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Third order sinusoidal integrator (TOSSI)-based control algorithm for shunt active power filter under distorted and unbalanced voltage conditions

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ABSTRACT

The performance of a shunt active power filter (SAPF) essentially depends on the accuracy of synchronization and harmonic components extraction. The conventional algorithms such as synchronous reference frame theory and instantaneous reactive power theory work well under sinusoidal and balanced grid voltage conditions. This research is mainly aimed at enhancing the performance of the SAPF when the grid voltages are unbalanced and distorted. The synchronizing signals of the voltage at the point of common coupling (PCC) and system frequency are extracted from the distorted voltages using third order sinusoidal signal integrator (TOSSI) based frequency adaptive pre-filters. In this study, the TOSSI-based filter is used to extract current harmonic components from the load current which increases the selectivity and the dynamic performance of extraction process. The performance of the proposed control approach for a SAPF under distorted and unbalanced voltage conditions is demonstrated through computer simulations and validated by experimental results.

1. Introduction

Increased penetration of power converters and renewable energy systems forces the power system to operate under distorted voltage conditions at the point of common coupling (PCC). Also the distribution system may continue to operate under distorted and highly unbalanced conditions during fault conditions or under partial compensation in isolated grid systems. Under these conditions, the shunt active power filters (SAPFs) connected to various non-linear loads are expected to work satisfactorily [1]. SAPF injects the harmonic currents which are equal in magnitude but in phase opposition to the load current harmonics [2]. Hence, for the satisfactory operation of a SAPF, the harmonic currents should be accurately extracted both in phase and magnitude. Therefore, a SAPF must operate in synchronization with the PCC voltages. In weak distributed systems or the systems with unbalanced or distorted conditions, the grid frequency may be varying. Hence, the harmonic component extraction algorithm must accurately track the frequency variation and should be synchronized with grid frequency.

The harmonic current extraction methods can be grouped into frequency domain and time domain methods. The time domain approaches are much faster, accurate and requires less memory compared to frequency domain methods. In this paper, a time-domain approach is used. The popular time-domain methods such as instantaneous p-q theory [3] and synchronous reference frame (SRF) theory [4,5] work well only with balanced and distortion free PCC voltage conditions. In [6,7], direct power control of SAPF is discussed where the controller performance is improved by using highly selective filters for harmonics extraction. But, the absence of phase locked loop (PLL) makes these methods unfit variable frequency systems. The load harmonics compensation under dynamic load conditions based on optimization methods for unbalanced conditions is given in [8], where the harmonics information is extracted using conventional low pass filters.

Recently, the research is focused on improving the performance of time-domain based harmonic currents extraction methods under distorted and unbalanced voltage conditions employing pre-filters. Harmonic currents extraction using various pre-filtering techniques are classified as (i) harmonic component extraction using artificial neural networks (ANNs) [9–11] and (ii) using second order pre-filters such as generalized integrators [12–14] and self tuning filters [15]. Both the approaches can offer good performance, but the pre-filter based methods are found to be quite simple and straight forward compared to ANN methods. In [15], the self-tuning filters (STF) are used to process the grid voltages in addition to separating the fundamental current component form nonlinear load currents. The performance of STF-based approach deteriorates under system frequency variation as its resonating frequency is kept fixed. Further, the STF method can only be applied to three-phase systems where as the generalized integrators-based methodologies can be employed to single-phase as well as three-phase systems. Harmonics extraction methods employing multiple pre-

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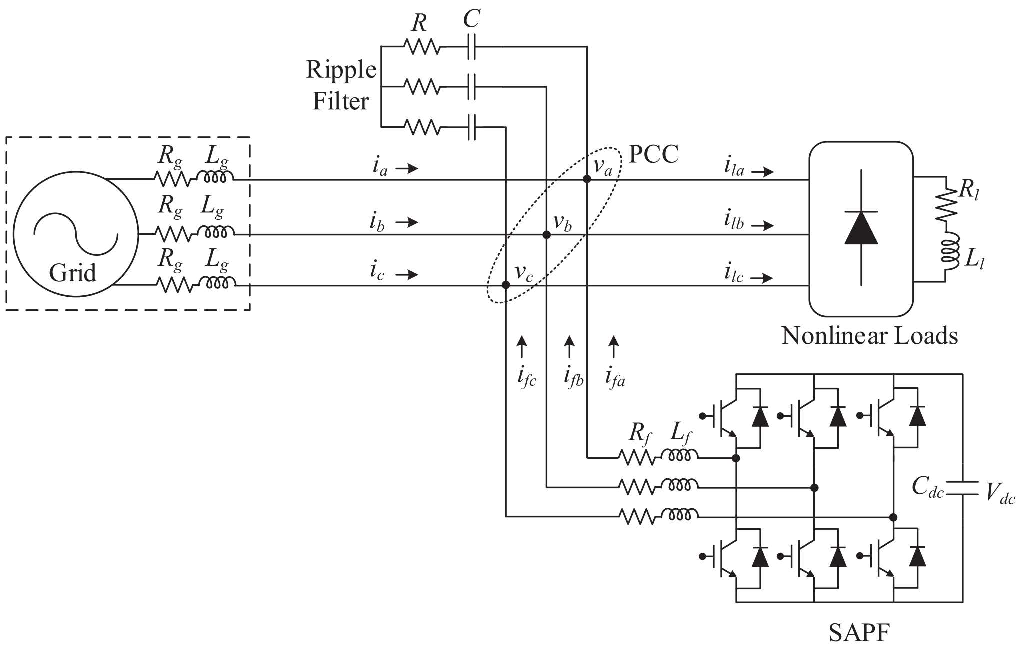

Fig. 1. Schematic of the SAPF system under study.

filters are reported in [16–18] to improve dynamic performance of the extraction process. However, these methods are useful only if the selective harmonic filtering is required. In [16], multiple adaptive vectorial filters (AVFs)-based harmonic decoupling network resting on a frequency-locked loop (FLL) is proposed. Application of FLL makes the harmonics estimation frequency adaptive. Second order generalized integrator (SOGI)-based multiple filters resonating at different frequencies are used in [18]. However, for a SAPF, multiple pre-filters based approach increases the complexity of the control algorithm when only the fundamental component has to be extracted.

Mainly, the harmonic current components extraction process involves two steps: (i) synchronization or estimation of system frequency and (ii) extraction of harmonic current components of load currents. PLLs and FLLs are used generally for system frequency extraction and to make the extraction process frequency adaptive. Under normal grid conditions, conventional SRF-based PLL is generally used for estimation of system frequency. However, now a days, advanced PLLs and FLLs are being preferred over the conventional SRF-PLL to deal with abnormal grid conditions such as unbalance and distortion in the grid voltages. An extension of the SRF-PLL known as decoupled double SRF-PLL (DDSRF-PLL) was proposed in [19] to deal with unbalanced nature of grid voltages. The DDSRF-PLL uses two SRFs and a decoupling network to isolate the effects of the positive-and the negative-sequence voltage components. Another modified PLL with conventional d-q theory is used in [20] for hybrid shunt active power filters under unbalanced voltage conditions. A two phase reference frame-based PLL and ANN-based PLL are proposed in [21,9] which are useful for balanced conditions only. In [22], a dual SOGI based FLL (DSOGI-FLL) has been reported to estimate the grid frequency under unbalanced grid voltages. To estimate the frequency of highly polluted harmonic grids, PLLs/FLLs employing multiple second order pre-filters such as SOGIs, and STFs are propsed to extract fundamental components of the grid voltages [16–18]. These extracted fundamental signals are fed to PLL/FLL units to extract the frequency information. Use of multiple filters may enhance the steady-state and dynamic performances of the PLL/FLL units, but it will lead to increased computational burden.

In order to overcome the shortcomings of the methods employing multiple second order pre-filters [16–18] in harmonics extraction and frequency estimation, a third order pre-filter based control of SAPF has been proposed in this paper. A third order pre-filter known as third order sinusoidal signal integrator (TOSSI) is proven to be offering better steady state and transient responses compared to second order filters [23,24]. The TOSSI-based filters exhibit fast dynamic response at the same level of filtering intensity compared to the second order filters. In [23,24], the TOSSI filter has been used only for the synchronization of grid-tied inverters where the fundamental components of the PCC voltages extracted by TOSSI filters are fed to the PLL unit. This work has been improved and extended its application to SAPFs in this paper. The TOSSI-based pre-filter requires the information of system frequency for the exact extraction of fundamental components of the PCC voltage. In the proposed approach, the system frequency is accurately estimated by using a frequency adaptive TOSSI-based PLL. First, the PCC voltages are processed through TOSSI pre-filters and applied to SRF-PLL to estimate the frequency. Thus the PLL and voltage TOSSI pre-filters work together. The estimated frequency is used to separate the harmonic components from the load current, which employs another set of TOSSI-based filters for current signals. The satisfactory performance of SAPF under different operating conditions such as (i) balanced voltages, (ii) distorted balanced voltages, (iii) distorted unbalanced voltages and (iv) system frequency fluctuations are studied and the results are presented. The main contributions of present work are.

1. Extending the TOSSI filter-based approach to SAPFs under distorted and unbalanced voltage conditions.
2. Development of TOSSI filter-based fundamental sequence components extractor for three-phase signals.
3. Experimental verification of the SAPF performance with the proposed approach.

The rest of the paper is organized as follows. The following section gives the description of the SAPF system. In Section 3, extraction of fundamental sequence components of PCC voltages, estimation of system frequency and extraction of harmonic currents using TOSSI-filters are explained. Section 4 gives the design of SAPF system parameters. Section 5 gives the simulation results and the experimental results. Finally, the conclusions are given in Section 6.

2. System description

The power circuit schematic of a three-phase SAPF is shown in Fig. 1. The SAPF is a three-phase two level voltage source inverter with a self-sustained dc link capacitor (C_{dc}) connected at PCC through filter