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Conceptual design of an efficient unified shunt active power filter based on voltage and current source converters

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ABSTRACT

This paper establishes a detailed design of a novel structure of Unified Shunt Active Power Filter (USAPF) in which both Voltage Source Converter (VSC) and Current Source Converter (CSC) operate simultaneously (VCSC scheme). In this unified scheme, separation of the frequency components of the reference current and dedication of low orders to the CSC section and high orders to the VSC section is the key point of the idea. The separation frequency based on a criterion is first computed, and then the contributions of CSC and VSC sections are determined. It is mathematically shown that such allocations can guarantee the minimization of the total active power losses of the unified filter among different types of allocations. The design procedure is initiated with deriving allowable operating ranges for the passive elements in dc and ac sides of the converters and continued to find the switching frequency for both converters. Simulation and experimental results not only confirm the correctness of the design, but also show the values of the passive elements become significantly lower than the values found in CSC and VSC based APF alone. This reduction can lead to a considerable reduction in overall losses in the VCSC scheme.

1. Introduction

Shunt active power filters, including voltage source converter (VSC) based filters, current source converter (CSC) based filters, are the most popular and commonly used equipment to improve power quality on account of simplicity of power structure and less complexity in control, especially in harmonic elimination. Although the proposes outlined in related papers partly increase the complexity and the overall cost, the complexity and cost are reasonable, because of the fact that most of these suggestions try to solve some serious problems with shunt active filters.

Hybrid Shunt Active Power Filters (HSAPFs) have become one of the main interesting research topics in field of active power filters in the recent years. Common hybrid structures include passive filter in parallel with shunt active power filter, passive filter in series with a shunt active power filter. In such filters, the passive elements help the active power filter in harmonics elimination. In fact, these elements are tuned in special frequency order(s) which can be selected based on some criterion or objects. In such structures, active power filters and passive elements are combined in the way that the final compensator performance is better than the performance of either of them alone. In other words, HSAPFs reduce the problems with passive and active filters, and filter harmonics more effectively [1]. In Ref. [2], a comparison is made between hybrid and conventional active filters. It is shown that in hybrid filters, when the load is changed, the switching ripple and voltage variation of the dc capacitor is less than the time when active or passive filters are used alone. Recently, a hybrid structure including four-switch inverter and series inductive-capacitive (LC) passive filter has been suggested in Ref. [3]. In this structure the complexity and expenses of the active part decreases but the design and control of the LC filter becomes more complicated. Such a hybrid structure has two main problems. First, it is necessary to tune the passive filter on a specified harmonic order in offline state. Moreover, the behavior of the load should be specified and invariable during the work. Secondly, when the load has non-integer order of harmonic current, tuning the passive filter is not possible and the filter does not work accurately.

In addition to these two types HAPF, two VSC based converters can work separately in parallel or in cascade structure. The last one has been focused in many papers for such advantages as reduced

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voltage rating of semiconductors, good harmonic spectrum which makes the use of smaller and less expensive filters possible, and fast dynamic response in tracking reference [4]. Perhaps in this structure, generation of reference currents and allocation of them to every converter cell is difficult, and the complexity of the control part increases. For example, in Refs. [5,6] which used direct Lyapunov method for setting appropriate reference currents, although the dynamic response is improved, the controller suffers from complicated mathematical equations.

In addition to the listed common hybrid structures, some new structures have also been proposed in different papers. For example, in Ref. [1], Improved Hybrid Filter system (IHF), with a self-supporting DC bus, was proposed to remove the current harmonics and voltage harmonics of the point of common coupling (PCC). This hybrid filter has solved some problems with hybrid shunt and series filters.

In the present paper, a unified shunt active power filters is proposed and studied from another point of view, so that a current source converter and a voltage source converter are used simultaneously and work in joint operation. The idea originated from the fact that a current source converter (CSC), and/or a voltage source converter (VSC), has unique advantages and disadvantages related to their nature of the performance. For example, a CSC has features that cannot be found in a VSC and vice versa. The most important of these characteristics can be mentioned as follows:

- Conventionally, a CSC has more losses than a VSC in a same situation. The losses are mainly due to the dc inductor and series diodes with the power semiconductors in a CSC [7]. However, the use of power switches with Reverse Voltage Blocking and the use of superconducting generation in inductor structures can increase the efficiency of the CSC [8].
- Since the main purpose of shunt active power filters in harmonic elimination is current injection to the load bus and the CSC acts basically as a current source, using a CSC instead of a VSC in a filter structure is more reasonable [9]. Also, this ability causes that in a CSC-based active filter, using an open loop control system is possible [10], while in a VSC based structure, a closed-loop control has to be used to track the reference.
- In active filters based on VSC, using second and third order passive filters as an interface is not always required whereas in the CSC-based filters, using at least a second order filter LC as an interface is necessary. Thus, the resonance problems exist in the CSC based structure. As a result, it is more complicated to design a filter based on CSC than VSC.
- A CSC has an inherent capability to limit the current in a short circuit whereas VSC does not.
- A capacitor in the dc side of a VSC generates less heat than an inductor installed in the dc side of a CSC. In other words, the loss of the dc side of a CSC is greater than a VSC.

This paper introduces an efficient unified filter that can cope with the shortcomings of shunt active power filters both the VSC and the CSC schemes when they operate stand alone and at the same time highlights their benefits. The duality property between the VSC and the CSC can be useful in merging two converters. Separating the reference current and assigning the low frequency components to the CSC and high frequency components to the VSC can be proposed for obtaining superior performance of this unified architecture. The contribution of each converter is determined by allocating the proper reference current to the CSC and the VSC sections. This allocation is computed so that total power losses of the UAPF become minimum. The power losses are considered as a function of the RMS value of the reference current.

Some merits of the proposed filter can be listed as follows:

1 The VSC has its own inherent advantage that the CSC does not have and vice versa. For instance, the CSC has inherent short circuit current capability. On the other hand, the VSC has less power losses in comparison with the CSC. Therefore, in a general view, all advantages of two topologies of the converter can be gathered in one APF. The critical point is the strategy of their work in a way that the advantages are kept and the disadvantages are removed.
2 The VSC has voltage harmonics problem especially in high power and low switching frequency applications and a LCL filter is needed. Therefore, the cost, power losses and the complexity of the filter design are increased. But in the proposed structure, when the higher frequency orders of the reference current are dedicated to the VSC part, in fact, the VSC works in high switching frequencies and low power and the necessity of using LCL is canceled.
3 In comparison with the VSC scheme, the problem of the short circuit current is decreased in the VCSC scheme. Because the power of the compensation is divided between the VSC and the CSC sections.
4 The CSC has resonant problem because of using a LC interface filter. In the proposed structure this problem can be removed by adding this limitation to the reference current allocation unit and considering the resonant frequency (f_r) larger than the separation frequency (f_{sp}) or even transferring the resonant frequency to the VSC part that does not have this problem.
5 Reliability of the proposed APF is more than CSC or VSC scheme alone. Because two converters are in joint operation and in the outage of one converter, another one can partly inject harmonics current.

According to the determined reference currents, the most effective parameters such as separation frequency (f_{sp}), converters switching frequency (f_{sw}), resonant frequency (f_r) and allowable ranges for elements of dc and ac sides of converters from viewpoint of design are derived.

2. Structure and function of VCSC-UAPF

In the proposed architecture, a VSC and a CSC are employed simultaneously and establish a cost effect filter. Fig. 1 shows an overview of compensator that is connected to bus B2 in a power system and works as a unified active power filter.

In this structure, at first the main reference current is generated by an algorithm based on instantaneous reactive power theory, and it is then applied to the filter. General block diagram of this theory is depicted in Fig. 2.

Firstly, three-phase voltages and currents of the harmonic load are received and transformed to α & β orthogonal components using $\alpha\beta$. transformation. Instantaneous active and reactive powers are calculated using these components. Then, the dc component of the active power are filtered using a High Pass Filter (HPF). Finally, after a mathematical process, three-phase reference currents are

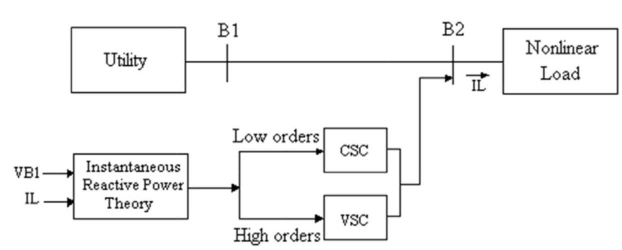

Fig. 1. Proposed unified active filter architecture.