UNIVERSITI PUTRA MALAYSIA

SHUNT ACTIVE POWER FILTER WITH MODIFIED SYNCHRONOUS REFERENCE FRAME TECHNIQUE AND FUZZY LOGIC CURRENT CONTROLLER FOR HARMONIC MITIGATION

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SHUNT ACTIVE POWER FILTER WITH MODIFIED SYNCHRONOUS REFERENCE FRAME TECHNIQUE AND FUZZY LOGIC CURRENT CONTROLLER FOR HARMONIC MITIGATION

By

MUSA SULEIMAN

This thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

September 2017

DEDICATION

To my Parents, in memory of my late Father may his soul rest in Janatul Firdaus. Ameen.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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September 2017

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Harmonics is a power quality problem which represents a steady-state problem. It leads to a number of issues, ranges from equipment mal-function, which result to overheating of rotating machinery and random tripping of relays for protection of devices. Shunt active power filter (SAPF) has been the most popular choice to address harmonic disturbances in power system networks.

For efficient compensation, SAPF greatly depends on fast and accurate detection of reference harmonic current. To generate the reference signals, modified synchronous reference frame (MSRF) technique is chosen. Low pass filter (LPF) has always been used to separate fundamental from harmonic components, and it provides adequate and reasonable results in harmonic mitigation. However, there is need for improvement due to presence of unwanted low order harmonics that cannot completely be eliminated by LPF.

Meanwhile, generation of compensation current by SAPF is also depending on switching strategy. Sinusoidal PWM is used with fuzzy controller for better output performance. However, if the number of membership functions is too large, due to hardware limitations such as memory, speed and cost, all sets of rules cannot adequately be implemented in a complex system. Also, there is no certainty that the rules are defined correctly with no confliction between each other at certain situations. Furthermore, the ability to select an optimized subset of fuzzy rules is a major challenge in designing the control system.

Therefore, in this research work, two modifications have been introduced to address the mentioned issues. First, harmonic extraction using SRF for three-phase three-wire system introduces a band pass filter, and second, simple three membership functions in fuzzy logic controller for inputs and five outputs are designed to improve performance of the switching algorithm. The SAPF was simulated in Matlab-Simulink platform and further verified with laboratory prototype.

The simulation and experimental results show ability of the proposed algorithms to accurately estimate harmonic reference signal which was utilized in switching pulses for the SAPF. The performance index is the THD which is clearly shown to be improved from 23.99 % to 0.92 % for RL nonlinear load and for the RC nonlinear load from 35.46 % to 1.49 %. From both results, the proposed algorithms show good performances when compared with the conventional algorithms. The THDs were reduced to acceptable level in conformity with the available standard.

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

PENAPIS AKTIF KUASA PIRAU DENGAN TEKNIK RANGKA RUJUKAN SEGERAK DIUBAH SUAI DAN PENGAWAL ARUS LOGIK KABUR BAGI PENGURANGAN HARMONIK

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Harmonik adalah masalah kualiti kuasa yang mewakili masalah keadaan mantap. Ia menyumbang kepada beberapa isu, bermula daripada kegagalan fungsi peralatan, yang menyebabkan kepada pemanasan lebih jentera putar dan belantikan rawak geganti bagi alat perlindungan. Penapis kuasa aktif pirau (SAPF) telah menjadi pilihan yang paling popular untuk menangani gangguan harmonik dalam rangkaian sistem kuasa.

Bagi pampasan yang cekap, SAPF banyak bergantung kepada pengesanan cepat dan tepat arus rujukan harmonik. Untuk menjana isyarat rujukan, teknik rangka rujukan segerak diubah suai (MSRF) dipilih. Penapis lulus rendah (LPF) telah selalu digunakan untuk mengasingkan komponen asas daripada harmonik, dan ia menyediakan keputusan yang mencukupi dan wajar dalam pengurangan harmonik. Walau bagaimanapun, terdapat keperluan untuk penambahbaikan oleh sebab kewujudan harmonik tertib rendah tidak diingini yang tidak boleh disingkirkan sepenuhnya oleh LPF.

Sementara itu, penjanaan arus pampasan oleh SAPF juga bergantung kepada strategi pensuisan. Teknik PWM bentuk sinus digunakan dengan pengawal kabur bagi prestasi keluaran lebih baik. Walau bagaimanapun, jika jumlah fungsi keahlian adalah terlalu besar, oleh sebab batasan perkakasan seperti memori, kelajuan dan kos, semua set peraturan tidak boleh secukupnya dilaksanakan dalam sistem yang kompleks. Juga, tidak ada kepastian bahawa peraturan telah ditentukan dengan tepat tanpa pertikaian antara satu sama lain pada situasi tertentu. Tambahan pula, keupayaan untuk memilih subset yang optimum bagi peraturan kabur merupakan cabaran utama dalam mereka bentuk sistem kawalan.

Oleh itu, dalam penyelidikan ini, dua pengubahsuaian telah diperkenalkan untuk menangani isu yang disebutkan. Pertama, pengekstrakan harmonik menggunakan SRF untuk sistem tiga fasa tiga dawai memperkenalkan penapis lulus jalur, dan kedua, tiga fungsi keahlian mudah dalam kawalan logik kabur untuk satu masukan dan lima keluaran direka untuk meningkatkan prestasi algoritma pensuisan. SAPF disimulasi dalam Matlab-Simulink dan disahkan kemudian dengan prototaip makmal.

Keputusan simulasi dan eksperimen menunjukkan keupayaan algoritma yang dicadangkan untuk menganggarkan dengan tepat isyarat rujukan harmonik yang digunakan dalam denyutan pensuisan untuk SAPF. Indeks prestasi adalah THD yang jelas ditunjukkan telah meningkat dari 23.99 % kepada 0.92 % untuk beban tidak linear RL dan untuk beban tidak linear RC dari 35.46 % kepada 1.49 %. Daripada kedua-dua keputusan, algoritma yang dicadangkan menunjukkan prestasi yang baik berbanding dengan algoritma konvensional. THD telah dikurangkan kepada tahap boleh diterima selaras dengan piawaian yang sedia ada

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I certify that a Thesis Examination Committee has met on 15 September 2017 to conduct the final examination of Musa Suleiman on his thesis entitled "Shunt Active Power Filter with Modified Synchronous Reference Frame Technique and Fuzzy Logic Current Controller for Harmonic Mitigation" 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.

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LIST OF ABBREVIATIONS

AC	Alternative current
APF	Active power filter
ASD	Adjustable speed drive
BPF	Band pass filter
BW	Bandwidth
CSI	Current source inverter
CSRF	Conventional Synchronous Reference Frame
DC	Direct current
DSP	Digital signal processor
FLC	Fuzzy logic controller
HPF	High pass filter
IRP	Instanteneous reactive power
LPF	Low pass filter
MSRF	Modified Synchronous Reference Frame
PI	Proportional integral
PID	Proportional integral and derivative
PLL	Phase locked loop
PWM	Pulse-width modulated
SAPF	Shunt active power filter
SDM	synchronous detection method
SPWM	Sinusoidal Pulse Width Modulation
SRF	Synchronous Reference Frame
THD	Total harmonic distortion
VSI	Voltage source inverter

LIST OF SYMBOLS

f_o	Centre frequency
C_{DC}	DC link capacitor
V_{DC}	DC bus voltage
V_{ca}	Fundamental element on the AC-side of PWM-inverter
V_s	Supply voltage
K	$k = 1,2,3,..$
M_a	Amplitude modulation factor
$V_c(t)$	Value of voltage including harmonic corresponding terms
$V_{(ch)max}$	Maximum voltage value of $V_c(t)$ which includes harmonic related terms to be compensated
Q_{ca}	Reactive power delivered from three-phase APF
m_f	Frequency modulation ration of the PWM converter
H	Harmonic
I_{ch}	Harmonic component ripple current
I_{sa}	Supply current
I_{ca}	Compensation current
I_h	h^{th} harmonic peak current
φ_h	h^{th} harmonic current phase
θ_h	h^{th} harmonic voltage phase
V_h	h^{th} harmonic peak voltage
$V_{drp-p(max)}$	Voltage ripple
V_{sm}	Peak value of source voltage
V_{sa}	Source voltage phase A
V_{sb}	Source voltage phase B
V_{sc}	Source voltage phase C
Θ	Angle
Q	Quality factor
f	fundamental frequency
f_2	Upper cut off frequency
f_1	Lower cut off frequency
$\propto$	Attenuation
W	Angular frequency

CHAPTER 1

INTRODUCTION

1.1 Introduction

Nowadays, the subject of generation, transmission, distribution and utilization of electric energy is a key issue to the electrical engineers. A well protected distribution system must ensure effective utilization of electrical power supply at specified voltage and frequency to the consumer. This will increase reliability and cost of any electrical power supply to consumer terminals which depends greatly on the quality of the power supplied. Power quality is concerned with characteristics of electrical power supply delivered under normal operation conditions that do not interrupt customer's process. Poor power quality creates a number of problems ranges from equipment mal-function, which result to overheating of rotating machinery, random tripping of relays for protection of devices. To guard against this problem, installation of power quality enhancement devices is necessary. Power quality is a broad term that covers many issues concerning electrical supply interruption or fluctuation, to includes, voltage sag, voltage spikes, under voltage, over voltage and harmonics (Some of these problems are sustained momentarily while others such as the harmonics represent a steady-state problem, for as long as the harmonic generating equipment in the system is in operation). There are both current and voltage harmonics; however, voltage harmonics are caused by the current harmonics that distort the waveform of voltage [1]. Current harmonics are the primary cause for poor supply quality of the distribution network due to numerous usages of non-linear load in both domestic and industrial premises [2]. The voltage harmonics affect not just the loads which are causing it but the entire system. Current harmonics are initiated by non-linear loads; their effect produces distortion of the fundamental sinusoidal current waveform alternating at fundamental frequency (50Hz). This problem affects the systems by loading the distribution system and also contributing to copper losses (I^2Z losses) in the feeder due to increase in the reactive power and this reduces the active power flow of the system. For many years, the problem of reactive power has been a source of concern for power engineers. This problem becomes more pronounce in harmonic environment due to presence of nonlinear load. Nowadays with increasing applications of harmonic producing devices, it becomes necessary to filter out these harmonics. Harmonics produced by nonlinear loads can be removed by various filtering techniques such as passive and active filters.

In the beginning, passive power filter is used to improve the power supply in the network. However, it cannot efficiently remove the harmonics entirely and has many setbacks such as great weight, occupy larger space, resonance and also affected with system parameter changes [1,3]. These drawbacks are effectively addressed by using Active Power Filter (APF). This device is connected either in series, parallel or their combination. The shunt APF is commonly used than the series APF, because many industrial, commercial and domestic applications require it to compensate current harmonics. It has ability to reduce harmonic distortion in current and reactive power component of non-linear loads in the system. Also, it can solve the problem of unbalance in a three-phase system. It is coupled to system network in parallel at Point of Common Coupling (PCC). The only major challenge related to effective operation of SAPF is in its controller's ability to compensate reactive power, harmonics, and unbalanced loading.

1.2 Problem Statement

Harmonic currents flowing in power distribution networks represent a steady state disturbance in the supply system. It deteriorated the quality of electrical power and this decreased the efficiency of the system. These problems affect the system by loading the distribution system and also contribute to copper losses (I^2Z losses) in the feeder. Effects of harmonics must be investigated once the distortion rate exceeds the thresholds (below 5 % in practice) fixed by the IEC 61000 and IEEE 519 standards.

Shunt active power filter (SAPF) has been proven to be the best device in addressing currents harmonics. It performance depends on effective and adequate reference compensation strategy for both reactive power and harmonic current compensation of the load. Several methods in time domain technique like Synchronous Reference Frame (SRF) d-q theory, instantaneous reactive power theory p-q theory, and Synchronous Detection Method (SDM), have been applied to address the effects of these harmonics in power system. SRF techniques is chosen beause of simplicity and easy implementation.

One issue that can be identified to improve performance of harmonic detection mechanism in time domain technique is the filtering approach used in d-q axis to determine accuracy and dynamic of the control strategy. Normally, Low Pass Filter (LPF) used in d-q frame of SRF technique produced a tolerable result in harmonics current mitigation. However, due to the presence of unwanted remaining current harmonics in the line, the performance of this technique can still be enhanced if the filtering device is improved. The operation of SAPF is affected when there is an incorrect compensation due to inadequate elimination of the harmonic current in the line and therefore needs to be addressed. In [4-5], conventional band pass filter (BPF) was used for harmonic extraction to generate the refernce current. This method however is difficult due to mathematical burden in tuning to specified harmonic current to be compensated. In this study, a simple and easy approach to implement technique is presented to generate the reference current using BPF developed with a high pass and a low pass second order filters.

Meanwhile, generation of compensation current by SAPF depends also on switching strategy adopted. The hysteresis and Sinusoidal Pulse Width Modulation (SPWM) current control techniques are generally used by many researchers, owing to simplicity and fast dynamic response. The major setback of hysteresis current control technique is uneven switching frequency which leads to acoustic noise and difficulty in designing input filters during load variations [6]. This switching frequency can be reduced by decreasing the band width of the hysteresis band. However, the current error will increase thereby producing more distortion in the output current. To eliminate drawbacks of the hysteresis technique, SPWM was used with fuzzy controller for better output performance. For effective performance of fuzzy controller, it depends on large number of the fuzzy rules. However, due to hardware limitations such as memory, speed and cost, all sets of rules cannot adequately be implemented in a complex system. Furthermore, there is no certainty that the rules are well defined with no confliction among each other at certain conditions. As reported in references [7-8], a high number of membership functions (5x5) and 25 rules considered to control the switcing pulse for VSI. This some how increases complexity of the designed current control algorithm. In this work, fuzzy logic is integrated with current control algorithm to improve mitigation performance of SAPF. The fuzzy logic is designed with reduced amount of fuzzy membership functions (3×3) and 9 rules to reduce complexities of the designed controller.

1.3 Aim and Objectives

The major aim of this work is to design a three-phase three-wire SAPF that can reduce the total harmonic distortion (THD) by mitigating line current harmonics. For efficient performance, the proposed SAPF involves reference current estimation technique using modified synchronous reference frame (MSRF) technique and current controller implemented with fuzzy-PWM technique to generate the desired switching pulses. The detailed objectives are:

1 To model a suitable filtering scheme using Band Pass Filter (BPF) developed by combining LPF and HPF in d-q frame of the MSRF algorithm, for extraction of current harmonics.
2 To develop a suitable PWM technique with fuzzy logic controller by simplified pattern of membership functions, for generating the required compensation current.
3 To investigate performance of the filtering scheme with both conventional and MSRF techniques with hysteresis technique, fuzzy and without fuzzy logic controller through simulation and practical implementation of three-phase SAPF.

1.4 Scope of Research

The main scopes and limitations of the works can be outlined as follows:
- The shunt APF is constructed using two-level PWM voltage source inverter (VSI) and connected to a balanced three-phase 70 V, 50 Hz supply system.
- Both simulation and experimental works are carried out in MATLAB/Simulink environment and digital signal processor (DSP) TMS320F28335 to validate the proposed algorithms.
- The efficiency of the proposed reference extraction algorithm is determined by amplitude and shape of the reference output signal obtained by combining a two second order filters (BPF) in the d-q frame of MSRF method.
- The effectiveness of fuzzy PWM current control algorithm to mitigate the current harmonic to a tolerable level, is evaluated based on the total harmonic distortion

(THD) value as to comply with international standards such as IEEE 519 and IEC 1000.

1.5 Thesis Layout

The thesis is organized as follows

Chapter two presents literature reviews of power quality related problems concerning harmonic distortion, effects of harmonics, mitigation tools, and the principle operation of SAPFs.

Chapter three covers the proposed control algorithms for three-phase three-wire SAPF involving the reference current extraction using MSRF technique and also the PWM switching technique implemented with fuzzy controller.

Chapter four presents simulation and experimental results, with analysis and discussion.

Chapter five presents general conclusion, and contributions derived from this work. This chapter also recommends some future directions for research in the area of SAPF

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