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Adaptive nonlinear control of three-phase shunt active power filters with magnetic saturation

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ABSTRACT

The problem of controlling three-phase shunt active power filters (SAPF) is addressed in presence of nonlinear loads. Previous works generally design control for SAPF based on standard models that assume the involved magnetic coil to be linear. In reality, the magnetic characteristics of these components are nonlinear (especially in the presence of large magnetic flux density in the ferromagnetic core). In this paper, a new oriented control model for SAPF-load system, taking into account for the nonlinearity of coil characteristics, is developed. The control objective is twofold: (i) compensating for the current harmonics and the reactive power absorbed by the nonlinear load; (ii) regulating the inverter DC capacitor voltage. To this end, based on the new model, a nonlinear controller is developed, using the backstepping technical design. It is therefore able to ensure good performances over a wide range of variation of the load current. Moreover, the controller is made adaptive for compensating the uncertainty on the switching loss power. The performances of the proposed adaptive controller are formally analyzed using tools from the Lyapunov stability and the averaging theory. The supremacy of the proposed controller with respect to standard control solutions is illustrated through simulation.

Introduction

Power grids and distribution networks are expected to simultaneously interact with a wide variety of loads. As a matter of fact, these loads (whatever their size), such as rectifiers, power supplies and speed drivers, involve nonlinear dynamics that entail the generation of current harmonics and the consumption of reactive power. If not appropriately compensated for, these current harmonics and reactive power result in several harmful effects e.g. distortion of the voltage waveform at the point of common coupling (PCC) and overheating of transformers and distribution lines. Moreover, the disturbing effect of current harmonics may go beyond the PCC and reach other loads and electronic equipments connected to the net, causing boosted ageing of those loads and making harder the synchronization with the network voltage in applications requiring such synchronization.

The modern solution to cope with harmonics pollution is to implement active power filters (APF). Indeed, compared to conventional passive filters, APFs feature a higher flexibility, a better filtering capability and a smaller physical size. There are various APF configurations but the most widely implemented in industrial scale products are the shunt configurations. The principle of shunt active power filters (SAPF) consists in injecting at the PCC a current that cancels all harmonics and reactive currents generated by the disturbing loads. Doing so, the harmonics and reactive currents are constrained to circulate within a loop including only the load and the SAPF i.e. the distribution network is not a part of that loop which prevents it from harmonic pollution. In addition to this energy quality objective, there is an operational requirement that consists in regulating the DC voltage of the energy storage capacitor, placed next to the SAPF inverter. This DC voltage regulation loop control is necessary for the SAPF to work conveniently. The achievement of the above two requirement, i.e. energy quality and DC voltage regulation, is made difficult by the controlled system nonlinearity, on the one hand, and by the fact that some system parameters may be unknown.

Over the last decade, a great deal of interest has been devoted to the problem of controlling energy systems involving SAPFs. But, most previous works have been devoted to the simpler case of single-phase SAPFs (e.g. [7,11,15]). The point is that, in industrial applications, electrical loads are generally three-phase. Many studies have examined the problem of modeling and controlling power systems that involves three-phase SAPFs (e.g. [22,24,19]). In these studies, the authors suppose that all passive components constituting the SAPF can be perfectly described by linear characteristics.

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This assumption is obviously not valid under all operational conditions, particularly for filter coils. In fact, due the saturation phenomena, the coil magnetic characteristic is non linear and consequently the inductance coefficients vary with the current, especially for high-power coils. Fig. 1 represents a typical curve representing the inductance vs the inductor current. Fig. 1 shows that the inductance is quasi-constant for small currents, but falls drastically for large currents. In the other hand, the problem of controlling power systems that involves three-phase SAPFs, has been dealt previously with using three categories of methods. The first category includes methods using hysteresis operators or fuzzy logics (e.g. [18,5,24]). These methods do not make use of the exact nonlinear SAPF model in the control design. Consequently, the obtained controllers are generally not backed by formal stability analysis and their performances are derived from simulations results. The second category of methods is limited to linear controllers (e.g. [4,9,22,16,23]). As a matter of fact, optimal performances are not guaranteed with linear controller, on a wide range variation of the operation point, due to the nonlinear nature of the controlled system. The third category of methods includes nonlinear regulators using different control design techniques: passivity approach (e.g. [8]), Lyapunov design (e.g. [19]), sliding mode control [6] and backstepping control [1]. However, the used SAPF control model, assumes that the coil magnetic characteristic is linear. Therefore, the obtained controller may not achieve the desired performances under operational conditions where the nonlinearity of the coil magnetic characteristic is not negligible. In fact, if the magnetic saturation effect is not accounted for in the controller design (this is the case in all previous paper), the performances of the current loops (designed to meet the current harmonic compensation requirement), get deteriorated while the load current get a large amplitude. In addition, the proposed nonlinear DC bus controllers (e.g. [1]), did not account for all terms in the DC bus state equation. In fact, the dynamics terms have been neglected both in the controller design and in the closed-loop analysis. Further limitation of the above nonlinear controllers (e.g. [6]) can be raised, namely the switching losses in the inverter are generally neglected in the control design model. In real-life systems, these losses can hardly be ignored as they act on the DC bus voltage.

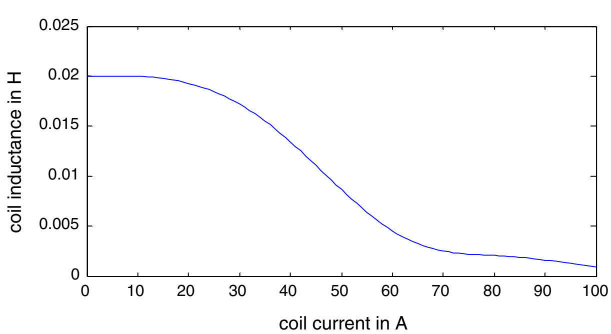

Fig. 1. Inductance vs current.

In this paper, we revisit the modeling of three-phase SAPF in order to account for the nonlinear feature of coil magnetic characteristics. Contrarily to the previous SAPF representation, our model allows the inductance coefficients to vary with the corresponding coils currents according to a well-defined law. More specifically, the model parameters, h_{ij} and g_{ij} (see Table 1), are computed in real time using nonlinear functions of the magnetic coil state. These nonlinear functions are determined based on the magnetic characteristic and its derivative (see Figs. 1 and 9). Based on this new model, a new control strategy is developed to simultaneously meet the previously discussed control requirements i.e. a satisfactory compensation of harmonic and reactive currents absorbed by the nonlinear three-phase load and a tight regulation of the inverter DC capacitor voltage. To this end, a two-loop cascade nonlinear controller are developed using the Lyapunov-like techniques. The inner loop involves a current regulator designed to cope with harmonics compensation. The outer-loop involves a voltage regulator that aims at regulating the DC line voltage. Contrarily to the previous papers (e.g. [1]), the present work is much more rigorous since the effect of dynamics terms in DC bus state equation is accounted for in the proof of the main theorem which describes the performances of the new controller. That is, the performance in the present paper is more complete and more technically sound compared to the previous one. Furthermore, the controller is provided with a parameter adaptation capability to cope with the uncertainty that prevails on the switching losses in the inverter. It is formally shown using tools from the Lyapunov stability and system averaging theory that, all control objectives are actually achieved in the mean. These theoretical results are confirmed by numerical simulations.

Moreover, the simulations show that, neglecting the nonlinear feature of the coils in the controller design may lead to drastic deterioration of the closed-loop performance.

The paper is organized as follows: The SAPF modeling with taking account, the nonlinear feature of the magnetic characteristic, is described in Section 'Three-phases SAPF modeling'; the control problem formulation, the references signals construction and, the cascade adaptive non linear regulator design are dealt with in Section 'Three-phase SAPF control design'; the theoretical analysis results are confirmed by simulation in Section 'Simulation and discussion of results'. A conclusion and a references list end the paper.

Three-phases SAPF modeling

The three phases SAPF under study has the structure of Fig. 2. It consists of a three-phase full-bridge inverter and an energy storage capacitor C_{dc}, placed at the DC side. From the AC side, the SAPF is connected to the network through a filtering inductor (L_f, R_f); this reduces the circulation of the harmonics currents generated by the inverter. The SAPF function is to produce reactive and harmonic current components to compensate undesirable current harmonics produced by the nonlinear load. The DC–AC inverter operates in accordance to the well-known of Pulse Width Modulation principle

Table 1
Model parameters.

$\left(i_{fa} = \frac{\sqrt{2}}{3} i_{f\alpha}\right)$, $\left(i_{fb} = -\frac{1}{\sqrt{6}} i_{f\alpha} + \frac{1}{\sqrt{2}} i_{f\beta}\right)$, $\left(i_{fc} = -\frac{1}{\sqrt{6}} i_{f\alpha} - \frac{\sqrt{2}}{3} i_{f\beta}\right)$	
$h_{11}(i_{f\alpha}, i_{f\beta}) = \frac{2}{3}\left(L_f(i_{fa}) + \frac{1}{4} L_f(i_{fb}) + \frac{1}{4} L_f(i_{fc})\right)$	$h_{12}(i_{f\alpha}, i_{f\beta}) = \frac{1}{\sqrt{3}}\left(-\frac{1}{2} L_f(i_{fb}) + \frac{1}{2} L_f(i_{fc})\right)$
$h_{21}(i_{f\alpha}, i_{f\beta}) = h_{12}(i_{f\alpha}, i_{f\beta})$	$h_{22}(i_{f\alpha}, i_{f\beta}) = \left(\frac{1}{2} L_f(i_{fb}) + \frac{1}{2} L_f(i_{fc})\right)$
$g_{11}(i_{f\alpha}, i_{f\beta}) = \frac{2}{3}\left(\frac{dL_f}{di}(i_{fa}) + \frac{1}{4}\frac{dL_f}{di}(i_{fb}) + \frac{1}{4}\frac{dL_f}{di}(i_{fc})\right)$	$g_{12}(i_{f\alpha}, i_{f\beta}) = \frac{1}{2\sqrt{3}}\left(-\frac{dL_f}{di}(i_{fb}) + \frac{dL_f}{di}(i_{fc})\right)$
$g_{21}(i_{f\alpha}, i_{f\beta}) = g_{12}(i_{f\alpha}, i_{f\beta})$	$g_{22}(i_{f\alpha}, i_{f\beta}) = \frac{1}{2}\left(\frac{dL_f}{di}(i_{fb}) + \frac{dL_f}{di}(i_{fc})\right)$