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Experimental modeling and control design of shunt active power filters

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ABSTRACT

One of the main issues when designing a control strategy for a power electronic system is the development of a reliable model of the real system. However, the evaluation of the actual plant parameters is difficult due to the mismatch between nameplate and actual values of components, and the presence of unmodeled dynamics and non-linearities. This paper presents a novel technique for both model parameters identification and optimized control design of a shunt active power filter system using genetic algorithms (GAs). Experimental results demonstrate that the proposed modeling and control design approach greatly improve the system performance.

1. Introduction

The use of grid connected power electronic converters to improve power quality in power distribution systems represents the best solution, in terms of performance and stability, for the elimination of harmonic distortion, power factor correction, balancing of loads, and voltage regulation (Singh, Al-Haddad, & Chandra, 1999). The most common example of this type of equipment is the active power filter (APF) which has two main configurations: the shunt connected active power filter is placed in parallel with a non-linear load (NLL) and controlled to cancel the current harmonics created by it; its dual, the series active power filter, is employed for voltage correction and is connected in line with the NLL. The effectiveness of active filters greatly depends both on the method used to determine their references and the internal control strategy. This paper will concentrate on the active shunt filter (ASF) as this device is now being considered for many commercial applications (Fig. 1).

The methods for extracting harmonic references from the measured load currents are classified as compensation techniques in the frequency domain and compensation techniques in the time domain. The frequency domain techniques are mainly based on the use of the Fourier harmonic analysis (Grady, Samatyj, & Noyola, 1990); although these methods usually provide an accurate reference value during steady-state operation, a large computational effort is required for the implementation consequently introducing a long time delay in the system response. For this reason many time domain-based techniques have been researched. The most common are those employing PQ theory, i.e. measuring the instantaneous active and reactive power, (Akagi, 1994; Nastran et al., 1994) and those which use one or more synchronous rotating frames (SRF) of reference—alternatively called *dq* methods (Soares, Verdelho, & Marques, 2000; Verdelho & Marques, 1997). These methods provide a faster response than frequency domain techniques, ensuring a more effective compensation under all operating conditions.

Once the current references have been determined, the APF must have the capability to track accurately such references even in presence of sudden slope variations. Among the current control techniques that have demonstrated the best compensating performance there are hysteresis control (Malesani, Mattavelli, & Tomasin, 1997), the use of single and multiple rotating reference frames (Butt, Sumner, & Clare, 1999), predictive control (Lu & Green, 1998; Mendalek, Faiech, Al-Haddad, & Dessaint, 2002) and resonant controllers (Lenwari, Sumner, & Zanchetta, 2006). Hysteresis control directly compares the measured and reference currents and selects a switching state accordingly. It can provide accurate reference tracking, but at the expense of introducing a variable switching frequency which can be difficult to prevent from penetrating the distribution network. The use of multiple reference frames initially appears to offer the advantages of steady-state error (PI controllers acting on dc references) coupled with fast response. It has however been shown that the coupling between reference frames at different frequencies and the influence of process delays is significant. These can only be reduced with a very accurate knowledge of system parameters, otherwise the bandwidth of these controllers must be kept low (Butt et al., 1999). Predictive controllers and resonant controllers

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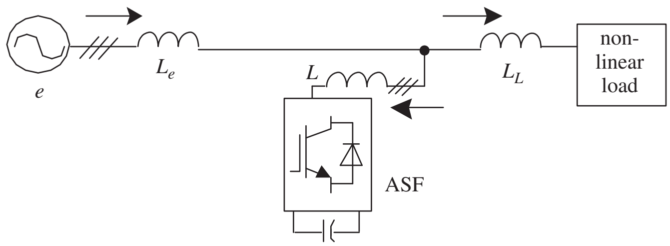

Fig. 1. Shunt active power filter connected to a power network.

both offer the advantages of fast response and accurate control, but both need to know accurately the system parameters. In addition to performance requirements, these "advanced" controllers require the active filter commissioning engineer to fully understand the whole design process, and field trails and commissioning can be a complicated and time consuming process. For that reason the single *dq* frame controller (see Section 2) is commonly found on commercial products, as it provides a good compromise between simplicity of implementation, a limited number of parameters which require tuning during commissioning and, at the same time the overall control can be robust and stable.

The choice and implementation of the current controllers is vital for the achievement of a satisfactory performance level. The control design procedure is traditionally based on the use of a model that reproduces the behavior of the real system. Recent literature has proposed an experimental use of heuristic optimization strategies like genetic algorithms (GAs) to tune the system controllers automatically and directly on the experimental rig, for current, speed, and position control loops in electrical drives, without the need of a model (Cupertino, Mininno, Naso, Turchiano, & Salvatore, 2004; Da Silva, Acarnley, & Finch, 2000; Okaeme, Zanchetta, & Sumner, 2006). However for applications of grid connected power electronic systems the design of the controllers using model-based techniques is essential. Under normal operation, the current controllers operate whilst maintaining a balance between two voltage sources—the dc link capacitor and the grid supply. There is little room for an experimental optimization, as any modifications which make the system response more oscillatory can cause system trips, or even device failure. This is an especially hard challenge when the current control loops must have a very high bandwidth ($>$350 Hz) to achieve accurate harmonic control (fifth and seventh from 50 Hz). Therefore, optimal selection of the control parameters off-line is required and this depends on the exact conformity of the model with the real system.

When dealing with the modeling of active filter systems, the attention of researchers is mainly devoted to modeling of the control system dynamics and very few papers dealing with the modeling of the true active filter characteristics have appeared in literature (Clare, Sumner, Butt, & Palethorpe, 1998; Guiotto & Smedley 2003; Jacobs et al., 2004; Kanaan et al., 2003; Mendalek & Al Haddad, 2000; Nasiri & Emadi, 2003). Some of these papers deal with the modeling of APF using bespoke code written in computational software, while others deal with the use of modeling software packages such as Matlab/Simulink, PSpice, and Saber. In most cases, these tools allow the entire system to be built in a straightforward manner, to include power circuits, load characteristics, control loops and thermal effects, but it is still difficult to obtain a model which accurately predicts the performance of the real system. Some effects due, for instance, to the non-linearities of the power devices (e.g. on state resistance vs. current), saturation and non-linear frequency dependence of the line inductors, deeply affect the behavior of the system but are not always easy to quantify and to take into account in the model. In addition some of the parameters of the electrical circuits, for instance the impedance of the network or the resistance of the conductors, are difficult to measure accurately in-situ. Small deviations between the simulation model and the real system can have significant effects on controller performance (Lenwari et al., 2006).

Mendalek and Al Haddad (2000) have discussed a mathematical model of a three-phase shunt APF based on the *abc/dq* transformation of the ac system variables. This model is derived supposing all the components are ideal and is used for control design. In order to validate the performance of the controllers, another model is developed using the "power system blockset" in Matlab/Simulink environment. Only simulation results are presented, leaving the accuracy of the model unproven. Nasiri and Emadi (2003) and Kanaan et al. (2003), have developed mathematical models of APFs using the state-space average modeling technique. Such models are based on small signal approximations which create a simplified linear system about a specific operating point. The simulation results are not compared with experimental results and the authors do not deal with the problem of deriving a model as close as possible to the real system. Clare et al. (1998) underline the importance of getting an accurate model of an APF and list advantages and disadvantages of using original software compared to a commercial package for simulating the system. Some interesting conclusions are made concerning two accurate APF models developed in both the Simulink/Matlab and Saber environments. Though experimental results are presented, a comparison between simulation and experimental results is omitted and the accuracy of the model is not verified.

Interesting results are presented by Guiotto and Smedley (2003) and Jacobs et al. (2004). In the former, a model of a shunt APF based on the switching flow-graph method is presented. This method is easy to use and accurate, even if ideal components have been considered. Such a model is implemented in Matlab/Simulink, and the simulation results are compared with those obtained from a PSpice model and from an experimental setup, showing a good agreement among them. In the latter an extremely accurate model is developed in the PSpice environment, using some components from the software library and some created by the user. This work is furthermore interesting since the C-code of the APF control algorithm is completely developed and tested in the PSpice environment and then downloaded into real-time DSP control board without any changes. Experimental results confirm the simulation results. Therefore, both Guiotto and Smedley (2003) and Jacobs et al. (2004) show that an accurate simulation model enables the design of controllers that will have performance in real applications comparable to those obtained in simulations.

The objective of the work described in this paper is to obtain high bandwidth, high performance current controllers for a shunt APF. This is achieved using a two stage optimization process. The first stage employs a genetic algorithm to tune several parameters of an APF model such that it provides the best representation possible for a real APF system (Depeng, 2006; Tan and Yang, 2006). The second stage then exploits this model to design high bandwidth current controllers, again using a GA optimization approach similar to those described by El-Habrouk and Darwish (2002), Diana, Sumner, Zanchetta, and Marinelli (2003), and Zanchetta, Sumner, Cupertino, Marinelli, and Mininno (2004). Experimental results demonstrate that the APF performance is noticeably improved by the proposed two stage GA-based optimization procedure. The practical benefits coming from the commercial implementation of the proposed method are the improvement of the control response and the significant