Electrical Power and Energy Systems 64 (2015) 328–339

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A novel control method for series hybrid active power filter working under unbalanced supply conditions

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ARTICLE INFO

Article history:
Received 23 November 2013
Received in revised form 30 May 2014
Accepted 6 July 2014
Available online 6 August 2014

Keywords:
Active power filter
Generalised instantaneous power theory
Passive filter
Power multi-vector
Reference voltage

ABSTRACT

In this paper a new control algorithm for a Series Hybrid Active Power Filter (SHAPF) is proposed. With the proposed control algorithm, the series active power filter simultaneously compensates for source voltage unbalance and source current harmonics generated by non-linear loads. The proposed control algorithm is based on the generalised instantaneous power theory where the instantaneous inactive power is represented as a second order tensor. The reference voltage is directly associated with three-phase instantaneous voltages and currents and are separated in three-phase co-ordinate systems. Therefore, the calculation of the compensation reference voltage is much simpler than the other available control algorithms. It can be applied for both voltage and current harmonic generating loads connected across balanced and unbalanced source voltages. The mathematical formulation of the proposed control algorithm with its applications to SHAPF is presented. The validity of the proposed control algorithm is verified with extensive experimental study and results are reported.

Introduction

With the increased use of power electronic converters in the power system, there has been increased concern for power quality and voltage stability. Power quality degradation generally results from non-linear loads and more complex steps are required to overcome these power quality problems. In addition to the compensation of harmonics produced by non-linear loads, the unbalance existing in electrical networks should also be corrected. The unbalance in current is several times because of the unbalance in the source voltage which results into the three-phase currents differ considerably and leads to single phasing.

Traditionally shunt passive power filters (PPFs) have been used to eliminate harmonic currents but many shunt PPFs would be required to eliminate wide range of harmonics. The filtering characteristic of the shunt PPF is strongly influenced by the source impedance and in addition, the hazards of series and parallel resonance become quite difficult to avoid [1]. Active power filters (APF) emerged as an alternate solution to the conventional PPFs; this is more expensive but has an advantage that it can eliminate wide range of frequency components. The required power rating of power converter in APF is comparable as compared to the load rating. This limits the applications of active filters in the power system. Hybrid active filter topologies have been developed to effectively solve the problems of harmonic currents and reactive power [2,3]. Using low cost passive filters in the hybrid active filter, the power rating of active converter is reduced compared with that of pure active filters. Hybrid active filters retain the advantages of both series and shunt APF and overcome the limitations of stand-alone passive and active filters. The hybrid active filters are cost effective and have become more practical in industry applications.

In an alternative approach, power factor correction (PFC) circuits integrated in the converter configuration are proposed for the compensation of harmonic current. Diode rectifier with the continuous-conduction mode (CCM) boost converter [4–7], pulse width modulated (PWM) rectifier [8], PWM AC choppers [9] are few topologies for implementing PFC. The closed loop operation of the static power converter with PFC assures satisfactory performance to achieve a high input power factor and regulate converter output voltage over a wide operating range. Increased complexity, conducted electromagnetic interference (EMI) and reduced robustness are distinct characteristics of these approaches [10]. These solutions address the compensation of source current harmonics but they do not compensate for source voltage unbalance. The application of these configurations is limited to low power level due to rating constraints of semiconductor switches and efficiency issues at high power levels.

Out of many APF configurations, the popularly used active power filter configurations are: shunt active power filter, which injects compensation currents [11–18]; series active power filter,

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http://dx.doi.org/10.1016/j.ijepes.2014.07.022

which injects compensation voltages through a transformer [19–23]; and the hybrid active power filter, which is a combined system of APF and PPF [24–37]. Two configurations of hybrid active power filter have become very popular: active filter connected in series with a shunt passive filter (injection type hybrid active power filter (IHAPF)) and series active filter combined with shunt passive filter (Series Hybrid Active Power Filter (SHAPF)) [32–36]. Both topologies are useful to compensate current harmonics generating load. However, when the load also generates voltage harmonics, the second topology is more appropriate [2,38].

The SHAPF works as a kind of harmonic isolator rather than a harmonic compensator and force the harmonic current to flow through the shunt passive filters. In addition, the SHAPF can regulate the voltage at the point of common coupling at a desired value by controlling the inverter output so as to compensate for abnormal utility voltage. The required rating of the series active filter in SHAPF configuration is much smaller than that of a conventional shunt active filter [24,25]. SHAPF configuration is preferred for simultaneous compensation of current harmonics and source voltage unbalances [22,32,39–43]. SHAPF has very good potential at high power levels, since it needs a very low rating voltage source inverter and this configuration overcomes all the problems of PPFs. This motivated the researcher to explore the application of active filters at very high power level which is otherwise restricted due to non-availability of high speed high power semiconductor switches. Due to these multi-functionalities and advantages, the SHAPF and its controlling methods are studied more in recent times [31–37,44–46].

The SHAPF filtering characteristics and efficiency of harmonic compensation depend on the control algorithm applied to calculate the reference voltage. Several direct and indirect control methods are proposed for generating reference signals. The direct method includes low-pass to band-pass transformation, indirect current control scheme, PI control strategy, S-transform to extract the fundamental component, etc. [31,32,36,44–48]. In indirect approaches, instantaneous power theory has been used for generating reference of the hybrid active power filters. Several publications appeared in the literature suggests different definitions of instantaneous power theories for deriving reference quantities. Instantaneous p–q theory, dual p–q theory, synchronous reference frame theory, vectorial theory, generalised a–b–c reference frame theory, etc. are few widely used definitions used by researchers for separating reference [28,29,34,46,48–50].

SHAPF configuration is suitable for simultaneous compensation of source current harmonics and source voltage unbalance and several control methods are also proposed to achieve this objective [22,32,39–43]. Most of these approaches use Fortescue sequence components, instantaneous power theories, PLL and numbers of low-pass filters in control circuit to extract final reference voltage. For separating reference voltage corresponding to source current harmonics, instantaneous power definitions are generally used. The end expression of existing control algorithms reported in the literature is generally complex, computationally intensive and requires selection of different gain factors for proper compensation [22,32,39–43]. A need have been felt therefore to have a simple and direct expression of reference voltage for SHAPF which simultaneously compensate for source voltage unbalance and source current harmonics.

In this paper, a novel control scheme for SHAPF is proposed which simultaneously compensates the source voltage unbalances and source current harmonics. In proposed method the reference voltage is derived in two parts viz., reference voltage for source unbalance and reference voltage for source current harmonics. The first part compensates for abnormal utility voltage and is derived using the instantaneous sequence component of the unbalance source voltages. For deriving the second component, the positive sequence component of source voltage is considered as the fundamental voltage applied to the nonlinear load. The reference voltage for SHAPF that compensates source current harmonics is derived using the generalised instantaneous power theory. It is proposed to decompose multiphase voltage vector into quantities that represent different components of power. Using vector algebra, it is possible to obtain the voltage vectors corresponding to these components of the power multivector [51–53]. The separated components of voltage vectors corresponding to unwanted components of instantaneous powers are used for generating a reference voltage of SHAPF which compensates source current harmonics. The addition of these two components gives a simplified direct formula for SHAPF reference voltage.

For experimental verification of proposed control algorithm, a prototype of SHAPF is developed and tested for compensating current harmonic generating load as well as voltage harmonic generating load working under balanced as well as unbalanced source conditions. An extensive experimental study is done to verify the effectiveness of proposed control algorithm and the results show that SHAPF adopting proposed control algorithm effectively compensate source voltage unbalance and source current harmonics. The performance of proposed control algorithm is also compared with other normally used algorithms. Since the numbers of calculation steps required to separate reference voltage are considerably less in proposed reference voltage expression its implementation is simpler and fast as compared to other expressions.

This paper is organised as follows: The detail of SHAPF system configuration is described in Section 'System configuration'. Section 'Proposed control algorithm' presents the proposed control scheme in different parts viz., finding fundamental unbalanced voltage, the formulation of generalised instantaneous power theory, decomposition of voltage vector and selection of proper voltage components for reference generation. The details of experimental model along with results obtained while compensating current and voltage harmonic generating load are presented in Section 'Experimental results and discussion'.

System configuration

SHAPF is a combination of shunt passive filter and series active filter. The series active filter improves the performance of the passive power filter (PPF) by providing a high impedance path to the harmonic components present in the load current. Fig. 1 shows the power circuit configuration of SHAPF, which has a series active power filter and a bank of shunt PPF. This configuration reduces the need for precise tuning of the PPF banks and eliminates the possibility of series and parallel resonance. The shunt PPF bank used in this study is made up of a 5th harmonic tuned filter, a 7th harmonic tuned filter and a high-pass filter which work as a harmonic current sink path. Since, dominating lower order harmonics have been eliminated by passive filters, the series active filter has to compensate only higher order harmonics and as a result the rating of the active filter needed will be less compared to conventional active filters [1].

The power circuit of the series active power filter is made up of the three-phase pulse width modulated voltage source inverter, the coupling transformers, and the ripple filter. The turns ratio of the series transformer connecting the active power filter to the power line is chosen as unity in this study. However, in the high power system, it is chosen to match the low power inverter rating with the system voltage and current. The ripple filter is used to suppress the switching ripples generated due to the high frequency switching of the PWM inverter.

The supply voltage is stepped down to 110 V using an auto transformer. The unbalance in the magnitude and phase is