UNIVERSITI PUTRA MALAYSIA

PHOTOVOLTAIC SHUNT ACTIVE POWER FILTER BASED ON INDIRECT SELF-CHARGING WITH STEP SIZE ERROR CANCELLATION AND SIMPLIFIED ADAPTIVE LINEAR NEURON

MUHAMMAD AMMIRRUL ATIQI B MOHD ZAINURI

FK 2017 34

PHOTOVOLTAIC SHUNT ACTIVE POWER FILTER BASED ON INDIRECT SELF-CHARGING WITH STEP SIZE ERROR CANCELLATION AND SIMPLIFIED ADAPTIVE LINEAR NEURON

By

MUHAMMAD AMMIRRUL ATIQI B MOHD ZAINURI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fullfilment of the Requirement for the Degree of Doctor of Philosophy

March 2017

© COPYRIGHT UPM

All material contained within the thesis, including without limitation text, logos, icons, photographs and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

PHOTOVOLTAIC SHUNT ACTIVE POWER FILTER BASED ON INDIRECT SELF-CHARGING WITH STEP SIZE ERROR CANCELLATION AND SIMPLIFIED ADAPTIVE LINEAR NEURON

By

MUHAMMAD AMMIRRUL ATIQI B MOHD ZAINURI

March 2017

Chair: Mohd Amran Mohd Radzi, PhD
Faculty: Engineering

Current harmonics is one of the main power quality problems which can be mitigated by using shunt active power filter (SAPF). Integrating SAPF with photovoltaic (PV), also known as PV SAPF, is among the best option as it provides alternative energy source to operate the SAPF rather than depending on energy from the grid supply and at the same time maintaining Total Harmonics Distortion (THD) below 5%.

DC-link capacitor voltage control and harmonics extraction algorithms, are giving high impact to overall SAPF's performance. In DC-link capacitor voltage control, the existing works on direct self-charging algorithm still have many drawbacks in terms of overshoot, undershoot and response time, especially during dynamic operation. Meanwhile, the existing harmonics extraction algorithm known as modified Widrow-Hoff adaptive linear neuron (ADALINE) algorithm, still has unnecessary features which unfortunately disturbs performance of the algorithm to extract harmonics accurately in both steady-state and dynamic operations.

Therefore, this research work proposes design and development of single-phase PV SAPF with a new DC-link capacitor voltage control algorithm named as indirect self-charging with step size error cancellation, and a new harmonics extraction algorithm named as simplified ADALINE. In the indirect self-charging with step size error cancellation, a new technique has been introduced in operation of the self-charging algorithm, known later as indirect control technique. Meanwhile, the simplified ADALINE algorithm has been improved from its existing version by removing cosine component according to symmetrical theory of periodic signal, minimizing large average square error by removing sum of elements, and by modifying weight updating technique leads to introduction of fundamental active current updating technique.

In methodology, topology of PV SAPF was designed first, and followed by all control algorithms with special attention to both proposed algorithms. For comparison purpose,

© COPYRIGHT UPM

the existing DC-link capacitor voltage control and harmonics extraction algorithms were modeled too. Two nonlinear loads, which are inductive and capacitive, and PV source with different level of irradiances were used to test the PV SAPF by focusing on the performances of both proposed algorithms, under steady-state operation. The testing under dynamic operation covers change of nonlinear loads, on-off operations between PV and SAPF, and change of irradiance levels. Laboratory prototype was then developed and digital signal processor (DSP) TMS320F28335 was used to perform the computation of algorithms. Similar tests as in the simulation work were carried out in the laboratory.

From both simulation and experimental results, PV SAPF with both proposed algorithms show better performances as compared to the existing algorithms. The indirect self-charging with step size error cancellation performs with high accuracy (99.96 to 100%), low overshoot and undershoot (0.13% to 1%), and fast response time (less than 0.5s). Reduction of energy losses between 36 J to 86 J has been achieved during various dynamic operations of the DC-link capacitor. Meanwhile, the simplified ADALINE performs with lower THD values between 1.5% to 3.24% and high percentages of source power reduction between 4.7% to 23.7% with different nonlinear loads and irradiance levels. In conclusion, PV SAPF with both proposed algorithms have successfully been developed and performed for better improvement of harmonics mitigation and renewable energy utilization.

© COPYRIGHT UPM

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENAPIS KUASA AKTIF PIRAU FOTOVOLTA BERDASARKAN PENGECASAN SENDIRI SECARA TIDAK LANGSUNG DENGAN PEMBATALAN RALAT SAIZ LANGKAH DAN NEURON LINEAR PENYESUAIAN MUDAH

Oleh

MUHAMMAD AMMIRRUL ATIQI B MOHD ZAINURI

Mac 2017

Pengerusi: Mohd Amran Mohd Radzi, PhD
Fakulti: Kejuruteraan

Harmonik arus adalah salah satu masalah utama kualiti kuasa yang boleh dikurangkan dengan menggunakan penapis kuasa aktif pirau (SAPF). Mengintegrasikan SAPF dengan fotovolta (PV), juga dikenali sebagai PV SAPF, adalah antara pilihan yang terbaik kerana ia memberi sumber tenaga alternatif untuk mengoperasikan SAPF daripada bergantung kepada tenaga daripada bekalan grid dan pada masa yang sama mengekalkan jumlah herotan harmonik (THD) di bawah 5% .

Algoritma kawalan voltan pemuat sambungan arus terus dan pengekstrakan harmonik, seperti yang difokuskan dalam tesis ini, memberi kesan yang tinggi kepada keseluruhan prestasi SAPF. Dalam kawalan voltan pemuat sambungan arus terus, kerja yang sedia ada pada algoritma pengecasan sendiri masih mempunyai banyak kelemahan daripada segi terlajak, lajak bawah, dan masa respon, terutama sekali ketika operasi dinamik. Sementara itu, algoritma pengekstrakan harmonik sedia ada iaitu algoritma Widrow-Hoff neuron linear penyesuaian (ADALINE) terubahsuai masih mempunyai ciri-ciri yang tidak diperlukan yang malangnya mengganggu prestasi algoritma itu untuk mengekstrak harmonik dengan tepat dalam kedua-dua keadaan operasi mantap dan dinamik.

Oleh yang demikian, kerja penyelidikan ini mencadangkan reka bentuk dan pembangunan PV SAPF satu fasa dengan algoritma kawalan voltan pemuat sambungan arus terus baru yang dinamakan sebagai algoritma pengecasan sendiri secara tidak langsung dengan pembatalan ralat saiz langkah, dan algoritma pengestrakan harmonik baru yang dinamakan sebagai algoritma ADALINE mudah. Dalam algoritma pengecasan sendiri secara tidak langsung dengan pembatalan ralat saiz langkah, teknik baru telah diperkenalkan dalam operasi algoritma pengecasan sendiri, dikenali kemudian sebagai teknik kawalan secara tidak langsung. Sementara itu, algoritma ADALINE mudah ditambah baik daripada versi yang sedia ada dengan membuang komponen kosinus mengikut teori simetri isyarat berkala, meminimumkan ralat persegi

© COPYRIGHT UPM

purata yang besar dengan mengeluarkan jumlah unsur, dan mengubah suai teknik mengemaskini berat yang membawa kepada pengenalan teknik mengemaskini arus aktif asas.

Dalam metodologi, topologi PV SAPF telah direka dahulu, dan kemudian disertai oleh semua algoritma kawalan dengan perhatian khusus kepada kedua-dua algoritma yang telah dicadangkan. Bagi tujuan perbandingan, algoritma kawalan voltan pemuat sambungan arus terus dan pengekstrakan harmonik yang sedia ada turut dimodelkan. Dua beban tak lelurus, iaitu beraruhan dan berkemuatan, dan sumber PV dengan tahap berbeza sinaran turut digunakan untuk menguji PV SAPF dengan memberi tumpuan kepada prestasi kedua-dua algoritma yang dicadangkan, di bawah operasi keadaan mantap. Ujian di bawah operasi dinamik merangkumi perubahan beban tak lelurus, operasi buka-tutup antara PV dan SAPF, dan perubahan tahap sinaran. Prototaip makmal kemudiannya dibangunkan dan pemproses isyarat digit (DSP) TMS320F28335 digunakan untuk melaksanakan pengiraan algoritma. Ujian yang sama seperti dalam kerja simulasi turut dijalankan dalam makmal.

Daripada kedua-dua keputusan simulasi dan eksperimen, PV SAPF dengan kedua-dua algoritma yang dicadangkan telah menunjukan prestasi yang lebih baik jika dibandingkan algoritma yang sedia ada. Algoritma pengecasan sendiri secara tidak langsung dengan pembatalan ralat saiz langkah beroperasi dengan ketepatan yang tinggi (99.96% hingga 100%), terlajak dan lajak bawah rendah (0.13% hingga 1%), dan masa respon yang cepat (kurang daripada 0.5 s). Pengurangan kehilangan tenaga antara 36 J hingga 86 J telah dicapai sepanjang pelbagai operasi dinamik pemuat sambungan arus terus. Sementara itu, algoritma ADALINE mudah beroperasi dengan nilai THD lebih rendah antara 1.5 % hingga 3.24 % dan peratusan tinggi pengurangan sumber kuasa antara 4.7% hingga 23.7% dengan beban tak lelurus dan tahap sinaran yang berbeza. Kesimpulannya, PV SAPF dengan kedua-dua algoritma yang dicadangkan telah berjaya dibangunkan dan dilaksanakan untuk peningkatan yang lebih baik bagi pengurangan harmonik dan penggunaan tenaga boleh diperbaharui.

© COPYRIGHT UPM

ACKNOWLEDGEMENTS

In the Name of ALLAH, Most Gracious, Most Merciful

First and foremost, I would like to thank and praise the Almighty Allah for lighting my way and directing me through each and every success I have had or may reach. I would like to thank and express my full appreciation to my supervisors, Associate Professor Dr. Mohd Amran Mohd Radzi, Associate Professor Dr. Azura Che Soh, Professor Dr. Norman Mariun and Professor Dr. Nasrudin Abd Rahim for their encouragement and patience during my research work. It has been my honor and privilege to work under their supervision. Their enthusiasm, guidance and insight throughout the duration of this study were invaluable to me. I would like to thank all staffs and my colleagues at the Department of Electrical and Electronic Engineering and UM Power Energy Dedicated Advanced Centre (UMPEDAC) who supported and helped me during my work.

I would like to express my sincere gratitude, thanks and love to my family, especially to my mother Nor Hasnah Fateh Mohammed, my father Mohd Aseral Jusman and my brother Loqmanul Hakeem Mohd Aseral for their continuous encouragement during my period of study. Special thanks to my uncle, Associate Professor Datuk Dr. Bahsir Ahmad Fateh Mohammed for his strong support to me in continuing my PhD degree. Finally, I would like to express my gratitude, and thanks to all my friends for giving me morale motivation to finish my research work and my studies.

© COPYRIGHT UPM

I certify that a Thesis Examination Committee has met on 23 March 2017 to conduct the final examination of Muhammad Ammirrul Atiqi b Mohd Zainuri on his thesis entitled "Photovoltaic Shunt Active Power Filter Based on Indirect Self-Charging with Step Size Error Cancellation and Simplified Adaptive Linear Neuron" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Mohd Nizar bin Hamidon, PhD
Associate Professor
Institute of Advance Technology
Universiti Putra Malaysia
(Chairman)

Norhisam bin Misron, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Jasronita binti Jasni, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

John Fletcher, PhD
Professor
University of New South Wales
Australia
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 2 June 2017

This thesis was submitted to the Senate of University Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohd Amran bin Mohd Radzi, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Azura binti Che Soh, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Norman bin Mariun, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Nasrudin bin Abd Rahim, PhD
Professor
UM Power Energy Dedicated Advanced Centre (UMPEDAC)
Universiti Malaya
(Member)

____
ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

© COPYRIGHT UPM

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________ Date: __________________

Name and Matric No.: Muhammad Ammirrul Atiqi B Mohd Zainuri, GS38766

© COPYRIGHT UPM

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- Supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________

Name of Chairman of Supervisory Committee: Mohd Amran bin Mohd Radzi, PhD

Signature: ______________________

Name of Member of Supervisory Committee: Azura binti Che Soh, PhD

Signature: ______________________

Name of Member of Supervisory Committee: Norman bin Mariun, PhD

Signature: ______________________

Name of Member of Supervisory Committee: Nasrudin bin Abd Rahim, PhD

© COPYRIGHT UPM

TABLE OF CONTENTS

© COPYRIGHT UPM

© COPYRIGHT UPM

LIST OF TABLES

© COPYRIGHT UPM

© COPYRIGHT UPM

LIST OF FIGURES

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

LIST OF ABBREVIATIONS

A/D	Analog to digital
AC	Alternating current
ADALINE	Adaptive Linear Neuron
ANN	Artificial neural network
APF	Active power filter
ASD	Adjustable speed drive
CCS	Code compressor studio
CE	Change of error
D	Duty cycle
DC	Direct current
DSP	Digital signal processing
E	Error
EMC	Electromagnetic compatibility
FFT	Fast Fourier transform
FLC	Fuzzy logic control
HV	High voltage
HVAC	Heating, ventilation, and air conditioning
I	Current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-gate bipolar transistor
LMS	Least-mean-square
MF	Membership function
MOSFET	Metal-oxide semiconductor field-effect transistor
MPPT	Maximum power point tracking
MV	Medium voltage
NOTC	Nominal Operating Cell Temperature
P&O	Perturb and Observe
p.u	per unit
PCB	Printed circuit board
PI	Proportional integral
PV	Photovoltaic
PWM	Pulse width modulation
RMS	Root mean square
SAPF	Shunt active power filter
SVC	Static Var compensator
TDD	Total demand distortion
THD	Total harmonics distortion
UPQC	Unified power quality conditioner
UPS	Uninterruptible power supply
V	Voltage
W-H	Widrow-Hoff
ZCD	Zero crossing detector

© COPYRIGHT UPM

CHAPTER 1

INTRODUCTION

1.1 Background

Harmonics, one of the most common power quality problems, are sinusoidal voltages or currents of frequencies that are integer multiples of the frequency at which the supply system is designed to operate. Current harmonics are more crucial than voltage harmonics which can normally and highly occur in operation of the power system. Current harmonics may come from nonlinear load operations produced by power electronic devices and applications which are injected into the supply network through point of common coupling (PCC). These problems may arise within the smart grid system with involvement of multiple energy sources and systems which include photovoltaic (PV) grid connected system [Du et al., 2015; Hu et al., 2015; Zhou et al., 2014; Datta and Senjyu, 2013; Wandhare and Agarwal, 2014]. Among the effects of current harmonics are capacitor damaged, equipment overheating, motor vibration and excessive neutral currents [Yongtao and Wenjin, 2008]. To compensate current harmonics, an active power filter (APF) is used. The main of this active filter is it can mitigate multiple harmonics instantaneously. For current harmonics mitigation, the shunt active power filters (SAPF) or transformer-less APF topology is used.

Renewable energy has become popular because of its advantages over other kinds of energy such as being less dependent on fossil fuel resources and environmentally friendly with less carbon released to the atmosphere [Faranda and Leva, 2008; Banos et al., 2011]. There are many types of renewable energy such as wind, solar, hydro, geothermal, bio-fuel and others. Solar energy or PV energy is among the popular renewable energy since it is much cleaner, inexhaustible, and free to harvest [Banos et al., 2011]. The efficiency of the power conversion between ultraviolet (UV) light to electrical energy is reported to be about 30% [Solar Cell Central, 2013]. However, with various research works, the PV technology is becoming more feasible with improved performance [Ko and Choa, 2012; Khatib et al., 2010].

Integration of renewable energy source such as PV with SAPF is an approach to be explored in various current research works. The integration of PV with SAPF, or known later as PV SAPF, gives two main advantages. First, it gives the option of having SAPF to be operated with alternative energy source, rather than to depend on the energy source from the grid supply. Second, current harmonics mitigation can dynamically be carried out in order to maintain total harmonic distortion (THD) of the grid to be below 5% [Lee et al., 2009; Barater et al., 2014]. Figure 1.1 shows the basic configuration of PV SAPF. As an additional element connected with the PV, a DC/DC converter is used to step up the PV voltage according to the desired voltage for the DC-link capacitor. PV SAPF's main control strategies consist of multiple algorithms with their specific tasks such as maximum power point tracking (MPPT), harmonics extraction, DC-link capacitor voltage control, synchronizer, current control and switching technique.

© COPYRIGHT UPM

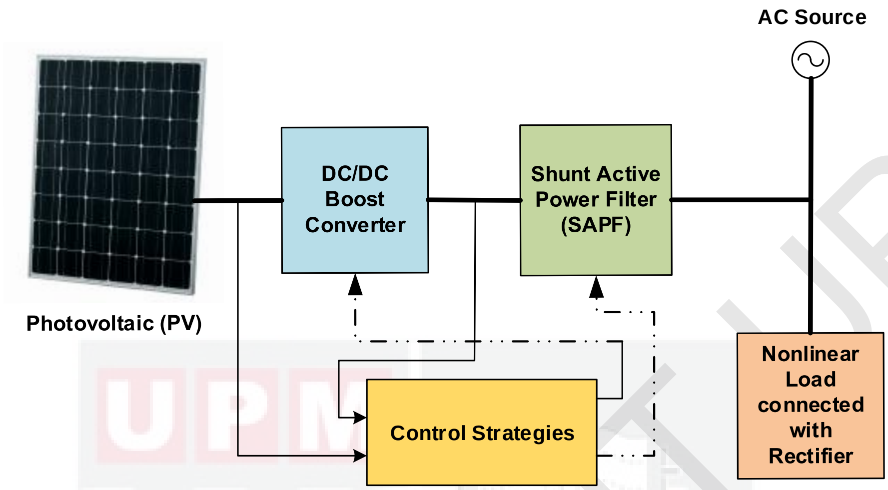

Figure 1.1: Single-phase photovoltaic based shunt active power filter

The harmonics extraction algorithm is one of the important control strategies in SAPF. By extracting harmonics accurately to further produce the reference current (injection current) and with fast and responsive action, the SAPF should be able to compensate harmonics optimally. The harmonics extraction algorithms can be classified to frequency domain, time domain and artificial intelligence techniques. In frequency domain, the algorithms using discrete Fourier transform (DFT), recursive discrete Fourier transform (RDFT) and fast Fourier transform (FFT) are widely reported [Green and Marks, 2005; Vijayvargiya and Nimonkar, 2013]. Meanwhile, for time domain, significant works on the major related algorithms such as synchronous fundamental d-q frame, synchronous harmonic d-q frame and instantaneous power theory (p-q theory) have been reported extensively [Sujitjorn et al., 2007; Peng et al., 1988; Forghani and Afsharnia, 2007; Shousha et al., 2011; Areerak et al., 2010]. The mentioned algorithms from both domains produce a good THD which is below 5% but mainly differs on convergence speed. As clearly reported, the algorithms in time domain are faster in term of convergence speed [Green and Marks, 2005; Vijayvargiya and Nimonkar, 2013].

As an alternative for the algorithms in frequency and time domains, the latest trend is by focusing to the artificial intelligence techniques. Artificial neural network (ANN) is famously considered due to its capability to perform fast and stable. It also has the ability to proses input and output mappings through parallel computation [Tey et al., 2005]. For APF functionality, ANN will accurately estimate or extract the time varying fundamental component, in terms of magnitude and phase angle to mitigate harmonic components [Sindhu et al., 2008; Bhattacharya and Chakraborty, 2008]. There are numerous ANN architectures that exist for harmonics extraction, such as adaptive linear neuron (ADALINE), perceptron, back propagation (BP), radial basis function (RBF), Hopfield, Hebbian, competitive, and Grossberg [Lega et al., 2008]. Among them, ADALINE is the most preferred because of its continued learning of weight,

© COPYRIGHT UPM

more precise and its simplicity to perform a good harmonics extraction. A number of works have been carried out using ADALINE for current harmonics extraction. It uses Fourier series that operates with a single linear neuron model method which is called as Widrow-Hoff (W-H) ADALINE neural network. However, the disadvantage of W-H ADALINE is it does learn multiple harmonic components which has negative effects on the learning time of the algorithm itself [Lega et al., 2008; Cirrincione et al., 2008; Singh et al., 2007]. Improvements has been carried out to enhance the algorithm by focusing directly to the extraction of the fundamental component with suitable learning rates in updating algorithm which is called modified W-H ADALINE [Radzi and Rahim, 2009; Tey et al., 2005; Rahman et al, 2013]. Although improvements have been made, there are still unnecessary features exist, as elaborated later in the next section. Despite the significant role of the harmonics extraction algorithm, DC-link capacitor voltage control algorithm has also a big impact to the overall system. The main function of DC-link capacitor is to provide constant DC for the inverter to produce the injection current (mitigation current). The conventional method to control the DC-link capacitor voltage is by using direct change between instantaneous voltage and desired DC-link voltage. However, by using this method, the DC-link capacitor voltage is not accurately controlled and regulated, and as a result, unclean voltage is produced [Zeng et al., 2010; Choi et al., 2013; Bhattacharya and Chakraborty, 2011; Afghoul and Krim, 2012; Mehta et al., 2011; Ponpandi and Durairaj, 2011]. This major disadvantage contributes to effects such as capacitor blowing and high THD due to unstable injection current [Mikkili and Panda, 2013].

In recent years, self-charging algorithm has received special attention from the researchers due to its advantages as compared to the conventional algorithm of DC-link capacitor voltage control [Farahat and Zobah, 2004; Abdel Aziz et al., 2006; Priya and Keerthana, 2013; Khoor et al., 2007; Kwan et al., 2012; Rahman et al., 2013]. The self-charging algorithm uses the energy conversion law to control the charging and discharging of the DC-link capacitor. Among its advantages are high accuracy and clean DC voltage, and regulated voltage is produced with almost no noise, spikes and ripples.

The voltage error in the self-charging algorithm has the highest effect towards determination the capacitor charging current. Voltage error is the difference between instantaneous voltage and referenced voltage of the DC-link capacitor. Uncontrolled voltage error will lead to low performances of the self-charging algorithm in terms of overshoot, undershoot and response time to achieve steady state. Proportional-integral (PI) [Farahat and Zobah, 2004; Aziz et al., 2006; Priya and Keerthana, 2013; Khoor et al., 2007; Kwan et al., 2012] and fuzzy logic control (FLC) [Rahman et al., 2013] are among the existing techniques used to control the voltage error produced from the self-charging algorithm. Use of them in the self-charging algorithms can be categorized as direct control technique of the self-charging algorithm. Between both, the self-charging with PI algorithm is more popular as it is considered simple; however, it has some drawbacks such as fluctuation and imbalance of the DC-link voltage [Zeng et al., 2010], large overshoot and slow response [Guo et al., 2012], and unsatisfactory performance under parameter variations, non-linearity, and load disturbances; it only works in steady-state operation [Ponpandi and Durairaj, 2011; Husen and Patel, 2014].

© COPYRIGHT UPM

As an alternative, with high growth of artificial intelligence techniques, and specifically FLC as one of them, has shown much better performance due to being faster, accurate, and very stable at the same time does not require specific and precise mathematical models for designing and tuning, and works well using imprecise inputs, and is more robust [Dehini and Ferdi, 2009; Tan et al., 2012]. However, even though the self-charging with FLC technique much better than PI technique, both as direct control technique have the same major drawbacks where their operations do not really consider parameter variations, non-linearity, and load disturbances; the previous works only considered the steady-state operation and no further analysis has been done with dynamic operation [Priya and Keerthana, 2013; Khoor et al., 2007; Kwan et al., 2012; Rahman et al., 2013].

1.2 Problem Statement

As mentioned before, the modified W-H ADALINE algorithm is an improvement of the conventional W-H ADALINE algorithm. The improvement contributes to a large average square error, thus learning rate is needed [Radzi and Rahim, 2009]. Although this algorithm has performed well in the previous works, it still has unnecessary internal features. These include the existing of cosine component and sum of elements which contribute to slow learning rate. As a result, accuracy and response time of the harmonics extraction algorithm are affected where the delay in compensation is introduced [Bhattacharya and Chakraborty, 2011]. It is recorded that by using ADALINE algorithm, the convergence speed must be around 1 cycle (20 ms) but the modified W-H ADALINE only managed to produce only 2 cycle (40 ms) [Qasim and Khadkikar, 2014; Dang et al., 2014]. A fast response of harmonics extraction algorithm is more efficient especially when handling in dynamic operation during interconnection between PV and SAPF. In addition, a high accuracy harmonic extraction algorithm provides better THD values. High THD can cause distortion power which leads to overconsumption power by the consumer [Suslov et al., 2013]. By keeping a very low THD values in a system, it will further ensure proper operation of equipment and longer equipment life span [Associated Power Technologies, 2016]. With very low THD values too, quality factor of sine wave also increases, in which the lower percentage of THD, the closer the current waveform is to be a true sine wave [Gaouda et al., 1999].

In the operation of PV SAPF, dynamic operation always happens in the power system especially for DC-link capacitor that exists within the system. The DC-link capacitor may damage when over voltage happens and possible disoperation of injection current may occur when under voltage happens. Moreover, if the voltage has high overshoot or undershoot, there is a high risk of premature switches failure due to over-stresses, and further increment to THD [Hoon Yap et al., 2016; Busquets-Monge et al., 2015]. Meanwhile, by using direct control technique, whenever there is a change of the load and on-off connection between PV and SAPF, the voltage across the DC-link capacitor also undergoes a corresponding change [Bhattacharya and Chakraborty, 2011]. As the current approach in the self-charging algorithm is by directly controlling the voltage error using the PI or FLC algorithm, it may lead to possible disturbance to the DC-link capacitor voltage, which could result in high overshoot and undershoot, and slow response time especially during dynamic operations. It is recorded that response time

© COPYRIGHT UPM

produced by a certain DC link capacitor voltage control algorithm which is over than 25 ms is considered as a slow response algorithm [Hoon Yap et al., 2016; Rahman et al., 2013; Zakzouk et al., 2014; Busquets-Monge et al., 2015]. In addition, it has limited flexibility because the voltage error still has to be processed and controlled even when there is no change.

Apart from the problems mentioned previously, to date, there are no comprehensive evaluation and analysis from previous research works on effects of harmonics extraction and DC-link capacitor voltage control algorithms with the interconnection between PV and SAPF. Therefore by improving the established DC-link capacitor voltage control and harmonics extraction algorithms with further comprehensive evaluation involving dynamic operations, overall performances of the SAPF and interconnection between PV and SAPF will increases.

1.3 Aim and Objectives

The main aim of this work is to develop a single-phase photovoltaic shunt active Power Filter (PV SAPF) with novel harmonics extraction and DC-link capacitor control algorithms. The detailed objectives are as follows:

1. To design and develop harmonics extraction algorithm based on ANN, named as simplified ADALINE.
2. To design and develop improved self-charging algorithm for DC-link capacitor voltage control algorithm, named as indirect self-charging with step size error cancellation.
3. To introduce evaluation performances of the interconnection between PV and SAPF in related to effects of harmonics extraction and DC-link capacitor voltage control algorithms.

1.4 Scope of Work

This research work only focuses on current harmonics where in the electrical power system, current harmonics are major power quality problems as compare to voltage harmonics. Furthermore, in various situations, voltage harmonics are mostly caused by current harmonics. The voltage provided by the voltage source will be distorted by current harmonics due to source impedance. This research work covers development of a single-phase PV SAPF by focusing on development of new harmonics extraction and DC-link capacitor voltage control algorithms. Both algorithms play significant roles to ensure the PV SAPF performs well in steady-state and dynamic conditions. Single-phase based system is considered in this work due to the huge growth of PV system for residential usages, especially for building integrated PV (BIPV) system. Meanwhile, due to wider applications of power electronic converters for single-phase applications, potential spread of harmonics cannot be neglected and needs to be mitigated efficiently.

To evaluate performance of PV SAPF, steady-state and dynamic tests have been carried out to ensure the proposed algorithms perform as expected. The irradiance is set to 200 W/m2, 600W/m2 and 1000W/m2 for low, medium and high irradiance values respectively, to cover all ranges in Malaysia's climate [Ghazali and Rahman, 2012). All

© COPYRIGHT UPM

mentioned irradiance values are used to test capability and robustness of each proposed algorithm. In experimental testing, PV simulator CHROMA 62100H-600S is used as it can perform exactly as a real PV array with high flexibility of usage time and accurate parameter settings.

The PV SAPF is tested with the operation of nonlinear loads, with inductive and capacitive loads separately for steady-state tests, and a combination of both of them for dynamic tests. On and off operations between PV and SAPF, and change of irradiances are also tested for interconnection analysis. There are five major performance factors to be highlighted in this research work. They are THD, response time during dynamic state operations, accuracy of DC-link capacitor voltage during steady-state operations, power consumption at the grid source, and energy losses during dynamic operations for DC-link capacitor.

1.5 Thesis Outline

This subchapter explains briefly about the content of the thesis by chapters. There are other 4 chapters that will be covered in this thesis and are organized as such.

Chapter 2 defines power quality and its problems, presents a survey of SAPFs including topologies and principles of operation, reviews previous and latest development of integration between PV and APF, discusses in general various harmonics extraction and DC-link capacitor voltage control algorithms applied to SAPF, and highlights and reviews self-charging with PI and FLC algorithms, and modified Widrow-Hoff ADALINE algorithm.

Chapter 3 describes the methodology of modeling a two stage of single-phase PV SAPF, design of new harmonics extraction and DC-link capacitor voltage control algorithms, which are named as simplified ADALINE and indirect self-charging with step size error cancellation algorithm respectively, and integration of MATLAB/Simulink and DSP, in both simulation and experimental works.

Chapter 4 presents findings and results obtained in simulation and experimental works for SAPF with and without PV, under two operations which are steady state and dynamic, including their related measured waveforms, THD, DC-link capacitor voltage, power consumption from the grid, energy losses of DC-link capacitor during dynamic operations and response time achieved by the proposed harmonics extraction and DC-link capacitor voltage control algorithms.

Chapter 5 concludes the entire thesis, highlights contributions and recommends possible future works.

© COPYRIGHT UPM

REFERENCES

Abdeslam, D. O., Wira, P., Mercklé, J., Flieller, D., and Chapuis, Y. A. (2007). A unified artificial neural network architecture for active power filters. IEEE Transactions on Industrial Electronics, 54(1), 61-76.

Afghoul, H., and Krim, F. (2012). Comparison between PI and fuzzy DPC control of a shunt active power filter. IEEE International on Energy Conference and Exhibition (ENERGYCON), 146-151.

Algazar, M. M., EL-halim, H. A., & Salem, M. E. E. K. (2012). Maximum power point tracking using fuzzy logic control. International Journal of Electrical Power & Energy Systems, 39(1), 21-28.

Aljebaly, A. (2012). Artificial Neural Network. Michigan University, 1-57.

Angélico, B. A., Campanhol, L. B., & da Silva, S. A. O. (2014). Proportional–integral/proportional–integral-derivative tuning procedure of a single-phase shunt active power filter using Bode diagram. IET Power Electronics, 7(10), 2647-2659.

Ann, M. M., Sudhakar, T. D., Mohanadasse, K., and Sharmeela, C. (2014). Performance comparison of electronic ballast topologies for low power compact fluorescent lamp application. International Conference on Circuit, Power and Computing Technologies (ICCPCT), 1251-1256.

Appalanaidu Menda, V.V., Sankaraprasad, B., and Kalyani K. (2012). Neural network based shunt active filter for harmonic reduction: A technological review. International Journal of Engineering Research and Development, 2(11), 32-41.

Areerak, K. L., and Areerak, K. N. (2010). The Comparison Study of Harmonic Detection Methods for Shunt Active Power Filters. World Academy of Science, Engineering and Technology, 70, 243-248.

Arrillaga, J., and Watson, N. R. (2003). Power System Harmonics. John Wiley & Sons, Ltd, 1-15.

Arrillaga, J., Bollen, M. H., and Watson, N. R. (2000). Power quality following deregulation. Proceedings of the IEEE, 88(2), 246-261.

Associated Power Technologies. (2016). Total Harmonic Distortion and Effects in Electrical Power Systems. Associated Power Technologies, 1-4.

Aziz, M. A., Zobaa, A. F., and Hosni, A. A. (2006). Neural network controlled shunt active filter for nonlinear loads. Eleventh International Middle East on Power Systems Conference MEPCON, 1, 180-188.

Bagi S.M., and Patil.S.V. (2015). Performance Evaluation Of Shunt Active Filter For Photovoltaic Generation System For Improving Power Quality. International Journal of Emerging Technology in Computer Science & Electronics (IJETCSE), 14(2), 394-397.

Balamurugan, R. (2015). Photovoltaic based shunt active power filter using pq theory for enhancing the power quality. IU-Journal of Electrical & Electronics Engineering, 15(2), 1959-1964.

Banos, R., Manzano-Agugliaro, F., Montoya, F. G., Gil, C., Alcayde, A., and Gómez, J. (2011). Optimization methods applied to renewable and sustainable energy: A review. Renewable and Sustainable Energy Reviews, 15(4), 1753-1766.

Barater, D., Buticchi, G., Lorenzani, E., & Concari, C. (2014). Active common-mode filter for ground leakage current reduction in grid-connected PV converters operating with arbitrary power factor. IEEE Transactions on Industrial Electronics, 61(8), 3940-3950.

Belaidi, R., Haddouche, A., Hatti, M., & Larafi, M. M. (2013). Shunt active power filter connected to a photovoltaic array for compensating harmonics and reactive

© COPYRIGHT UPM

power simultaneously. Fourth International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), 1482-1486.
Beres, R. N., Wang, X., Liserre, M., Blaabjerg, F., and Bak, C. L. (2016). A Review of Passive Power Filters for Three-Phase Grid-Connected Voltage-Source Converters. IEEE Journal of Emerging and Selected Topics in Power Electronics, 4(1), 54-69.
Bhattacharya, A., & Chakraborty, C. (2011). A shunt active power filter with enhanced performance using ANN-based predictive and adaptive controllers. IEEE transactions on industrial electronics, 58(2), 421-428.
Bhattacharya, A., and Chakraborty, C. (2008). ANN (Adaline) based harmonic compensation for shunt active power filter with capacitor voltage based predictive technique. In 2008 IEEE Region 10 and the Third international Conference on Industrial and Information Systems, 1-6.
Blajszczak, G., and Antos, P. (2010). Power Quality Park-Idea and feasibility study. Electric Power Quality and Supply Reliability Conference, 17-22.
Blake, C., & Bull, C. (2001). IGBT or MOSFET: choose wisely. International Rectifier. 1-5.
Blumensath, T., and Davies, M. E. (2008). Gradient pursuits. IEEE Transactions on Signal Processing, 56(6), 2370-2382.
Bojoi, R. I., Griva, G., Bostan, V., Guerriero, M., Farina, F., & Profumo, F. (2005). Current control strategy for power conditioners using sinusoidal signal integrators in synchronous reference frame. IEEE Transactions on Power Electronics, 20(6), 1402-1412.
Buso, S., Malesani, L., & Mattavelli, P. (1998). Comparison of current control techniques for active filter applications. IEEE Transactions on Industrial Electronics, 45(5), 722-729.
Busquets-Monge, S., Maheshwari, R., Nicolas-Apruzzese, J., Lupon, E., Munk-Nielsen, S., & Bordonau, J. (2015). Enhanced DC-link capacitor voltage balancing control of DC–AC multilevel multileg converters. IEEE Transactions on Industrial Electronics, 62(5), 2663-2672.
Campanhol, L. B. G., da Silva, S. A. O., & Goedtel, A. (2014). Application of shunt active power filter for harmonic reduction and reactive power compensation in three-phase four-wire systems. IET Power Electronics, 7(11), 2825-2836.
Casada, D. A., Kueck, J. D., Staunton, H., and Webb, M. C. (2000). Efficiency testing of motors powered from pulse-width modulated adjustable speed drives. IEEE Transactions on Energy Conversion, 15(3), 240-244.
Chamat, N. M., Bhandare, V. S., Diwan, S. P., & Jamadade, S. (2014). Instantaneous reactive power theory for real time control of three-phase shunt Active Power Filter (SAPF). International Conference on Circuit, Power and Computing Technologies (ICCPCT), 792-796.
Chang, G. W., & Chen, S. K. (2005). An analytical approach for characterizing harmonic and interharmonic currents generated by VSI-fed adjustable speed drives. IEEE Transactions on Power Delivery, 20(4), 2585-2593.
Chang, G. W., and Chen, W. C. (2006). A new reference compensation voltage strategy for series active power filter control. IEEE transactions on power delivery, 21(3), 1754-1756.
Chang, G. W., Shih, M. F., Chen, Y. Y., and Liang, Y. J. (2014). A hybrid wavelet transform and neural-network-based approach for modelling dynamic voltage-current characteristics of electric arc furnace. IEEE Transactions on Power Delivery, 29(2), 815-824.

© COPYRIGHT UPM

Chaouachi, A., Kamel, R. M., & Nagasaka, K. (2010). A novel multi-model neuro-fuzzy-based MPPT for three-phase grid-connected photovoltaic system. Solar energy, 84(12), 2219-2229.

Chicco, G., Postolache, P., and Toader, C. (2007). Analysis of three-phase systems with neutral under distorted and unbalanced conditions in the symmetrical component-based framework. IEEE transactions on power delivery, 22(1), 674-683.

Chien, C. H., & Bucknall, R. W. (2009). Harmonic calculations of proximity effect on impedance characteristics in subsea power transmission cables. IEEE Transactions on Power Delivery, 24(4), 2150-2158.

Choi, W. H., Lam, C. S., Wong, M. C., and Han, Y. D. (2013). Analysis of dc-link voltage controls in three-phase four-wire hybrid active power filters. IEEE transactions on power electronics, 28(5), 2180-2191.

Cirrincione, M., Pucci, M., and Vitale, G. (2008). A single-phase DG generation unit with shunt active power filter capability by adaptive neural filtering. IEEE Transactions on Industrial Electronics, 55(5), 2093-2110.

Cirrincione, M., Pucci, M., Vitale, G., & Miraoui, A. (2009). Current harmonic compensation by a single-phase shunt active power filter controlled by adaptive neural filtering. IEEE Transactions on industrial electronics, 56(8), 3128-3143.

Compatibility, E. (2002). Part 4-7: Testing and Measurement Techniques—General Guide on Harmonics and Interharmonics Measurements and Instrumentation, for Power Supply Systems and Equipment Connected Thereto. IEC, 61000, 4-7.

Dall'Anese, E., Dhople, S.V., and Giannakis, G.B. (2014). Optimal Dispatch of Photovoltaic Inverters in Residential Distribution Systems. IEEE Transactions on Sustainable Energy, 5(2), 487-497.

Dang, P., Ellinger, T., & Petzoldt, J. (2014). Dynamic interaction analysis of APF systems. IEEE Transactions on Industrial Electronics, 61(9), 4467-4473.

Datta, M., and Senjyu, T. (2013). Fuzzy control of distributed PV inverters/energy storage systems/electric vehicles for frequency regulation in a large power system. IEEE Transactions on Smart Grid, 4(1), 479-488.

Daut, I., Hasan, S., and Taib, S. (2013). Magnetizing Current, Harmonic Content and Power Factor as the Indicators of Transformer Core Saturation. Journal of Clean Energy Technologies, 1(4), 304-307.

Dehini, R., Bassou, A., and Ferdi, B. (2009). Artificial neural networks application to improve shunt active power filter. International Journal of Computer and Information Engineering, 3(4), 247-254.

Dey, P., and Mekhilef, S. (2015). Current harmonics compensation with three-phase four-wire shunt hybrid active power filter based on modified D–Q theory. IET Power Electronics, 8(11), 2265-2280.

Dionise, T. J. (2014). Assessing the performance of a static var compensator for an electric arc furnace. IEEE Transactions on Industry Applications, 50(3), 1619-1629.

Dogan, H., and Akkaya, R. (2014). A control scheme employing an adaptive hysteresis current controller and an uncomplicated reference current generator for a single-phase shunt active power filter. Turkish Journal of Electrical Engineering & Computer Sciences, 22(4), 1085-1097.

Du, Y., Lu, D. D. C., Chu, G. M., and Xiao, W. (2015). Closed-form solution of time-varying model and its applications for output current harmonics in two-stage PV inverter. IEEE Transactions on Sustainable Energy, 6 (1), 142-150.

Dugan, R. C., McGranaghan, M. F., & Beaty, H. W. (1996). Electrical power systems quality. New York, NY: McGraw-Hill, 1-11.

© COPYRIGHT UPM

Dugan, R.C., McGranaghan, M.F., Santoso, S., and Beaty H.W. (2003). Electrical Power Systems Quality. New York: McGraw-Hill. 2-11.

Emanuel, A. E. (1990). Powers in nonsinusoidal situations-a review of definitions and physical meaning. IEEE Transactions on Power Delivery, 5(3), 1377-1389.

Enrique, J. M., Duran, E., Sidrach-de-Cardona, M., & Andujar, J. M. (2007). Theoretical assessment of the maximum power point tracking efficiency of photovoltaic facilities with different converter topologies. Solar Energy, 81(1), 31-38.

Eskandarian, N., Beromi, Y. A., and Farhangi, S. (2014). Improvement of dynamic behavior of shunt active power filter using fuzzy instantaneous power theory. Journal of power Electronics, 14(6), 1303-1313.

Esposito, F., Isastia, V., Meo, S., & Piegari, L. (2008). An improved perturbe and observe algorithm for tracking maximum power points of photovoltaic power systems. International Review on Modelling and Simulations (IREMOS), 10-16.

Fan, W., and Liao, Y. (2012). Impacts of Flickers, Harmonics and Faults on Synchronous Generator Operations. IEEE Southeastern Symposium on System Theory, 220-225.

Farahat, M. A., and Zobah, A. (2004). Active filter for power quality improvement by artificial neural networks technique. Universities Power Engineering Conference, 2, 878-883.

Faranda, R., and Leva, S. (2008). Energy comparison of MPPT techniques for PV Systems. World Scientific and Engineering Academy and Society transaction on power systems, 3(6), 446-455.

Forghani, M., & Afsharnia, S. (2007). Online wavelet transform-based control strategy for UPQC control system. IEEE transactions on power delivery, 22(1), 481-491.

Fujita, H., and Akagi, H. (1998). The unified power quality conditioner: the integration of series and shunt-active filters. IEEE transactions on power electronics, 13(2), 315-322.

Gao, F., Li, D., Loh, P. C., Tang, Y., & Wang, P. (2009). Indirect dc-link voltage control of two-stage single-phase PV inverter. Energy Conversion Congress and Exposition, 1166-1172.

Gaouda, A. M., Salama, M. M. A., Sultan, M. R., & Chikhani, A. Y. (1999). Power quality detection and classification using wavelet-multiresolution signal decomposition. IEEE Transactions on power delivery, 14(4), 1469-1476.

Gardell, J. D., and Kumar, P. (2014). Adjustable-Speed Drive Motor Protection Applications and Issues. IEEE Transactions on Industry Applications, 50(2), 1364-1372.

Garrido, J.L.F., and Revuelta, P.S. (2011). Harmonic detection by using different artificial neural network topologies. The International Conference on Renewable Energies and Power Quality, 1-7.

George, S., and Agarwal, V. (2007). A DSP-based control algorithm for series active filter for optimized compensation under nonsinusoidal and unbalanced voltage conditions. IEEE transactions on power delivery, 22(1), 302-310.

Ghazali, A. M., & Rahman, A. M. A. (2012). The performance of three different solar panels for solar electricity applying solar tracking device under the Malaysian climate condition. Energy and Environment Research, 2(1), 235-243.

Glinkowski, M., Simmons, L., Loucks, D., Becker, D., Bitterlin,, I., Campbell, B., Handlin, H, Lembke, P., Earp, T., LeRoy, D., Lynch, A., McCluer, S., and Spitaels, J. (2007). Data center power system harmonics: an overview of effects on data center efficiency and reliability. The green grid, 1-28.

© COPYRIGHT UPM

Gowtami, D., Ravindra, S., and Kalavathi, S.S. (2012). Implementation of ANN Based Controllers to Improve the Dynamic Performance of a Shunt Active Power Filter. International Journal of Modern Engineering Research, 2(4), 2352-2357.

Green, T. C., & Marks, J. H. (2005). Control techniques for active power filters. IEE Proceedings-Electric Power Applications, 152(2), 369-381.

Guo, X., Wang, D., Chen, R., Liu, S., and Li, Y. (2012). Active Power Filter DC Bus Voltage Control Based on Fuzzy PI Compound Control. World Automation Congress (WAC), 1-4.

Hamasaki, S., and Kawamura, A. (2003). Improvement of current regulation of line-current detection-type active filter based on deadbeat control. IEEE Transaction on Industrial Application, 39(2), 536-541.

Han, S., Ng, W. K., Wan, L., and Lee, V. C. (2010). Privacy-preserving gradient-descent methods. IEEE Transactions on Knowledge and Data Engineering, 22(6), 884-899.

Hohm, D. P., & Ropp, M. E. (2000). Comparative study of maximum power point tracking algorithms using an experimental, programmable, maximum power point tracking test bed. Conference record of the twenty-eighth IEEE photovoltaic specialists conference, 1699-1702.

Hoon, Y., Mohd Radzi, M. A., Hassan, M. K., & Mailah, N. F. (2016). DC-Link Capacitor Voltage Regulation for Three-Phase Three-Level Inverter-Based Shunt Active Power Filter with Inverted Error Deviation Control. Energies, 9(7), 533-568.

Houssamo, I., Locment, F., & Sechilariu, M. (2010). Maximum power tracking for photovoltaic power system: Development and experimental comparison of two algorithms. Renewable Energy, 35(10), 2381-2387.

Hsu, C. T., & Chuang, H. J. (2005). Power quality assessment of large motor starting and loading for the integrated steel-making cogeneration facility. Industry Applications Conference on Fourtieth IAS Annual Meeting. 1, 59-66.

Hu, H., Shi, Q., He, Z., He, J., and Gao, S. (2015). Potential harmonic resonance impacts of PV inverter filters on distribution systems. IEEE Transactions on Sustainable Energy, 6(1), 151-161.

Husen, S.S., and Patel, P.J. (2014). A Literature Review and Industrial Survey on Active Power Filter. International Journal of Engineering Development and Research, 2(1), 118-125.

IEEE Standard 1159. (2009). IEEE Recommended Practice for Monitoring Electric Power Quality. New York: Institute of Electrical and Electronics Engineers. 1-8.

Institute of Electrical and Electronics Engineers 100. (2000). The authoritative dictionary of IEEE standards terms. IEEE Press Standards Information Network, 1-1362.

Institute of Electrical and Electronics Engineers 446-1995. (1996). IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications, IEEE Orange Book, 1-320.

Institute of Electrical and Electronics Engineers 519-1992 updated version. (2014). IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, New York: Institute of Electrical and Electronics Engineers, 1-29.

Iqbal, A., Abu-Rub, H., and Ahmed, S.K.M. (2010). Adaptive Neuro-Fuzzy Inference System based Maximum Power Point Tracking of a Solar PV Module. IEEE International Energy Conference, 51-56.

ISIS Malaysia. (2014). Reforming Peninsular Malaysia's Electricity Sector: Challenges and Prospects. Kuala Lumpur: Institute of Strategic and international Studies (ISIS) Malaysia, 1-40.

© COPYRIGHT UPM

Jacob, A., Abraham, B.T., Prakash, N., and Philip, R.(2014). A Review of Active Power Filters In Power System Applications. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, 3(6), 10253-10261.

Jain, S. K., Agrawal, P., and Gupta, H. O. (2002). Fuzzy logic controlled shunt active power filter for power quality improvement. IEE Proceedings-Electric Power Applications, 149(5), 317-328.

Jain, S. K., and Singh, S. N. (2013). Fast harmonic estimation of stationary and time-varying signals using EA-AWNN. IEEE Transactions on Instrumentation and Measurement, 62(2), 335-343.

Jain, S. K., and Singh, S. N. (2014). Low-order dominant harmonic estimation using adaptive wavelet neural network. IEEE Transactions on Industrial Electronics, 61(1), 428-435.

Janpong, S., Areerak, K. L., & Areerak, K. N. (2011). A literature survey of neural network applications for shunt active power filters. J. World Acad. Sci., Eng. Technol, 60, 392-398.

Jeevananthan, K.S. (2014). Designing of Single Phase Shunt Active Filter Using Instantaneous Power Theory. International Journal of Electrical and Electronics Research, 2(2), 1-10.

Jettanasen, C., and Ngaopitakkul, A. (2014). Study of harmonics issued from electronic ballast used to reduce energy consumption in Thailand's building. International Conference on Intelligent Green Building and Smart Grid (IGBSG), 1-4.

Jiang, J. A., Huang, T. L., Hsiao, Y. T., & Chen, C. H. (2005). Maximum power tracking for photovoltaic power systems. Tamkang Journal of Science and Engineering, 8(2), 147-153.

Jorge, S. G., Busada, C. A., and Solsona, J. (2014). Reduced order generalised integrator-based current controller applied to shunt active power filters. IET Power Electronics, 7(5), 1083-1091.

Kalaignan, T. P., Kumar, J. S., and Suresh, Y. (2014). PSO and GA Based Performance Optimization of PI Controller in Three Phase Shunt Hybrid Filter. International Journal of Engineering Research and Technology, 3(8), 255-260.

Kandil, T., Lopes, L. and Xu, W. (2005). Analysis and design of a new current controlled switched capacitor filter for harmonic mitigation. Elect. Power Comp. and Syst, 33, 1-20.

Kazmierkowski, M. P., & Malesani, L. (1998). Current control techniques for three-phase voltage-source PWM converters: a survey. IEEE Transactions on Industrial Electronics, 45(5), 691-703.

Kesler, M., and Ozdemir, E. (2011). Synchronous-reference-frame-based control method for UPQC under unbalanced and distorted load conditions. IEEE Transactions on Industrial Electronics, 58(9), 3967-3975.

Khadkikar, V., Chandra, A., & Singh, B. N. (2009). Generalised single-phase pq theory for active power filtering: simulation and DSP-based experimental investigation. IET Power Electronics, 2(1), 67-78.

Khaehintung, N., Sirisuk, P., & Kurutach, W. (2003). A novel ANFIS controller for maximum power point tracking in photovoltaic systems. The Fifth International Conference on Power Electronics and Drive Systems, 2, 833-836.

Khalid, S., & Dwivedi, B. (2011). Power quality issues, problems, standards & their effects in industry with corrective means. International Journal of Advances in Engineering & Technology, 1(2), 1-11.

© COPYRIGHT UPM

Khatib, T. T., Mohamed, A., Mahmoud, M., & Amin, N. (2010). An efficient maximum power point tracking controller for a standalone photovoltaic system. International Review on Modelling and Simulations, 3(2), 129-139.
Khoor, M. S., and Machmoum, M. (2007). A low voltage dynamic voltage restorer with self-charging capability. European Conference on Power Electronics and Applications, 1-9.
Kim, Y. S., Kim, J. S., and Ko, S. H. (2004). Three-phase three-wire series active power filter, which compensates for harmonics and reactive power. IEE Proceedings-Electric Power Applications, 151(3), 276-282.
Kinhal, V. G., Agarwal, P., & Gupta, H. O. (2011). Performance investigation of neural-network-based unified power-quality conditioner. IEEE transactions on power delivery, 26(1), 431-437.
Kiran, C. N., Dash, S. S., & Latha, S. P. (2011). A Few Aspects of Power Quality Improvement Using Shunt Active Power Filter. International Journal of Scientific & Engineering Research, 2(5), 1-11.
Kjaer, S. B., Pedersen, J. K., & Blaabjerg, F. (2002). Power inverter topologies for photovoltaic modules-a review. IAS annual meeting conference record of the industry applications conference, 2, 782-788.
Ko, S. H., and Chao, R. M. (2012). Photovoltaic dynamic MPPT on a moving vehicle. Solar Energy, 86(6), 1750-1760.
Komurcugil, H., & Kukrer, O. (2006). A new control strategy for single-phase shunt active power filters using a Lyapunov function. IEEE Transactions on Industrial Electronics, 53(1), 305-312.
Kumar, N. M. G., Raju, P. S., & Venkatesh, P. (2012). Control Of Dc Capacitor Voltage In A Dstatcom Using Fuzzy Logic Controller. International Journal of Advances in Engineering & Technology, 4(1), 679-691.
Kwan, K. H., So, P. L., and Chu, Y. C. (2012). An output regulation-based unified power quality conditioner with Kalman filters. IEEE Transactions on Industrial Electronics, 59(11), 4248-4262.
Ladyada. (2012). Boost dc-dc converter calculation; DIY boost dc-dc converter. https://learn.adafruit.com/diy-boost-calc/the-calculator. (assessed 22/3/2016).
Lee, G. J., Albu, M. M., & Heydt, G. T. (2004). A power quality index based on equipment sensitivity, cost, and network vulnerability. IEEE Transactions on Power Delivery, 19(3), 1504-1510.
Lee, G. M., Lee, D. C., and Seok, J. K. (2004). Control of series active power filters compensating for source voltage unbalance and current harmonics. IEEE Transactions on industrial electronics, 51(1), 132-139.
Lee, S. J., Kim, J. M., An, D. K., & Hong, J. P. (2014). Equivalent circuit considering the harmonics of core loss in the squirrel-cage induction motor for electrical power steering application. IEEE Transactions on Magnetics, 50(11), 1-4.
Lega, A., Mengoni, M., Serra, G., Tani, A., and Zarri, L. (2008). General theory of space vector modulation for five-phase inverters. IEEE International Symposium on Industrial Electronics, 237-244.
Liu, C., Blaabjerg, F., Chen, W., and Xu, D. (2012). Stator current harmonic control with resonant controller for doubly fed induction generator. IEEE transactions on power electronics, 27(7), 3207-3220.
Lu, Y., Xiao, G., Wang, X., Blaabjerg, F., & Lu, D. (2016). Control Strategy for Single-Phase Transformerless Three-Leg Unified Power Quality Conditioner Based on Space Vector Modulation. IEEE Transactions on Power Electronics, 31(4), 2840-2849.

© COPYRIGHT UPM

Mattavelli, P., and Marafao, F. P. (2004). Repetitive-based control for selective harmonic compensation in active power filters. IEEE Transactions on Industrial Electronics, 51(5), 1018-1024.

Mehta, G., Patidar, R. D., and Singh, S. P. (2011). Design, analysis and implementation of DSP based single-phase shunt active filter controller. International Conference on Emerging Trends in Electrical and Computer Technology (ICETECT), 166-173.

Mikkili, S., and Panda, A. K. (2013). Types-1 and-2 fuzzy logic controllers-based shunt active filter I d-I q control strategy with different fuzzy membership functions for power quality improvement using RTDS hardware. IET Power Electronics, 6(4), 818-833.

Mishra, G., and Gopalakrishna, S. (2013). Design of passive high pass filter for shunt active power filter application. International Conference on Circuits, Power and Computing Technologies (ICCPCT), 17-21.

Mittal, K., and Kosti A. (2014). Hybrid Active Power Filter for Power Quality Improvement, International Journal of Emerging Technology and Advanced Engineering, 4(5), 402-405.

Mohamed, S. E. G., & Mohamed, A.Y. (2012). Study of Load Side Harmonics Sources Effects and Elimination. In Zaytoonah University International Engineering Conference on Design and Innovation in Infrastructure, pp. 18-20.

Monfared, M., Golestan, S., and Guerrero, J. M. (2013). A new synchronous reference frame-based method for single-phase shunt active power filters. Journal of power Electronics, 13(4), 692-700.

Moreno, V. M., Lopez, A. P., & Garcias, R. I. D. (2004). Reference current estimation under distorted line voltage for control of shunt active power filters. IEEE Transactions on Power Electronics, 19(4), 988-994.

Moreno, V. M., Pigazo, A., Liserre, M., and Dell'Aquila, A. (2008). Unified power quality conditioner (UPQC) with voltage dips and over-voltages compensation capability. signal, 12, 1-13.

Mortezaei, A., Lute, C., Simoes, M. G., Marafão, F. P., and Boglia, A. (2014). PQ, DQ and CPT control methods for shunt active compensators-A comparative study. IEEE Energy Conversion Congress and Exposition (ECCE), 2994-3001.

Moyra, T., Parui, S. K., and Das, S. (2011). Design and Development of Lowpass Filter and Harmonics Reduction. International Journal on Electrical Engineering and Informatics, 3(3), 336-349.

Mulla, M. A., Rajagopalan, C., and Chowdhury, A. (2013). Hardware implementation of series hybrid active power filter using a novel control strategy based on generalised instantaneous power theory. IET Power Electronics, 6(3), 592-600.

Murthy-Bellur, D., Kondrath, N., and Kazimierczuk, M. K. (2011). Transformer winding loss caused by skin and proximity effects including harmonics in pulse-width modulated DC/DC flyback converters for the continuous conduction mode. IET Power Electronics, 4(4), 363-373.

Nagarajan, D. A., Murthy-Bellur, D., and Kazimierczuk, M. K. (2012). Harmonic winding losses in the transformer of a forward pulse width modulated DC-DC converter for continuous conduction mode. IET Power Electronics, 5(2), 221-236.

Neves, P., Gonçalves, D., Pinto, J. G., Alves, R., & Afonso, J. L. (2009). Single-phase Shunt Active Filter interfacing renewable energy sources with the power grid. Annual Conference of IEEE on Industrial Electronics, 3264-3269.

Patnaik, S. S., and Panda, A. K. (2013). Real-time performance analysis and comparison of various control schemes for particle swarm optimization-based

© COPYRIGHT UPM

shunt active power filters. International Journal of Electrical Power & Energy Systems, 52, 185-197.
Paul, P. J. (2011). Shunt Active and Series Active Filters-Based Power Quality Conditioner for Matrix Converter. Advances in Power Electronics, 2011, 1-9.
Peng, F. Z., Ott, G. W., and Adams, D. J. (1998). Harmonic and reactive power compensation based on the generalized instantaneous reactive power theory for three-phase four-wire systems. IEEE Transactions on Power Electronics, 13(6), 1174-1181.
Ponpandi, R., Durairaj, D. (2011). A Novel Fuzzy-Adaptive Hysteresis Controller Based Three Phase Four Wire-Four Leg Shunt Active Filter for Harmonic and Reactive Power Compensation. Energy and Power Engineering, 3, 422-435.
Priya, S. M., and Keerthana, K. (2013). Regulating unified power quality conditioner output using Kalman filters. International Journal Of Modern Engineering Research, 62-73.
Qasim, M., & Khadkikar, V. (2014). Application of artificial neural networks for shunt active power filter control. IEEE Transactions on Industrial Informatics, 10(3), 1765-1774.
Qasim, M., Kanjiya, P., and Khadkikar, V. (2014). Optimal current harmonic extractor based on unified ADALINEs for shunt active power filters. IEEE Transactions on Power Electronics, 29(12), 6383-6393.
Radzi, M. A. M., and Rahim, N. A. (2009). Neural network and bandless hysteresis approach to control switched capacitor active power filter for reduction of harmonics. IEEE Transactions on Industrial Electronics, 56(5), 1477-1484.
Rahimo, M. T., & Shammas, N. Y. (2001). Freewheeling diode reverse-recovery failure modes in IGBT applications. Industry Applications, IEEE Transactions on, 37(2), 661-670.
Rahman, N. A., Radzi, M. A. M., Mariun, N., Soh, A. C., and Rahim, N. A. (2013). Integration of dual intelligent algorithms in shunt active power filter. IEEE Conference on Clean Energy and Technology (CEAT), 259-264.
Rahman, N. F. A., Radzi, M. A. M., Soh, A. C., Mariun, N., and Rahim, N. A. (2015). Dual Function of Unified Adaptive Linear Neurons Based Fundamental Component Extraction Algorithm for Shunt Active Power Filter Operation. International Review of Electrical Engineering (IREE), 10(4), 544-552.
Rahmani, S., Al-Haddad, K., & Kanaan, H. Y. (2008). Two PWM techniques for single-phase shunt active power filters employing a direct current control strategy. IET Power Electronics, 1(3), 376-385.
Rao, U. K., Mishra, M. K., and Vincent, G. (2008). An optimization based algorithm for shunt active filter under unbalanced and nonsinusoidal supply voltages. IEEE Conference on Industrial Electronics and Applications, 1475-1480.
Rashid M.H. (2003). Dc-dc Converter. Power Electronics circuits, devices, and applications. 3rd Edition, Pearson, 168-179.
Rashid, C., Yahia, B., and Hind, D. (2012). Application of an Active Power Filter on Photovoltaic Power Generation System. International Journal of Renewable Energy Research (IJRER), 2(4), 583-590.
Ross, T. J. (2009). Fuzzy logic with engineering applications. John Wiley & Sons, 1-15.
Routimo, M., Salo, M., & Tuusa, H. (2007). Comparison of voltage-source and current-source shunt active power filters. IEEE Transactions on Power Electronics, 22(2), 636-643.
Rüstemli, S., & Cengiz, M. S. (2015). Active filter solutions in energy systems. Turkish Journal of Electrical Engineering & Computer Sciences, 23(6), 1587-1607.

© COPYRIGHT UPM

Salcone, M., and Bond, J. (2009). Selecting film bus link capacitors for high performance inverter applications. IEEE International on Electric Machines and Drives Conference, 1692-1699.

Santos, W. R. N., de Moura Fernandes, E., da Silva, E. R. C., Jacobina, C. B., Oliveira, A. C., & Santos, P. M. (2016). Transformerless Single-Phase Universal Active Filter With UPS Features and Reduced Number of Electronic Power Switches. IEEE Transactions on Power Electronics, 31(6), 4111-4120.

Sattar, A. (1998). Insulated gate bipolar transistor (IGBT) basics. In IXYS Corporation. IXAN0063.1-15.

Sawant, R.R., and Chandorkar, M.C. (2009). A multifunctional four-leg grid-connected compensator. IEEE Transaction on Industrial Application, 45(1), 249-259.

Shah, N. (2013). Harmonics in power systems causes, effects and control. Whitepaper design engineering low-voltage drives, 1-23.

Shousha, M. F., Zaid, S. A., and Mahgoub, O. A. (2011). A comparative study on four time-domain harmonic detection methods for active power filters serving in distorted supply. In Proceedings of the International Multi Conference of Engineers and Computer Scientists, 2, 1-4.

Sindhu, M. R., Nair, M. G., and Nambiar, T. N. P. (2008). An ANN based Digital Controller for a Three-phase Active Power Filter. International Conference on Power System Technology and IEEE Power India Conference, 1-7.

Singh, B. N., Rastgoufard, P., Singh, B., Chandra, A., & Al-Haddad, K. (2004). Design, simulation and implementation of three-pole/four-pole topologies for active filters. IEE Proceedings-Electric Power Applications, 151(4), 467-476.

Singh, B., Al-Haddad, K., & Chandra, A. (1999). A review of active filters for power quality improvement. IEEE transactions on industrial electronics, 46(5), 960-971.

Singh, B., Chandra, A., & Al-Haddad, K. (2014). Power quality: problems and mitigation techniques. John Wiley & Sons, 1, 12-16.

Singh, B., Verma, V., and Solanki, J. (2007). Neural network-based selective compensation of current quality problems in distribution system. IEEE Transactions on Industrial Electronics, 54(1), 53-60.

Singh, S., Bist, V., Singh, B., and Bhuvaneswari, G. (2015). Power factor correction in switched mode power supply for computers using canonical switching cell converter. IET Power Electronics, 8(2), 234-244.

Singh, S., Singh, B., Bhuvaneswari, G., and Bist, V. (2015). Power factor corrected zeta converter based improved power quality switched mode power supply. IEEE Transactions on Industrial Electronics, 62(9), 5422-5433.

Solar Cell Central. (2013). The Shockley Queasier Efficiency Limit. http://solarcellcentral.com/limits_page.html. (accessed 7 Jan 2013).

Soltani, H., Blaabjerg, F., Zare, F., and Loh, P. C. (2016). Effects of passive components on the input current interharmonics of adjustable-speed drives. IEEE Journal of Emerging and Selected Topics in Power Electronics, 4(1), 152-161.

Somlal, J., and Gopala Rao, M.V. (2014). Power Conditioning in Distribution Systems Using ANN Controlled Shunt Hybrid Active Power Filter. Smart Electric Grid (ISEG), 1-5.

Srivastava, K. K., Shakil, S., and Pandey, A. V. (2013). Harmonics & Its Mitigation Technique by Passive Shunt Filter. International Journal of Soft Computing and Engineering (IJSCE) ISSN, 2231-2307.

Stones, J., and Collinson, A. (2001). Power quality. Power Engineering Journal, 15(2), 58-64.

© COPYRIGHT UPM

Sujitjom, S., Areerak, K. L., and Kulworawanichpong, T. (2007). The DQ axis with fourier (DQF) method for harmonic identification. IEEE transactions on power delivery, 22(1), 737-739.

Sukhadia, M. R. P., Makwana, N. K. V., & Vishwavidyalaya, K. S. (2015). A review on series active filter performance for harmonic reduction. International Journal For Technological Research In Engineering, 2(6), 521-525.

Suresh, Y., Panda, A. K., & Suresh, M. (2012). Real-time implementation of adaptive fuzzy hysteresis-band current control technique for shunt active power filter. IET Power Electronics, 5(7), 1188-1195.

Suslov, K. V., Stepanov, V. S., & Solonina, N. N. (2013). Smart grid: Effect of high harmonics on electricity consumers in distribution networks. In Electromagnetic Compatibility (EMC EUROPE), 841-845.

Swamy, M. M. (2015). An electronically isolated 12-pulse autotransformer rectification scheme to improve input power factor and lower harmonic distortion in variable-frequency drives. IEEE Transactions on Industry Applications, 51(5), 3986-3994.

Tang, X., Tsang, K. M., and Chan, W. L. (2012). A power quality compensator with DG interface capability using repetitive control. IEEE Transactions on Energy Conversion, 27(2), 213-219.

Tey, L. H., So, P. L., & Chu, Y. C. (2005). Improvement of power quality using adaptive shunt active filter. IEEE transactions on power delivery, 20(2), 1558-1568.

Tu, W. H., & Chang, K. (2006). Compact second harmonic-suppressed bandstop and bandpass filters using open stubs. IEEE Transactions on Microwave Theory and Techniques, 54(6), 2497-2502.

Tumbelaka, H. H., and Miyatake, M. (2010). Simple integration of three-phase shunt active power filter and photovoltaic generation system with Fibonacci-search-based MPPT. IEEE Symposium on Industrial Electronics & Applications (ISIEA), 2010 94-99.

Valenzuela, J., and Pontt, J. (2009). Real-time interharmonics detection and measurement based on FFT algorithm. Applied Electronics, 259-264.

Vazquez, J. R., and Salmeron, P. (2003). Active power filter control using neural network technologies. IEE Proceedings-Electric Power Applications, 150(2), 139-145.

Vijayakumar, G., and Anita, R. (2015). Photovoltaic Based Shunt Active Filter For Power Quality Improvement Using Icosφ Theory. Journal of Engineering Science and Technology, 10(11), 1422-1440.

Vijayvargiya, S., and Nimonkar, Y. (2013). Comparative Analysis of Different Harmonics Detection Techniques for Power Quality. Indian Journal of Research, 2(3), 141-143.

Vodyakho, O., and Kim, T. (2009). Shunt active filter based on three-level inverter for three-phase four-wire systems. IET Power Electronics, 2(3), 216-226.

Walker, G. (2001). Evaluating MPPT converter topologies using a MATLAB PV model. Journal of Electrical & Electronics Engineering, 21(1), 49-56.

Wandhare, R. G., and Agarwal, V. (2014). Reactive power capacity enhancement of a PV-grid system to increase PV penetration level in smart grid scenario. IEEE Transactions on Smart Grid, 5(4), 1845-1854.

Wang, T., Fang, F., Wu, X., & Jiang, X. (2013). Novel filter for stator harmonic currents reduction in six-step converter fed multiphase induction motor drives. IEEE Transactions on Power Electronics, 28(1), 498-506.

© COPYRIGHT UPM

Wang, W., Luo, A., Xu, X., Fang, L., Chau, T. M., and Li, Z. (2013). Space vector pulse-width modulation algorithm and DC-side voltage control strategy of three-phase four-switch active power filters. IET Power Electronics, 6(1), 125-135.

Wang, Y., Yao, L., Peng, J., Wang, Y., and Mao, X. (2012). Analysis of Harmonic Current Suppression and Reactive Power Compensation on 125 MVA Motor Generator. IEEE Transactions on Plasma Science, 40(3), 705-709.

Wang, Z. Q., Manry, M. T., and Schiano, J. L. (2000). LMS learning algorithms: misconceptions and new results on converence. IEEE Transactions on Neural Networks, 11(1), 47-56.

Wang, Z., Wang, Q., Yao, W., and Liu, J. (2001). A series active power filter adopting hybrid control approach. IEEE Transactions on Power Electronics, 16(3), 301-310.

Wu, T. F., Hsieh, H. C., Hsu, C. W., & Chang, Y. R. (2016). Three-Phase Three-Wire Active Power Filter With D–Digital Control to Accommodate Filter-Inductance Variation. IEEE Journal of Emerging and Selected Topics in Power Electronics, 4(1), 44-53.

Wu, Y., Zhang, B., Lu, J., & Du, K. L. (2011). Fuzzy logic and neuro-fuzzy systems: A systematic introduction. International Journal of Artificial Intelligence and Expert Systems, 2(2), 47-80.

Xiao, Z., Deng, X., Yuan, R., Guo, P., and Chen, Q. (2014). Shunt active power filter with enhanced dynamic performance using novel control strategy. IET Power Electronics, 7(12), 3169-3181.

Yongtao, D., and Wenjin, D. (2008). Harmonic and reactive power compensation with artificial neural network technology. 7th World Congress on Intelligent Control and Automation, 9001-9006.

Zainuri, M. A. A. M., Radzi, M. A. M., Soh, A. C., & Rahim, N. A. (2014). Development of adaptive perturb and observe-fuzzy control maximum power point tracking for photovoltaic boost dc-dc converter. IET Renewable Power Generation, 8(2), 183-194.

Zakzouk, N. E., Abdelsalam, A. K., Helal, A. A., & Williams, B. W. (2014, May). DC-link voltage sensorless control technique for single-phase two-stage photovoltaic grid-connected system. In Energy Conference (ENERGYCON), 58-64.

Zeng, F. P., Tan, G. H., Wang, J. Z., and Ji, Y. C. (2010). Novel single-phase five-level voltage-source inverter for the shunt active power filter. IET Power Electronics, 3(4), 480-489.

Zhang, W., Han, L., Ma, R., & Mao, J. (2007). Multi-harmonic suppression band-pass filter for communication system. ETRI journal, 29(4), 533-535.

Zhou, Y., and Li, H. (2014). Analysis and suppression of leakage current in cascaded-multilevel-inverter-based PV systems. IEEE Transactions on Power Electronics, 29(10), 5265-5277.

Zorrozua, M. A., Lazaro, J., Miñambres, J. F., Larrea, B., & Sanchez, M. (2012). Estimation of Power System Harmonics and Interharmonics in the Presence of Aperiodic Components. International Conference on Renewable Energies and Power Quality (ICREPQ’12), 1-6.

© COPYRIGHT UPM