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Optimal Control of Active Power Filters using Fractional Order Controllers Based on NSGA-II Optimization Method

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ABSTRACT

Elitist Non-Dominated Genetic Algorithm (NSGA-II) optimization method offers optimal solution to multidimensional objective functions. In this paper, this optimization method is used for designing Fractional Order PI controller that features a better performance than the Integer Order PI controller for improving the performance of a Shunt Active Power Filter. Controller synthesis is based on required Total Harmonic Distortion and transient specifications. The characteristic equation is minimized to obtain an optimal set of controller variables. This process is done by using the Integer Order PI controller and Fractional Order PI controller with the high performance Repetitive Controller. Simulation results are obtained by using the Fractional Order PI controller are better than the ones are obtained by using the Integer Order PI controller.

Introduction

Nowadays, with the wide use of nonlinear loads and electronic equipment in distribution systems, the problem of power quality (PQ) has become increasingly serious. This fact has lead to more stringent requirements regarding PQ which include the search for solutions for such problems [5,16]. Active Power Filters are devices which are designed to improve the power quality in distribution networks. In order to reduce the injection of non sinusoidal load currents, Shunt Active Power Filters (APFs) can be connected in parallel with the nonlinear loads.

In the case of harmonic distortion, the Shunt Active Power Filter (APF) appears as the best dynamic solution for harmonic compensation. This paper offers a good way to optimize the performance of a Shunt Active Power Filter. Good performance means having an appropriate transient response and an appropriate steady-state response. Low settling time and low transient time includes a good transient response and a low THD includes good steady-state response. Here, the goal is to reduce settling time, transient time and THD by using Fractional Order PI controller based on NSGA-II multiobjective optimization method applying the high performance Repetitive Controller. This paper proposes an opinion of a designing method of the Fractional Order PI (FOPI) controller for Shunt Active Power Filter by using the Elitist Non Dominated Genetic Algorithm (NSGA-II) as a powerful multi-objective optimization approach for the design of a FOPI controller, also this paper presents the performance of the Repetitive Controller. In this research THD and settling time, THD and Transient time are two pairs objective functions in a Shunt Active Power Filter, settling time and transient time can affect on transient response, that each pair of objective functions have been selected to be minimized simultaneously. The result of this optimization is a set of optimal solutions, that it is called Pareto Optimal Set (POS), that in this paper, POS for FOPI controller of Repetitive Controller has the parameters of K_p, K_i, V_i or α, V_{dc}. The obtained different values from POS members are known as Pareto Optimal Front (POF) that the POF is corresponding to the values of the objective functions, and for the different values of each pair of the objective functions in this research, values of POS members are different.

Fractional systems

Fractional-Order systems are known by fractional-order equations. The FOPID controller is a Fractional Order System. FOPID controller is an English acronym which means Fractional-Order Proportional-Integral-Derivative controller.

Fractional Calculus

Fractional Calculus is a branch of mathematics that dealing with real number powers of differential or integral operators. It

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generalizes the common concepts of derivative and integral. There are several definitions for fractional order derivatives. The definition which has been proposed by Riemann and Liouville is the simplest and easiest definition to use [19]. The definition is given by Eq. (1):

$$ {}_cD_x^{-n}f(x) = \int_c^x \frac{(x-t)^{n-1}}{(n-1)!} f(t)dt, \quad n \in R \tag{1}$$

The general definition of D is given by Eq. (2):

$$ {}_cD_x^{v}f(x) = \begin{cases} \int_c^x \frac{(x-t)^{-v-1}}{\Gamma(-v)} f(t)dt, & \text{if } v < 0 \\ f(x) & \text{if } v = 0 \\ D^n[{}_cD_x^{v-n}f(x)] & \text{if } v > 0 \end{cases} \quad n = \min\{K \in R,\ K > v\} \tag{2}$$

And $\Gamma(\cdot)$ is the gamma function.

Approximation of fractional order derivative and integral

The approximation method which is considered in this paper is based on the approximation of the fractional-order system behavior in the frequency domain. For the frequency-domain transfer function $C(s)$ which is given by Eq. (3):

$$C(s) = Ks^v \quad v \in R \tag{3}$$

One of the best-known approximations is due to Oustaloup and is given by Oustaloup [13] The Crone method, which uses a recursive distribution of N poles and N zeros. Crone is a French acronym which means 'robust fractional order control' [8]. Transfer function is given by Eq. (4):

$$C(s) = K' \prod_{n=1}^{N} \frac{1 + \frac{s}{\omega_{zn}}}{1 + \frac{s}{\omega_{pn}}} \tag{4}$$

where K' is adjusted so that if K is 1 then $|C(s)| = 0$ dB at 1 rad/s. Zeros and poles are found inside a frequency interval $[\omega_l; \omega_h]$ where the approximation is valid, and they are given, for a positive, by Eqs. (5)–(7).

$$\omega_{z1} = \omega_l \sqrt{\eta} \tag{5}$$

$$\omega_{pn} = \omega_{z,n-1} \propto \quad n = 1 \ldots N \tag{6}$$

$$\omega_{zn} = \omega_{p,n-1} \eta \quad n = 2 \ldots N \tag{7}$$

where α and η can be obtained by Eqs. (8) and (9).

$$\propto = \left(\frac{\omega_h}{\omega_l}\right)^{\frac{v}{N}} \tag{8}$$

$$\eta = \left(\frac{\omega_h}{\omega_l}\right)^{\frac{1-v}{N}} \tag{9}$$

For a negative v the role of zeros and poles is interchanged. The number of poles and zeros is selected at first and the desired performance of this approximation depends on the order N. Simple approximation can be provided with lower order N, but it can cause ripples in both gain and phase characteristics. When $|v| > 1$, the approximation is not satisfactory. The fractional order v usually is separated as Eq. (10) and only the first term s^β needs to be approximated [8].

$$s^v = s^\beta s^n, \quad v = n + \beta, \quad n \in R, \quad \beta \in [0, 1] \tag{10}$$

Fractional-Order Proportional-Integral-Derivative controller

In recent years, researchers found that controllers making use of factional-order derivatives and integrals could achieve better performance and robustness than those with conventional integer-order controllers [7]. The fractional-order PID controller is more flexible and can provide an opportunity to better adjust the dynamical characteristics of the control system [9]. This controller which first time was proposed by Podlubny in 1999, is the expansion of the conventional PID controller based on Fractional Calculus [2,4]. The most common form of a Fractional Order PID controller is the $PI^\alpha D^\beta$ controller [4], involving an integrator of order $\propto$ and a differentiator of order β where $\propto$ and β can be any real numbers. For this controller, besides selecting K_p, K_i, and K_d, it needs to select α and β which are not necessarily integer numbers [6]. It can be expected that the $PI^\propto D^\beta$ controller may enhance the systems control performance. One of the most important advantages of the $PI^\propto D^\beta$ controller is the better control of dynamical systems, which are described by fractional order mathematical models. Another advantage lies in the fact that the $PI^\propto D^\beta$ controllers are less sensitive to changes of parameters of a controlled system [18]. The transfer function of such a controller is given by Eq. (11):

$$G_c(s) = K_p + K_i s^{-\alpha} + K_d s^\beta \tag{11}$$

The calculation of the five parameters that can be done through optimization makes the design scenario of an FOPID controller more challenging than conventional PID controllers. Several methods have been proposed for this design by using optimization methods [19,2,6,12]. Since the design of FOPID can be considered as a parameter-optimization problem and the features of our system are conflicting, we used a multi-objective optimization method called Non-Dominated Sorting Genetic Algorithm (NSGA-II) for this problem. In this paper, K_d and β are zero.

Multi-objective optimization

Optimization methods

In the optimization problems of control systems, normally simultaneous optimization of different and often conflicting objectives is needed [8]. In this optimization case, there is a set of optimal solutions that this set is called Pareto Optimal Set (POS). Each point in this set is optimal in the sense that no improvement can be achieved on one optimization objective that does not lead to degradation in at least one of the remaining objectives. In the absence of any further information, none of these POS members could be considered as being better than the others [3]. In this paper, POS for FOPI controller of Repetitive Controller has the following parameters:

$K_p,\ K_i,\ \alpha,\ V_{dc}$.

The obtained different values from POS members are known as Pareto Optimal Front (POF), the POF is corresponding to the values of the objective functions.

The general multi-objective optimization problem is posed as follows:

Where x is called design

$$\begin{aligned} &\text{Minimize} \\ &g = f(x) = (f_1(x), \ldots, f_i(x), \ldots, f_k(x)) \\ &\text{Subject To :} \\ &x = (x_1, x_2, \ldots, x_n) \in X \end{aligned} \tag{12}$$

where k is the number of objective functions, n is the number of inequality constraints, and e is the number of equality constraints. x is a vector of design variables, and $f(x)$ is a vector of objective functions to be minimized.