electronics.* 2002. 49(4): 724-738.

67. Shukla, A., Ghosh, A., and Joshi, A. Static shunt and series compensations of an SMIB system using flying capacitor multilevel inverter. *IEEE Transactions on Power Delivery.* 2005. 20(4): 2613-2622.

68. Peng, F. Z. and Lai, J.-S. Dynamic performance and control of a static var generator using cascade multilevel inverters. *Industry Applications Conference, 1996. Thirty-First IAS Annual Meeting, IAS'96., Conference Record of the 1996 IEEE*: IEEE 1996. 1009-1015.

69. Shibano, Y. and Akagi, H. A Phase-Shifted-PWM D-STATCOM Using a Modular Multilevel Cascade Converter (SSBC): Part II. Zero-Voltage-Ride-Through (ZVRT) Capability. 2015

70. Akagi, H., Inoue, S., and Yoshii, T. Control and performance of a transformerless cascade PWM STATCOM with star configuration. *IEEE Transactions on Industry Applications.* 2007. 43(4): 1041-1049.

71. Zargari, N. and Rizzo, S. Medium voltage drives in industrial applications. *Technical Seminar, IEEE Toronto Section*: 2004.

72. Akagi, H. Classification, terminology, and application of the modular multilevel cascade converter (MMCC). *IEEE Transactions on Power Electronics.* 2011. 26(11): 3119-3130.

73. Rahim, N. A. and Selvaraj, J. Multistring five-level inverter with novel PWM control scheme for PV application. *IEEE transactions on industrial electronics.* 2010. 57(6): 2111-2123.

74. Malinowski, M., Gopakumar, K., Rodriguez, J., and Perez, M. A. A survey on cascaded multilevel inverters. *IEEE Transactions on Industrial Electronics.* 2010. 57(7): 2197-2206.

75. Colak, I., Kabalci, E., and Bayindir, R. Review of multilevel voltage source inverter topologies and control schemes. *Energy Conversion and Management.* 2011. 52(2): 1114-1128.

76. Sirisukprasert, S., "The modeling and control of a cascaded-multilevel converter-based STATCOM," Virginia Tech, 2004.

77. Chen, B.-S. and Hsu, Y.-Y. An analytical approach to harmonic analysis and controller design of a STATCOM. *IEEE Transactions on Power Delivery.* 2007. 22(1): 423-432.

78. Saeedifard, M., Iravani, R., and Pou, J. Control and DC-capacitor voltage balancing of a space vector-modulated five-level STATCOM. *Iet Power Electronics.* 2009. 2(3): 203-215.

79. Soto, D. and Pena, R. Nonlinear control strategies for cascaded multilevel STATCOMs. *IEEE Transactions on Power Delivery.* 2004. 19(4): 1919-1927.

80. Liang, Y. and Nwankpa, C. A new type of STATCOM based on cascading voltage-source inverters with phase-shifted unipolar SPWM. *IEEE Transactions on Industry Applications.* 1999. 35(5): 1118-1123.

81. Behrouzian, E., Bongiorno, M., and Teodorescu, R. Impact of Switching Harmonics on Capacitor Cells Balancing in Phase-Shifted PWM Based Cascaded H-Bridge STATCOM. 2016

82. Wu, B. and Narimani, M. *High-power converters and AC drives.* John Wiley & Sons. 2016

83. Shu, Z., Ding, N., Chen, J., Zhu, H., and He, X. Multilevel SVPWM With DC-Link Capacitor Voltage Balancing Control for Diode-Clamped Multilevel Converter Based STATCOM. *IEEE Transactions on Industrial Electronics.* 2013. 60(5): 1884-1896.

84. Turnbull, F. Selected harmonic reduction in static DC—AC inverters. *IEEE Transactions on Communication and Electronics.* 1964. 83(73): 374-378.

85. Patel, H. S. and Hoft, R. G. Generalized techniques of harmonic elimination and voltage control in thyristor inverters: Part I--harmonic elimination. *IEEE Transactions on Industry Applications.* 19733): 310-317.

86. Duffey, C. K. and Stratford, R. P. Update of harmonic standard IEEE-519: IEEE recommended practices and requirements for harmonic control in electric power systems. *IEEE Transactions on Industry Applications.* 1989. 25(6): 1025-1034.

87. Patel, H. S. and Hoft, R. G. Generalized techniques of harmonic elimination and voltage control in thyristor inverters: part II---voltage control techniques. *IEEE Transactions on Industry Applications*. 19745): 666-673.

88. Amjad, A. M., Salam, Z., and Saif, A. M. A. Application of differential evolution for cascaded multilevel VSI with harmonics elimination PWM switching. *International Journal of Electrical Power & Energy Systems*. 2015. 64(447-456.

89. Agelidis, V. G., Balouktsis, A., and Balouktsis, I. On applying a minimization technique to the harmonic elimination PWM control: the bipolar waveform. *IEEE Power Electronics Letters*. 2004. 2(2): 41-44.

90. Kato, T. Sequential homotopy-based computation of multiple solutions for selected harmonic elimination in PWM inverters. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*. 1999. 46(5): 586-593.

91. Swift, F. and Kamberis, A. A new Walsh domain technique of harmonic elimination and voltage control in pulse-width modulated inverters. *IEEE Transactions on Power Electronics*. 1993. 8(2): 170-185.

92. Chiasson, J., Tolbert, L. M., Mckenzie, K., and Du, Z. A complete solution to the harmonic elimination problem. *Applied Power Electronics Conference and Exposition, 2003. APEC'03. Eighteenth Annual IEEE*: IEEE 2003. 596-602.

93. Enjeti, P. N., Ziogas, P. D., and Lindsay, J. F. Programmed PWM techniques to eliminate harmonics: A critical evaluation. *IEEE Transactions on Industry Applications*. 1990. 26(2): 302-316.

94. Taghizadeh, H. and Hagh, M. T. Harmonic elimination of cascade multilevel inverters with nonequal DC sources using particle swarm optimization. *IEEE Transactions on Industrial Electronics*. 2010. 57(11): 3678-3684.

95. Dahidah, M. S. and Agelidis, V. G. Selective harmonic elimination PWM control for cascaded multilevel voltage source converters: A generalized formula. *IEEE Transactions on power electronics*. 2008. 23(4): 1620-1630.

96. Rahimpour, M. R., Aboosadi, Z. A., and Jahanmiri, A. H. Differential evolution (DE) strategy for optimization of methane steam reforming and hydrogenation of nitrobenzene in a hydrogen perm-selective membrane thermally coupled reactor. *International Journal of Energy Research*. 2013. 37(8): 868-878.

97. Atif, M. and Al-Sulaiman, F. A. Development of a mathematical model for optimizing a heliostat field layout using differential evolution method. *International Journal of Energy Research.* 2015

98. Storn, R. and Price, K. Differential evolution - A simple and efficient heuristic for global optimization over continuous spaces. *Journal of Global Optimization.* 1997. 11(4): 341-359.

99. Salam, Z., Majed, A., and Amjad, A. M. Design and implementation of 15-level cascaded multi-level voltage source inverter with harmonics elimination pulse-width modulation using differential evolution method. *IET Power Electronics.* 2015

100. Zielinski, K., Weitkemper, P., Laur, R., and Kammeyer, K.-D. Parameter study for differential evolution using a power allocation problem including interference cancellation. *2006 IEEE International Conference on Evolutionary Computation*: IEEE 2006. 1857-1864.

101. Storn, R. System design by constraint adaptation and differential evolution. *IEEE Transactions on Evolutionary Computation.* 1999. 3(1): 22-34.

102. Storn, R. and Price, K. Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces. *Journal of global optimization.* 1997. 11(4): 341-359.

103. Akagi, H. Active harmonic filters. *Proceedings of the IEEE.* 2005. 93(12): 2128-2141.

104. Townsend, C., Summers, T., and Betz, R. Comparison of modulation strategies for a cascaded H-bridge StatCom—Part 1: Theoretical background. *IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society*: IEEE 2010. 2019-2024.

105. Zhao, G., Liu, J., and Han, M. Design of input filters considering the stability of STATCOM systems. *Journal of Power Electronics.* 2011. 11(6): 904-913.

106. Farivar, G., Agelidis, V. G., and Hredzak, B. A fast filtering scheme for capacitor voltages of a cascaded H-bridge multilevel converter based STATCOM. *Power Electronics and Applications (EPE'14-ECCE Europe), 2014 16th European Conference on*: IEEE 2014. 1-5.

107. Lu, X., Ge, B., and Peng, F. Z. Minimizing DC capacitance requirement of cascadeded H-bridge multilevel inverters for photovoltaic systems by 3 rd

harmonic injection. *Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE*: IEEE 2012. 240-245.

108. Farivar, G., Hredzak, B., and Agelidis, V. G. Reduced-Capacitance Thin-Film H-Bridge Multilevel STATCOM Control Utilizing an Analytic Filtering Scheme. *IEEE Transactions on Industrial Electronics*. 2015. 62(10): 6457-6468.

109. Sao, C. K., Lehn, P. W., Iravani, M. R., and Martinez, J. A. A benchmark system for digital time-domain simulation of a pulse-width-modulated D-STATCOM. *IEEE Transactions on Power Delivery*. 2002. 17(4): 1113-1120.

110. Maharjan, L., Inoue, S., and Akagi, H. A transformerless energy storage system based on a cascade multilevel PWM converter with star configuration. *IEEE Transactions on Industry Applications*. 2008. 44(5): 1621-1630.

111. Blaabjerg, F., Teodorescu, R., Liserre, M., and Timbus, A. V. Overview of control and grid synchronization for distributed power generation systems. *IEEE Transactions on Industrial Electronics*. 2006. 53(5): 1398-1409.

112. Jaalam, N., Rahim, N., Bakar, A., Tan, C., and Haidar, A. M. A comprehensive review of synchronization methods for grid-connected converters of renewable energy source. *Renewable and Sustainable Energy Reviews*. 2016. 59(1471-1481.

113. Hsieh, G.-C. and Hung, J. C. Phase-locked loop techniques. A survey. *IEEE Transactions on Industrial Electronics*. 1996. 43(6): 609-615.

114. Giroux, P., Sybille, G., and Le-Huy, H. Modeling and simulation of a distribution STATCOM using Simulink's Power System Blockset. *Industrial Electronics Society, 2001. IECON'01. The 27th Annual Conference of the IEEE*: IEEE 2001. 990-994.

115. Aghdam, G. H. Optimised active harmonic elimination technique for three-level T-type inverters. *IET Power Electronics*. 2013. 6(3): 425-433.

116. Kumle, A. N., Fathi, S. H., Jabbarvaziri, F., Jamshidi, M., and Yazdi, S. S. H. Application of memetic algorithm for selective harmonic elimination in multi-level inverters. *IET Power Electronics*. 2015. 8(9): 1733-1739.

117. Shah, N. M., Sood, V. K., and Ramachandran, V. EMTP simulation of a chain-link STATCOM. *IEEE Transactions on Power Delivery*. 2008. 23(4): 2148-2159.