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Experimental investigations on Ant Colony Optimized PI control algorithm for Shunt Active Power Filter to improve Power Quality

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ABSTRACT

Active Power Filters (APFs) have become a potential option in mitigating the harmonics and reactive power compensation in single-phase and three-phase AC power networks with Non-Linear Loads (NLLs). Conventionally, the assessment of gain values for Proportional plus Integral (PI) controllers used in APF employs model based controllers. The gain values obtained using traditional method may not give better results under various operating conditions. This paper presents Ant Colony Optimization (ACO) technique to optimize the gain values of PI controller used in Shunt Active Power Filter (SAPF) to improve its dynamic performance. The minimization of Integral Square Error (ISE), Integral Time Square Error (ITSE), Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE) are considered as cost functions for the proposed system. The proposed SAPF is modeled and simulated using MATLAB software with Simulink and SimPowerSystem Blockset Toolboxes. The simulation results of the SAPF using the proposed methodology demonstrates improved settling time (T_s) with ISE as cost function. For instance, the T_s for ISE 4.781 is found to be 28.5 ms. Finally, hardware implementation of the proposed SAPF system is done using Xilinx XCS500E Spartan 3E FPGA board.

1. Introduction

Utility system generates pure sinusoidal waveform at their terminals. This sinusoidal waveform is the pure form of the AC voltage and any deviation from it is called as distortion, which degrades the quality of electric power. Many loads absorb non-sinusoidal current from the utility mains called as NLLs, which leads to harmonic distortion. These distortion in mains supply system is due to large harmonic currents drawn by residential, commercial and industrial NLLs such as adjustable speed drives, arc furnaces, air conditioners, battery chargers, copier machines, computers, fluorescent lightings, frequency converters, medical equipments, switch-mode power supplies, printers, uninterrupted power supplies, welding machines and x-ray equipment. NLLs act as a source of harmonic current and inject harmonic currents into the grid system. These currents can interact adversely with a wide range of power system equipments causing additional losses, overheating, overloading, interference with telecommunication networks and also results in erroneous readings in watthour and demand meters (Dugan, McGranaghan, Santoso, & Beaty, 2002; Kennedy., 2000; Cividino, 1992; Mahmoud & Owen, 1983). The IEEE 519-1992 (Institute of Electrical and Electronics Engineers) standard furnishes guidelines for harmonic voltage and current distortion limits at the Point of Common Coupling (PCC).

Traditionally, passive LC filters are used to suppress the harmonic distortion in power systems. Parallel passive filters are used to reduce harmonics in current source type harmonic generating loads. The principle of the parallel passive filter is to provide a low impedance shunt path to the harmonic current, thus reducing harmonic current flowing into the source. Series passive filters on the other hand are used to compensate for voltage source harmonic generating loads. In general, passive filters have the demerits of fixed compensation, larger size and resonance. To overcome these limitations, APF is used as an alternative. APF is a power electronic converter that produces and injects into the system the necessary harmonic components to cancel the harmonic present in the load current. It can be connected at PCC of an AC system to compensate one or more loads. The voltage source Pulse Width Modulated (PWM) inverter based SAPF is preferred by the utilities due to its larger efficiency compared to current source PWM inverter (Akagi, 1994; Grady, Samotyj, & Noyola, 1990; Routimo, Salo, & Tuusa, 2007).

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The performance of SAPF depends on many factors, but mainly on the selected reference generation scheme. The reference signal (voltage or current) that has to be processed by the PI controller is the main component, which ensures the proper operation of SAPF. Several methods are available for extracting the reference switching current for the APF (Singh, Al-Haddad, & Chandra, 1999; El-Habrouk, Darwish, & Mehta, 2000; Salam, Perng Cheng, & Jusoh, 2006). Bhim Singh et al. proposed PI control algorithm for single-phase SAPF (Singh, Chandra, & Al-Haddad, 1996). In PI control scheme, reference current is calculated by sensing only the line currents (Chatterjee, Fernandes, & Dubey, 1999; Jain, Agarwal, & Gupta, 2003; Jain, Agarwal, & Gupta, 2002; Bhende & Mishra, 2006). The PI control algorithm (Singh et al., 1996) is used in three-phase SAPF for sinusoidal supply conditions (Chatterjee et al., 1999), non-ideal supply conditions (Huang & Wu, 1999) and for hybrid filter (Singh et al., 1999). The gain values of controller used in the PI control algorithm of SAPF are assessed conventionally using linearized model and fine-tuned by trial and error approach, which is a time consuming process. In addition, the values obtained may not give better results for certain operating conditions (Mishra & Bhende, 2007; Kumar & Mahajan, 2009).

In order to enhance the performance of the PI controller in SAPF, non-model based controllers viz; fuzzy logic (Jain et al., 2002; Bhende & Mishra, 2006; Kumar & Mahajan, 2009; Mikkili & Panda, 2012), neural network (Janpong, Areerak, & Areerak, 2011), Genetic Algorithm (GA) (Singh & Singhal, 2007; Zanchetta, Sumner, & Marinelli, 2009), Bacterial Foraging (BF) technique (Mishra & Bhende, 2007; Singh, Singh, & Kumar, 2011), particle swarm optimization (Singh et al., 2011) and ACO technique (Singh et al., 2011; Berbaoui, Ferdi, Benachaiba, & Dehini, 2010) are employed. The dynamic performance analysis using PI control algorithm for 5-kVA SAPF is investigated using fuzzy logic controllers (Jain et al., 2002; Bhende & Mishra, 2006), BF Technique (Mishra & Bhende, 2007). Simple performance criterion viz; percentage peak overshoot ($\% M_p$), DC bus voltage settling time ($V_{dc}\_T_s$) were used to measure the performance (Jain et al., 2002; Bhende & Mishra, 2006) and choose PI controller gain values (Mishra & Bhende, 2007) for the proposed optimization technique. However, these metrics do not give sufficient data to completely describe the dynamic response of the PI controller, since the estimates consider only the isolated characteristics of the DC bus voltage response. Unlike these metrics, dynamic performance index such as ISE, ITSE, IAE and ITAE are based on the complete response of the process (George Stephanopoulos, 2009; Stanley 1998). Approaches in (Bhende & Mishra, 2006; Mishra & Bhende, 2007), (Singh et al., 2011) consider only ITSE and ITAE as objective functions for estimating gain values of PI controller used in SAPF. However, the detailed investigation on choice of objective function is not being explored in these approaches.

In this manuscript, the PI controller parameters of PI control algorithm based SAPF were selected based on off-line evaluation of objective function using ACO technique through simulations considering ISE, ITSE, IAE and ITAE as the objectives. The performance of proposed ACO technique is compared with other evolutionary computing approaches viz. GA, Differential Evolution (DE) technique and BF algorithm. Based on the simulation and hardware experimental results, it is concluded that the proposed algorithm using ISE as objective function brings the SAPF system into compliance with IEEE 519-1992 standards with minimum settling time. The rest of the paper is organized as follows. Section 2 presents reference current extraction methodology. ACO technique and tuning approach is detailed in Section 3. Section 4 describes the design of conventional PI controller parameter followed by simulation results in Section 5. The hardware implementation of the proposed controller is given in Section 6 and the conclusions are drawn in Section 7.

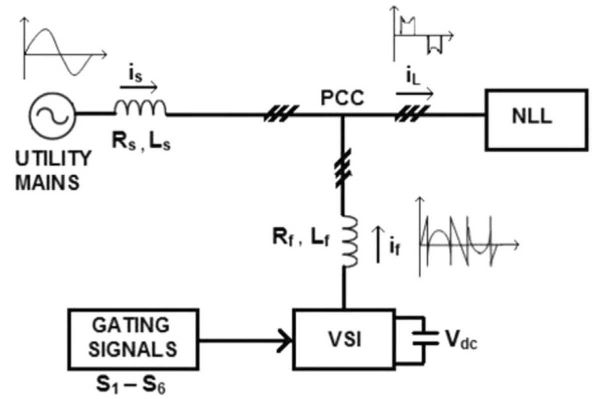

Fig. 1. Compensation principle of SAPF.

2. Reference source current extraction method

The utility mains current is distortion free and is in phase with mains voltage once the SAPF is injecting the harmonic currents in to the PCC. Fig. 1 shows the compensation principle of three-phase SAPF. The SAPF is controlled to inject the compensating current in order to make the supply current harmonics free irrespective of the load characteristics. Initially, the shape of the source current and load current are same. Once the SAPF is connected at PCC the shape of source current would become sinusoidal, hence harmonics free.

From Fig. 1, the instantaneous current at PCC is given by Eq. (1),

$$i_s(t) = i_L(t) - i_f(t) \tag{1}$$

where $i_s(t)$ – source current supplied by utility mains, $i_L(t)$ – load current drawn by NLL from utility mains, $i_f(t)$ – compensation current supplied by SAPF.

The utility mains voltage is as given in Eq. (2),

$$v_s(t) = V_m \sin \omega t \tag{2}$$

NLL will draw current in a non-sinusoidal shape when it is connected to utility mains. This implies that load current consists of more than one frequency component, which can be expressed as in Eq. (3).

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \Phi_n)$$

$$i_L(t) = I_1 \sin(\omega t + \Phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \tag{3}$$

The instantaneous load power then can be given in Eq. (4),

$$\begin{aligned} p_L(t) &= v_s(t) * i_L(t) \\ &= V_m I_1 \sin^2 \omega t * \cos \Phi_1 + V_m I_1 \sin \omega t * \cos \omega t * \sin \Phi_1 \\ &\quad + V_m \sin \omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \end{aligned} \tag{4}$$

$$p_L(t) = p_f(t) + p_r(t) + p_h(t) \tag{5}$$

where $p_f(t)$ – instantaneous fundamental power, $p_r(t)$ – instantaneous reactive power, $p_h(t)$ – instantaneous harmonic power.

It is seen from Eqs. (4) and (5), fundamental power (6) drawn by the load is given by,

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos \Phi_1 = v_s(t) * i_s(t) \tag{6}$$