A SINGLE-PHASE HYBRID ACTIVE POWER FILTER WITH PHOTOVOLTAIC APPLICATION

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Special dedicated to my beloved mother and Chai Ling

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ABSTRACT

The past several years have seen a rapid increase of power electronics-based loads connected to the distribution system. These types of loads draw nonsinusoidal current from the mains, degrading the power quality by causing harmonic distortion. This thesis proposes a single-phase hybrid active power filter with photovoltaic application. The proposed topology interconnects a passive high-pass filter in parallel with a shunt active power filter and a DC source that represents the photovoltaic array. The uniqueness of the proposed topology is the fact that it improves the harmonic filtering performance of a basic shunt active power filter, as well as simultaneously supplies the power from the photovoltaic array to the load. The compensation current reference for the proposed topology is obtained by using the extension instantaneous reactive-power theorem. This theorem simplifies the equations for the current reference estimation, thus leading to a more efficient implementation in digital signal processor. To generate the compensation current that follows the current reference, the fixed-band hysteresis current control method is adopted. This work describes the design of circuit topology, control system, high-pass filter and compensation current reference estimation. The system is verified by simulation using MATLAB/Simulink simulation package. To validate the result, a 500 VA laboratory prototype is constructed. It is based on the dSPACE DS1104 digital signal processor. Experimental results show that the system effectively reduces the total harmonic distortion of the source current from 130.2 % to 19.6 %. Furthermore, it is demonstrated that the system can also supply active power to the load.

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LIST OF SYMBOLS

a	-	Constant of $H1(z)$
a_{LPF1}, a_{LPF2}	-	Coefficients of $G_{LPF}(z)$
A	-	Gain coefficient of $Z_{hp}(s)$
c	-	Constant of $H2(z)$
C	-	Capacitor
C_0, C_1	-	Coefficients of Δz
C_d	-	DC Smoothing capacitor
C_f	-	DC-bus capacitor
C_{hp}	-	High-pass filter capacitor
E_{Cf}	-	Energy in DC-bus capacitor
$E_{Cf,ref}$	-	Reference energy in DC-bus capacitor
f_0	-	Resonant frequency of passive high-pass filter
f_c	-	Cut-off frequency of analogue prefilter
f_{c1}	-	Cut-off frequency 1 of analogue prefilter
f_{c2}	-	Cut-off frequency 2 of analogue prefilter
f_{LPF}	-	Cut-off frequency of low-pass filter
f_r	-	Parallel resonant frequency of low-pass filter
f_s	-	Sampling frequency of discrete system
f_{s1}	-	Sampling frequency 1 of the proposed scheme
f_{s2}	-	Sampling frequency 2 of the proposed scheme
$G_{LPF}(s)$	-	Transfer function of low-pass filter in s-domain
G_{LPF}	-	Coefficient of $G_{LPF}(z)$

GD_1 - Gate driver circuit 1
GD_2 - Gate driver circuit 2
H - Hysteresis tolerance band of current controller
$H(s)$ - Closed-loop transfer function of phase-lock loop in s-domain
$H(z)$ - Closed-loop transfer function of phase-lock loop in z-domain
$H1(z)$ - Loop filter transfer function in z-domain
$H2(z)$ - Digitally-controlled oscillator transfer function in z-domain
$H_{cds}(s)$ - Transfer function of source current to injected current in s-domain
$H_{\max}$ - Maximum crest of $H_{cds}(s)$
I_{Cf} - Amplitude of DC-bus capacitor charging current
i_f - Compensation current
$i_{f,f}$ - Compensation current fundamental component
$i_{f,h}$ - Compensation current harmonics components
$i_{f,ref}$ - Compensation current reference signal
$i_{f,ref1}$ - First component of compensation current reference signal
$i_{f,ref2}$ - Second component of compensation current reference signal
i_{hp} - High-pass filter current
I_{hp} - rms value of high-pass filter current
$i_{hp,p}$ - High-pass filter current active component
$i_{hp,q}$ - High-pass filter current reactive component
$i_{hysteresis}$ - Error of hysteresis current comparator
i_L - Load current
I_L - rms value of load current
$i_L^{'}$ - Load current shifted by 90°
$i_{L,f}$ - Load current fundamental component
$i_{L,h}$ - Load current harmonics component
$i_{L,q}$ - Load current reactive component

i_{noise} - Noise current

i_{PV} - PV current

I_{PV} - Amplitude of PV current

i_s - Source current

$i_{s,f}$ - Source current fundamental component

$i_{s,h}$ - Source current harmonics components

i_{sw} - Switching ripple of the compensation current

i_α - α-axis of load current

i_β - β-axis of load current

K_I - Integration constant of PI controller

K_p - Proportional constant of PI controller

L - Inductor

L_f - APF interfacing inductor

L_{hp} - High-pass filter inductor

L_s - Source inductor

L_{smooth} - AC smoothing inductor

M_h - rms value of harmonic component h of the quantity M

p - Instantaneous active power

$\overline{p}$ - DC component of instantaneous active power

$\tilde{p}$ - AC component of instantaneous active power

p_L - Instantaneous active load power

P_{PV} - Active power of PV array/DC source

q - Instantaneous reactive power

Q - Quality factor of $Z_{hp}(s)$

$\overline{q}$ - DC component of instantaneous reactive power

$\tilde{q}$ - AC component of instantaneous reactive power

q_{hp} - Instantaneous reactive HPF power

q_L - Instantaneous reactive load power

R - Resistor

R_B - Bleed resistor

R_{hp} - High-pass filter resistor

R_L - Load resistor

s_0, s_1 - Poles of $H(s)$

S_n - Rectifier load nominal complex power

$\sin(\omega t)$ - Reference sinewave

$\sin(\omega t - 90^\circ)$ - 90° delayed reference sinewave

T - Period of source voltage

T_s - Sampling period of discrete system

T_{sw} - Period of switching ripple

V_{Cf} - DC-bus voltage

v_f - Compensation voltage

$v_{f,ref}$ - Compensation voltage reference signal

v_s - Source voltage

V_s - rms value of source voltage

$v_s^{'}$ - Source voltage shifted by 90°

$v_{s,f}$ - Source voltage fundamental component

$v_{s,h}$ - Source voltage harmonics components

v_u - Distribution voltage

v_α - α-axis of source voltage

v_β - β-axis of source voltage

ω - Damped frequency

ω_0 - Series resonant frequency of $Z_{hp}(s)$

ω_1 - Parallel resonant frequency of $H_{cds}(s)$

ω_n - Natural undamped frequency of low-pass filter

ω_p - Pole frequency of $Z_{hp}(s)$

z_0, z_1 - Poles of $H(z)$

z^{-1} - Unit delay

Z_{eq} - Series APF equivalent impedance

Z_f - Series APF impedance

$Z_{hp}(s)$ - High-pass filter impedance transfer function

Z_s - Source impedance

$Z_s(s)$ - Source impedance transfer function

$Z_{s,f}$ - Source impedance fundamental component

$Z_{s,h}$ - Source impedance harmonics components

ΔE_{Cf} - Energy loss of DC-bus capacitor in one cycle

ΔI_L - Peak rms value of reactive and harmonic load current

$\Delta I_{sw,p-p}$ - Peak-to-peak switching ripple

ΔV_{Cf} - Maximum/minimum DC-bus capacitor voltage

Δz - Characteristic equation of $H(z)$

θ - Phase angle of load current

θ_n - Phase angle of n-th load current component

$\theta_{fd}(z)$ - Feedback signal of digital phase-lock loop

$\theta_{in}(z)$ - Input signal of digital phase-lock loop

ϕ - Phase angle of source voltage

σ - Damping factor

$\alpha\beta 0$ - Orthogonal coordinates of stationary reference frame

ζ - Damping ratio

LIST OF ABBREVIATIONS

AC	-	Alternating current
ADC	-	Analogue-to-digital converter
APF	-	Active power filter
ASD	-	Adjustable-speed motor drive
CPU	-	Central processing unit
DAC	-	Digital-to-analogue converter
DC	-	Direct current
DCO	-	Digitally-controlled oscillator
DSP	-	Digital signal processor
EMI	-	Electromagnetic interference
ESL	-	Equivalent series inductance
ESR	-	Equivalent series resistance
FFT	-	Fast Fourier Transform
HPF	-	High-pass filter
I/O	-	Input/output
IGBT	-	Insulated gate bipolar transistor
LPF	-	Low-pass filter
MOSFET	-	Power metal oxide-semiconductor field-effect transistor
p-q	-	Instantaneous reactive-power
PCC	-	Point of common coupling
PCI	-	Peripheral component interconnect
PI	-	Proportional-integral controller
PLL	-	Phase-lock loop
PQ	-	Power quality
PV	-	Photovoltaic
PWM	-	Pulse width modulation

rms	-	Root-mean-square
RE	-	Renewable energy
RTI	-	Real-time interface
RTLib	-	Real-time library
RTW	-	Real-time workshop
THD	-	Total harmonic distortion
$\mathrm{THD}_{12.5\ \mathrm{kHz}}$	-	Total harmonic distortion calculated up to 12.5 kHz
VSI	-	Voltage source inverter

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CHAPTER 1

INTRODUCTION

1.1 Overview

The power quality (PQ) problems in power distribution systems are not new, but only recently the effects of these problems have gained public awareness. Advances in semiconductor device technology have fuelled a revolution in power electronics over the past decade, and there are indications that this trend will continue [1]. However these power equipments which include adjustable-speed motor drives (ASDs), electronic power supplies, direct current (DC) motor drives, battery chargers, electronic ballasts are responsible for the rise in related PQ problems [2]-[4]. These nonlinear loads are constructed by nonlinear devices, in which the current is not proportional to the applied voltage. A simple circuit as shown in Figure 1.1 illustrates the concept of current distortion. In this case, a sinusoidal voltage is applied to a simple nonlinear resistor in which the voltage and current vary according to the curve shown. While the voltage is perfectly sinusoidal, the resulting current is distorted.

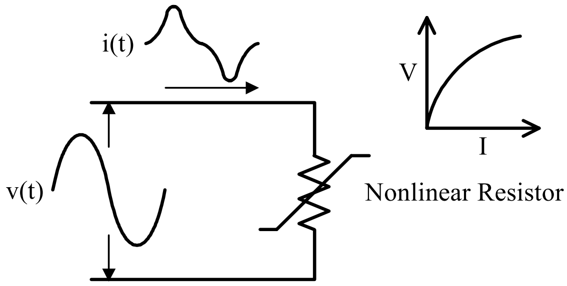

Figure 1.1 Current distortion caused by nonlinear resistance

Nonlinear loads appear to be prime sources of harmonic distortion in a power distribution system. Harmonic currents produced by nonlinear loads are injected back into power distribution systems through the point of common coupling (PCC). These harmonic currents can interact adversely with a wide range of power system equipment, most notably capacitors, transformers, and motors, causing additional losses, overheating, and overloading [2]-[4].

There are set of conventional solutions to the harmonic distortion problems which have existed for a long time. The passive filtering is the simplest conventional solution to mitigate the harmonic distortion [5]-[7]. Although simple, these conventional solutions that use passive elements do not always respond correctly to the dynamics of the power distribution systems [8]. Over the years, these passive filters have developed to high level of sophistication. Some even tuned to bypass specific harmonic frequencies. However, the use of passive elements at high power level makes the filter heavy and bulky. Moreover, the passive filters are known to cause resonance, thus affecting the stability of the power distribution systems [9]. As the regulatory requirements become more stringent, the passive filters might not be able to meet future revisions of a particular Standard.

Remarkable progress in power electronics had spurred interest in active power filter (APF) for harmonic distortion mitigation [10]-[15]. The basic principle of APF is to utilise power electronics technologies to produce currents components that cancel the harmonic currents from the nonlinear loads [10]. Previously, majority of controllers developed for APF are based on analogue circuits [11], [12]. As a result, the APF is inherently subjected to signal drift. Digital controller using digital signal processor (DSP) or microprocessor is preferable, primarily due to its flexibility and immunity to noise signals [13]-[15]. However it is known that using digital methods, the high order harmonics are not filtered effectively. This is due to the hardware limitation of sampling rate in real-time application [15]. Moreover, the utilisation of fast switching transistors (i.e. IGBT) in APF application causes switching frequency noise to appear in the compensated source current. This switching frequency noise requires additional filtering to prevent interference with other sensitive equipments.

The idea of hybrid APF has been proposed by several researchers [16]-[18]. In this scheme, a low cost passive high-pass filter (HPF) is used in addition to the conventional APF. The harmonics filtering task is divided between the two filters. The APF cancels the lower order harmonics, while the HPF filters the higher order harmonics. The main objective of hybrid APF, therefore is to improve the filtering performance of high-order harmonics while providing a cost-effective low order harmonics mitigation.

Recently, there is an increasing concern about the environment. The need to generate pollution-free energy has triggered considerable effort toward renewable energy (RE). RE sources such as sunlight, wind, flowing water and biomass offer the promise of clean and abundant energy [19]-[21]. They do not generate any greenhouse gases and are inexhaustible [22]. Solar energy, in particular, is especially attractive in a sunshine country like Malaysia. This energy is in DC form from photovoltaic (PV) arrays. It is converted into a more convenient alternating current (AC) power through an inverter system. Efforts have been made to combine the APF with PV array [23]-[25]. However, it appears that no attempt has been made to combine a hybrid APF with PV array.

1.2 Objective of Research

The objective of the research is two-fold: (1) to propose a new variation of hybrid APF topology with PV application. (2) to propose a simple current reference estimation method for the proposed topology.

To achieve the first objective, this research proposes a hybrid APF topology for a single-phase system, connected to a DC source that represents the PV array. The topology is unique because it effectively filters harmonic currents of low and high frequencies to obtain sinusoidal source current. Furthermore, it simultaneously supplies the power from the PV array to the load.

For the second objective, this research proposes the application of the extension instantaneous reactive-power (p-q) theorem to estimate the compensation current reference. Although the estimation of current reference based on extension p-q theorem is not new [24]-[26], this approach has not yet being applied to a single-phase hybrid APF system involving passive HPF, shunt APF and a PV array. Using the extension p-q theorem, the resulting equations for the current reference is simpler compared with the conventional p-q theorem presented in [27]. This will lead to more efficient digital controller implementation using DSP.

1.3 Methodology of Research

In the elaboration of the research, a harmonic analysis of source current distortion has been carried out. It has featured a nonlinear full-bridge diode rectifier with DC smoothing capacitor and resistive load as a harmonic currents source. The time domain simulation is performed using MATLAB/Simulink simulation package. Afterwards, an extensive computer simulation involving the power circuit of the shunt APF, passive HPF, a DC source that represents the PV array, current reference estimation based on extension p-q theorem, phase-lock loop (PLL) circuit and fixed-band hysteresis current controller is carried out.

Once satisfactory simulation results are obtained, the proposed topology is tested in the laboratory with an experimental prototype. The prototype is designed to compensate the distorted current produced by nonlinear load, as well as simultaneously supplies the power from the PV array to the load. The proposed algorithm and control system are implemented using a dSPACE DS1104 DSP controller board.

Although the original work is intended to include the PV array, the experimental set-up using PV array is not possible due to facility and time constraints. However, the PV array can be adequately replaced with a DC source. This is because the PV array is fundamentally a DC source that produces electricity in DC form.

Finally, a harmonic analysis is carried out to validate the filtering performance of the proposed hybrid APF in comparison to a basic shunt APF. The experimental results are analyzed and compared with the results obtained from the computer simulation.

1.4 Thesis Organisation

This thesis consists of this introductory chapter and six other chapters arranged as follows:

Chapter 2 covers the literature review and a brief discussion of harmonic distortion problems, conventional mitigation methods using passive filters and improved mitigation methods using APF approaches. The efforts in combining the PV array with the APF are discussed briefly. Different types of compensation reference signal estimation techniques suitable for APF applications are reviewed. A brief overview of the control strategies for APF is also provided in this chapter.

Chapter 3 presents the proposed hybrid APF topology. This chapter elucidates the topology, operating principles and control of the proposed hybrid APF and illustrates how this system can be used to supply the PV power to the load. Emphasis is given to a discussion on the design consideration of the passive HPF.

Chapter 4 concerns the system level simulation using MATLAB/Simulink. The computer simulation design is described in detail.

Chapter 5 describes the design and construction of the experimental prototype to validate the proposed hybrid APF. Detailed description of each hardware components is provided.

Chapter 6 provides the simulation and experimental results. Comparison between the simulation and experimental results is discussed in detail. A harmonic analysis is carried out to evaluate the filtering performance of the proposed hybrid APF in comparison to a basic shunt APF.

Chapter 7 summarises the research undertaken and highlights the contribution of this thesis. It offers recommendations for further research.

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