DESIGN A FILTER FOR HARMONICS CAUSED BY NON-LINEAR LOAD AND RESONANCE CAUSED BY POWER FACTOR CORRECTION CAPACITOR

NOR FAEZAH BINTI ADAN

A thesis submitted in
fulfillment of the requirement for the award of the
Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JANUARY 2016

For my beloved mother and father

ACKNOWLEDGEMENT

Alhamdulillah, praise be upon Him whom has given me a good health, body and mind to complete this Projek Sarjana. I would like to express my sincere gratitude to Dr. Dur Muhammad Soomro, my supervisor for the support and guidance given throughout the duration of this project.

The co-operation given by the Faculty of Electrical and Electronic Engineering, UTHM is also highly appreciated. Appreciation also goes to everyone involved directly or indirectly towards the compilation of this thesis. Last but not least, thank you to all my friends and family for the generous moral support given throughout completing this task.

ABSTRACT

The traditional approach to power factor correction (PFC) in industrial applications involves installation of power factor correction capacitor banks (PFCC). However, with the expanding use of non-linear equipment such as adjustable speed drives (ASDs), power converters etc., power factor (PF) improvement has become difficult due to the presence of harmonics generated by the non-linear equipment. The resulting capacitive impedance of the PFCC may form a resonant circuit with the source inductive reactance at a certain frequency, which is likely to coincide with one of the harmonic frequency of the load. This condition will trigger large oscillatory currents and voltages that may stress the insulation and cause subsequent damage to the PFCC and equipment connected to the power system (PS). Besides that, high PF cannot be achieved due to power distortion. These have imposed the need for an approach to PFC by addressing the harmonics problem. This project analyzes both passive filter and shunt active power filter (SAPF) techniques to mitigate resonance and overall harmonics in the PS through simulation using PSCAD software. A test case is presented to demonstrate the applicability of the proposed techniques for harmonics reduction and PFC at the same time. The implementation of SAPF together with passive filter have resulted in significant improvement on both total harmonic distortion for voltage (THD_V) and total demand distortion for current (TDD_I) with maximum values of only 2.93% and 9.84% respectively which are within the IEEE 519-2014 standard limits. In terms of PF improvement, the combined filters have excellently achieved the desired PF, 0.95 for firing angle, α values up to 40^o.

ABSTRAK

Bank kapasitor seringkali digunakan di industri untuk menambahbaik faktor kuasa. Namun, dengan peningkatan penggunaan alatan-alatan tidak linear seperti pemacu kelajuan boleh laras (ASDs), penukar kuasa dan sebagainya, penambahbaikan faktor kuasa menjadi lebih sukar. Ini adalah kerana kehadiran harmonik yang dihasilkan oleh alatan-alatan tidak linear tersebut. Bank kapasitor menghasilkan galangan kapasitif yang mungkin akan bertembung dengan galangan induktif punca kuasa pada salah satu frekuensi harmonik yang dihasilkan oleh beban lantas menyebabkan terjadinya resonan. Keadaan ini akan menyebabkan terhasilnya ayunan besar arus and voltan yang akan menyebabkan kerosakan kepada penebat seterusnya bank kapasitor dan alatan-alatan lain yang terdapat di dalam sistem kuasa. Selain itu, herotan kuasa menyebabkan faktor kuasa yang tinggi tidak dapat dicapai. Oleh kerana itu, satu langkah perlu diambil untuk penambahbaikan faktor kuasa dengan cara mengurangkan harmonik. Projek ini telah menganalisis teknik *passive filter* dan *shunt active power filter (SAPF)* dalam mengurangkan masalah resonan dan keseluruhan harmonik melalui simulasi menggunakan perisian PSCAD. Satu kes ujian telah dibentangkan untuk menunjukkan kesesuaian teknik yang telah dicadangkan dalam mengurangkan harmonik dan pada masa yang sama meningkatkan faktor kuasa. Hasil implementasi *SAPF* dan *passive filter* telah menunjukkan penambahbaikan yang tinggi terhadap jumlah keseluruhan herotan harmonik bagi voltan (THD_V) dan arus (TDD_I), kepada hanya 2.93% dan 9.84% nilai maksimum yakni di bawah paras yang ditetapkan oleh *standard* IEEE 519-2014. Dari segi penambahbaikan faktor kuasa, gabungan kedua-duanya telah berjaya mencapai faktor kuasa sasaran iaitu 0.95 untuk *firing angle*, α dari 0^o-40^o.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ω_n	Harmonic frequency
AC	Alternating current
ASDs	Adjustable speed drives
C	Capacitor
CCA	Conventional control algorithm
DC	Direct current
DF	Distortion factor
DPF	Displacement power factor
DTHF	Double tuned hybrid active power filter
DTPF	Double tuned passive filter
FFT	Fast Fourier transform
f_o	Fundamental frequency
f_r	Resonance frequency
HAPF	Hybrid active power filter
HPF	High pass filter
HVAC	Heating, ventilating and air conditioning
L	Inductor
P	Active power
PC	Personal computer
PCA	Proposed control algorithm
PCC	Point of common coupling
PE	Power electronics
PF	Power factor
PFC	Power factor correction
PFCC	Power factor correction capacitor

PLL	Phase locked loop
PQ	Power quality
PS	Power system
Q	Reactive power
R	Resistor
ROF	Reactance one-port filter
S	Apparent power
SAPF	Shunt active power filter
SCC	Sinusoidal current control
SeAPF	Series active power filter
SMPS	Switched-mode power supplies
SPWM	Sinusoidal pulse width modulation
STHF	Single tuned hybrid active power filter
STPF	Single tuned passive filter
TDD	Total demand distortion
TDD_I	Total harmonic distortion for current
THD	Total harmonic distortion
THD_V	Total harmonic distortion for voltage
TNB	Tenaga Nasional Berhad
UPS	Uninterruptible power supply
VSC	Voltage source converter
VSDs	Variable speed drives

CHAPTER 1

INTRODUCTION

1.1 Background of study

In the past, harmonics represented less of a problem due to the conservative design of power equipment. When electronic power converters first became commonplace in the late 1970s, many utility engineers became quite concerned about the ability of power system (PS) to accommodate the harmonic distortion as the harmonics problems defy many of the conventional rules of PS design and operation that consider only the fundamental frequency [1]. Results of their concern have sparked the research that has eventually led to much of the knowledge about all aspects of power quality (PQ).

Harmonics in PS is defined as a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency. Malaysia uses a 50 Hz fundamental frequency, thus a 3rd harmonic frequency will be 3 times 50 Hz, or 150 Hz. Likewise, a 5th harmonic frequency is 250 Hz and so on. The odd integer harmonics frequencies (3rd, 5th, 7th and so on) are the most predominant [2-4]. The waveform of electric power at generation stage is purely sinusoidal and free from any distortion but this situation is hardly achievable at consumer's end that has a lot of non-linear equipment in operation.

Non-linear equipment like power electronics (PE) devices are the most significant cause of harmonics and inter-harmonics. They generate harmonic frequencies by drawing non-linear current waveforms. Rectifiers, adjustable speed drives (ASDs), soft starters, electronic ballast for discharge lamps, switched-mode power supplies (SMPS), and heating, ventilating, and air conditioning (HVAC) system using ASDs among the list of common PE devices used which generate harmonics. Meanwhile, inter-harmonics are produced by static frequency converters, cyclo-converters, induction motors & arcing devices. The effects of harmonics on a PS include equipment premature failure and degradation, low power factor (PF) [5], nuisance trips, resonance etc. Equipment affected by harmonics includes transformers, motors, cables, interrupters, and power factor correction capacitors (PFCC).

Large industrial equipment like transformers, induction motors, generators etc. are among the equipment that may contribute to lower PF. Ideally, users would want to ensure their PS to maintain a unity PF but it is not easily achievable especially for larger commercial buildings or plants that have different sizes and types of loads. Lower PF causes higher apparent power required by the equipment to achieve the same amount of output. Thus, overloading the component. The continuous additional work if not mitigated will shortens the life of the equipment. In worse cases, equipment may work excessively beyond rated parameters and thus lead to total failure. In Malaysia, penalties will be charged on users that fail to meet the PF requirement set by the Tenaga Nasional Berhad (TNB). Table 1.1 shows the surcharge imposed on users with electricity supply below 132kV.

Table 1.1: PF surcharge rate for users at 132kV and below

PF requirement	Surcharge rate
For every 0.01 less than 0.85	1.5 % of current bill
For every 0.01 less than 0.75	3 % of current bill

1.2 Problem statement

PFCC is commonly used in the industry to improve PF of the PS due to its lower cost. However, when harmonics are present, the resulting reactive impedance of the PFCC may form a resonant circuit with the source or system inductive reactance at a certain frequency, which is likely to coincide with one of the harmonic frequency of the load. This condition will trigger large oscillatory currents and voltages that may stress the insulation and cause subsequent damage to the capacitor banks and equipment connected to the PS [6]. In order to solve this issue and optimize the operating cost, a practical approach must be implemented to reduce the problem to an acceptable level. In this case, harmonics filters such as passive, active or hybrid can be applied at the point of common coupling (PCC) to absorb the large oscillatory currents caused by resonance and reduces the overall current and voltage harmonics.

From literature review, there are fewer references that are focused on mitigating resonance effect caused by PFCC on the PS with harmonics presence. Therefore, this project has been undertaken to study the harmonic amplification problem caused by PFCC and the overall effects of harmonics on PF. The result of the study is used to develop the necessary passive filter to reduce or eliminate resonance and also used to design an active filter to reduce the other harmonic components in order to improve the PF.

1.3 Objectives of study

1) To simulate the effects of PF correction (PFC) on PS frequency.
2) To design passive and active power filter separately to mitigate harmonics and resonance problem caused by PFCC.

1.4 Scopes of study

1) Simulation models are developed using PSCAD software.
2) The test case [7] consists of a bridge rectifier and an RL load.
3) Single tuned passive filter is designed to address the resonance problem.
4) Shunt active power filter (SAPF) is designed to address the other harmonic components.
5) P-Q theory is implemented to calculate the compensation reference current for the SAPF.

1.5 Thesis outline

After the introduction section, the outline of the thesis is organized as follows;

Chapter 2 presents reviews of past researches on harmonic analysis of domestic and industrial non-linear PS, application of harmonic filters to improve PF, mitigate harmonics and harmonics resonance caused by non-linear loads and PFCC followed by a brief introduction to PFC theory. The literature review is concluded with details of harmonic limits outlined by IEEE 519-2014 standard.

Chapter 3 describes modeling of a 3 phase distribution system with non-linear load and PFCC, passive filter and SAPF using PSCAD software. This chapter also includes mathematical equations of PFCC and passive filter.

Chapter 4 discusses voltage and current harmonics caused by the non-linear load on the distribution system with and without PFCC implementation. The results of the implemented passive filter and SAPF are also presented.

In Chapter 5, the conclusions of the thesis are given and the future work studies are proposed.

Finally all references used in this thesis study are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents reviews of past researches on harmonic analysis of domestic and industrial non-linear PS, application of harmonic filters to improve PF, mitigate harmonics and harmonics resonance caused by non-linear loads and PFCC followed by a brief introduction to PFC theory. The literature review is concluded with details of harmonic limits outlined by IEEE 519-2014 standard.

2.2 Related works

The traditional approach to PFC in industrial applications involves installation of PFCC. But with the widespread use of non-linear loads, PF improvement has becoming more difficult. It is known that a circuit consisting both capacitors (C) and inductors (L) will generate resonance at a certain frequency [6]. For a purely sinusoidal PS, resonance may not even happen, but not in the case where the PS contains harmonics profile whereby the integral multiple of the fundamental frequency (f_o) have a high probability to coincide with the resonance frequency (f_r).

Harmonics filter is essential in PS that contains harmonics profile drawn by the non-linear loads. They are designed to provide a bypass for the harmonic currents, to block them from entering the PS or to compensate them by locally supplying harmonic currents and/or harmonic voltages. Different methods have been proposed to overcome harmonics and harmonics resonance such as by using passive filter, active power filters, hybrid active power filters (HAPF) and other method like phase shifting approach.

2.2.1 Test model

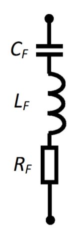
Prior to developing a solution to eliminate the harmonics and its adjacent effects, it is critical to identify the harmonics profile produced by each of the non-linear loads and also the overall harmonics profile at PCC. Studies conducted by [7-8] have developed several simulation models of typical domestic and industrial non-linear loads. It is more convenient to perform harmonics analysis using computer simulation given the system components are modeled accurately. Models developed in [7] include television, refrigerator, washing machine, battery charger, lamps, fans, air-conditioner, antenna using servomotors, air heating unit, adjustable speed drive (ASD) and uninterruptable power supply (UPS) which were implemented to estimate the harmonics characteristics of a distribution system of CARTOSAT-2A satellite launching station at ISRO, Bangalore, India.

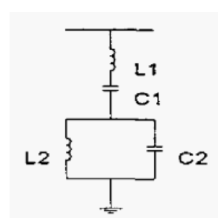
On the other hand, research conducted in [8] performed harmonic analysis on a residential house, small residential area and a small-scale industrial supply system. The study concluded that, a residential house having all types of electronics and electrical home appliances performed within the total harmonic distortion for voltage (THD_V), and total demand distortion for current (TDD_I) limits respectively. Analysis performed on a small residential area consisting three villages have shown that Village 2 and 3 with lower income residents, did not contribute to high harmonics compared to Village 1 as they can’t afford expensive equipment like air-conditioners, water heaters, dryer etc. Village 1 produces acceptable TDD_I but high THD_V (9.4%) thus requires harmonics filter to reduce the voltage harmonics. Meanwhile, harmonics analysis performed on the small-scale industrial supply system, which comprises of ASDs, DC motors, arc welders, cyclo-converter, personal computer (PC), air conditioners, fans and lamps resulted in both THD_V and TDD_I exceeding the limits at 6.1% and 61.6% respectively.

Based on [8], it is profound to assume that an office building may also produce high THD_V as the equipment used is similar to residential houses while mechanical and electrical laboratories in the university which has a close resemblance to the small scale industrial system may also exceed both its TDD_I and THD_V limits. Therefore, harmonics filters are definitely required to reduce the total harmonic distortion (THD) to an acceptable level.

2.2.2 Passive filters

Passive filters can be broadly classified into two types, series and shunt filter. Series filters with high series impedance are used to block the relevant harmonic currents. Therefore they must carry the full load current and be insulated for full line voltage. On the other hand, shunt filters are used to divert the relevant harmonic currents to the ground by providing a low impedance bypass path. The latter carry only a fraction of the current that a series filter must carry, making the cost cheaper, thus more attractive to users [9-10]. Figure 2.1 illustrates the configuration of single tuned passive filter (STPF) and double tuned passive filter (DTPF). STPF is specifically designed to eliminate distortion of one harmonic order only while DTPF as the name imply, eliminates two harmonics components simultaneously.





(a) STPF (b) DTPF

Figure 2.1: Shunt passive filters

The research in [11] focused on designing passive filters to mitigate harmonics problem on a small-scale industrial loads i.e. 13-bus medium voltage industrial distribution system. Similar non-linear models in [7-8] were adopted. Two types of passive filters were designed and discussed in this paper, single/double tuned passive filter (STPF / DTPF) and reactance one-port (ROF) arrangement. ASDs loads were connected to bus 7 and 10, PFCC connected to bus 3 and active filter connected at PCC. Initial simulation with the PFCC offline and no filters application has shown that both the ASD load buses exceeded the 5%

and 20% THD_V and TDD_I limits with 6.1% and 7.3% THD_V and 24.9% and 26.2% TDD_I respectively. The other buses monitored include bus 3 and 9 with bus 3 readings well below the limits and bus 9 exceeds TDD_I limits at 25.6%. It was found that DTPF reduces THD better than STPF. The researcher has also simulated the effect of PFCC to the distribution system. As expected, the THD level is higher when PFCC is energized.

The simplicity and cost-effective of STPF are the main reasons why they are often installed to mitigate harmonic problem. However, they are not always the most practical solution. A study conducted by [12] have identified that STPF can be a culprit to harmonic amplification. The problem started when four STPFs of 5^{th}, 7^{th}, 11^{th} and 13^{th} were commissioned as shown in Figure 2.2, many cases of STPF capacitor failures were reported. Through computer simulation, it was found that there was a parallel resonance between the LC filters and the PS. Simulation on different filter structures have also shown that the resonant frequency varied accordingly i.e. 4^{th} order harmonic were amplified when the 13^{th} order filter was disconnected and both 4^{th} and 8^{th} order harmonic decreases reasonably when the 11^{th} and 13^{th} order STPFs were offline. It was concluded that the filter set-up were not suitable for a PS experiencing very infrequent unequal loading condition and thus proposed a more practical solution, a 17^{th} and 35^{th} order high pass damped filters as replacement to the original set-up.

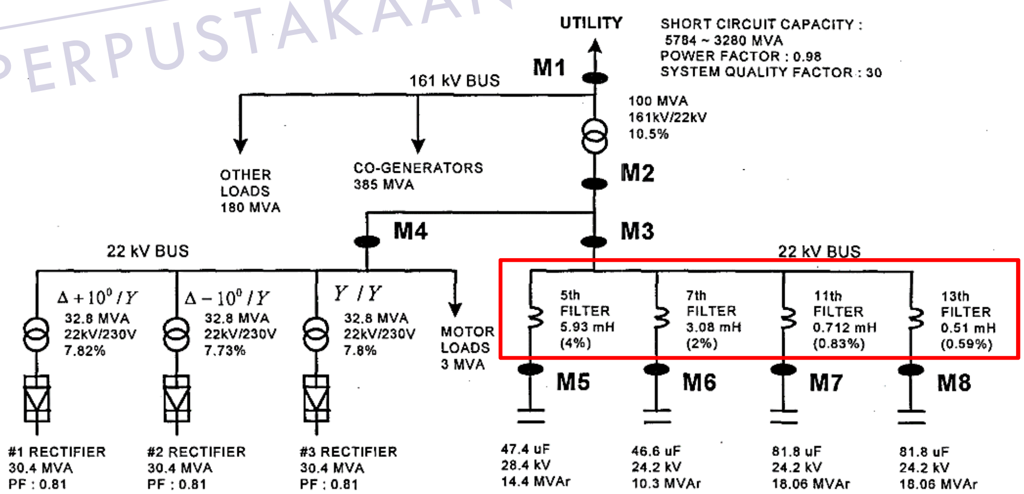


Figure 2.2: 5^{th}, 7^{th}, 11^{th} and 13^{th} order STPF in plastic plant distribution system

The system parameters are dynamically changed according to the power system configurations and loads. Therefore, even with passive filters implemented other harmonics problems can still appear which means for a wider range of harmonic frequencies, an STPF or DTPF alone is not sufficient to reduce the THD.

2.2.3 Active power filters

Active filters are the new trend in harmonic filtering technology. They make use of power electronic switches and advanced control techniques. Hence, their responses are much quicker than passive filters. The basic principle of operation of an active filter is to inject a suitable non-sinusoidal voltage and current into the system in order to compensate the harmonic contents. Active filters are still characterized by their relatively high cost compared to the cost of passive filters [13]. According to their connection to the network, active filters can be a series type (SeAPF), which prevents the transfer of harmonic current or the shunt type (SAPF), which reduces harmonic content in the network.

The function of passive series filter and SeAPF is identical and thus faced the same issues related to higher implementation cost especially for application in severe harmonics conditions. Mainly because they must be designed to withstand the full load current and full line voltage. In order to make it more practical, it has to be combined with some type of passive filtering. The passive filter is there to absorb the harmonic currents while the active filter blocks the transfer of harmonics to the rest of the PS. Details of this combination will be covered in hybrid filter. Meanwhile the SAPF's main function is to reduce or cancel the harmonic currents produced by the non-linear load by injecting a compensating current into the utility system. Figure 2.3 showed the configuration of a shunt active filter where it is connected in parallel to the non-linear loads.

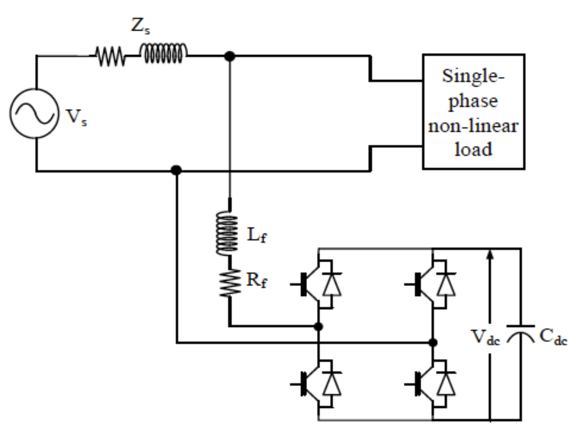


Figure 2.3: Single phase shunt active filter configuration

The filter above consists of four power electronic switches which produce an output current that will be injected to the PS for harmonic compensation. The switches are controlled by an integrated circuit. A lot of control methods have been studied by past researchers, which includes neural network, instantaneous p-q theory (instantaneous reactive power theory), synchronous d-q reference frame theory, fast Fourier transform technique (FFT) etc. Among all, the most commonly used due to their accuracy, robustness and simple calculation are the p-q and d-q theory [14].

The p-q theory is implemented to control a single phase SAPF in [15]. The block diagram of the implemented SAPF controller using p-q theory is shown in Figure 2.4. The designed control system is then implemented on the ATMEL NGW100 development board to ensure simultaneous real-time acquisition of voltage and current data.

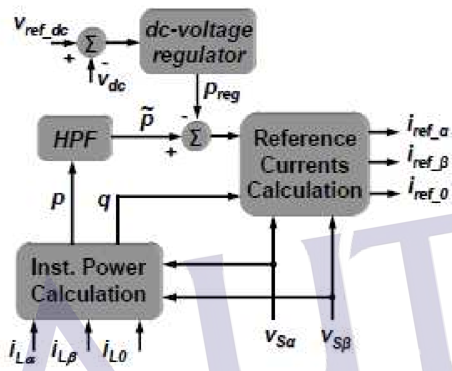


Figure 2.4: Block diagram of SAPF controller using p-q theory

Similar approach using p-q theory to control an SAPF has also been conducted on [16]. The proposed filter is designed to improve PF and generate harmonics current compensation. The SAPF controller which is based on p-q theory has been proven to be a powerful tool through experimental results. The set-up is also simple enough to allow digital implementation using a standard and inexpensive 16-bits microcontroller (Intel 80296SA) with minimum additional hardware.

In [17], a d-q theory is used instead to control the 3 phase voltage source converter (VSC) based SAPF. This method was chosen because it has greater and better performance when the supply voltage is distorted. The main difference of this method from p-q theory is that the d-q method requires the determination of the angular position of the synchronous reference of the source voltages. Phase locked loop (PLL) algorithm is used in this research to determine the angular position and a decoupled controller is used to generate the required firing pulses to the SAPF. The d-q based SAPF simulated in MATLAB/Simulink was capable in compensating the reactive power and thus mitigate harmonics.

The d-q theory has also been implemented on a VSC based SAPF in [18]. The only difference with [17] was that, the filter designed used sinusoidal pulse width modulation

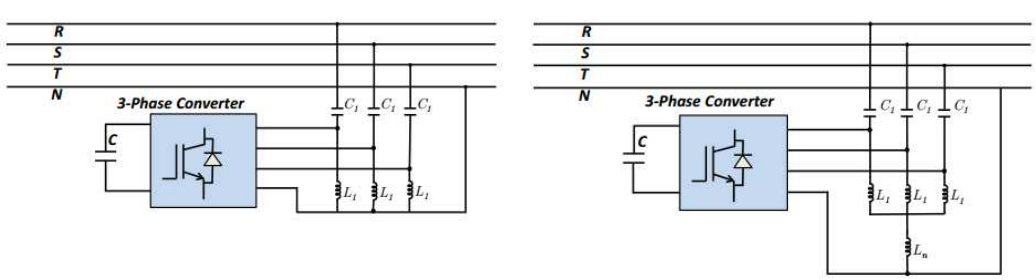
(SPWM) to generate the required firing pulses to the SAPF switches. This research has also proven the capability of d-q based SAPF in mitigating harmonics.

It is critical to decide the most suitable control method to mitigate harmonics on a PS. A study conducted on [19] evaluates the performance of a 3 phase 3 wire SAPF using both p-q theory and d-q theory under distorted supply and non-linear load conditions. The SAPF performance under both control methods were validated using MATLAB/Simulink. Based on the simulation result, p-q theory gives a better approach than d-q theory for compensation of harmonic currents and thus improving THD.

Other than the common control method, a novel control method introduced in [20] have successfully employed SAPF to mitigate harmonics distortion while also improving the PF. The methods, namely proposed control algorithm (PCA) and conventional control algorithm (CCA) were carried out and the result have shown that both control methods improved the PF up to 0.982 while keeping the total demand distortion (TDD) within an acceptable level. Another novel control method called sinusoidal current control strategy (SCC) was developed in [21]. This control method was modified from the p-q theory. The main advantage of this new method is that it can also be applied to unbalanced supply condition.

2.2.4 Hybrid active power filters (HAPF)

This filter combines both active and passive shunt filters. There are many possible combinations in hybrid filter design like the single tuned hybrid active power filter (STHF) and double tuned hybrid active power filter (DTHF) as shown in Figure 2.5. Hybrid filters provide a viable alternative to the use of active filters only, since the unit may be sized to only a fraction of the total compensating power [22], thus limiting the overall cost.



(a) (b)

Figure 2.5: (a) STHF, (b) DTHF in 3-phase distribution system [23]

REFERENCES

[1] Roger C. Dugan, Mark F. McGranaghan, Surya Sontoso, H. Wayne Beaty. *Electrical Power System Quality*. 2nd edition. McGraw-Hill. 2003.

[2] Douglas Andrews, martin T. Bishop, John F. Witte. (1996). Harmonic Measurements, Analysis, and Power Factor Correction in a Modern Steel Manufacturing Facility. *IEEE Transactions on Industry Applications*. 32(3): pp. 617-624.

[3] Belgin Turkay (2001). Harmonic Filter Design and Power Factor Correction in a Cement Factory. *IEEE Porto Power Tech Conference*. Porto, Portugal: IEEE. Volume 1.

[4] Babak Badrzadeh *et al* (2012). Power System Harmonic Analysis in Wind Power Plants - Part I: Study Methodology and Techniques. *IEEE Industry Applications Society Annual Meeting (IAS)*. Las Vegas, NV: IEEE. pp. 1-11.

[5] D. D. Reljic, V.V. Vasic, Dj. V. Oros (2012). Power Factor Correction and Harmonics Mitigation Based On Phase Shifting Approach. *15th International Power Electronics and Motion Control Conference (EPE/PEMC)*. Novi Sad, Serbia: IEEE. pp. DS3b.12-1 - DS3b.12-8.

[6] Shwehdi M. H., Sultan M. R (2000). Power Factor Correction Capacitors; Essentials and Cautions. *Power Engineering Society Summer Meeting*. Seattle, WA: IEEE. pp. 1317-1322. Volume 3.

[7] C. Venkatesh, Srikanth Kumar, Siva Sarma, M. Sydulu (2008). Modelling Of Nonlinear Loads and Estimation of Harmonics in Industrial Distribution System. *Fifteenth National Power System Conference (NPSC)*. Bombay: Indian Institute of Technology Bombay. pp. 592-297.

[8] Purushothama Rao Nasini, Narrender Reddy Narra, Santosh A. (2012). Modelling and Harmonic Analysis of Domestic/Industrial Loads. *International Journal of Engineering Research and Applications (IJERA)*. 2(5): pp. 485-491.

[9] R. Sastry Vedam, Mulukutla S. Sarma. *Power Quality – VAR Compensation in Power Systems*. CRC Press. 2009.

[10] Haozhong Cheng, Sasaki H., Yorino N. (1995). A New Method for Both Harmonic Voltage and Harmonic Current Suppression and Power Factor Correction in Industrial Power Systems. *Industrial and Commercial Power Systems Technical Conference*. San Antonio, TX, USA. IEEE. pp. 27.

[11] Raneru Nageswara Rao. (2013). Harmonic Analysis of Small Scale Industrial Loads and Harmonics Mitigation Technique in Industrial Distribution System. *International Journal of Engineering Research and Applications (IJERA)*. 3(4): pp. 1511-1540.

[12] Chi-Jui Wu *et al*. (1998). Investigation of Harmonic Amplification Problems Caused by Single-Tuned Filters. *IEEE Transactions on Power Delivery*. IEEE. 13(3). pp. 800-806.

[13] Enrique Acha, Manuel Madrigal. *Power Systems Harmonics – Computer Modelling and Analysis*. Wiley. 2001.

[14] Avadhesh Kumar Murya, R.K. Singh, Vishwa Nath Maurya, Ram Bilas Misra. (2014). Analysis and Simulation of Harmonics Current in Power Electronics Equipment Generated by Non-Linear Loads: Hysteresis Current Control Approach. *American Journal of Engineering Technology*. 2(1). pp. 1-13.

[15] Silva V., Pinto J. G., Cabral J., Afonso J. L., Tavares A. (2012). Real Time Digital Control System for A Single Phase Shunt Active Power Filter. *10th IEEE International Conference on Industrial Informatics (INDIN).* Beijing. IEEE. pp. 869-874.

[16] Joao Afonso, Mauricio Aredes, Edson Watanabe, Julio Martins. (2000). Shunt Active Filter for Power Quality Improvement. *International Conference UIE – Electricity for a Sustainable Urban Development.* pp. 683-691.

[17] Ramereddy Vinod, T. Rama Subba Reddy. (2015). Modelling and Analysis of D-Q Based Controller for Shunt Active Power Filter to Improve Power Quality. *International Journal of Advanced Electrical and Electronics Engineering*. 4(3).

[18] Sunitha M., Kartheek B. N. (2013). Elimination of Harmonics Using Active Power Filter Based on DQ Reference Frame Theory. *International Journal of Engineering Trends and Technology (IJETT).* 4(4). pp. 781-785.

[19] Wamane S. S., Baviskar J. R., Wagh S. R. A. (2013). Comparative Study on Compensating Current Generation Algorithms for Shunt Active Filter under Non-Linear Load Conditions. *International Journal of Scientific and Research Publications*. 3(6).

[20] Parag Kanjiya, Vinod Khadkikar, H. H. Zeineldin (2012). Achieving Maximum Possible Power Factor with Single-Phase Shunt Active Power Filter under Distorted Supply Condition. *IEEE 5th Power India Conference*. Murthal: IEEE. pp 1-6.

[21] Sanjay Mathur, Niaz Kazmi, Talaha Chisti, Anurag Tripathi. (2015). A Review of Control Strategies for Shunt Active Power Filter for Harmonics Compensation. *International Journal of Scientific and Innovative Research*. 3(1). pp. 55-60.

[22] Hideaki Fujita, Takahiro Yamasaki, Hirofumi Akagi. (2000). A hybrid active filter for damping of harmonic resonance in industrial power systems. *IEEE Transaction on Power Electronics*. 15(2). pp. 215-222.

[23] Francisco Kleber A. Lima *et al* (2013). A comparison between a single and a double tuned hybrid power filter under power quality analysis. *Brazillian Power Electronics Conference (COBEP)*. Gramado: IEEE. pp. 1291-1296.

[24] IEEE. *IEEE recommended practice and requirements for harmonic control in electric power systems*. IEEE Std 519. 2014.

[25] Muhammad H. Rashid. *Power Electronics Handbook*. Academic Press. 2001.

[26] Daniel W. Hart. *Power Electronics*. McGraw-Hill. 2010.

[27] Francisco C. De La Rosa. *Harmonics and Power Systems*. CRC Press, Taylor and Francis Group. 2006.

[28] Young-Sik Cho, Hanju Cha. (2011). Single-tuned Passive Filter Design Considering Variances of Tuning and Quality Factor. *Journal of International Council on Electrical Engineering*. Taylor and Francis Group, LLC. 1(1). pp. 7-13.