

**ENHANCEMENT OF PERFORMANCE AND  
RESPONSE TIME OF CASCADED VSC  
STATCOM IN THE PRESENCE OF VOLTAGE  
VARIATION AND LOW POWER FACTOR**

**MOHAMAD MILOOD MOHAMAD ALMELIAN**

**DOCTOR OF PHILOSOPHY**

**UNIVERSITI MALAYSIA PAHANG**



### **SUPERVISOR'S DECLARATION**

We hereby declare that We have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

A handwritten signature in blue ink, appearing to read 'Jhim'.

---

(Supervisor's Signature)

Full Name : IZZELDIN IBRAHIM MOHAMED ABDELAZIZ

Position : SENIOR LECTURER

Date : 10 MAY 2022

A handwritten signature in black ink, appearing to read 'i Zaharin'.

(Co-supervisor's Signature)

Full Name : ABU ZAHARIN BIN AHMAD

Position : PROFESOR MADYA

Date : 10 MAY 2022



### **STUDENT'S DECLARATION**

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

A handwritten signature in black ink, appearing to read "Mohamad Milood".

---

(Student's Signature)

Full Name : MOHAMAD MILOOD MOHAMAD ALMELIAN

ID Number : PEL17003

Date : 10 MAY 2022

**ENHANCEMENT OF PERFORMANCE AND RESPONSE TIME OF CASCADED  
VSC STATCOM IN THE PRESENCE OF VOLTAGE VARIATION AND LOW  
POWER FACTOR**

**MOHAMAD MILOOD MOHAMAD ALMELIAN**

Thesis submitted in fulfillment of the requirements  
for the award of the degree of  
**Doctor of Philosophy**

Faculty of Electrical and Electronic Engineering Technology  
**UNIVERSITI MALAYSIA PAHANG**

**MAY 2022**

## **ACKNOWLEDGEMENTS**

Praise to Allah, the Most Gracious and Most Merciful.

Sincere appreciation is expressed to my supervisor, Dr.Izzeldin Ibrahim Mohamed Abdelaziz, and my co-supervisor, Associate Professor Dr.Abu ZaharinBin Ahmad. It has been a great fortune and pleasure to work with you during the past years. Their guidance, support, and encouragement throughout my research have significantly influenced my Ph.D. career and made it possible.

I also would like to thank all my friends for their assistance towards the successful completion of this work especially, Dr.Emad Almarghani and Dr.Mohamed Salem. I am also indebted to Universiti Malaysia Pahang (UMP) for their assistance in supplying the relevant literature. Furthermore, I would like to express my sincere gratitude to the academic and management staff in the Faculty of Electrical Engineering and the staff of the Institute of Postgraduate Studies (IPS) in UMP. Special thanks go to my colleague Mr. Mohamed Asghaiyer for his helpful comments and suggestions during the technical talks. I thank all Malaysian people whom I met, for their openness, friendship, and hospitality.

At last and most important, I would like to thank my parents, wife, and all family members for their open-mindedness and endless support. They are in my heart. Without the help and support of Allah, supervisors and all these people, this thesis would not be completed.

## **ABSTRAK**

Sistem kuasa adalah satu sistem yang amat tidak linear dengan beberapa beban saling hubung. Apabila beberapa beban tiba-tiba disambungkan pada hujung pengagihan atau apabila sistem kuasa adalah tertakluk kepada kesilapan; kestabilan sistem akan terganggu. Masalah utama di sini ialah kenduran voltan, pembengkakkan voltan dan faktor kuasa rendah (PF). Pemampas segerak statik (STATCOM) merupakan salah satu sistem peranti penghantaran arus ulang-alik fleksibel (FACTS) yang paling berkesan dimana ianya boleh menyuntik atau menyerap kuasa reaktif yang sepatutnya untuk mendapatkan semula reliabiliti sistem yang disambungkan dengan grid sekiranya terdapat gangguan yang dinyatakan. Litar STATCOM terdiri daripada litar kawalan, pengubah sumber voltan (VSC), dan teknik PWM. Prestasi STATCOM ini bergantung terutamanya pada ketepatan dan kepantasan isyarat ralat (input unit kawalan) yang diimbangi. Pelbagai variasi pengawalan untuk litar kawalan STATCOM telah dicadangkan untuk mengawal prestasinya, rangkaian saraf buatan (ANN) berdasarkan litar kawalan STATCOM adalah penyelesaian dominan dan liberal untuk meningkatkan prestasi STATCOM dalam tempoh gangguan yang berbeza. Penyelidikan terkini sedang melatih STATCOM berdasarkan ANN untuk menangani satu atau dua kes gangguan, yang memberi kesan STATCOM yang lemah dan tidak boleh direalisabiliti semasa tempoh gangguan yang boleh berlaku pada operasi harian biasa, yang mana STATCOM akan berfungsi dengan realibiliti jika ANN dilatih dengan pelbagai keadaan operasi yang berbeza. Selain itu, walaupun ruang vektor PWM (SVPWM) yang digunakan dengan STATCOM ialah kaedah PWM termaju dan mungkin yang terbaik di antara semua teknik PWM, namun litar SVPWM yang digunakan pada masa ini dianggap rumit kerana ia memerlukan masa untuk mengubah dan mengenal sektor kawasan. Selain itu, walaupun teknik PWM dan VSC adalah sebahagian daripada litar STATCOM, terdapat kekurangan kajian tentang kesan tahap VSC dan pengubah frekuensi atas prestasi peningkatandan masa tindak balas semasa menangani gangguan. Dalam tesis ini, satu pendekatan yang dibangunkan untuk litar STATCOM telah diperkenalkan. Litar STATCOM yang dicadangkan adalah litar yang diubahsuai SVPWM untuk mengurangkan kerumitan pelaksanaan dalam teknik konvensional, dengan itu meminimumkan saiz isipadu, dan realibiliti unit kawalan ANN yang mampu meningkatkan prestasi dan masa tindak balas dari segi meningkatkan magnitud voltan, amplitud faktor kuasa (PF) dan Jumlah Gangguan Harmonik (THD). Semasa STATCOM dengan kehadiran lima jenis gangguan, iaitu kenduran voltan (kes kerosakan SLG dan LL), pembengkakkan voltan, beban PF yang tertinggal dan beban PF utama. Selain itu, tesis ini membentangkan ciri-ciri faktor yang mempengaruhi (tahap VSC dan pengubah frekuensi) yang meningkatkan prestasi STATCOM dan masa tindak balasnya sambil menangani gangguan yang disebutkan di atas. Hasil simulasi menunjukkan bahawa litar STATCOM yang dibangunkan dapat meningkatkan voltan dan PF dengan cepat dalam masa 0.02 saat dengan THD kurang daripada 5% semasa semua gangguan. Selain itu, keputusan perubahan faktor dari sudut tahap VSC dan pengubah frekuensi telah membuktikan kemungkinan peningkatan masa tindak balas dan prestasi STATCOM, di mana masa tindak balas dan peningkatan voltan bas meningkat apabila STATCOM tahap VSC 5 berbanding tahap VSC 3. Sebaliknya, masa tindak balas berkurangan tanpa peningkatan voltan apabila pengubah frekuensi meningkat, manakala amplitud PF dan nilai THD dipertingkatkan apabila tahap VSC dan pengubah frekuensi meningkat.

## ABSTRACT

The power system is an extremely non-linear system with several interconnected loads. When several loads are suddenly connected at distribution ends or when the power system is subjected to the fault, the stability of the system will be disturbed. The major problems here are the voltage sag, voltage swell and low power factor (PF). A static synchronous compensator (STATCOM) is one of the most effective flexible alternating current transmission systems (FACTS) device that can inject or absorb proper reactive power to retrieve the reliability of the grid-connected systems in presence of mentioned disturbances. STATCOM circuit comprises a control circuit, voltage source converter (VSC), and PWM technique. The STATCOM performance is mainly relying on how accurately and quickly the error signal (input of control unit) is compensated. Various controllers for STATCOM control circuit have been proposed to regulate its performance, artificial neural network (ANN)- based STATCOM control circuit is the dominant and liberal solution for enhancing STATCOM performance during the period of different disturbances. The recent researches are training ANN-based STATCOM upon tackling one or two case of disturbances, which leads to creating a weak and unreliable STATCOM during the period of other disturbances that could happen through normal daily operations, whereby the STATCOM will work in reliability if ANN trains on a different range of operating states. Also, although space vector PWM (SVPWM) that uses with STATCOM is an advanced PWM method and possibly the best among all the PWM techniques, the currently used SVPWM circuit is considered complexity since it requires the calculation of switching time and sector identification. Moreover, even-though the PWM technique and VSC are parts of the STATCOM circuit, there is a lack of investigation on the effect of VSC level and switching frequency on enhancement of performance and response time while tackling disturbances. In this thesis, a developed approach for the STATCOM circuit has been introduced. The proposed STATCOM circuit includes a modified circuit of SVPWM to reduce the implementation complexity in conventional technique, hence minimizing volumetric size, and a reliable ANN control unit able to enhance performance and response time in terms of improving voltage magnitude, power factor (PF) amplitude, and STATCOM current's total harmonic distortion (THD) in the presence of five various types of disturbances, which are voltage sag ( SLG and LL fault case), voltage swell, lagging PF load, and leading PF load. Also, this thesis presented the characteristic responses of affecting factors (VSC level and switching frequency) that enhances STATCOM performance and its response time while tackling aforementioned disturbances. The simulation outcomes showed that the developed STATCOM circuit was able to enhance voltage and PF rapidly in 0.02 sec with THD less than 5% during all disturbances. Moreover, the results of changing the factors from the point of VSC level and switching frequency have proven the possibility of enhancing response time and performance of STATCOM, whereby the response time and improvement in bus voltage increase when the STATCOM based on 5-level VSC rather than 3-level VSC. In contrast, response time decreases without enhancement in voltage when the switching frequency is raising, whereas the PF amplitude and THD value are enhanced once the VSC level and switching frequency increases.

## **TABLE OF CONTENT**

### **DECLARATION**

### **TITLE PAGE**

<b>ACKNOWLEDGEMENTS</b>	ii
-------------------------	----

<b>ABSTRAK</b>	iii
----------------	-----

<b>ABSTRACT</b>	iv
-----------------	----

<b>TABLE OF CONTENT</b>	v
-------------------------	---

<b>LIST OF TABLES</b>	x
-----------------------	---

<b>LIST OF FIGURES</b>	xii
------------------------	-----

<b>LIST OF SYMBOLS</b>	xviii
------------------------	-------

<b>LIST OF ABBREVIATIONS</b>	xxi
------------------------------	-----

<b>CHAPTER 1 INTRODUCTION</b>	1
-------------------------------	---

1.1    Introduction	1
---------------------	---

1.2    Problem Statement	2
--------------------------	---

1.3    Objectives of research	3
-------------------------------	---

1.4    Scopes of the Research	4
-------------------------------	---

1.5    Significance of the Research	4
-------------------------------------	---

1.6    Structure of the Research	4
----------------------------------	---

<b>CHAPTER 2 LITERATURE REVIEW</b>	6
------------------------------------	---

2.1    Introduction`	6
----------------------	---

2.2    Power Quality	6
----------------------	---

2.3    Problems Related to Power Quality	7
--	---

2.3.1    Voltage Sag	7
----------------------	---

2.3.2    Voltage Swell	8
------------------------	---

2.3.3	Harmonics	10
2.3.4	Power Factor	11
2.4	Classification of Power Quality Issues	12
2.5	Mitigation of Power Quality Problems Using Facts Devices	14
2.6	Control Methods of Shunt Converters for FACTS Applications	18
2.6.1	Sinusoidal PWM (SPWM)	18
2.6.2	Space Vector PWM (SVPWM)	18
2.6.3	Selective Harmonic Elimination PWM (SHEPWM)	21
2.6.4	Hysteresis Current Control (HCC)	21
2.7	Multilevel VSC Topology	22
2.7.1	Diode-Clamped Multilevel Converter	23
2.7.2	Flying Capacitor Multilevel Converter	23
2.7.3	Cascaded Multilevel Converters with Separated DC Sources	23
2.7.4	Comparison among Multilevel Converters	25
2.8	Factors Affecting Power Quality of VSC Output	26
2.8.1	Topology of VSC	26
2.8.2	Switching Frequency	27
2.9	Attenuation of VSC Harmonics Using Filters	27
2.9.1	L Filter	28
2.9.2	LC Filter	28
2.9.3	LCL Filter	28
2.9.4	Filters Design	29
2.10	STATCOM	29
2.11	PI Control Unit	32
2.12	ANN Control Unit	34
2.12.1	Back-propagation Method	35

2.12.2	Neural Network Transfer Function	36
2.13	Strengths and Weaknesses of PWM Techniques and Control Units For STATCOM	37
2.14	Previous Research	38
2.15	Summary of previous research	43
<b>CHAPTER 3 METHODOLOGY</b>		<b>54</b>
3.1	Introduction	54
3.2	Stages of Research	56
3.3	Configuration of Power System and proposed STATCOM Circuit	57
3.3.1	Cascaded 3 and 5-level VSC	59
3.3.2	Modified Circuit of SVPWM Technique	61
3.3.3	STATCOM Control Circuit	65
3.4	PI Controller Design	73
3.5	ANN Controller Design	75
3.5.1	Stage-1: Define and organize data of input and target	77
3.5.2	Stage-2: Create neural network	77
3.5.3	Stage-3: Train neural network	78
3.5.4	Stage-4: Generate block of ANN control	81
3.6	Flowchart of How the investigation of the effect of Affecting Factors on Performance and Response Time of STATCOM	83
3.7	Summary	84
<b>CHAPTER 4 RESULTS AND DISCUSSION</b>		<b>85</b>
4.1	Introduction	85
4.2	Simulation Model of Power System with STATCOM in Matlab/Simulink	85
4.2.1	Power System Description	85

4.2.2	STATCOM Structure	87
4.3	Simulation Results of Cascaded 3-Level VSC STATCOM Based on PI and ANN controller.	87
4.3.1	Performance and RT of STATCOM During Voltage Sag Period	87
4.3.2	Performance and RT of STATCOM During Voltage Swell Period	96
4.3.3	Performance and RT of STATCOM During Lagging Power Factor Load (Inductive Load) Period	101
4.3.4	Performance and RT of STATCOM During Leading Power Factor Load (Capacitive Load) Period	103
4.3.5	Summary of Cascaded 3-level VSC STATCOM Performance Results	107
4.4	Simulation Results of Cascaded 5-Level VSC STATCOM Based on PI and ANN controller.	109
4.4.2	Performance and RT of STATCOM During Voltage Swell Period	116
4.4.3	Performance and RT of STATCOM During Lagging Power Factor Load (Inductive Load) Period	119
4.4.4	Performance and RT of STATCOM During leading Power Factor Load (Capacitive Load) Period	121
4.4.5	Summary of Cascaded 5-level VSC STATCOM Performance Results	123
4.5	Comparison of Proposed STATCOM with Other Existing STATCOM	124
4.6	Effect of Affecting Factors on Performance and Response Time of Cascaded Multilevel VSC STATCOM.	127
4.6.1	Effect of VSC Level on Performance and Response Time of STATCOM	127
4.6.2	Effect of Switching Frequency on Performance and Response Time of STATCOM.	129
4.7	Analysis of STATCOM Performance and Its Response Time under Different Design Parameters	133

4.8 Summary	133
<b>CHAPTER 5 CONCLUSION</b>	<b>135</b>
5.1 Introduction	135
5.2 Conclusion	135
5.3 Research Contributions	136
5.4 Recommendations for Future Work	137
<b>REFERENCES</b>	<b>138</b>
<b>APPENDICES</b>	<b>146</b>
<b>APPENDIX A: MODES OF SWITCHING SEQUENCE FOR CASCADED H-BRIDGE THREE AND FIVE-LEVEL</b>	<b>146</b>
<b>APPENDIX B: MODELED MATLAB CIRCUIT FOR STATCOM STRUCTURE</b>	<b>148</b>
<b>APPENDIX C: THD VALUE OF BUS-3 (PCC) VOLTAGE DURING PERIOD OF VOLTAGE SAG (CASE OF SLG AND LL FAULT)</b>	<b>154</b>
<b>APPENDIX D: ACTIVE AND REACTIVE POWER, TRANSFERRED BETWEEN CASCADED MULTILEVEL VSC STATCOM AND IEEE 3-BUS SYSTEM.</b>	<b>157</b>
<b>LIST OF PUBLICATIONS</b>	<b>160</b>

## REFERENCES

- Ahmad, M. T., Kumar, N., & Singh, B. (2017). Generalised neural network-based control algorithm for DSTATCOM in distribution systems. *IET Power Electronics*, 10(12), 1529-1538.
- Alatshan, M. S., AlHamrouni, I., Sutikno, T., & Jusoh, A. (2020). Improvement of the performance of STATCOM in terms of voltage profile using ANN controller. *Int J Pow Elec & Dri Syst ISSN*, 2088, 8694.
- Anooja, C. L., & Leena, N. (2013). Passive Filter For Harmonic Mitigation Of Power Diode Rectifier And SCR Rectifier Fed Loads. International Journal of Scientific & Engineering Research, 4(6).
- Arpaia, P. (2014). Power measurement. Measurement, Instrumentation, and Sensors Handbook: Electromagnetic, optical, radiation, chemical, and biomedical measurement, 2, 1.
- Ashtekar, Y. R., Mude, A. A., & Khubalkar, S. A. (2018, January). Power quality improvement by using modular multilevel cascade converter based STATCOM. In *2018 2nd International Conference on Inventive Systems and Control (ICISC)* (pp. 169-173). IEEE.
- Augustine, A., Paul, E., Prakash, R. D., Balakrishna, B. M., & Xavier, R. (2016, March). Voltage regulation of STATCOM using fuzzy self tuning PI controller. In *Circuit, Power and Computing Technologies (ICCPCT), 2016 International Conference on* (pp. 1-7). IEEE.
- Balavar, M. (2012). Using neural network to control STATCOM for improving transient stability.
- Behrouzian, E. (2017). On control of cascaded H-bridge converters for STATCOM applications. Chalmers University of Technology.
- Biabani, M. A. K. A., Ali, S. M., & Jawed, A. (2016, October). Enhancement of power quality in distribution system using D-Statcom. In *Signal Processing, Communication, Power and Embedded System (SCOPES), 2016 International Conference on* (pp. 2093-2098). IEEE.
- Blorfan, A., Wira, P., Flieller, D., Sturtzer, G., & Mercklé, J. (2011, November). A three-phase hybrid active power filter with photovoltaic generation and hysteresis current control. In *IECON 2011-37th Annual Conference of the IEEE Industrial Electronics Society* (pp. 4316-4321). IEEE.
- Carrasco, J. M., Franquelo, L. G., Bialasiewicz, J. T., Galván, E., PortilloGuisado, R. C., Prats, M. M., ... & Moreno-Alfonso, N. (2006). Power-electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Transactions on industrial electronics*, 53(4), 1002-1016.
- Chamundeswari, K., & Raju, Y. B. (2017, November). Adaptive fuzzy control strategy of STATCOM for the regulation of voltage. In *2017 7th International*

- Conference on Communication Systems and Network Technologies (CSNT)(pp. 309-313). IEEE.
- Chen, H., & Zhao, H. (2016). Review on pulse-width modulation strategies for common-mode voltage reduction in three-phase voltage-source inverters. *IET Power Electronics*, 9(14), 2611-2620.
- Christian, L. E., Putranto, L. M., & Hadi, S. P. (2019, August). Design of Microgrid with Distribution Static Synchronous Compensator (D-STATCOM) for Regulating the Voltage Fluctuation. In *2019 IEEE 7th International Conference on Smart Energy Grid Engineering (SEGE)* (pp. 48-52). IEEE.
- Colak, I., Kabalci, E., & Bayindir, R. (2011). Review of multilevel voltage source inverter topologies and control schemes. *Energy Conversion and Management*, 52(2), 1114-1128.
- Corzine, K., & Familiant, Y. (2002). A new cascaded multilevel H-bridge drive. *IEEE Transactions on power electronics*, 17(1), 125-131.
- Dahiya, A. K., Dahiya, R., & Kothatri, D. P. (2011). A Comparison of ANN and Fuzzy Controlled STATCOM-SMES for Improving Transient Stability and Frequency Stabilization of SMIB. *MIT International Journal of Electrical and Instrumentation Engineering*, 1(2), 55-63.
- Eckel, H.G. and Runge, J. (2011) Comparison of the semiconductor losses in self commutated inverter topologies for HVDC. *Power Electronics and Applications (EPE 2011)*, Proceedings of the 2011–14th European Conference on, 30 August 2011–1 September 2011, pp. 1–8.
- Eriksson, E. (2017). Distribution grid capacity for reactive power support.
- Emam, A. S., Azmy, A. M. R., & Rashad, E. E. M. (2019, December). Model Predictive Control-based Optimal STATCOM Operation for Mitigating Voltage Sag in Electric Networks Comprising Large Wind Farms. In *2019 21st International Middle East Power Systems Conference (MEPCON)* (pp. 371-376). IEEE.
- Escalante, M. F., Vannier, J. C., & Arzandé, A. (2002). Flying capacitor multilevel inverters and DTC motor drive applications. *IEEE Transactions on Industrial Electronics*, 49(4), 809-815.
- Fuchs, E., & Masoum, M. A. (2011). Power quality in power systems and electrical machines. Academic press.
- Gunasekari, R., Dhanalakshmi, R., & Raja, P. K. (2016, January). Power flow stability improvement in renewable hybrid power system using SVPWM technique. In *2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE)* (pp. 1-5). IEEE.
- Gupta, S. (2014). Comprehensive STATCOM Control For Distribution And Transmission System Applications.

- Haghipour, S., & Sokouti, B. (2009). Approaches in RSA cryptosystem using artificial neural network. *Oriental journal of computer science and technology*, 2(1), 11-17.
- Hammad, A. E. (1996). Comparing the voltage control capabilities of present and future var compensating techniques in transmission systems. *IEEE Transactions on Power Delivery*, 11(1), 475-484.
- Hamoud, F., Doumbia, M. L., & Chériti, A. (2015, November). Power factor improvement in WECS using cascade PI control of passive damping LCL-filter. In Sustainable Mobility Applications, Renewables and Technology (SMART), 2015 International Conference on (pp. 1-7). IEEE.
- Hashempour, M. M., & Lee, T. L. (2017, June). Integrated power factor correction and voltage fluctuation mitigation of microgrid using STATCOM. In Future Energy Electronics Conference and ECCE Asia (IFEEC 2017-ECCE Asia), 2017 IEEE 3rd International (pp. 1215-1219). IEEE.
- Henini, N., Benzerafa, F., & Tlemçani, A. (2015, March). Design and simulation of five-level inverter based DSTATCOM using fuzzy logic. In Renewable Energy Congress (IREC), 2015 6th International (pp. 1-6). IEEE.
- H. Demuth and M. Beale. MATLAB Neural Network Toolbox. Retrieved on 5 April 2013, from <http://www.varpa.org/Docencia/Files/nnet.pdf>
- IEEE Guide for Application and Specification of Harmonic Filters., IEEE Std. 1531-2003
- IEEE Std 1100-2005. (Revision of IEEE Std 1100-1999). IEEE Recommended Practice for Powering and Grounding Electronic Equipment. pp.1-703, 2006.
- Imanishi, T., Nagatomo, Y., Iwasaki, S., Masaki, K., Fujii, T., & Ieda, J. (2014, May). 130MVA-STATCOM for transient stability improvement. In Power Electronics Conference (IPEC-Hiroshima 2014-ECCE-ASIA), 2014 International (pp. 2663-2667). IEEE.
- Ivry, P. M. (2016). *Predicting Stochastic Harmonics of Multiple Converters in a Power System (microgrid)* (Doctoral dissertation, University of Nottingham).
- Jose, C., Perez, S., & Todeschini, G. (2018, August). Impact of STATCOM Design Parameters on Voltage Distortion at the PCC. In *2018 IEEE Power & Energy Society General Meeting (PESGM)* (pp. 1-5). IEEE.
- Jovcic, D., & Pillai, G. N. (2005). Analytical modeling of TCSC dynamics. *IEEE Transactions on Power Delivery*, 20(2), 1097-1104.
- Kamel, K., Laid, Z., Abdallah, K., & Anissa, K. (2018, March). Comparative Analysis on Shunt Active Power Filter Based PQ Control Strategy Using HCC, SPWM and SVPWM Switching Signal Generation Techniques. In *2018 15th International Multi-Conference on Systems, Signals & Devices (SSD)* (pp. 936-940). IEEE.

- Karare, S., & Harne, V. M. (2017, April). Modelling and simulation of improved operation of D-STATCOM in distribution system for power quality improvement using MATLAB Simulink tool. In Electronics, Communication and Aerospace Technology (ICECA), 2017 International conference of (Vol. 2, pp. 346-350). IEEE.
- Karthikeyan, K., & Sreenivasan, R. (2017, April). Analysis of power system stability using fuzzy-PID based STATCOM-controller. In Electrical, Instrumentation and Communication Engineering (ICEICE), 2017 IEEE International Conference on(pp. 1-6). IEEE.
- Kaur, S., Singh, A., & Khela, R. S. (2015). Load Flow Analysis of IEEE-3 bus system by using Mipower Software. *International Journal of Engineering Research & Technology (IJERT)*, 4(03), 9-16.
- Kumar, T. A., & Rao, L. S. (2017, April). Improvement of power quality of distribution system using ANN-LMBNN based D-STATCOM. In Power and Advanced Computing Technologies (i-PACT), 2017 Innovations in (pp. 1-6). IEEE.
- Law, K. H., Dahidah, M. S., Konstantinou, G. S., & Agelidis, V. G. (2012, June). SHE-PWM cascaded multilevel converter with adjustable DC sources control for STATCOM applications. In Power Electronics and Motion Control Conference (IPEMC), 2012 7th International (Vol. 1, pp. 330-334). IEEE.
- Li, Z., Wang, J., Zhang, F., Li, B., Qi, L., Xu, P., & Xia, X. (2011, October). Study of harmonic elimination in switching devices in STATCOM. In Electric Power Equipment-Switching Technology (ICEPE-ST), 2011 1st International Conference on (pp. 224-228). IEEE.
- Lin, W. M., Zhan, T. S., & Tsay, M. T. (2004). Multiple-frequency three-phase load flow for harmonic analysis. *IEEE transactions on Power Systems*, 19(2), 897-904.
- Lou, H., Mao, C., Wang, D., Lu, J., & Wang, L. (2014). Fundamental modulation strategy with selective harmonic elimination for multilevel inverters. *IET Power Electronics*, 7(8), 2173-2181.
- Madhusudan, R., & Rao, G. R. (2012, March). Modeling and simulation of a distribution STATCOM (D-STATCOM) for power quality problems-voltage sag and swell based on Sinusoidal Pulse Width Modulation (SPWM). In Advances in Engineering, Science and Management (ICAESM), 2012 International Conference on (pp. 436-441). IEEE.
- Majed, A., & Salam, Z. (2015, October). Multilevel D-STATCOM for sag and swell mitigation using modulation index control. In 2015 IEEE Conference on Energy Conversion (CENCON) (pp. 187-192). IEEE.
- Manjrekar, M. D., & Lipo, T. A. (1998, February). A hybrid multilevel inverter topology for drive applications. In Applied Power Electronics Conference and Exposition, 1998. APEC'98. Conference Proceedings 1998., Thirteenth Annual (Vol. 2, pp. 523-529). IEEE.

- Masood, T., Aggarwal, R. K., Qureshi, S. A., & Khan, R. A. J. (2010, March). STATCOM model against SVC control model performance analyses technique by matlab. In International Conference on Renewable Energies and Power Quality (p. 8).
- Mauboy, E. R., Lie, T. T., & Anderson, T. N. (2015). Stability enhancement of a power system with wind generation using ANN based STATCOM.
- Meynard, T. A., & Foch, H. (1992, June). Multi-level conversion: high voltage choppers and voltage-source inverters. In Power Electronics Specialists Conference, 1992. PESC'92 Record., 23rd Annual IEEE (pp. 397-403). IEEE.
- Milasi, R. M., Lynch, A. F., & Li, Y. W. (2013). Adaptive control of a voltage source converter for power factor correction. IEEE Transactions on Power Electronics, 28(10), 4767-4779.
- Mittal, C., & Srivastava, S. (2020, July). Comparison of ANN and ANFIS Controller Based Hysteresis Current Control Scheme of DSTATCOM for Fault Analysis to Improve Power Quality. In *2020 International Conference on Electronics and Sustainable Communication Systems (ICESC)* (pp. 149-156). IEEE.
- Moghbel, M., & Masoum, M. A. (2016, September). D-STATCOM based on hysteresis current control to improve voltage profile of distribution systems with PV solar power. In Power Engineering Conference (AUPEC), 2016 Australasian Universities (pp. 1-5). IEEE.
- Moghbel, M. (2016). *Online Control of Modular Active Power Line Conditioner to Improve Performance of Smart Grid*(Doctoral dissertation, Curtin University).
- Mohan, N., & Undeland, T. M. (2007). Power electronics: converters, applications, and design. John Wiley & Sons.
- Mohanty, K. B., & Pati, S. (2016, April). Fuzzy logic controller based STATCOM for voltage profile improvement in a micro-grid. In Systems Conference (SysCon), 2016 Annual IEEE (pp. 1-6). IEEE.
- Morati, M., Girod, D., Terrien, F., Peron, V., Poure, P., & Saadate, S. (2016). Industrial 100-MVA EAF voltage flicker mitigation using VSC-based STATCOM with improved performance. IEEE Transactions on Power Delivery, 31(6), 2494-2501.
- Mukassir, S. M., Amer, G., Mudassir, S. M. M., & Kabra, P. (2016, March). Power quality improvement using a novel D-STATCOM-control scheme for linear and non-linear loads. In Electrical, Electronics, and Optimization Techniques (ICEEOT), International Conference on (pp. 2147-2153). IEEE.
- Mukherjee, P., & Rao, V. V. (2016, December). Power system transient stability with SMES controlled by Artificial Intelligent Techniques. In *2016 IEEE International WIE Conference on Electrical and Computer Engineering (WIECON-ECE)* (pp. 108-111). IEEE.
- Nabae, A., Takahashi, I., & Akagi, H. (1981). A new neutral-point-clamped PWM inverter. IEEE Transactions on industry applications, (5), 518-523.

- Norouzi, A. H., & Sharaf, A. M. (2003, September). A novel control scheme for the STATCOM stability enhancement. In Transmission and Distribution Conference and Exposition, 2003 IEEE PES (Vol. 1, pp. 24-29). IEEE.
- Patane, A. R., Jadhav, H. T., & Maske, P. F. (2016, April). A 13-level inverter with D-STATCOM capability for distributed energy systems. In Computation of Power, Energy Information and Commuincation (ICCPEIC), 2016 International Conference on (pp. 694-700). IEEE.
- Patil, K. (2013). Harmonic Analysis of Sine PWM and hysteresis current controller. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, 2(11).
- Purushothaman, V., & Mathew, B. K. (2014, July). Voltage sag correction in distribution system using DSTATCOM with PI and Hysteresis controllers. In Emerging Research Areas: Magnetics, Machines and Drives (AICERA/iCMMMD), 2014 Annual International Conference on (pp. 1-6). IEEE.
- Raja, S. R., Rajendran, S., & Kannan, S. (2015, March). d-qControl based statcom for reactive power compensation. In Circuit, Power and Computing Technologies (ICCPCT), 2015 International Conference on (pp. 1-6). IEEE.
- Rajasekaran, D., Dash, S. S., Mayilvaganan, A. B., Subramani, C., & Krishnan, S. (2013). Artificial Neural Network Controller Based Distribution Static Compensator For Voltage Sag Mitigation. *American Journal Of Applied Sciences*, 10(7), 688.
- Rashad, A., Kamel, S., Jurado, F., Abdel-Nasser, M., & Mahmoud, K. (2019). ANN-based STATCOM tuning for performance enhancement of combined wind farms. *Electric Power Components and Systems*, 47(1-2), 10-26.
- Reddy, C. L., Kumar, P. S., Sushama, M., & Babu, N. S. (2015, November). A five level cascaded H-bridge multilevel STATCOM. In Microelectronics and Electronics (PrimeAsia), 2015 IEEE Asia Pacific Conference on Postgraduate Research in (pp. 36-41). IEEE.
- Reddy, D. M., & Gowrimanohar, T. (2014, July). Optimal hybrid modulation scheme for 11-level CMC based DSTATCOM for power quality improvement. In Current Trends in Engineering and Technology (ICCTET), 2014 2nd International Conference on (pp. 296-303). IEEE.
- Reddy, G. M., & Gowrimanohar, T. (2016, October). Fuzzy controller based multi level inverter STATCOM for grid connected wind energy conversion system. In Signal Processing, Communication, Power and Embedded System (SCOPES), 2016 International Conference on (pp. 742-747). IEEE.
- Renault, A., Ayala, M., Pacher, J., Comparatore, L., Gregor, R., & Rivera, M. (2019, November). Analysis of H-Bridge STATCOM with Fault Phase Controlled by Modulated Predictive Current Control. In 2019 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON) (pp. 1-5). IEEE.

- Rockhill, A. A., Liserre, M., Teodorescu, R., & Rodriguez, P. (2011). Grid-filter design for a multimegawatt medium-voltage voltage-source inverter. *IEEE Transactions on Industrial Electronics*, 58(4), 1205-1217.
- Saha, A., Ahmad, S., Soma, A. A., & Chowdhury, M. Z. A. (2017, September). Modelling and control of STATCOM to ensure stable power system operation. In *Advances in Electrical Engineering (ICAEE), 2017 4th International Conference on* (pp. 12-17). IEEE.
- Sankaran, C. (2001). Power quality. LLC press.
- Sao, C. K., Lehn, P. W., Iravani, M. R., & Martinez, J. A. (2002). A benchmark system for digital time-domain simulation of a pulse-width-modulated D-STATCOM. *IEEE Transactions on Power Delivery*, 17(4), 1113-1120.
- Saravanan A, Selvakumar G, Maheswari A, Muthulakshmi P, Mohamed Haroon K. H. (2017). D-STATCOM for Power Quality Improvement Trained by ANN, *International Journal of Scientific Engineering and Research (IJSER)*, 5(2), 37 – 42.
- Sarvghadi, P., Ghazi, R., & Heydari-doostabad, H. (2017, February). A new approach for predictive control system design to improve power factor and reduce harmonic current injection using D-STATCOM. In *Power Electronics, Drive Systems & Technologies Conference (PEDSTC), 2017 8th* (pp. 401-406). IEEE.
- Schauder, C., & Mehta, H. N. (1993, July). Vector analysis and control of advanced static VAR compensators. In *IEE Proceedings C (Generation, Transmission and Distribution)* (Vol. 140, No. 4, pp. 299-306). IET Digital Library.
- Sedaghati, R., Afrooz, N. M., Nemati, Y., Rohani, A., Toorani, A. R., Javidtash, N., ... & Islam, M. R. (2013). A Survey of Voltage Sags and Voltage Swells Phenomena in Power Quality Problems. *Meta*, 1(2).
- Shahid, U., Shafique, A., Khan, I., Kashif, R., & Abdul, S. (2016). Implementation Of Multilevel Inverter Using Space Vector Pulse Width MODULATION. *Science International*, 28(3).
- Shinde, S. U., Sharmila, M., Patil, R. S., & Malkhede, D. V. (2016, March). Performance comparison of PI & ANN based STATCOM for 132 KV transmission line. In *Electrical, Electronics, and Optimization Techniques (ICEEOT), International Conference on* (pp. 2730-2734). IEEE.
- Singh, G. (2013, June). Electric Power Quality-Issues, Effects And Mitigation.
- Singh, P. K., & Dahiya, A. K. (2018, March). Analysis Modelling & Simulation of VSC based D-Statcom for Reactive VAR Compensation. In *2018 International Conference on Current Trends towards Converging Technologies (ICCTCT)*(pp. 1-6). IEEE.

- Slawinski, M., Villbusch, T., Heer, D., & Buschkuehle, M. (2016, May). Demonstration of superior SiC MOSFET Module performance within a Buck-Boost Conversion System. In PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (pp. 1-8). VDE.
- Sumi, Y., Harumoto, Y., Hasegawa, T., Yano, M., Ikeda, K., & Matsuura, T. (1981). New static var control using force-commutated inverters. IEEE Transactions on Power Apparatus and Systems, (9), 4216-4224.
- Sumper, A., & Galceran-Arellano, S. (2008). Monitoring Power Quality. Handbook of power quality, 445-461.
- Tareen, W. U. K., Aamir, M., Mekhilef, S., Nakaoka, M., Seyedmahmoudian, M., Horan, B., ... & Baig, N. A. (2018). Mitigation of power quality issues due to high penetration of renewable energy sources in electric grid systems using three-phase APF/STATCOM technologies: A review. *Energies*, 11(6), 1491.
- Titus, S., Vinothbabu, B. J., & Nishanth, I. M. A. (2013). Power System Stability Enhancement Under Three Phase Fault with FACTS Devices TCSC, STATCOM and UPFC. *IJITR*, 1(1), 066-073.
- Tiwa, S. (2017). Space vector pulse width modulation based two level inverter. *Research Journal of Engineering Sciences*, 6(8), 8-12.
- Tolbert, L. A., Peng, F. Z., Cunningham, T., & Chiasson, J. N. (2002). Charge balance control schemes for cascade multilevel converter in hybrid electric vehicles. *IEEE Transactions on Industrial Electronics*, 49(5), 1058-1064.
- Tolbert, L. M., & Peng, F. Z. (2000). Multilevel converters as a utility interface for renewable energy systems. In Power Engineering Society Summer Meeting, 2000. IEEE (Vol. 2, pp. 1271-1274). IEEE.
- Tolbert, L. M., Peng, F. Z., & Habetler, T. G. (2000). A multilevel converter-based universal power conditioner. *IEEE Transactions on Industry Applications*, 36(2), 596-603.
- Varma, B. K., Vineesha, G., Sasank, K., & Yasavvi, P. N. (2012, March). Simulated control system design of a multilevel STATCOM for reactive power compensation. In Advances in Engineering, Science and Management (ICAESM), 2012 International Conference on (pp. 257-263). IEEE.
- Vasudevamurthy, S. (2013). "Swetha" Simulation And Comparison Of Space Vector Pulse Width Modulation For Three Phase Voltage Source Inverter. *International Journal of Engineering Research & Technology*, 2(5).
- Xu, Y., & Li, F. (2014). Adaptive PI control of STATCOM for voltage regulation. *IEEE transactions on power delivery*, 29(3), 1002-1011.
- Yazdani, A., & Iravani, R. (2010). Voltage-sourced converters in power systems: modeling, control, and applications. John Wiley & Sons.