Design and Analysis of Optimized Hybrid Active Power Filter for Electric Arc Furnace Load

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1 Introduction

The power quality aims to develop and maintain the standard voltage and standard current with proper frequency for the normal operation of the customer equipment. In last few decades, usage of computers, adjustable speed drives, and process control has increased exponentially which led to an increase in power quality problems. This research paper states a confirmation for the current and voltage harmonic minimization induced by nonlinear loads particularly for Electric Arc Furnace (EAF) load. A random variation in nonlinear loads, generally large and continuous, refers mainly to electric metal-melting arc furnaces connected directly to the transmission network. It consists of the carbon electrodes in contact with iron having dissimilar impedances between the positive and negative flows of current. An electric arc furnace produces a quantity of interfering emissions, such as flicker voltage and stress wear caused by arc phenomena. Voltage cutting complicates the construction of an accurate filter system in the 0–200 kHz frequency range [1].

Here, an analysis of current and voltage harmonic issues arising from the operation of furnace load and the applicability of the proposed systems to mitigate those problems are being carried out.

The objective of this paper is that the Hybrid Active Power Filter (HAPF) is used to compensate harmonic content in voltages and currents, besides Selective Reactive Power Compensation (SVC). The proposed HAPF has the objective of up gradation of different types of APF compensation performance [2], reduction of cost and complexity of compensation systems, etc. From previous investigations, it seems that the electric arc furnace issues are compensated with the help of SVC and series inductance [3–5]. In response to these hybrid/composite filter factors, one of the best options is to be considered by reducing cost, simple design, high reliability, and better control compared to other options for power quality refinement [5–7]. The impact of harmonics and voltage flicker can occur in the electrical power distribution system in the industry and in another power supply unit of the substation [8]. Minimization of the impact of EAFs

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can improve electric efficiency and reduce power fluctuations in the system. The importance of mitigation devices, such as passive filters, active line filter, and hybrid filtering, has been proposed [9]. It has been observed that Genetic Algorithm (GA) tuned controllers give high Total Harmonic Distortion (THD) value and also, Particle Swarm Optimization (PSO) tuned controllers take more time for specific iterations [10]; to overcome these problems, the proposed algorithm is implemented. This paper presents the performance optimization of the conventional PI controller and optimized PI controller for three phase HAPF with Harmony Search Algorithm (HSA). Harmony search method is inspired by harmony improvisation; it has two distinct operators: one is Harmony Memory Considering Rate (HMCR) and another one is Pitch Adjusting Rate (PAR) [11].

2 System Modeling

2.1 Modeling of Electric Arc Furnace

An EAF not only uses power strongly but also uses reactive one. The typical process in the furnace is irregular in nature, in which one or more electrodes with the electric arc are present between the furnace and scrap. In order to know the proper characteristics of an arc furnace, it is needed to design an appropriate three-phase electric arc furnace system for voltage and current harmonic analysis. The voltage drop due to reactive power current acts by reacting to spurious flickering and into the blinking light of fluorescent lamps supplied from the contaminated feeder [12–14]. The proposed arc furnace model is designed in a random time-varying signal in the form of band-limited white noise. It is used to obtain the arc furnace voltage fluctuations in terms of voltage harmonics [9].

2.2 Vigorous Nature of Electric Arcs

The unrestrained, multivalued characteristics of an arc are determined by using an adopted dynamic furnace model in the form of the equations derived in [13]. The arc parameters on different phases are found in [13, 14]. For an arc, power balance equation is as shown in (1).

$$p_1 + p_2 = p_3 \tag{1}$$

where p_1 depicts the power transferred to the external environment in the form of heat; p_2 shows the power, which enhances the inherent energy of the electric arc, and which in turn affects the radius; and p_3 is the gross power produced in the arc and transformed into heat. An assumption is considered that the cooling effect is a function of the electric arc radius (r). Thus, we get (2).

$$p_1 = k_1 r^n \tag{2}$$

where n = 1 and k_1 represents an arbitrary constant.

The dependence of arc on temperature may be ignored for low voltage circuits. Thus, the arc radius r only describes the mathematical state of arc.

For n = 2, p_2 is analogous to the differentiation of energy in the arc, given by (3). Hence,

$$p_2 = k_2 r \frac{dr}{dt} \quad (3)$$

Again, from (1), we get the sum as (4). Finally,

$$p_3 = vi = \frac{k_3}{r^{m+2}} \quad (4)$$

where k_2 and k_3 are also arbitrary constants.

In (4), the resistance of the arc is considered to be varying inversely with r^m, where m = 0…2. Now, the arc differential equation is given by (5).

$$k_1 r^n = k_2 r \frac{dr}{dt} = \frac{k_3}{r^{m+2}} \quad (5)$$

Here "r" the arc radius is taken as a variable function instead of arc conductance or resistance. Hence, the voltage of arc is as shown in (6).

$$v = \frac{i}{g} \quad (6)$$

where i is the arc current and g is conductance of arc described by (7).

$$g = \frac{r^{m+2}}{k_3} \quad (7)$$

2.3 Design of Hybrid Filter

The performance of the hybrid active filter, designed by HSA, turns out to be excellent at eliminating the line harmonics as compared with Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). Figure 1 displays the simplified configuration of the hybrid active power filter. The proposed technique is based on the theory of introduction of harmonic current into the alternating current system of the same dimensions of load current harmonics to meet the IEEE 519-1992 limits [15]. The system configuration of hybrid filter comprises a shunt active filter with a shunt passive filter as shown in Fig. 2.

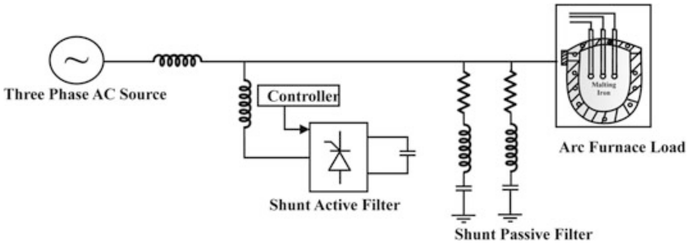

Fig. 1. Test diagram of HAPF with furnace load

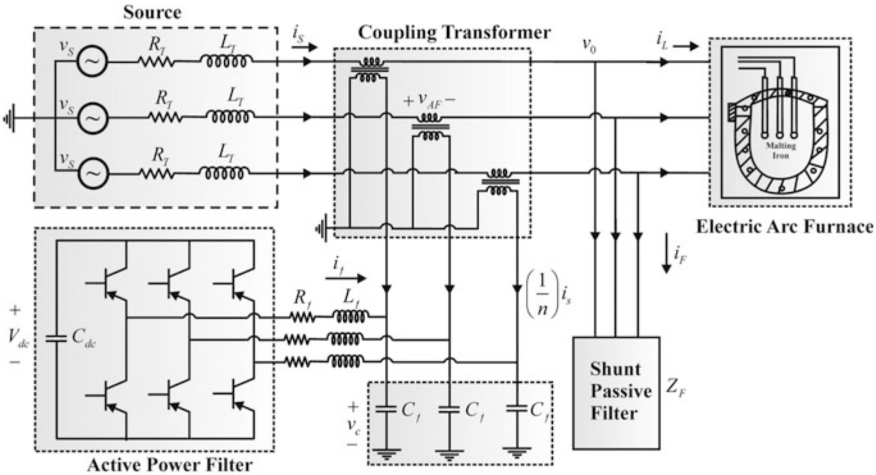

Fig. 2. Configuration of HAPF

2.4 Controller Design

The control input receives an error wave with respect to reference voltage and the RMS magnitude of measured supply voltage. The PI controller ensures that the incorrect signal, generated from the desired angle to zero, i.e., the error signal which is the difference between load RMS voltage and reference voltage, is minimum [16]. The values of K_p and K_i are selected iteratively as discussed in the literature [17, 18] using any of the methods available for tuning it. Here, K_p and K_i are selected arbitrarily and iterated intuitively. The THD value minimization is considered as the objective, and the issue becomes nonlinear due to the variation of THD with respect to various K_p and K_i values.

2.5 Objective Function

The mean value of THD data is achieved from time-domain simulation, and the values are passed to the harmony search solver as objective function. The K_p and K_i values are randomly populated, and the minimization of objective function is made. The PI controller equation at DC link voltage control part in hybrid active power filter is defined as shown by (8).

$$I_{af} = K_p \times (V_{dcref} - V_{dcmesured}) + K_p \times \int_0^t (V_{dcref} - V_{dcmesured})dt \tag{8}$$

where

I_{af} = compensation current, $V_{dcmesured}$ = DC measured voltage at DC link, V_{dcref} = DC reference voltage, K_p = proportional constant, and K_i = integral constant. The objective function is to minimize the sum of mean values of THD as given by (9).

$$\text{Objective Function} = \text{Minimized} \sum_{i=0}^{n} \text{Mean(THD)} \tag{9}$$

where i represents the number of data samples for mean values of THD.

Subjected to

$$P_1 \le K_p \le P_2 \tag{10}$$

$$I_1 \le K_i \le \mathrm{I}_2 \tag{11}$$

Here,

P_1= lower limit of K_p, P_2= upper limit of K_p, I_1= lower limit of K_i, and I_1= upper limit of K_i.

3 Optimization Technique

3.1 Genetic Algorithm

Genetic algorithm was first introduced by John Holland. This is the optimization technique which uses the natural selection procedure for calculating its parameters [10].

3.2 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an optimization technique designed by Dr. Eberhart and Dr. Kennedy in [10]. It is an optimization technique based on the social behavior of fish schooling and bird flocking.

3.3 Harmony Search Algorithm

The HSA is in reality inspired by the functioning principles of the harmony characterization. Harmony search is a music-based metaheuristic optimization algorithm [11].

4 Results and Discussion

The implementation of the proposed system is analyzed for its application in the electric arc furnace load for shunt hybrid active filters. In the current study, the fifth matched passive filter branches are taken into consideration.

4.1 Simulation Result of Shunt Hybrid Active Filter

The harmonic content of source voltage and current using the FFT (Fast Fourier Transform) waveform analysis without any filter at the Point of Common Coupling (PCC) and then with tuned hybrid active power filters with GA, PSO, and HSA optimization techniques has been analyzed.

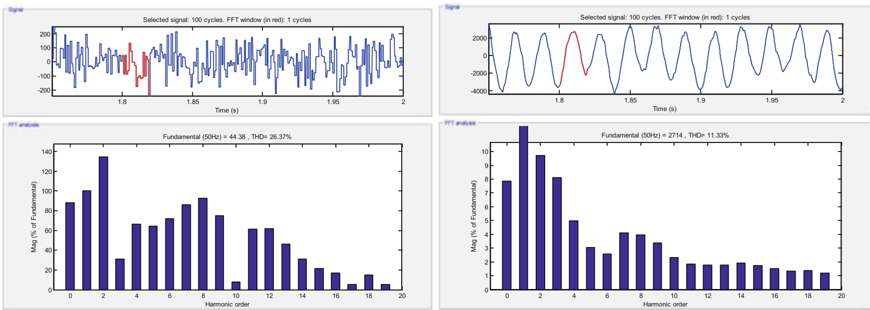

Fig. 3. Voltage and current FFT waveforms at PCC with arc furnace load without any filter

Figure 3 shows the simulation results of system without shunt hybrid active power filter. Here, the THD in source voltage and current is 26.37% and 11.33%, respectively.

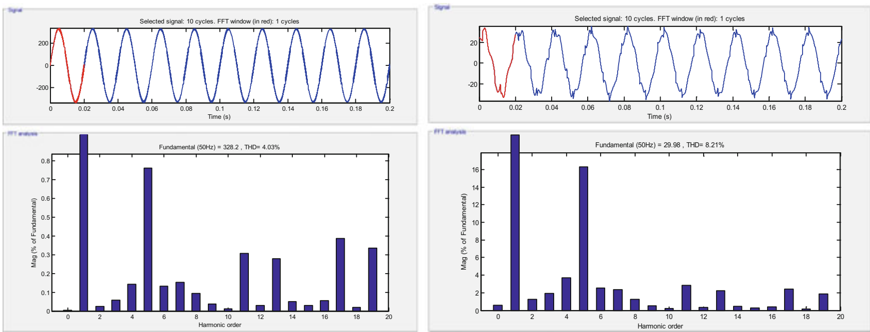

Fig. 4. Voltage and current FFT waveforms at PCC for HAPF with optimized PI using GA

Figure 4 shows the simulation result of system with shunt hybrid active power filter optimized by genetic algorithm. Here, the THD in source voltage and current is 4.03% and 8.21%, respectively.

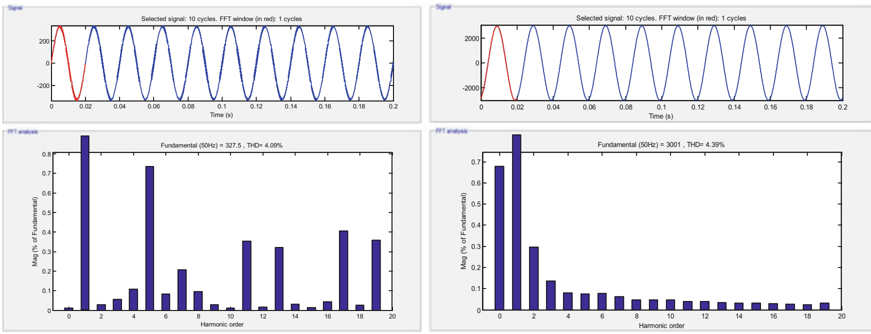

Fig. 5. Voltage and current FFT waveforms at PCC for HAPF with optimized PI using PSO

Figure 5 shows the simulation result of system with shunt hybrid active power filter optimized by particle swarm optimization. Here, the THD in source voltage and current is 4.09% and 4.39%, respectively.

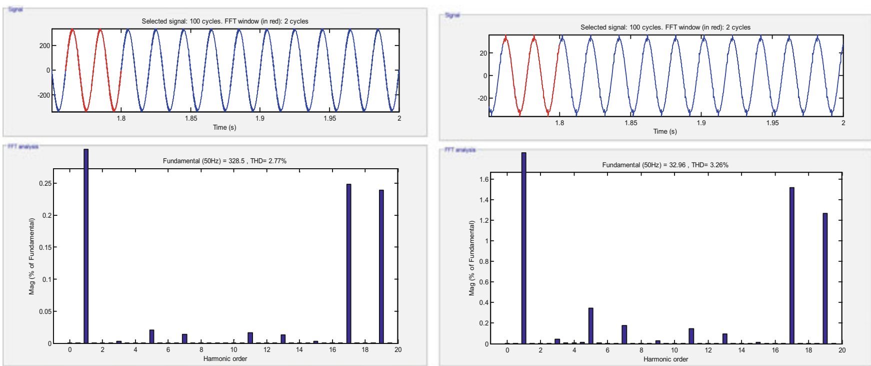

Fig. 6. Voltage and current FFT waveforms at PCC for HAPF with optimized PI using HSA

Finally, Fig. 6 shows the simulation result of system with shunt hybrid active power filter optimized by harmony search algorithm. The THD in source voltage and current is 2.77% and 3.26%, respectively.

5 Conclusion

In this paper, the issue of harmonic reduction is comparatively performed and analyzed. PI tuning using GA, PSO, and HSA optimization method is carried out and compared with the THD values for a shunt hybrid active power filter. It has been observed that THD in the magnitudes of current and voltage has been reduced significantly by using the HSA optimization as compared to GA and PSO optimized PI controllers as shown in Table 1. Hence, the proposed analysis verifies the applicability of the optimized hybrid power filtering method for electric arc furnace load variations.

Table 1. Comparison of THD with different conditions

Type of controller	K_p	K_i	Comparison analysis of THD	
			Voltage THD (%)	Current THD (%)
Nonlinear load connected without filter	–	–	26.37	11.33
HAPF with optimized PI using GA	6.854	3.1771	4.03	8.21
HAPF with optimized PI using PSO	4.231	1.695	4.09	4.39
HAPF with optimized PI using HSA	7.262	2.6833	2.77	3.26

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