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Sliding mode control of a shunt hybrid active power filter based on the inverse system method

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ABSTRACT

In this paper, an inverse system method based sliding mode control strategy is proposed for the shunt hybrid active power filter (SHAPF) to enhance the harmonic elimination performance. Based on the inverse system method, the *d*-axis and *q*-axis current dynamics of the SHAPF system are firstly linearized and decoupled into two pseudolinear subsystems. Then a sliding mode controller is designed to reject the influence of load changes and system parameter mismatches on the system stability and performance. It is proved that the current dynamics are exponentially stabilized at their reference states by the controller. Moreover, the stability condition of the zero dynamics of the SHAPF system is presented, showing that the zero dynamics can be bounded by adding an appropriate DC component to the reference of the *q*-axis current dynamics. Furthermore, a proportional-integral (PI) controller is employed to facilitate the calculation of the DC component. Simulation and experimental results demonstrate the effectiveness and reliability of the SHAPF with the proposed control strategy.

1. Introduction

The widespread application of power electrical devices (e.g., diode rectifiers) has increased the harmonic pollution in modern power transmission/distribution systems. The harmonics generated by nonlinear loads can cause additional power losses, interfere with nearby communication networks and disturb sensitive loads [1,2]. Therefore, many international standards such as IEEE 519-1992 and IEC 61000-3-2 have been recommended to limit the harmonic pollution.

Traditionally, low-cost passive power filters (PPFs) with high efficiencies were widely used to eliminate the harmonics. However, the bulky PPFs only provide fixed harmonic compensation and they detune with age [3]. These drawbacks can be overcome by the power converter based active power filters (APFs), but they are usually expensive and have high operating losses [4–8]. For the sake of improving the compensation performance and reducing the cost of the APFs, a number of topologies of hybrid active power filters (HAPFs) have been proposed [9–15]. Peng et al. proposed a HAPF system combining a series APF and a shunt PPF [9]. In this system, the APF endured high load currents works as a "harmonic isolator" between the source and the nonlinear load. A novel topology is proposed in [10], where the APF is connect in series with a C-type PPF. However, an additional power supply is needed to support the DC-link capacitor. Ref. [11] presented a combined system of many PPFs connected in series with an APF via a matching transformer. This topology might not be preferable since many passive components are required. In particular, a novel shunt hybrid active power filter (SHAPF), where three tuned PPFs are connected in series with a small-rated APF without any matching transformers, has attracted much attention [12–15]. Since the source voltage is applied across the PPF, the required rating of the APF can be substantially reduced. Furthermore, no additional output filters are needed to suppress the switching ripples produced by the power converter.

The control strategy is important to enhance the harmonic elimination performance of the SHAPF. Many control strategies have been proposed for the SHAPF. In [13], a linear feedback-feedforward controller is designed for the SHAPF. Because the dynamic model of the SHAPF system contains multiplication terms of the control inputs and the state variables, it is not easy to achieve both satisfactory steady-state and transient-state performances with the linear control strategy. To deal with the nonlinear characteristic of the SHAPF, a sliding mode controller was presented in [14], which has the property of robustness against load changes and system parametric uncertainties. But the steady-state errors may still be nonzero due to the absence of integrators in the closed loop system. In [15], a Lyapunov function based control strategy is developed to globally stabilize the SHAPF system. Unfortunately, owing to the difficulty in estimating the ripple component of the

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DC-link capacitor voltage, the obtained controller is an approximate one.

In this paper, an inverse system method based sliding mode control strategy is proposed for the SHAPF. The inverse system method is one of the linearization and decoupling (L&D) methods, which does not need complicated coordinate transformation compared with the differential geometric L&D based methods [16–21]. For the control of power converters [18,19] and moment gyros [20,21], it has exhibited desirable steady and dynamic performances. Here we decouple the nonlinearity of the SHAPF system with the inverse system method, such that the d-axis and q-axis current dynamics of the SHAPF system can be regulated independently. In addition, the sliding mode control [22–27] is applied to the decoupled pseudolinear system to reject the influence of external disturbances and system parameter mismatches. Since the SHAPF system has three internal dynamic variables, the internal stability is analyzed based on the derived stability condition of the zero dynamics. Moreover, to avoid the difficulty in calculating the DC component from the stability condition, a PI controller over the square of the DC-link capacitor voltage is adopted.

This paper is organized as follows. In Section 2, the nonlinear mathematic model of the SHAPF system in the d–q reference frames is described. A novel control strategy combining the sliding mode control and the inverse system method is presented in Section 3. The stability of the SHAPF including the internal and external dynamics is analyzed in Section 4. Simulations for testing the effectiveness and reliability of the proposed control strategy are conducted in Section 5. Experimental results of a laboratory prototype are presented in Section 6. Finally, conclusions are given in Section 7.

2. The SHAPF model

The topology of the SHAPF is shown in Fig. 1. A small-rated APF using a voltage-source power inverter is directly connected in series with three tuned PPFs. Since the source voltage is taken by the PPF, the required ratings of the inverter and DC-link capacitor voltage are much smaller than those of a stand-alone shunt APF. The three-phase diode bridge rectifier with RL loads is considered as a nonlinear load. In this figure, v_{Sj}, v_{Lj}, v_{Cj}, i_{Sj}, i_{Lj} and i_{Fj}, j = a,b,c, represent the three-phase source voltage, the point of common coupling (PCC) voltage, the PPF capacitor voltage, the source current, the load current and the compensating current, respectively. C_{dc} and v_{dc} are the capacitance of the DC-link capacitor and the voltage across the capacitor. L_F, C_F and R_F represent the inductance, the capacitance and the resistance of the PPF, respectively.

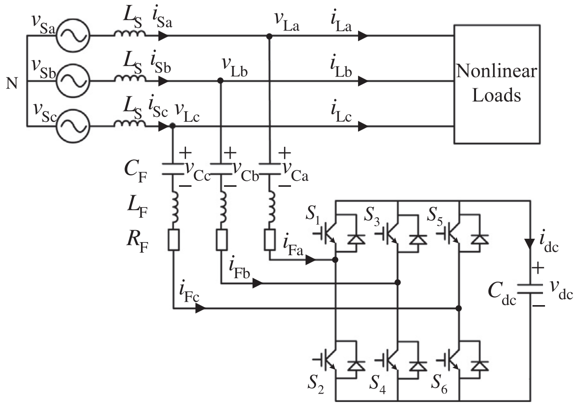

Fig. 1. Topology of the SHAPF.

The dynamic model of the SHAPF under the synchronous rotating d–q reference frame can be expressed by the following differential equations [15]:

$$\begin{cases} L_F\dot{i}_{Fd} = -R_F i_{Fd} + \omega L_F i_{Fq} - v_{Cd} - u_d v_{dc} + v_{Ld} \\ L_F\dot{i}_{Fq} = -R_F i_{Fq} - \omega L_F i_{Fd} - v_{Cq} - u_q v_{dc} + v_{Lq} \\ C_F\dot{v}_{Cd} = i_{Fd} + \omega C_F v_{Cq} \\ C_F\dot{v}_{Cq} = i_{Fq} - \omega C_F v_{Cd} \\ C_{dc}\dot{v}_{dc} = u_d i_{Fd} + u_q i_{Fq} \end{cases}, \quad (1)$$

where i_{Fd} and i_{Fq} denote the d–q axis compensating currents, v_{Cd} and v_{Cq} are the d–q axis PPF capacitor voltages, v_{Ld} and v_{Lq} represent the d–q axis PCC voltages, u_d and u_q are the d–q axis duty ratio functions, and ω is the source angle frequency of the source voltage.

To facilitate the controller design, the SHAPF system model can be formally rewritten as follows:

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}(\boldsymbol{x})\boldsymbol{u} \\ \boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x}) \end{cases}, \quad (2)$$

where $\boldsymbol{x} = [i_{Fd}, i_{Fq}, v_{Cd}, v_{Cq}, v_{dc}]^T$ stands for the system state vector, the vector $\boldsymbol{u} = [u_d, u_q]^T$ is taken as the system control variables, the vector $\boldsymbol{y} = [y_1, y_2]^T = [i_{Fd}, i_{Fq}]^T$ represents the system outputs. The functions $\boldsymbol{f}(\boldsymbol{x})$, $\boldsymbol{g}(\boldsymbol{x})$ and $\boldsymbol{h}(\boldsymbol{x})$, respectively, are given as

$$\boldsymbol{f}(\boldsymbol{x}) = \begin{bmatrix} (-R_F i_{Fd} + \omega L_F i_{Fq} - v_{Cd} + v_{Ld})/L_F \\ (-R_F i_{Fq} - \omega L_F i_{Fd} - v_{Cq} + v_{Lq})/L_F \\ (i_{Fd} + \omega C_F v_{Cq})/C_F \\ (i_{Fq} - \omega C_F v_{Cd})/C_F \\ 0 \end{bmatrix}, \quad \boldsymbol{g}(\boldsymbol{x}) = \begin{bmatrix} -v_{dc}/L_F & 0 \\ 0 & -v_{dc}/L_F \\ 0 & 0 \\ 0 & 0 \\ i_{Fd}/C_{dc} & i_{Fq}/C_{dc} \end{bmatrix}$$

$$\text{and} \quad \boldsymbol{h}(\boldsymbol{x}) = \begin{bmatrix} i_{Fd} \\ i_{Fq} \end{bmatrix}.$$

It should be noted that the obtained multi-input multi-output (MIMO) system model (2) is affine nonlinear due to the multiplication terms of the state variables and the control variables. In addition, the state variables are strongly coupled to each other. These two problems can be properly handled by the inverse system method, which aims at directly finding the relationship between the control variables and the system outputs.

3. Controller design

In this section, the synthesis of the sliding mode controller based on the inverse system method for the SHAPF is presented.

3.1. L&D of the SHAPF

For the L&D of the SHAPF system with the inverse system method, we firstly prove the invertibility of the system according to the Interactor algorithm [16].

Based on the system model (2), we differentiate the output vector y with respect to the time until the control variables u_d and u_q appear explicitly, which leads to the following equation:

$$\boldsymbol{J}(\boldsymbol{u}) = \begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = \begin{bmatrix} (-R_F i_{Fd} + \omega L_F i_{Fq} - v_{Cd} + v_{Ld} - v_{dc}u_d)/L_F \\ (-R_F i_{Fq} - \omega L_F i_{Fd} - v_{Cq} + v_{Lq} - v_{dc}u_q)/L_F \end{bmatrix}. \quad (3)$$

The Jacobi matrix of $\boldsymbol{J}(\boldsymbol{u})$ with respect to the control vector $\boldsymbol{u}$ can be calculated as follows:

$$\frac{\partial \boldsymbol{J}(\boldsymbol{u})}{\partial \boldsymbol{u}^T} = \begin{bmatrix} -v_{dc}/L_F & 0 \\ 0 & -v_{dc}/L_F \end{bmatrix}. \quad (4)$$

Because the DC-link capacitor voltage v_{dc} is positive in the operation range, $\partial \boldsymbol{J}(\boldsymbol{u})/\partial \boldsymbol{u}^T$ is nonsingular. Moreover, the relative degree vector of the system is $\boldsymbol{\alpha} = [\alpha_1, \alpha_2]^T = [1, 1]^T$, and $\alpha_1 + \alpha_2 = 2$ is strictly less than the system order $n = 5$. Therefore, there are two