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A partial feedback linearization based control design and simulation for three phase shunt active power filter

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ABSTRACT

This paper exploited partial feedback linearization technique to control design of a three phase shunt active power filter (APF) by considering it as a Multiple Input Multiple Output (MIMO) system. The averaged dynamic model of the three phase APF has been derived considering the single phase equivalent circuit of the system. This averaged dynamic model is used to partially feedback linearize the MIMO nonlinear system dynamics. New control input to the linearized system is obtained considering the stability of the complete APF system. After that, control input to APF is derived by nonlinear transformation. Stability of the internal dynamics of the system is analyzed considering zero dynamics of the system. MATLAB/Simulink based simulation results are provided to validate the performance of the controller.

1. Introduction

Due to extensive use of nonlinear loads such as computers, printers and fax machines, harmonics are induced in the power system. Thus, elimination of harmonics is an important research challenge. Use of passive filters is undesirable due to their large size, high cost and fixed harmonic compensation characteristics. Active power filter (APF) is an alternative effective solution to filter harmonics. Depending on harmonics compensation characteristics, APF are classified into two types, such as series APF and shunt APF. Series APF is used to compensate voltage harmonics, whereas shunt APF which is used to compensate current harmonics from grid by injecting equal amount of harmonics to the grid but with opposite polarity. Control of single phase shunt APF has been presented in this paper. Shunt APF is connected in parallel at the point of common coupling in between source and load.

Several control strategies have been proposed in the literature to control the power electronic systems such as sliding mode control [1,2,13], Lyapunov based control [3], adaptive control [4,5], feedback linearization based control [6,8–10]. Among the above control strategies, feedback linearization based control of power converters is an effective means to analyze stability of the complete nonlinear system.

The nonlinear system having relative degree lower than the order of the system can be partially linearizable. However by application of Tellegen's theorem, the system can be exactly linearizable [6]. Single phase shunt APF, DC–DC boost converters are examples of second order system and they have relative degree one [6,9]. Partial feedback linearization (PFL) method has been applied to DC–DC boost converter in [9], whereas exact feedback linearization (EFL) technique has been applied to boost converter in [10]. Due to difficulties in practical implementation of EFL based control of APF system, EFL technique via sliding mode control has been proposed in [6] to control the single phase shunt APF system for improving the performance. In this method authors used an alternating switching scheme to implement the control algorithm. Due to this switching scheme, original property of feedback linearization control technique is lost. Also different output functions can be derived using Tellegen's theorem to control the compensating current in EFL based controller of APF. As shunt APF falls under the category of systems having relative degree lower than the order of the system, the straightforward PFL based controller can be applied to shunt APF system. Using PFL based controller in APF, compensating current can be controlled directly by considering it as the output function.

In three phase systems such as three phase UPS inverter [12] and three phase grid connected photo voltaic system [7], PFL based control technique has been applied to improve their performance. Authors of [12] applied PFL based control technique by considering the system as both single input single output (SISO) and multiple input multiple output (MIMO) system. Similarly authors of [7]

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considered grid connected photovoltaic system as MIMO system for applying PFL based control technique. Unlike single phase shunt APF, a three phase shunt APF [16,17] can be considered as a MIMO system. Compensating currents of three phases can be assumed as three outputs of the system for applying the PFL based control method.

In PFL based controller, it is required to ensure the stability of the internal dynamics of the system. The dynamics of the system which are not linearized or remain unobservable during feedback linearization are treated as internal dynamics of the system. The averaged dynamic model of shunt APF has used for PFL and internal dynamic stability analysis of APF system. In this paper the system stability is ensured using feedback linearization method, which is simpler than small signal analysis method of determination of system stability. It improves the performance of APF by analyzing the stability of the complete system. The average model of the active power filter system is obtained by averaging the filter capacitor voltage and coupling inductor currents over a complete switching cycle.

This paper is organized as follows. Averaged dynamical model of the active power filter is described in Section 2. PFL based controller design of shunt APF and analysis of stability of its internal dynamics has been carried out in Section 3. Simulation results and analysis are provided in Section 4. Finally in Section 5 conclusions are given.

2. Averaged dynamic model of three phase shunt APF

A structure of three phase APF is shown in Fig. 1. For making the system analysis using PFL based control technique easier, a little modification has been carried out in the basic structure of three phase shunt APF. A high resistance connected across the filter capacitor, signifies the leakage current flow from positive plate to negative plate of the capacitor throughout the switching cycle.

Fig. 2 shows the equivalent circuit for phase 1 of three phase APF. Similar equivalent circuits can also be obtained for other two phases. I_{L_1} is the compensating current in phase 1. Similarly I_{L_2} and I_{L_3} are taken as the compensating currents of phase 2 and 3 respectively. For analysis V_1, V_2 and V_3 are assumed as the phase to neutral voltages of phase 1, 2 and 3 respectively. The averaged dynamic model of three phase APF can be obtained by averaging the inductor currents and capacitor voltage over a complete switching cycle. Consider u_1, u_2 andu_3 are the duty ratios or the control inputs to legs of APF which are coupled to phase 1, 2 and 3 respectively through coupling inductor and T is the total switching period, which remain constant for all legs of APF.

The coupling inductance value for all three phases is kept same for making the analysis easier. So that, one can writes $L_1 = L_2 = L_3 = L$. Considering the equivalent circuit of all three phases, one can get the averaged dynamic model of three phase shunt APF as follows:

$$L\frac{dx_{11}}{dt} = \left(V_1 - \frac{V_C}{2}\right)u_1 + \left(V_1 + \frac{V_C}{2}\right)(1 - u_1) \tag{1}$$

$$L\frac{dx_{12}}{dt} = \left(V_2 - \frac{V_C}{2}\right)u_2 + \left(V_2 + \frac{V_C}{2}\right)(1 - u_2) \tag{2}$$

$$L\frac{dx_{13}}{dt} = \left(V_3 - \frac{V_C}{2}\right)u_3 + \left(V_3 + \frac{V_C}{2}\right)(1 - u_3) \tag{3}$$

$$C\frac{dx_{14}}{dt} = \frac{1}{2}\left\{\left(I_{L_1} - \frac{V_C}{2R_L}\right)u_1 + \left(I_{L_2} - \frac{V_C}{2R_L}\right)u_1 + \left(I_{L_3} - \frac{V_C}{2R_L}\right)u_1 + \left(-\frac{V_C}{2R_L} - I_{L_1}\right)(1 - u_1) + \left(-\frac{V_C}{2R_L} - I_{L_2}\right)(1 - u_2) + \left(-\frac{V_C}{2R_L} - I_{L_3}\right)(1 - u_3)\right\} \tag{4}$$

The average values of compensating currents for phase 1, 2, 3 and capacitor voltage over a switching cycle are respectively chosen as state variables x_{11}, x_{12}, x_{13} and x_{14}. Thus, x_{11}, x_{12}, x_{13} and x_{14} can be expressed as

$$x_{11} = \frac{1}{T}\int_t^{t+T} I_{L_1}(k)dk \tag{5}$$

$$x_{12} = \frac{1}{T}\int_t^{t+T} I_{L_2}(k)dk \tag{6}$$

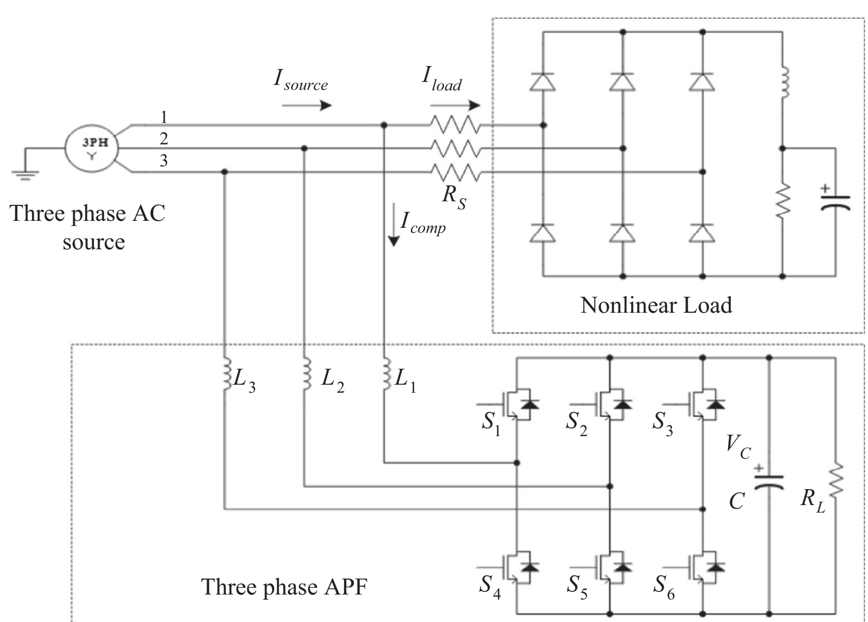

Fig. 1. Three phase shunt active power filter.