Available online at www.sciencedirect.com

SCIENCE DIRECT®

Mathematics and Computers in Simulation 71 (2006) 345–359

MATHEMATICS AND COMPUTERS IN SIMULATION

www.elsevier.com/locate/matcom

A comparative study of shunt hybrid and shunt active power filters for single-phase applications: Simulation and experimental validation

Salem Rahmani [a,*], Kamal Al-Haddad [a], Hadi Youssef Kanaan [b,1]

[a] *Canada Research Chair in Energy Conversion and Power Electronics, École de Technologie Supérieure, 1100 Notre-Dame West Street, Montreal, Que., Canada H3C1K3*

[b] *Saint-Joseph University, Faculty of Engineering-ESIB, Campus des Sciences et Technologies, Mar Roukos, Mkallès, B.P. 11-0514, Riad El-Solh 1107 2050, Beirut, Lebanon*

Available online 5 May 2006

Abstract

The aim of this paper is to compare the performance of the single-phase shunt active power filter (SPSAPF) and the single-phase shunt hybrid power filter (SPSHPF) that adopt both an indirect current control scheme with a unipolar pulse width modulation (U-PWM) strategy. The SPSHPF topology includes, in addition to the components of the SPSAPF, a power factor correction capacitor connected in series with a transformer. The primary winding of the transformer is connected to the single-phase voltage–source inverter, which is the main part of the filter. The indirect current control technique that is implemented for both filters is based on extracting the source current reference from the distorted waveform of the load current. The U-PWM control technique is based on comparing simultaneously a triangular high frequency carrier signal with a slow-varying regulation signal and its opposite. The double comparison process results in the gate signals for the semiconductors. A laboratory prototype for each filter is built. It is demonstrated that the rating of the inverter used in the SPSHPF is three to four times lower than the one corresponding to the SPSAPF. In addition, the performance of the SPSHPF is found to be much better than that of the SPSAPF as far as the line current distortion is concerned.

Keywords: Hybrid power filters; Active power filter; Harmonics and reactive power compensation; Indirect current control; PWM control

1. Introduction

Active power filters are basically power electronic devices that are used to compensate the current or voltage harmonics and the reactive power flowing in the power grid. The reduction of the harmonic and reactive currents becomes an increasingly required issue owing to the wide use of power electronic equipment. Traditionally, passive LC filters have been used to remove line current harmonics and to improve the power factor. However, when implemented, these passive filters present many drawbacks such as tuning problems, series and parallel resonance. Other industrial applications use power factor correction (PFC) devices for reactive power and current harmonics compensation. In these circuits, switched capacitors banks are typically connected in parallel to current–source-type loads. Seen from

* Corresponding author. Tel.: +1 514 396 8874; fax: +1 514 396 8684.
E-mail addresses: Salem.Rahmani@esstt.rnu.tn (S. Rahmani), kamal@ele.etsmtl.ca (K. Al-Haddad), hadi.kanaan@fi.usj.edu.lb (H.Y. Kanaan).
[1] Tel.: +961 3 333179; fax: +961 4 532645.

0378-4754/$32.00 © 2006 Published by Elsevier B.V. on behalf of IMACS.
doi:10.1016/j.matcom.2006.02.018

the load side, the capacitance of the PFC and the source inductor create a parallel resonant circuit. Looking from the source side, the PFC capacitors and the line inductor represent a series resonant circuit. To prevent resonance due to current harmonics in power systems with PFC equipment, typical shunt or series active topologies have been proposed [3,10,11]. However, these topologies suffer from a high kVA-rating of the filter power stage [1,5]. The boost-type rectifier that constitutes the shunt active filter requires generally a high DC-link voltage [4,9,11] in order to compensate effectively the high order harmonics. On the other hand, a series active filter needs a transformer capable to withstand full load current in order to compensate the voltage distortion. Therefore, a hybrid filter topology has been developed achieving the desired damping performance with a significant reduction of the kVA-rating required by the power active filter [3,4,6,11].

In voltage–source inverter applications, the majority of the published papers use a cutting first-order filter L_c through which the inverter is connected to the power grid. This inductor ensures, firstly, the controllability of the active filter current and, secondly, acts as a first-order passive filter attenuating the high frequency ripples generated by the PWM inverter. A relatively low value of L_c improves the dynamics of the active filter but, on the other hand, does not attenuate sufficiently the switching frequency component in the line current. Conversely, a relatively high value of L_c will prevent these high frequency harmonics from flowing through the network but will affect negatively the dynamics of the active filter and degrade, consequently, the quality of compensation. Moreover, these papers do not consider the high frequency harmonics in the evaluation of the total harmonic distortion (THD) of the line current. They give theoretically a THD after compensation lower than 5%. Indeed, a more accurate calculation of the THD that take into account the high frequency harmonics would give easily more than 10%, which is higher than the limit required by international standards such as IEEE-519 and IEC-555-2. However, in this paper, the suggested unipolar PWM control strategy naturally compensates these high frequency harmonics.

In this paper, the operating characteristics of a SPSAPF and a SPSHPF are presented and compared on an economical basis. Both topologies use the indirect current control strategy with the U-PWM technique for current wave shaping. The SPSHPF uses a power factor correction capacitor connected in series with the secondary winding of the transformer. The primary winding of the transformer is connected to a single-phase voltage–source inverter. The compensation capacitor needed for PFC is used as part of the filter to create a single harmonic trap. A relatively low-rated active filter compensates the residual harmonics and prevents the excitation of the resonant circuit [2]. The indirect current control technique is based on the classic demodulation method that allows extracting easily the source current reference from the distorted waveform of the load current. Contrary to the existing methods, the indirect method eliminates switching spikes in the mains current [7,8] and allows a straightforward determination of the proportional gain K_p, which is considered as a hard task for the direct method, especially when high quality compensation is required. The adopted unipolar PWM control technique is based on comparing simultaneously a triangular high frequency carrier signal with a slow-varying regulation signal (given by the current regulator) and its opposite. This comparison process generates the gate signals for the power switches. The U-PWM pushes back the first significant harmonics towards twice the switching frequency. Furthermore, it eliminates the families of rays that are centered on the odd multiples of the switching frequency. Computer simulation and experimental results will show that better results are achieved with the SPSHPF topology.

2. Single-phase shunt active power filter topology

The SPSAPF consists of a single-phase full-bridge voltage–source PWM inverter, a DC bus capacitor C_{DC} and an inductor L_c. The inductance, through which the inverter is connected to the power supply network, ensures, firstly, the controllability of the active filter current and acts, secondly, as a first-order passive filter attenuating, thus, the high frequency ripples generated by the inverter. Fig. 1 shows the system under study where the SPSAPF is connected in parallel with the non-linear load. The filter operates as current source, which cancels the current-type harmonics and exchanges the necessary reactive energy required by the non-linear load. A single-phase diode bridge rectifier feeding a series *R*–*L* circuit is chosen to represent the non-linear load.

3. Single-phase shunt hybrid power filter topology

Fig. 2 shows the configuration of the SPSHPF. It consists of a full-bridge voltage–source PWM inverter, a DC side capacitor C_{DC}, an inductor L_c, a transformer and a PFC capacitor C_c. The primary winding of the transformer is fed by