Electrical Power and Energy Systems 51 (2013) 106–118

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Frequency domain design of fractional order PID controller for AVR system using chaotic multi-objective optimization

Indranil Pan [a], Saptarshi Das [b,c,*]

[a] Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110 016, India
[b] Department of Power Engineering, Jadavpur University, Salt Lake Campus, LB-8, Sector 3, Kolkata 700 098, India
[c] Communications, Signal Processing and Control Group, School of Electronics and Computer Science, University of Southampton, Southampton SO17 1BJ, United Kingdom

ARTICLE INFO

Article history:
Received 25 July 2012
Received in revised form 3 February 2013
Accepted 22 February 2013
Available online 31 March 2013

Keywords:
Automatic Voltage Regulator (AVR)
Chaotic Henon map
Evolutionary multi-objective optimization
Fractional order PID controller
Frequency domain controller design
Phase margin-gain crossover frequency trade-off

ABSTRACT

A fractional order (FO) PID or FOPID controller is designed for an Automatic Voltage Regulator (AVR) system with the consideration of contradictory performance objectives. An improved evolutionary Non-dominated Sorting Genetic Algorithm (NSGA-II), augmented with a chaotic Henon map is used for the multi-objective optimization based design procedure. The Henon map as the random number generator outperforms the original NSGA-II algorithm and its Logistic map assisted version for obtaining a better design trade-off with an FOPID controller. The Pareto fronts showing the trade-offs between the different design objectives have also been shown for both the FOPID controller and the conventional PID controller to enunciate the relative merits and demerits of each. The design is done in frequency domain and hence stability and robustness of the design is automatically guaranteed unlike the other time domain optimization based controller design methods.

1. Introduction

Large power distribution networks must keep the overall voltage profiles at an acceptable level at all times. The connected equipments are designed for a particular nominal voltage and frequency of operation and any aberration from the nominal case generally leads to a decrease in performance and reduction in life time of these equipments. Frequent fluctuations in the load of the power network affects the voltage profile and hence the power utility companies employ a wide range of devices like capacitor banks, on-load tap changing transformers, Automatic Voltage Regulators (AVRs), etc. [1–3] to keep the operational voltage profile at an acceptable level. Additionally, the amount of line losses due to the flow of real power depends on the reactive power which in turn depends on the system voltage. Hence, control of the system voltage is a crucial aspect in the effective operation of the power system. To alleviate these issues to some extent, the AVR is connected to the power generating plants. The AVR system maintains the terminal voltage of the alternator in the generating station and also helps in suitable distribution of the reactive power amongst the parallel connected generators [4].

Traditionally the PID controller has been used in the AVR loop due to its simplicity and ease of implementation [5]. However, recently the fractional order PID (FOPID) controller has been used in the design of AVR systems and has been shown to outperform the PID in many cases [6,7]. In Zamani et al. [8], the FOPID has been tuned for an AVR system using the Particle Swarm Optimization (PSO) algorithm employing time domain criterion like the Integral of Absolute Error (IAE), percentage overshoot, rise time, settling time, steady state error, controller effort, etc. In Tang et al. [6], the optimal parameters of the FOPID controller for the AVR system, has been found using a chaotic ant swarm algorithm. In [6] a customized objective function has been designed using the peak overshoot, steady state error, rise time and the settling time. The above mentioned literatures perform optimization considering only a single objective. But in a practical control system design multiple objectives need to be addressed. In the study by Pan and Das [9], the AVR design problem has been cast as a multi-objective problem and the efficacy of the PID and the FOPID controllers are compared with respect to different contradictory objective functions like the Integral of Time Multiplied Squared Error (ITSE) and the controller effort, etc. However, the optimization is done in the time domain and the obtained controller values are checked for robustness against gain variation by varying different parameters of the control loop. All these above mentioned literatures which employ time

* Corresponding author at: Communications, Signal Processing and Control Group, School of Electronics and Computer Science, University of Southampton, Southampton SO17 1BJ, United Kingdom. Tel.: +44 7448572598.

E-mail addresses: indranil.jj@student.iitd.ac.in (I. Pan), saptarshi@pe.jusl.ac.in, s.das@soton.ac.uk (S. Das).

0142-0615/$ - see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2013.02.021

domain optimization techniques cannot guarantee a certain degree of gain or phase margins which are important for the plant operator. These margins are useful from a control practitioner's view point as they can give an estimate of how much uncertainty the system can tolerate before it becomes unstable. Uncertainties can arise not only due to load variations in the power system, but there can be significant uncertainty due to modelling approximations or other stochastic phenomena. Hence frequency domain designs are mostly preferred over time domain design from the implementation and operation point of view of a control system. In spite of the importance of AVR in power systems, very few literatures consider a multi-objective formalism. A co-ordinated tuning of AVR and Power System Stabiliser (PSS) has been done in Viveros et al. [10] using the Strength Pareto Evolutionary Algorithm (SPEA). However, the contradictory objectives considered are the integrated time domain response for the AVR and the closed loop eigenvalue damping ratio of the PSS. This is a coupled time–frequency domain approach and does not address the inherent contradictory objectives in the AVR itself. In Ma et al. [11] a multi objective problem has been formulated for finding out the optimal solution for coordinate voltage control. A hierarchical genetic algorithm has been proposed for multi objective optimization and a Pareto trade-off is obtained. In Mendoza et al. [12] a micro-genetic algorithm is used to solve the multi objective problem of finding the AVR location in a radial distribution network in order to reduce energy losses and improve the energy quality. In [13], a similar problem has been attempted using a multi objective fuzzy adaptive PSO algorithm. However none of these papers consider the inherent design trade-off in the AVR tuning itself, which is one of the main focus of the present paper.

In this paper an evolutionary multi-objective optimization algorithm, the Non-dominated Sorting Genetic Algorithm-II or NSGA-II [14], augmented with a chaotic Henon map, is used for designing a FOPID controller in frequency domain with contradictory objectives. The proposed frequency domain design methodology show that the FOPID controller is better than its PID counterpart for the considered set of objective functions. To the best of the author's knowledge, this is the first paper to make a comparative investigation into the multi-objective design trade-offs in frequency domain for the FOPID and the PID controller for an AVR system, using a chaotic map augmented multi-objective optimization algorithm.

The rest of the paper is organized as follows. Section 2 briefly introduces the concept of fractional calculus and the FOPID controller. In Section 3, the need for multi-objective optimization, the description of the AVR system, the contradictory objective functions and the chaotic NSGA-II algorithm is discussed in detail. Section 4 illustrates the simulation results along with a few discussions. The paper ends in Section 5 with the conclusions followed by the references.

2. Fractional calculus and the fractional order PID (FOPID) controller

Fractional calculus is an extension of the integer order differentiation and integration for any arbitrary number. The fundamental operator representing the non-integer order differentiation and integration is given by ${}_aD_t^\alpha$ where $\alpha \in \mathbb{R}$ is the order of the differentiation or integration and a and t are the bounds of the operation. It is defined as

$$ {}_aD_t^\alpha = \begin{cases} \frac{d^\alpha}{dt^\alpha}, & \alpha > 0 \\ 1, & \alpha = 0 \\ \int_a^t (d\tau)^\alpha, & \alpha < 0 \end{cases} \tag{1} $$

There are three main definitions of fractional calculus, the Grünwald–Letnikov (GL), Riemann–Liouville (RL) and Caputo definitions. Other definitions like that of Weyl, Fourier, Cauchy, Abel and Nishimoto also exist. In the fractional order systems and control related literatures mostly the Caputo's fractional differentiation formula is referred. This typical definition of fractional derivative is generally used to derive fractional order transfer function models from fractional order ordinary differential equations with zero initial conditions. According to Caputo's definition, the αth order derivative of a function $f(t)$ with respect to time is given by (2) and its Laplace transform can be represented as (3).

$$ D^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)} \int_0^t \frac{D^m f(t)}{(t-\tau)^{\alpha+1-m}} d\tau, \quad \alpha \in \mathbb{R}^+, \ \mathbb{m} \in \mathbb{Z}^+ m-1 \leqslant \alpha < m \tag{2} $$

$$ \int_0^\infty e^{-st} D^\alpha f(t) dt = s^\alpha F(s) - \sum_{k=0}^{m-1} s^{\alpha-k-1} D^k f(0) \tag{3} $$

where $\Gamma(\alpha) = \int_0^t e^{-t} t^{\alpha-1} dt$ is the Gamma function and $F(s) = \int_0^\infty e^{-st} f(t) dt$ is the Laplace transform of $f(t)$. This definition is used in the present paper for realizing the fractional integro-differential operators of the FOPID controller.

The fractional order PID controller is a generalization of its integer order counterpart where the integro-differential orders are two additional tuning knobs [15]. Thus in addition to the conventional proportional, integral and derivative gains $\{K_p, K_i, K_d\}$, there are also the integration and the differentiation orders $\{\lambda, \mu\}$. In the present study, 5th order Oustaloup's recursive approximation is done for the integro-differential operators within a frequency band of the constant phase elements (CPEs) as $\omega \in \{10^{-2}, 10^2\}$ rad/s. This frequency domain rational approximation method of realization is preferred over the others like Grunwald–Letnikov method since the realized approximate transfer functions can be easily implemented in real hardware using higher order Infinite Impulse Response (IIR) type analog or digital filters. The transfer function for the fractional order controller is given by the following equation:

$$ C(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \tag{4} $$

3. Multi-objective optimization framework for FOPID controller design

3.1. Requirement for frequency domain multi-objective controller design

There are many controller design procedures like the H_2, H_∞ or L_1 norm based designs where the controller design problem is reduced to that of minimizing the weighted norm of a closed loop transfer function. However, each of these norms addresses a specific performance criterion of the control system. For example in Herreros et al. [16], minimizing the H_2 norm implies closed loop stabilization in the presence of disturbances and minimizing H_∞ norm gives closed loop robust stability. However, the control system designed with the H_2 norm minimization technique would have an arbitrary robustness as it has not been explicitly taken into the design criteria. Similarly for the H_∞ norm case, the stabilization in the presence of disturbance is not addressed. In a practical control system design problem, the designer should design a system which ideally should have both properties to some extent. Hence the design algorithm must be capable of handling multiple objectives at the design phase itself. The NSGA-II algorithm is an evolutionary multi-objective optimization algorithm which is suitable for designing such controllers with multiple objectives as shown in [9,17,18]. In [9], the multi objective design for fractional order controllers have been done by considering different conflicting time domain design criteria. However, the time domain design