CONTROL STRATEGIES FOR UNIFIED POWER QUALITY CONDITIONER TO MITIGATE VOLTAGE SAG DUE TO LARGE MOTOR STARTING DURING FAULT

SHARIFAH FAZILAH BT WAN ABDUL HAMID

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical Power)

School of Electrical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

FEBRUARY 2022

DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Dr. AHMAD SAFAWI BIN MOKHTAR, for encouragement, guidance, critics and friendship. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Universiti Teknologi Malaysia (UTM) for funding my MSC study. Librarians at UTM, also deserve special thanks for their assistance in supplying the relevant literatures.

My fellow postgraduate student should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family member.

ABSTRACT

As induction motors are the heart of industrial industries for electromechanical conversion, voltage sags during large motor starting have become the most frequent Power Quality (PQ) problem. Induction motors are one of the most prominent sources of voltage sag problem. These disturbances can cause loads that re sensitive to voltage in buildings or factories to malfunction, contributing to the deterioration of power quality in industrial power systems or utility. The Unified Power Quality Conditioner (UPQC), which incorporates a series and shunt active filter capable of compensating supply voltage sag, swell, current imbalance, harmonics, and reactive power, is one of the devices that will combat voltage sag occurrence. The goal of this project is to develop several control techniques for the UPQC in order to overcome voltage sag caused by large motor starting during a failure. UPQC's Active Power Filters (APFs) are linked to the system through series and shunt transformers. The voltage swell is then injected through the source, and various sorts of faults are simulated to produce the voltage sag at the Point of Common Coupling (PCC). The switching pulses are created using a Proportional Integral (PI) controller, which compares the observed load voltages to the reference voltages. The measured source currents, on the other hand, are compared to their reference values, and the shunt APF switching pulses are generated using a hysteresis band controller. The suggested model is implemented in MatLAB Simulink and is anticipated to include voltage sag/swell compensation capabilities, as well as the capacity to maintain load voltage constant.

ABSTRAK

Disebabkan motor aruhan merupakan nadi industri perindustrian untuk penukaran elektromekanik, kendur voltan semasa permulaan motor besar telah menjadi masalah Kualiti Daya (PQ) yang paling kerap. Motor aruhan adalah salah satu sumber masalah voltan kendur yang paling ketara. Gangguan ini boleh menyebabkan beban yang sensitif terhadap voltan di bangunan atau kilang untuk tidak berfungsi, menyumbang kepada kemerosotan kualiti kuasa dalam sistem kuasa elektrik atau utiliti. Perapi Kualiti Kuasa Bersatu (UPQC), yang menggabungkan penapis aktif siri dan selari yang mampu mengimbangi voltan bekalan, bengkak, ketidakseimbangan semasa, harmonik, dan daya reaktif, adalah salah satu peranti yang akan memerangi berlakunya penurunan voltan. Matlamat projek ini adalah untuk mengembangkan beberapa teknik kawalan untuk UPQC untuk mengatasi kendur voltan yang disebabkan oleh motor besar bermula semasa kegagalan. Penapis Daya Aktif UPQC (APF) dihubungkan ke sistem melalui transformer siri dan selari. Pembengkakan voltan kemudian disuntikkan melalui sumbernya, dan pelbagai jenis kesalahan disimulasikan untuk menghasilkan kendur voltan pada Titik Biasa (PCC). Denyut pensuisan dibuat menggunakan pengawal Proportional Integral (PI), yang membandingkan voltan beban yang dibandingkan dengan voltan rujukan. Arus sumber yang diukur, sebaliknya, dibandingkan dengan nilai rujukannya, dan denyut beralih APF shunt dihasilkan menggunakan pengawal jalur histeresis. Model yang disarankan dilaksanakan dalam MatLAB Simulink dan diharapkan dapat merangkumi kemampuan pampasan kendur / bengkak voltan, serta kemampuan untuk mengekalkan voltan beban tetap.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

PQ	-	Power Quality
UPQC	-	Unified Power Quality Conditioner
PCC	-	Point of Common Coupling
APF	-	Active Power Filters
PI	-	Proportional Integral
RMS	-	Root Mean Square
SAF	-	Series Active Filter
PAF	-	Parallel Active Filter
IEEE	-	Institute of Electrical and Electronics Engineers
SVC	-	Static VAR Compensators
DSTATCOM	-	Distribution Static Compensators
DVR	-	Dynamic Voltage Restorers
SHAF	-	Shunt Active Filter
SEAF	-	Series Active Filter
VSI	-	Voltage Source Inverter
CSC		Current Source Converter
VSC		Voltage Source Converter

CHAPTER 1

INTRODUCTION

1.1 Overview

In today's industrialized world, electrical power networks have been contaminated by undesired voltage and current fluctuations. Power quality concerns arise largely as a result of the ever-increasing sources of disturbances that occur in linked power grids, which comprise vast numbers of power sources, transmission lines, transformers, and loads, as well as environmental disturbances such as lightning strikes. Voltage quality has become increasingly essential as the quantity of sensitive devices in distribution networks grows [1].

Voltage disturbances, which include voltage sags, swells, harmonics, transients, unbalances, and flickers, are the most prevalent power quality (PQ) concern in industrial distribution systems. [2]. However, numerous power quality assessments have found that voltage sags account for more than 90% of all voltage-related incidents. [3-4]. Short-circuit failures, such as a single-line-to-ground fault in a power system, and the start-up of large-capacity motors, produce voltage sag, resulting in huge financial output losses.

Based on the aforementioned power quality concerns, the focus of this study will be on the consequences of voltage sag during induction motor start-up and three-phase-to-ground fault. Voltage sag is defined as a brief reduction in the RMS ac voltage (10%–90% of the nominal voltage) at a power frequency of 0.5 cycles to a few seconds, according to IEEE regulation [5]. Failures such as a three-phase-to-ground fault in a power system, and the start-up of large-capacity motors, produce voltage sag, resulting in huge financial output losses. Depending on the degree and length of the sag, the effect generated by this disruption on industrial customers varies. As a result, protecting sensitive loads from voltage sags is a critical concern. [6].

1.2 Problem Statement

Induction motors have been widely utilized in industry in comparison to other rotating machinery, however they are considered to be particularly sensitive to voltage sags due to their huge inductances, which might decrease their ride-through capacity. Electromagnetic and electromechanical transients make up the electromagnetic and electromechanical transients of induction motors. The voltage sag phenomenon is generally linked to a fault and its subsequent clearing for a few mains frequency cycles. Thus, the electromagnetic transients of the DV R-motor system are dominating for such a short duration. The electrical torque of the motor (proportional to the square of the RMS supply voltage) decreases during voltage sag. It's also fair to assume that the mechanical speed of the motor remains constant during this time span. The air gap flux will be rebuilt once the voltage sag is eliminated, resulting in a high inrush current. The voltage recovery will be temporarily slowed, following which the motor will accelerate again until it achieves its pre-sag speed. The motor will absorb a considerable current during the re-acceleration. Some sensitive electronics that have survived the sag may be tripped as a result of this post-sag phenomena. In any event, the more complicated sag profile makes the compensating procedure more difficult [7].

1.3 Research Objectives

The objectives of the research are:

1. To investigate the effect of large current motor starting during fault to voltage profile.
2. To apply control strategies for UPQC to mitigate voltage sag occurred due to large current induction motor starting during fault.

1.4 Scopes of projects

The following are the considered scopes of this project:

(a) Proposes UPQC model using MatLAB Simulink..
(b) Only three-phase-to-ground fault is applied.
(c) The developed model only considers to mitigate voltage sags.

1.5 Contribution

Several international organizations' studies demonstrate that the economic losses caused by power quality issues are currently quite substantial, and they argue that a little investment in equipment and processes to improve power quality can result in a significant decrease in these losses. [8]. In this context, developing equipment to improve power quality, such as the UPQC previously mentioned, is critical to ensuring a favourable environment for the efficient running of industries, leading to improved productivity and lowering economic losses resulting from power quality issues. In addition to its capacity to mitigate power quality issues, the UPQC can also measure a variety of electrical signals that might be valuable to other Smart Grid devices.

1.6 Organization of report

This project report consists of five chapters that are organized as below:

Chapter 1 consists of a background overview of the project, problem statements, objectives, scopes and contribution of the project.

Chapter 2 describes the literature review on topics related to the project. The topics include existing related work induction motors, voltage sags, available power quality compensators in the market and state-of-the-art UPQC.

Chapter 3 describes the methodology used in the project by explaining the workflow of the project, tools and software used.

Chapter 4 provides the results and discussions of the project.

Chapter 5 concludes the report with outcomes and future works of the project.

REFERENCES

[1] I. Hunter, “Power quality issues: a distribution company perspective,” *Power Eng. J.*, vol. 15, no. 2, pp. 75–80, 2001.

[2] A. Elnady and M. M. A. Salama, “Unified approach for mitigating voltage sag and voltage flicker using the DSTATCOM,” *IEEE trans. power deliv.*, vol. 20, no. 2, pp. 992–1000, 2005.

[3] W. E. Brumsickle, G. A. Luckjiff, R. S. Schneider, D. M. Divan, and M. F. McGranaghan, “Dynamic sag correctors: cost effective industrial power line conditioning,” in Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No.99CH36370), 2003.

[4] H. Ribeiro, H. Marques, and B. V. Borges, “Characterizing and monitoring voltage transients as problem to sensitive loads,” *Int. j. electr. power energy syst.*, vol. 43, no. 1, pp. 1305–1317, 2012.

[5] IEEE Std. 1159-2009, IEEE Recommended Practice for Monitoring Electric Power Quality, Jun, 2009.

[6] A. Honrubia-Escribano, E. Gómez-Lázaro, A. Molina-García, and J. A. Fuentes, “Influence of voltage dips on industrial equipment: Analysis and assessment,” *Int. j. electr. power energy syst.*, vol. 41, no. 1, pp. 87–95, 2012.

[7] A. Leiria, P. Nunes, A. Morched, and M. T. C. de Barros, “Induction motor response to voltage dips,” *Electric Power Syst. Res.*, vol. 76, no. 8, pp. 676–680, 2006.

[8] “Cost of poor power quality in industrial plants,” in *May 17-18, 2017 Istanbul (Turkey)*, 2017.

[9] M. Aredes, K. Heumann, and E. H. Watanabe, “An universal active power line conditioner,” *IEEE trans. power deliv.*, vol. 13, no. 2, pp. 545–551, 1998.

[10] J. A. Munoz, J. R. Espinoza, L. A. Moran, and C. R. Baier, “Design of a modular UPQC configuration integrating a components economical analysis,” *IEEE trans. power deliv.*, vol. 24, no. 4, pp. 1763–1772, 2009.

[11] K. Palanisamy, J. Sukumar Mishra, I. J. Raglend, and D. P. Kothari, “Instantaneous power theory based Unified Power Quality Conditioner (UPQC),” in *2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India*, 2010.

[12] V. Khadkikar, A. Chandra, A. Barry, and T. Nguyen, “Conceptual study of unified power quality conditioner (UPQC),” in *2006 IEEE International Symposium on Industrial Electronics*, 2006.

[13] A. M. A. Haidar, C. Benachaiba, F. A. F. Ibrahim, and K. Hawari, “Parameters evaluation of Unified Power Quality Conditioner,” in *2011 Ieee International Conference On Electro/Information Technology*, 2011.

[14] M. T. Haque, T. Ise, and S. H. Hosseini, “A novel control strategy for unified power quality conditioner (UPQC),” in *2002 IEEE 33rd Annual IEEE Power Electronics Specialists Conference. Proceedings (Cat. No.02CH37289)*, 2003.

[15] J. Le, Y. Xie, Z. Zhi, and C. Lin, “A nonlinear control strategy for UPQC,” 2008 International Conference on Electrical Machines and Systems, 2008.

[16] A. Mokhtatpour and H. A. Shayanfar, “Power quality compensation as well as power flow control using of unified power quality conditioner,” *in 2011 Asia-Pacific Power and Energy Engineering Conference*, 2011.

[17] Kannan, p.k.mani & Naidu, K. , “Unified power quality conditioner (UPQC) with Pi and hysteresis controller for power quality improvement in distribution systems” in *2015 International Journal of Applied Engineering Research*, 2015.

[18] G. Jianjun, X. Dianguo, L. Hankui, and G. Maozhong, “Unified power quality conditioner (UPQC): the principle, control and application,” in *Proceedings of the Power Conversion Conference-Osaka 2002 (Cat. No.02TH8579)*, 2003.

[19] LMP Forum, "Induction Motor Control Theory." Internet: www.lmpforum.com/inforum, March 16, 2007 [March 27, 2007].

[20] J. Cathey, Electric Machines Analysis and Design Applying MA TLAB, McGraw Hill Series in Electrical and Computer Engineering, New York, 2001.

[21] M.T. Aung, and J. Milanovic, "Analytical Assessment of the effects of Voltage Sags on Induction Motor Dynamic Responses," IEEE St. Petersburg, Russia, Power Tech, Jun. 2005

[22] Goh, H. H., Kok, B. C., & Looi, M. S. (2010). A study of induction motor starting methods in terms of power quality.

[23] El-Gammal, M. A., Abou-Ghazala, A. Y., and El-Shennawy, T. I. (2010). Effects of Voltage Sags on a Refinery with Induction Motors Loads. Iranian Journal of Electrical and Computer Engineering, 9(1), 67-72.

[24] Baggini, A. B. (Ed.). (2008). Handbook of power quality (Vol. 520). Chichester: John Wiley and Sons.

[25] J. C. Das, Power System Harmonics and Passive Filter Designs: Application of Shunt Capacitor Banks. Hoboken, NJ, USA: Wiley-IEEE Press, 2015, pp.872- 102.

[26] H. Jouybari-Moghaddam, T. S. Sidhu, M. R. Dadash Zadeh and P. P. Parikh, "Enhanced fault-location scheme for double wye shunt capacitor banks," IEEE Trans. Power Del., vol. 32, no. 4, pp. 1872-1880, Aug. 2017.

[27] H. L. Santos, J. O. S. Paulino, W. C. Boaventura, L. M. R. Baccarini and M. L. Murta, "Harmonic distortion influence on grounded wye shunt capacitor banks protection: experimental results," IEEE Trans. Power Del., vol. 28, no. 3, pp. 1289-1296, Jul. 2013.

[28] S. Mukhopadhyay, D. Maiti, A. Banerji, S. K. Biswas and N. K. Deb, "A new harmonic reduced three-phase thyristor-controlled reactor for static var compensators," IEEE Trans. Ind. Electron., vol. 64, no. 9, pp. 6898-6907, Sep. 2017.

[29] J. G. Mayordomo, M. Izzeddine and R. Asensi, "Load and voltage balancing in harmonic power flows by means of static var compensators," IEEE Trans. Power Del., vol. 17, no. 3, pp. 761-769, Jul. 2002.

[30] J. G. Singh, S. N. Singh and S. C. Srivastava, "An Approach for Optimal Placement of Static VAr Compensators Based on Reactive Power Spot Price," IEEE Trans. Power Syst., vol. 22, no. 4, pp. 2021-2029, Nov. 2007.

[31] J. H. Tovar-Hernandez, C. R. Fuerte-Esquivel and V. M. Chavez-Ornelas, "Modeling of static VAR's compensators in fast decoupled load flow," IEEE Trans. Power Syst., vol. 20, no. 1, pp. 512-514, Feb. 2005.

[32] S. Biricik and H. Komurcugil, "Optimized sliding-mode control to maximize existence region for single-phase dynamic voltage restorers," IEEE Trans. Ind. Informat., vol. 12, no. 4, pp. 1486–1497, Aug. 2016.

[33] D. M. Vilathgamuwa, P. C. Loh, and Y. Li, "Protection of microgrids during utility voltage sags," IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1427–1436, Oct. 2006.

[34] C. Meyer, R. W. De Doncker, Y. W. Li, and F. Blaabjerg, "Optimized control strategy for a medium-voltage DVR—theoretical investigations and experimental results," IEEE Trans. Power Electron., vol. 23, no. 6, pp. 2746-2754, Nov. 2008.

[35] F. B. Ajaei, S. Afsharnia, A. Kahrobaeian, and S. Farhangi, "A fast and effective control scheme for the dynamic voltage restorer," IEEE Trans. Power Del., vol. 26, no. 4, pp. 2398-2406, Oct. 2011.

[36] F. B. Ajaei, S. Afsharnia, A. Kahrobaeian, and S. Farhangi, "A fast and effective control scheme for the dynamic voltage restorer," IEEE Trans. Power Del., vol. 26, no. 4, pp. 2398-2406, Oct. 2011.

[37] A Ghosh, AK. Jindal, and A. Joshi, "Design of a capacitor-supported dynamic voltage restorer (DVR) for unbalanced and distorted loads," IEEE Trans. Power Del., vo1.19, no.l, pp.405-413, Jan. 2004.

[38] P. Kanjiya, B. Singh, A. Chandra, and K. A Haddad "SRF theory revisited to control self-supported dynamic voltage restorer for unbalanced and nonlinear loads" IEEE Trans. Ind. Appl., vo1.49, no.5, pp.2330-2340, 2013.

[39] S. S. Choi, B. H. Li, and D. M. Vilathgamuwa, "Dynamic voltage regulation with minimum energy injection," IEEE Trans. Power Syst., vol. 15, no. 1, pp. 51–57, Feb. 2000.

[40] D. M. Vilathgamuwa, A. A. D. R. Perera, and S. S. Choi, "Voltage sag compensation with energy optimized dynamic voltage restorer," *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 928–936, Jul. 2003.

[41] L. Tzung-Lin, H. Shang-Hung, and C. Yu-Hung Chan, "D-STATCOM with positive-sequence admittance and negative-sequence conductance to

mitigate voltage fluctuations in high-level penetration of distributed generation systems," *IEEE Trans. Ind. Electron*., vol. 60, no. 4, pp. 1417–1428, Apr. 2013.

[42] S. C. Hsieh, "economic evaluation of the hybrid enhancing scheme with DSTATCOM and active power curtailment for PV penetration in taipower distribution systems," *IEEE Trans. Ind. Appl*., vol. 51, no. 3, pp. 1953-1961, May 2015.

[43] S. Civanlar, J. J. Grainger, H. Yin, and S. S. H. Lee, ''Distribution feeder reconfiguration for loss reduction,'' *IEEE Trans. Power Del*., vol. 3, no. 3, pp. 1217–1223, Jul. 1988.

[44] JY Wong (2022). IEEE 16-bus Distribution Test System (Civanlar, 1988) (https://www.mathworks.com/matlabcentral/fileexchange/75518-ieee-16-bus-distribution-test-system-civanlar-1988), MATLAB Central File Exchange. Retrieved January 25, 2022.

[45] Axente, I. (2008) *Unified Power Quality Conditioner: protection and performance enhancement.* Doctoral thesis, Technological University Dublin. doi:10.21427/D7FG83

[46] Ye, J. (2018). *Optimal design and control implementation of unified power quality conditioner*. Doctoral thesis, Nanyang Technological University, Singapore.

[47] P. E. Meli´ın, J. R. Espinoza, J. A. Mu˜noz, C. R. Baier, and E. E. Espinosa, "Decoupled control of a unified power quality conditioner based on a current source topology for fast AC mains disturbance compensation," in Proc. *IEEE Int. Conf. Ind. Technol*., Mar. 14–17, 2010, pp. 730–736.

[48] K. Senthilnathan and I. Annapoorani, "Implementation of unified power quality conditioner (UPQC) based on current source converters for distribution grid and performance monitoring through LabVIEW Simulation Interface Toolkit server: a cyber physical model," *IET Generation, Transmission & Distribution*, vol. 10, no. 11, pp. 2622-2630, Aug. 2016.

[49] N. Farokhnia, S. H. Fathi, and H. R. Toodeji, "Voltage sag and unbalance mitigation in distribution systems using multi-level UPQC," in *Proc. Power Quality Conf.*, Sep. 14–15, 2010, pp. 1–5.

[50] H. Ryoo, G. Rim, T. Kim, and D. Kisek, “Digital-controlled single-phase unified power quality conditioner for non-linear and voltage sensitive load,” in *Proc. 30th Annu. Conf. IEEE Ind. Electron. Soc.,* Nov. 2–6, 2004, pp. 24–29.

[51] H. Toodeji, S. H. Fathi, and G. B. Gharehpetian, “Power management and performance improvement in integrated system of variable speed wind turbine and UPQC,” in *Proc. Int. Conf. Clean Electr. Power*, Jun.9–11, 2009, pp. 609–614.

[52] F. Wu and S. Pei, “Analysis and research of control strategy and signal detection based on UPQC,” in *Proc. 2nd Int. Workshop Intell. Syst. Appl.,* May 22–23, 2010, pp. 1–4

[53] A. Moghadasi, S. M. Torabi, and M. Salehifar, “Combined operation of the unified power quality conditioner with SFCL and SMES,” *in Proc. Power Quality Conf.,* Sep. 14–15, 2010, pp. 1–7.

[54] S. B. Karanki, M. K. Mishra, and B. K. Kumar, “Particle swarm optimizationbased feedback controller for unified power-quality conditioner,” *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2814–2824, Oct.2010.

[55] A. K. Jindal, A. Ghosh, and A. Joshi, “Interline unified power quality conditioner,” *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 364–372, Jan. 2007.

[56] M. Shahparasti, A. H. Rajaei, A. Yazdian and M. Mohamadian, "Interline unified power quality conditioner based on single stage nine switch inverter," *in Proc. 3rd Power Electronics and Drive Systems Technology (PEDSTC)*, 2012, pp. 319-323.

[57] M. C. Wong, C. J. Zhan, Y. D. Han, and L. B. Zhao, “A unified approach for distribution system conditioning: Distribution system unified conditioner (DS UniCon),” in *Proc. Power Eng. Soc. Winter Meet.,* Jan. 23–27, 2000, pp. 2757– 2762.

[58] P. Li, Q. Bai, and G. Li, “Coordinated control strategy for UPQC and its verification,” in *Proc. IEEE Power Eng. Soc. Gen. Meet.*, Jun. 2006, pp. 1–8

[59] H. R. Mohammadi, R. Y. Varjani, and H. Mokhtari, “Multiconverter unified power-quality conditioning system: MC-UPQC,” *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 1679–1686, Jul. 2009.

[60] Han, B. Bae, S. Baek, and G. Jang, “New configuration of UPQC for medium voltage application,” *IEEE Trans. Power Del.*, vol. 21, no. 3,pp. 1438–1444, Jul. 2006.

[61] I. Rubilar, J. Espinoza, J. Munoz, and L. Moran, “DC link voltage unbalance control in three-phase UPQCs based on NPC topologies,” in *Proc. 42nd Ind. Appl. Soc. Annu. Meet. Ind. Appl. Conf.*, Nov. 5–8, 2007, pp. 597–602.

[62] J. A. Munoz, R. R. Espinoza, L. A. Moran, and C. R. Baier, “Design of a modular UPQC configuration integrating a components economical analysis,” *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 1763–1772, Oct. 2009.

[63] C. B. Jacobina, A. D. P. D. Queiroz, A. C. N. Maia, E. R. C. Da Silva, and A. C. Oliveira, “AC-DC-AC multilevel converters based on three-leg converters,” in *Proc. IEEE Energy Convers. Congr. Expo.*, 2013, pp. 5312–5319.

[64] M. Ayslan, C. N. Jacobina, C. B. Carlos, and A. A. Gregory, “A new three-phase AC-DC-AC multilevel converter based on cascaded three-leg converters,” in *Proc. IEEE Energy Convers. Congr. Expo*., 2015, pp. 4685–4692.

[65] J. A. Munoz, J. R. Espinoza, C. R. Baier, L. A. Moran, E. E. Espinosa, P. E. Melin, and D. G. Sbarbaro, “Design of a discrete-time linear control strategy for a multicell UPQC,” *IEEE Trans. Ind. Electron*., vol. 59, no. 10, pp. 3797–3807, Oct. 2012.

[66] J. A. Munoz, J. R. Espinoza, I. A. Rubilar, L. A. Moran, and P. E. Melin, “A modular approach for integrating harmonic cancellation in a multi-cell based UPQC,” in *Proc. 34th Annu. Conf. IEEE Ind. Electron. Soc.*, 2008, pp. 3069– 3074.

[67] Q. Xu, F. Ma, A. Luo, Z. He and H. Xiao, "Analysis and control of M3C-based UPQC for power quality improvement in medium/high-voltage power grid," *IEEE Trans. Power Electron.*, vol. 31, no. 12, pp. 8182-8194, Dec. 2016.

[68] T. K. A. Brekken, H. T. Ozkan-Haller, and A. Simmons, “A methodology for large-scale ocean wave power time-series generation,” *IEEE Journal of Oceanic Engineering*, vol. 37, no. 2, pp. 294-300, Apr. 2012.

[69] H. Patel and V. Agarwal, "MATLAB-based modeling to study the effects of partial shading on PV array characteristics," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 302-310, Mar. 2008.

[70] X. Sun, M. Cheng, Y. Zhu, and L. Xu, “Application of electrical variable transmission in wind power generation system,” *IEEE Trans. Ind. Appl., vol. 49*, no. 3, pp. 1299-1307, Jun. 2013.

[71] A. Mokhtarpour, M. Bathaee and H. A. Shayanfar, "Power quality compensation in smart grids with a single phase UPQC-DG," in *Proc. Iranian Conf. on Smart Grids*, 2012, pp. 1-5.

[72] M. K. Elango and T. Tamilarasi, "Improvement of power quality using a hybrid UPQC with distributed generator," in *Proc. Int. Conf. on Circuit, Power and Computing Technologies*, 2016, pp. 1-8.

[73] M. Vilathgamuwa, H. Y. Zhang, and S. S. Choi, “Modelling, analysis and control of unified power quality conditioner,” in *Proc. Harmonics Quality Power,* Oct. 14–18, 1998, pp. 1035–1040.

[74] R. Rajasree and S. Premalatha, “Unified power quality conditioner(UPQC) control using feed forward (FF)/ feedback (FB) controller,” in *Proc. Int. Conf. Comput., Commun. Electr. Technol. Conf.,* Mar. 18–19,2011, pp. 364–369.

[75] M. Basu, S. P. Das, and G. K. Dubey, “Performance study of UPQC-Q for load compensation and voltage sag mitigation,” in *Proc. IEEE 28thAnnu. Conf. Ind. Electron. Soc.*, Nov. 5–8, 2002, pp. 698–703.

[76] M. Basu, S. P. Das, and G. K. Dubey, “Investigation on the performance of UPQC-Q for voltage sag mitigation and power quality improvement at a critical load point,” *IET Generation, Transmiss. Distrib.*, vol. 2, no. 3,pp. 414–423, May 2008.

[77] G. S. Kumar, P. H. Vardhana, B. K. Kumar, and M. K. Mishra, “Minimization of VA loading of unified power quality conditioner (UPQC),” in *Proc. Power Eng., Energy Electr.Drives,*Mar. 18–20, 2009, pp. 552–557.

[78] W. C. Lee, D. M. Lee, and T. K. Lee, "New control scheme for a unified power quality compensator-Q with minimum active power injection," *IEEE Trans. Power Del.*, vol. 25, no. 2, pp. 1068–1076, Apr. 2010.

[79] V. Khadkikar and A. Chandra, "UPQC-S: A novel concept of simultaneous voltage sag/swell and load reactive power compensations utilizing series inverter of UPQC," *IEEE Trans. Power Electron.*, vol. 26, no. 9,pp. 2414–2425, Sep. 2011.

[80] Arindam Ghosh and Gerard Ledwich, Power quality enhancement using custom power devices. *Boston: Kluwer Academic Publishers*, 2002.

[81] S.K. Jain, P. Agrawal and H.O. Gupta, "Fuzzy logic controlled shunt active power filter for power quality improvement", *IEE Proc.-Electr. Power Appl.*, vol. 149, no.5, pp. 317 – 328, September 2002.

[82] N. Mohan, T. M. Undeland and W. Robbins. Power Electronics: Converters, Applications, and Design. *John Willey & sons, INC. New York*. 1995.

[83] K. Chatterjee, B. G. Fernandes and G.K. Dubey, "An Instantaneous Reactive VoltAmpere Compensator and Harmonic Suppressor System", *IEEE Transactions on Power Electronics*, vol. 14, no. 2, pp. 381 - 392, March 1999.

[84] J.C. Wu and H.L. Jou, "Simplified control method for the single-phase active power filter", *IEE Proc.-Electr. Power Appl.*, vol. 143, no.3, pp. 219 - 224, May 1996.

[85] Shyh-Jier Huang and Jinn-Chang Wu, "A control algorithm for three-phase three-wired active power filter under nonideal mains voltages", *IEEE Transactions on Power Electronics*, vol. 14, no. 4, pp. 753 – 760, July 1999.

[86] Muhammad H. Rashid, *Power Electronics Handbook: devices, circuits, and applications*. Elsevier, 2007.

[87] L. Malesani, P. Tenti, "A Novel Hysteresis Control Method for Current-Controlled Voltage-Source PWM Inverters with Constant Modulation Frequency", *IEEE Transactions on Industry Applications*, vol. 26. no. 1, pp. 88 – 92, Jan./Feb. 1990.

[88] D. Sutanto, L.A. Snider and K.L.Mok, "Hysteresis control over UPFC", *Proceedings of the 5th International Conference on Advances in Power*

System Control, Operation and Management, APSCOM 2000, Hong Kong, 30 Oct.-1 Nov. 2000, vol. 2, pp. 376- 379, 2000.

[89] D. M. Vilathgamuwa, A. A. D. R. Perera, and S. S. Choi, "Voltage sag compensation with energy optimized dynamic voltage restorer," *IEEE Trans. Power Del.,* vol. 18, no. 3, pp. 928–936, Jul. 2003.

[90] Y. Pal, A. Swarup, and B. Singh, "Performance of UPQC for power quality improvement," in *Proc. Int. Conf. Power Electron. Drives Energy Syst.,* Dec. 20– 23, 2010, pp. 1–7

[91] Y. Pal, A. Swarup, and B. Singh, "A comparative analysis of three-phase four-wire UPQC topologies," in *Proc. Int. Conf. Power Electron. Drives Energy Syst,* Dec. 20–23, 2010, pp. 1–6.