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

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By

MUHAMMAD AMMIRRUL ATIQI B MOHD ZAINURI

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March 2017

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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,

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.

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

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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

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.

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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.

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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

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.

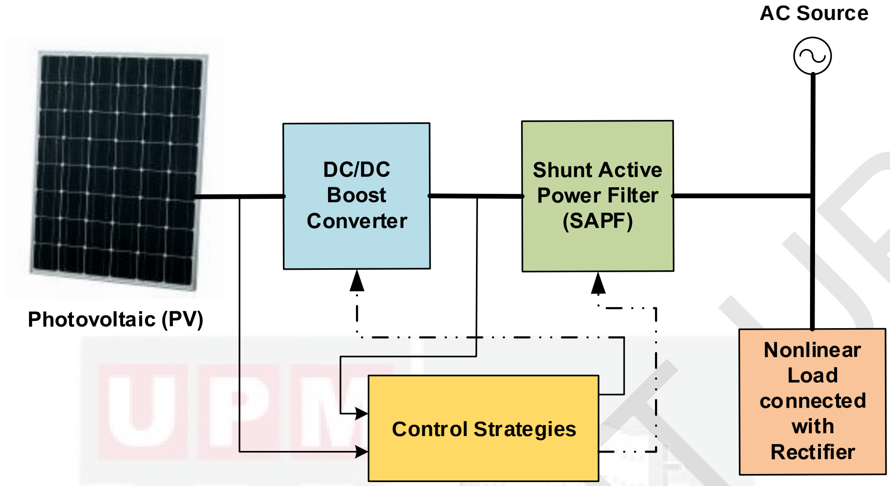

Figure 1.1: Single-phase photovoltaic based shunt active power filter

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, 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].

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 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 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.

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