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SHUNT ACTIVE POWER FILTER USING HYBRID FUZZY-PROPORTIONAL AND CRISP-INTEGRAL CONTROL ALGORITHMS FOR TOTAL HARMONIC DISTORTION IMPROVEMENT

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By

NOR FARAHAIDA ABDUL RAHMAN

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May 2016

Chair: Mohd Amran Mohd Radzi, PhD
Faculty: Engineering

Utilization of soft-computing algorithms in the operation of Shunt Active Power Filters (SAPFs) becomes a latest trend. In previous work, an Adaptive Linear Neuron (ADALINE) based extraction algorithm has been developed to generate reference currents. Nevertheless, it has limited function in which it requires a supported conventional synchronization algorithm. On the other hand, Fuzzy-Proportional-Integral (Fuzzy-PI) current and voltage controllers have been introduced in SAPFs' control system. However, the performance of these controllers depends on simultaneous execution of two input variables and large fuzzy rules. Hence, this complicated structure and operation will affect the capability of SAPFs to work efficiently.

Therefore, this work proposes three soft-computing algorithms for generating reference currents, and controlling current and voltage of a three-phase three-leg three-wire SAPF.

First, unified ADALINEs based fundamental component extraction algorithm is proposed for dual functionality. It is developed to generate a reference current, and synchronize it with the phase of any operating power system. Hence, the use of conventional synchronization algorithms can be neglected.

Second, an adaptive Hybrid Fuzzy-Proportional and Crisp-Integral (HFP+CI) current control algorithm is proposed, by using the indirect control strategy together with an integration of Fuzzy-Proportional (Fuzzy-P) and Crisp-Integral (Crisp-I) current controllers. The Fuzzy-P current controller is used to adaptively tune both current proportional and integral gain values simultaneously, and to perform the proportional control action. Meanwhile, the Crisp-I current controller is developed to perform the integral control action, in which a controllable integral gain value is introduced.

Third, a HFP+CI self-charging dc-link voltage control algorithm is constructed, using the self-charging control strategy together with a combination of Fuzzy-P and Crisp-I voltage controllers. In this work, the Fuzzy-P voltage controller is used to adaptively tune only the voltage proportional gain value, and to execute the proportional control action. Subsequently, the Crisp-I voltage controller with a fixed voltage integral gain value is installed.

The effectiveness of all the proposed algorithms to perform their respective functions during steady-state and dynamic-state operations is tested, in both simulation and experimental work. Additionally, in simulation work, comparison of the performance of using the proposed HFP+CI, Fuzzy-PI and Crisp-Proportional-Integral (Crisp-PI) current and voltage control algorithms is conducted.

According to the shape and the phase of resulted instantaneous supply currents, the proposed extraction algorithm is capable to work as both reference current generator and synchronizer. Other than that, the proposed HFP+CI current control algorithms has resulted better performance with the lowest current ripple, Total Harmonic Distortion (THD) values, and power loss than using Fuzzy-PI and Crisp-PI current control algorithms. Additionally, the proposed HFP+CI voltage control algorithm has resulted fastest response time; it is 94% faster than using the Fuzzy-PI voltage control algorithm and 6% faster than using the Crisp-PI voltage control algorithm.

Hence, it can be concluded that the proposed algorithms have successfully performed their functions by effectively enhancing the operation of the SAPF.

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

PENAPIS AKTIF KUASA PIRAU MENGGUNAKAN ALGORITMA PENGAWAL HIBRID BERKADARAN-KABUR DAN KAMIRAN-TEGAS UNTUK MENAMBAHBAIK JUMLAH HEROTAN HARMONIK

Oleh

NOR FARAHAIDA ABDUL RAHMAN

Mei 2016

Pengerusi: Mohd Amran Mohd Radzi, PhD
Fakulti: Kejuruteraan

Penggunaan algoritma lembut pengkomputeran dalam operasi Penapis Aktif Kuasa Pirau (SAPF) menjadi trend terkini. Dalam kerja-kerja sebelum ini, Neuron Linear Penyesuaian (ADALINE) berasaskan algoritma pengekstrakan telah dibina untuk menghasilkan arus rujukan. Walau bagaimanapun, ia mempunyai fungsi yang terhad, di mana ia memerlukan sokongan algoritma penyegerakan konvensional. Sebaliknya, pengawal arus dan voltan Berkadaran-Kamiran-Kabur (Fuzzy-PI) telah diperkenalkan di dalam system kawalan SAPF. Namun begitu, prestasi pengawal ini bergantung kepada pelaksanaan serentak dua pembolehubah input dan peraturan kabur yang banyak. Oleh itu, struktur dan operasi rumit tersebut akan memberi kesan kepada keupayaan SAPF untuk bekerja dengan lebih cekap.

Oleh itu, kerja ini mencadangkan tiga algoritma pengkomputeran lembut untuk menjana arus rujukan, dan mengawal arus dan voltan bagi tiga-fasa tiga-kaki tiga-wayar SAPF.

Pertama, ADALINE bersatu berasakan algoritma pengekstrakan komponen asas dicadangkan untuk dwi fungsi. Ia dibangunkan untuk menhasilkan arus rujukan, dan menyegerakkannya dengan fasa sistem kuasa yang beroperasi. Oleh itu, penggunaan algoritma penyegerakan konvensional boleh diabaikan.

Kedua, algoritma pengawal arus suai Hibrid Berkadaran-Kabur dan Kamiran-Tegas (HFP+CI) dicadangkan, ia menggunakan strategi kawalan tidak langsung bersama-sama integrasi pengawal arus Berkadaran-Kabur (Fuzzy-P) dan Kamiran-Tegas (Crisp-I). Pengawal arus Fuzzy-P digunakan untuk menala suai kedua-dua nilai gandaan arus berkadaran dan kamiran secara serentak, dan melaksanakan tindakan kawalan berkadaran. Sementara itu, pengawal arus Crisp-I dibangunkan untuk melaksanakan tindakan kawalan kamiran, di mana nilai boleh kawal gandaan arus kamiran diperkenalkan.

Ketiga, algoritma pengawal voltan pengecasan-diri HFP+CI dibina, menggunakan strategi kawalan pengecasan-diri dan kombinasi pengawal voltan Fuzzy-P dan Crisp-I. Dalam kerja ini, pengawal voltan Fuzzy-P digunakan untuk menala suai nilai gandaan voltan berkadaran sahaja, dan melaksanakan tindakan kawalan berkadaran. Selepas itu, pengawal voltan Crisp-I dengan nilai gandaan voltan kamiran yang tetap digunakan untuk melaksanakan tindakan kawalan kamiran.

Keberkesanan semua algoritma yang dicadangkan untuk melaksanakan fungsi masing-masing semasa operasi keadaan mantap dan dinamik diuji, dalam kedua-dua kerja simulasi dan eksperimen. Tambahan pula, dalam kerja simulasi, perbandingan prestasi antara algoritma kawalan arus dan voltan HFP+CI, Fuzzy-PI, dan Berkadaran-Kamiran-Tegas (Crisp-PI) dijalankan.

Berdasarkan bentuk dan fasa arus seketika yang terhasil, algoritma pengekstrakan yang dicadangkan mampu untuk bekerja sebagai penjana arus rujukan dan penyegerak. Selain daripada itu, algoritma kawalan arus suai HFP+CI yang dicadangkan telah menunjuk prestasi yang lebih baik dengan menghasilkan riak arus, Jumlah Herotan Harmonik (THD), dan kehilangan kuasa yang lebih rendah berbanding penggunaan algoritma kawalan arus Fuzzy-PI dan Crisp-PI. Tambahan pula, algoritma kawalan voltan HFP+CI yang dicadangkan telah menyebabkan masa tindak balas yang paling cepat; ia adalah 94% lebih cepat daripada menggunakan algoritma kawalan voltan Fuzzy-PI dan 6% lebih cepat daripada menggunakan algoritma kawalan voltan Crisp-PI.

Oleh itu, dapat disimpulkan bahawa algoritma-algoritma yang dicadangkan telah berjaya melaksanakan fungsi mereka dengan berkesan bagi meningkatkan operasi SAPF.

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I certify that a Thesis Examination Committee has met on 16 May 2016 to conduct the final examination of Nor Farahaida binti Abdul Rahman on her thesis entitled "Shunt Active Power Filter using Hybrid Fuzzy-Proportional and Crisp-Integral Control Algorithms for Total Harmonic Distortion Improvement" 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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Gorakanage Arosha Chandima, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Zainal Abidin bin Ab. Kadir, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Hashim bin Hizam, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Bhim Singh, PhD
Professor
Indian Institute of Technology Delhi
India
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 June 2016

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

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

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

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

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

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

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Signature: ______________________________
Name of Chairman of Supervisory Committee: Mohd Amran Mohd Radzi, PhD
Associate Professor

Signature: ______________________________
Name of Member of Supervisory Committee: Azura Che Soh, PhD
Associate Professor

Signature: ______________________________
Name of Member of Supervisory Committee: Dr. Norman Mariun, PhD
Professor Ir.

Signature: ______________________________
Name of Member of Supervisory Committee: Nasrudin Abd Rahim, PhD
Professor

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a	Phase A
$ae(k)$	Area under the digital time-varying error signal
b	Phase B
c	Phase C
C_{dc}	Dc-link capacitor
c_{dc}	Capacitance value of dc-link capacitors
$ce(k)$	Change of digital time-varying error signal
$e(k)$	Digital time-varying error signal
$e_c(k)$	Digital time-varying current error signal
$e_v(k)$	Digital time-varying voltage error signal
F_h	Amplitude of digital time-varying signals
$f(k)$	Digital time-varying signal
F_{Fund}	Fundamental component of $f(k)$
$f_{Fund}(k)$	Digital time-varying fundamental signal
h	Numbers of harmonic components
I_1	RMS value of fundamental current
$i_{controlled}$	Controlled current
$I_{dc,rms}$	RMS value of instantaneous dc-link charging currents
I_{dc}	Peak amplitude of instantaneous dc-link charging currents
$i_{dc}(k)$	Digital time-varying dc-link charging current signal
$i_{dc}(t)$	Instantaneous dc-link charging current
$I_{dc,est}$	Estimated dc-link charging current amplitude
$i_{dc,est}(k)$	Digital time-varying estimated dc-link charging current signal
I_h	RMS value of harmonic currents
$I_{F1,rated}$	Rated amplitude of instantaneous fundamental compensation currents
I_{Fh}	Ripple current of SAPFs
$i_F(k)$	Digital time-varying compensation current signal
$i_F(t)$	Instantaneous compensation current
$i_{F1}(t)$	Instantaneous fundamental compensation current
$i_{Fund}(t)$	Instantaneous fundamental load current
$I_{Fund,ext}$	Extracted fundamental load current amplitude
$i_{Fund,est}(k)$	Digital time-varying extracted fundamental load current signal
$i_H(t)$	Instantaneous harmonic load current
$i_L(k)$	Digital time-varying load current signal
$i_L(t)$	Instantaneous load current
i_{ref}	Reference current
I_S	Peak amplitude of instantaneous supply currents
$i_S(k)$	Digital time-varying supply current signal
$i_S(t)$	Instantaneous supply current
I_{S1}	Peak amplitude of instantaneous fundamental supply currents
$i_{S1}(t)$	Instantaneous fundamental supply current
$i_{S,comp}(t)$	Compensated instantaneous supply current
$i_{ref}(k)$	Digital time-varying reference current signal
k	Numbers of sampling data
K_d	Derivative gain

K_i	Integral gain
K_{ic}	Current integral gain
$K_{ic}ae_c(k)$	Digital time-varying current integral output variable
$K_{ic}e_c(k)$	Product of K_{ic} and $e_c(k)$
K_{iv}	Voltage integral gain
$K_{iv}ae_v(k)$	Digital time-varying voltage integral output variable
$K_{iv}e_v(k)$	Product of K_{iv} and $e_v(k)$
K_p	Proportional gain
K_{pc}	Current proportional gain
$K_{pc}e_c(k)$	Fuzzified digital time-varying current proportional output variable
$K_{pc}e_c(k)_i$	Point of resulted $K_{pc}e_c(k)$ set
K_{pv}	Voltage proportional gain
$K_{pv}e_v(k)$	Fuzzified digital time-varying voltage proportional output variable
$K_{pv}e_v(k)_i$	Point of the resulted $K_{pv}e_v(k)$ set
L	Inductance of filter inductors
L_f	Filter inductor
L_s	Line inductor
m_a	Modulation factor
n	Maximum number of sample data
P	Instantaneous power of dc-link capacitors
Q_F	Reactive power of SAPFs
R	Resistance of filter inductors
$\sin(k\omega\Delta t + \theta)$	Sine function of generated reference currents
T	Time period
V_1	RMS value of fundamental voltage
V_{dc}	Dc-link voltage
$V_{dc}(k)$	Digital dc-link voltage signal
$V_{dc,maxPP}$	Maximum peak-to-peak dc-link voltage
$V_{dc,ref}$	Reference dc-link voltage
V_{F1}	Peak amplitude of instantaneous fundamental SAPF voltage
$v_{F1}(t)$	Instantaneous fundamental SAPF voltage
V_{Fh}	Harmonic voltage of SAPFs
$V_{Fund,ext}$	Extracted fundamental supply voltage amplitude
V_h	RMS value of harmonic voltages
V_S	Peak amplitude of instantaneous supply voltages
$v_S(k)$	Digital time-varying supply voltage signal
$v_S(t)$	Instantaneous supply voltage
$V_{S,rms}$	The RMS value of instantaneous supply voltages
w	Enegy of dc-link capacitors
$\bar{W}(k)$	Matrix of weights
$\bar{W}(k+1)$	Matrix of the next iteration weights
W_{hc}	Weight of cosine functions
W_{hs}	Weight of sine functions
x_i	Point of resulted conclusion set
$\bar{Y}(k)$	Matrix of sine and cosine functions
$\bar{Y}(k)^T\bar{Y}(k)$	Square of the norm of $\bar{Y}(k)$

$\delta e(k)$	Digital time-varying control signal
$\delta e_c(k)$	Digital time-varying current control signal
$\delta e_v(k)$	Digital time-varying voltage control signal
$\mu(K_{pc}e_c(k)_i)$	Membership degree of resulted $K_{pc}e_c(k)$ set
$\mu(K_{pv}e_v(k)_i)$	Membership degree of resulted $K_{pv}e_v(k)$ set
$\mu_A(x_i)$	Membership grade of resulted conclusion set
θ_v	Phase angle of instantaneous supply currents
Δt	Sampling time
α	Learning rate
θ	Phase angle of reference currents
ω	Angular frequency of operating power systems

LIST OF ABBREVIATIONS

ADALINE	Adaptive Linear Neuron
ADC	Analogue-to-Digital Converter
AH	Adaptive-band Hysteresis
ANN	Artificial Neural Network
APF	Active Power Filter
COG	Centre of Gravity
Crisp-I	Crisp-Integral
Crisp-PI	Crisp-Proportional-Integral
Crisp-PID	Crisp-Proportional-Integral-Derivative
CSI	Current Source Inverter
DAC	Digital to Analogue Converter
DSP	Digital Signal Processing
FFT	Fast Fourier Transform
FH	Fixed-band Hysteresis
FLS	FL Smidth
Fuzzy-P	Fuzzy-Proportional
Fuzzy-PD	Fuzzy-Proportional-Derivative
Fuzzy-PI	Fuzzy-Proportional-Integral
GA	Genetic Algorithm
HB	Hysteresis Band
HFP+CI	Hybrid Fuzzy-Proportional and Crisp-Integral
HPF	High Pass Filter
IEC	International Electrotechnical Committee
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-Gate Bipolar Transistor
LMS	Least Mean Square
LPF	Low Pass Filter
MF	Membership Function
MIMO	Multiple-Input Multiple Output
MISO	Multiple-Input Single-Output
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NB	Negative Big
NM	Negative Medium
NPC	Neutral-Point Diode-Clamped
NS	Negative Small
PB	Positive Big
PCC	Point of Common Coupling
PF	Power Factor
PI	Proportional-Integral
PLL	Phase-Locked Loop
PM	Positive Medium
PQ	Power Quality
PS	Positive Small
PWM	Pulse-Width Modulation
RMS	Root Mean Square
SAPF	Shunt Active Power Filter
SISO	Single-Input Single-Output
THD	Total Harmonic Distortion

THD_i	THD value of current waveforms
THD_v	THD value of voltage waveforms
TS	Takagi-Sugeno
VSI	Voltage Source Inverter
W-H	Widrow-Hoff
WT	Wavelet-packet Transform
ZCD	Zero-Crossing Detector
ZE	Zero

CHAPTER 1

INTRODUCTION

1.1 Background

For a few decades, electrical power systems have been struggling with various Power Quality (PQ) problems. They are transients, overvoltages, undervoltages, voltage interruptions, voltage sags or dips, voltage swells, voltage imbalances and harmonics. These problems have resulted in deterioration of the performance of power systems; hence, negatively impact both electric utilities and end-users.

According to [1], harmonics is one of PQ problems that adversely affect electric utilities and end-users economically. Due to the additional power loss generated by harmonics, electric utilities need to invest lot of money to purchase or develop effective mitigation tools. Hence, it reduces their profit. On the consumer side, they need to spend more to repair or replace the affected equipment. Thus, it disrupts their expenses and daily life. Therefore, harmonics have become the main focus of this research work. In particular, this work concerns more on the implications of harmonic currents than the consequences of harmonic voltages. It is because the terminal voltage of the Point of Common Coupling (PCC) is normally maintained within the standard limit of voltage sags and harmonic voltages [2].

Distortion of supply currents is normally related to the existence of unwanted harmonic currents. Practically, passive filters and Shunt Active Power Filters (SAPFs) are utilized to mitigate harmonic currents. According to previous work, both filters have demonstrated good filtering capability with some limitations; such as the ability to filter various harmonic currents simultaneously, and dependency on the use of reference currents and control algorithms.

Unlike passive filters, SAPFs have been recognized as the most effective and versatile filters, in compensating numerous harmonic currents simultaneously. Furthermore, they can also be employed to compensate reactive power, for Power Factor (PF) correction [3]. Nevertheless, their operation relies on the effectiveness of reference current generation, current control and dc-link voltage control algorithms (for SAPFs using inverter topologies). Hence, the complexity of SAPFs operation increases.

Despite of all constraints, research and implementation of SAPFs are still growing. It is due to their fascinating performance characteristics, and fast evolution of prompt, accurate, and cheap digital signal processing devices.

1.2 Problem Statements

This work focuses on the implementation of reference current generation, current control and dc-link voltage control algorithms, for improving the performance of a SAPF in generating and synchronizing reference currents, compensating harmonic currents and regulating dc-link voltage value.

In order to generate a reference current, an ADALINE based fundamental component extraction algorithm has been introduced in [4-7]. It is designed using a simple and fast computational algorithm. However, owing to its limited function (to generate a reference current only); this extraction algorithm requires a supported synchronization algorithm, for coordinating the phase of the generated reference current with the phase of operating power systems. Commonly, a conventional synchronization algorithm such as Phase-Locked Loops (PLL) and Zero-Crossing Detectors (ZCD) is being implemented [4, 5]. Nevertheless, by employing the conventional synchronization algorithm, the complexity of the implementation of the extraction algorithm increases. At the same time, there is still less work on expanding more functions of the extraction algorithm, although it is known with simple features. Therefore, a new approach of optimizing the function of the ADALINE based fundamental component extraction algorithm is proposed; to replace the function of the conventional synchronization algorithm. In this work, two ADALINEs are unified together to perform two functions; first, to generate a reference current for a SAPF, and second, to synchronize the SAPF operation with any operating power system.

Other than reference current generation algorithms, the implementation of current and dc-link voltage control algorithms is also very crucial to ensure SAPFs work appropriately. The operation of each control algorithm is normally supervised using various types of controllers. According to previous work, Crisp-PI controllers have become the simplest controllers in SAPFs operation [8-10].

Generally, a Crisp-PI controller is developed to regulate a controlled variable, by eliminating its steady-state error. It can be achieved by applying a fixed value of proportional and integral gains. Hence, the steady-state operation of controlled systems improves. However, because of the use of fixed gain values, this controller is unable to work satisfactorily, in controlling nonlinear or time-varying systems [11, 12]. Hence, affecting the SAPF capability to compensate harmonic currents and regulate dc-link voltage. Furthermore, the tuning procedure for the determination of optimal gain values is very time consuming [13]. Nonetheless, it is not worthwhile to allocate such a long time, just to obtain a fixed value of gains.

Thus, development of Fuzzy-Proportional-Integral (Fuzzy-PI) current [14] and voltage [15-17] controllers for modifying both proportional and integral gains values has been presented in [14-17]. Both gains values are tuned based on the change of control variables. Hence, they inherit better steady-state control mechanism than Crisp-PI controllers. Subsequently, the SAPF performance also increases. However, these controllers exhibit some limitations.

In [14], the effectiveness of the Fuzzy-PI current controller depends on the execution of large fuzzy rules (forty nine rules). Therefore, it complicates the hardware development. Additionally, these fuzzy rules are constructed using the internal losses model of a SAPF, in which it is difficult to be obtained. Other than that during practical implementation, this current controller exhibits unsatisfactory performance during the steady-state operation.

Similarly, the effectiveness of Fuzzy-PI voltage controllers presented in [15-17] also depends on the execution of large fuzzy rules (forty nine rules). However, there is no detail explanation of how these fuzzy rules are constructed. Furthermore, according to [15], these voltage controllers inherit slow response time during the dynamic-state operation. It is because they need to evaluate two input variables simultaneously, and they run at low speed (as compared to SAPFs' current controller).

In addition, owing to requirement of evaluating two input variables simultaneously, the complexity of the structure of both Fuzzy-PI current [14] and voltage [15-17] controllers increases.

Therefore, in order to improve the structure and the performance of a Fuzzy-PI (current or voltage) controller, a new control approach must be proposed. The possible enhancement involves the reconstruction of the controller's structure. In this work, a Crisp-Integral (Crisp-I) controller is implemented, for substituting the integral control action of the Fuzzy-PI controller. Subsequently, by applying the Crisp-I controller, the complex structure and fuzzy rules of the Fuzzy-PI controllers can also be simplified. Eventually, the proposed controller should be able to perform both steady-state and dynamic-state control mechanisms optimally; improving the SAPF performance in harmonic current compensation and dc-link voltage regulation.

1.3 Aim and Objectives

The aim of this work is to enhance the operation of a three-phase three-leg three-wire SAPF in reducing Total Harmonic Distortion (THD) values of instantaneous supply currents by compensating harmonic currents and regulating dc-link voltage. It involves the development and implementation of a reference current extraction and synchronizing algorithm using ADALINE technique, and current and voltage control algorithms using hybrid fuzzy and crisp controllers.
The objectives of this work are as follows:

1. To develop a dual function unified ADALINEs based fundamental component extraction algorithm for generating a reference current and synchronizing the SAPF operation.
2. To develop an adaptive Hybrid Fuzzy-Proportional and Crisp-Integral (HFP+CI) current control algorithms to indirectly regulate an instantaneous compensation current for compensating harmonic currents and reactive power simultaneously.
3. To develop a HFP+CI self-charging dc-link voltage control algorithm for regulating the SAPF's dc-link voltage value.
4. To verify the performance of the SAPF using a combination of two or all proposed algorithms in related to harmonic currents compensation and dc-link voltage regulation.

1.4 Scopes and Limitations

Scopes and limitations of this work are as following:

1. The proposed algorithms are implemented on a three-phase three-wire SAPF using a three-phase three-leg voltage source inverter topology. The SAPF is connected to a balanced three-phase 100 V, 50 Hz power system. Additionally, the power system operates with undistorted supply voltage and fixed operating frequency.
2. The effectiveness of the proposed extraction algorithm to generate reference currents is assessed based on the shape and the phase of three-phase instantaneous supply current.
3. The effectiveness of the proposed current control algorithm to compensate harmonic currents and reactive power is measured based on Total Harmonic Distortion (THD) values, the Institute of Electrical and Electronics Engineers (IEEE) Standard 519-2014 and PFs.
4. The effectiveness of the proposed voltage control algorithm to regulate dc-link voltage is evaluated based on the average value of dc-link voltage (during the steady-state operation), and the overshoot, undershoot and response-time of dc-link voltage (during the dynamic-state operation).
5. All proposed algorithms are developed and simulated in MATLAB / Simulink. Additionally, Digital Signal Processing (DSP) TMS320F28335 board is employed to execute all the proposed algorithms for experimental verification. Both MATLAB and DSP board are operated using 150 kHz sampling frequency.

1.5 Thesis Organization

The thesis is organized based on the following subjects.

Chapter 2 discusses about harmonic distortion, harmonic mitigation tools, and the principle operation of SAPFs. Also, it elaborates about the role of the control system of SAPFs.

Chapter 3 explains about the development of a three-phase three-wire SAPF using a three-phase three-leg voltage source inverter topology, the proposed control strategy, and the proposed algorithms.

Chapter 4 presents and discusses both simulation and experimental results.

Chapter 5 concludes the findings and contributions of the proposed algorithms. Some recommendations for future work are deliberated.

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