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Full Length Article

Performance enhancement of automatic voltage regulator by modified cost function and symbiotic organisms search algorithm

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ABSTRACT

This article attempts to solve the problem of efficient design of proportional + integral + derivative (PID) controller applied to popular automatic voltage regulator (AVR) system by employing recently introduced symbiotic organisms search (SOS) algorithm, for the first time. PID controller design needs proper determination of three control parameters. Such a design problem can be taken as an optimization task and SOS is invoked to find out better controller parameters through a new cost function defined in the paper, which allows to evaluate the control behavior in both time-domain and frequency-domain. For the performance analysis, distinct analysis techniques are deployed such as transient response analysis, root locus analysis and bode analysis. Besides, robustness analysis of the closed-loop control system tuned by SOS is performed with regard to parameter uncertainties and external disturbance. The efficacy of the presented technique is widely illustrated by comparing the obtained results with those reported in some prestigious journals and it is shown that our proposal leads to a more satisfactory control performance from the perspective of both time-domain and frequency-domain specifications while with a good robustness to parameter uncertainties and unknown changes in the system output.

1. Introduction

In an electric power network, ensuring a constant voltage level under various circumstances is one of the significant control issues of power systems having a close relation to power quality, grid security and grid reliability. When facing a deviation in grid voltage level, it leads to remarkable changes in the system dynamics and accordingly there may be a deterioration in the performance of the devices connected with this power grid and drop in their life expectancy, because all equipment can operate efficiently only for a particular voltage level termed as nameplate or rated voltage [1,2]. Moreover, controlling the bus voltage in a local sense has another aspect of regulating reactive power flow, thus rendering it possible to reduce real line losses because of the reactive current components in electric power network. In order to fulfill the aforesaid objectives, automatic voltage regulator (AVR) system is installed in electrical power systems. An AVR is equipment aimed to sustain the output voltage of a synchronous generator (SG) at a desirable voltage level by keeping its excitation voltage under control, where the exciter voltage is regulated to match the voltage drop or rise according to the new conditions [3].

In the hope of implementing and enhancing dynamic response of an AVR system, several control techniques have been studied in the literature based on optimal control, robust control, fuzzy logic, conventional and fractional order proportional + integral + derivative (PID) techniques and adaptive control, which have individual advantages and disadvantages. Among the reported controllers, the classical PID is no doubt the one that is the most preferred owing to its robust performance regardless of variations in system parameters and structural simplicity which requires tuning of only three control parameters, such as proportional gain, integral gain and derivative gain [4]. However, proper determination of PID gains is fairly difficult and there is no universal methodology that assists the operator in designing this controller. When the literature is evaluated, it can be seen that a vast number of artificial intelligence algorithms have been paid much attention by many researchers particularly since 2000, so as to acquire an almost optimal solution in their PID design by exploiting the unique search ability of governed optimization algorithm and/or their cost function definition. In this context, in 2012, artificial bee colony (ABC) algorithm is suggested to enhance the performance of PID-controlled AVR system, where a comparison with

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particle swarm optimization (PSO) and differential evolution (DE) algorithm are also presented [1]. From the findings, ABC is found to exhibit better performance than the others. Subsequently, many optimizing liaisons (MOL) algorithm, which is the simplified revision of the original PSO, is applied to the same optimization problem of searching for better PID parameters [2]. The results are compared to those in [1] and it is shown that MOL-based PID controller can enhance the system performance with regard to both time-domain and frequency-domain measures. In 2016, biogeography-based optimization (BBO) algorithm is introduced into searching for optimal PID parameters for the concerned control system [5]. Comparative results with ABC-based obtained results in [1] demonstrate that BBO algorithm outperforms the ABC approach, thereby it yields an improvement in the system dynamic response. In [6], PSO and global neighborhood algorithm (GNA) are adopted to optimize the output response of a PID-controlled AVR system. From the results of transient response analysis, GNA is found to perform better than PSO with regard to settling time and rise time. However, peak overshoot of the response with GNA is greater than that of PSO. An application of chaotic PSO (CPSO) is made in [7] to optimize the AVR system performance. A comparison is also presented with the results obtained by the standard PSO in [6]. It is shown that CPSO-based AVR system performance is improved considering peak overshoot and settling time. However, it can be said that the validation of these two studies [6,7] is not properly justified because no published work is used for comparison.

Symbiotic organisms search (SOS) algorithm is a relatively straightforward and effective metaheuristic proposed by Cheng and Prayogo in 2014 [8]. In the algorithm, simulation of symbiotic interaction strategies observed amongst organisms in order to keep alive in the ecosystem is realized. A significant advantage of the algorithm is that it requires only two common tuning parameters such as population size and maximum iteration number. Preliminary tests of applying SOS to some mathematical benchmark problems and engineering design problems affirm the excellence of the SOS compared with other remarked optimization algorithms. In addition, superior performance of the SOS for optimizing PI parameters in an off-line sense for a DC servo motor drive is demonstrated based on simulated and experimental results in [9] as compared to PSO, genetic algorithm and classical Ziegler-Nichols tuning rule. To the authors' knowledge, it has not been yet addressed in the open literature whether the application of SOS leads to more optimal PID controller gains or not in presence of AVR control application.

In the light of the consequences of the above paragraphs, the authors of this article are encouraged to present a unique design methodology for the studied AVR system that improves the trade-off between the dynamic response and the stability margin of the system, which is, as figured out by the earlier works, in an insufficient level in the literature. To fill this research gap, the design problem is contemplated as an optimization task and a new composite cost function in the time-domain and frequency-domain is suggested. Then, SOS is invoked to optimize the PID controller gains so that the controlled system may yield the aspired response and degree of stability as depicted by the suggested cost function. Using transient response analysis, root locus analysis and bode analysis, the performance of presented AVR system is widely established in comparison with those based on ABC [1], MOL [2] and BBO [5]. The extensive results reported in this article show that the output voltage profile settles to the unit step reference with the least peak overshoot without compromising on settling time much. This outcome has improved the stability margin of the AVR system compared to other reported approaches. In order to complement the contribution of this study, robustness of the presented controller is also validated under the variations of the model time constants within the range of +50% to −50% in steps of 25% and also in the face of external disturbances in the system output.

2. PID controller-based AVR design

In spite of many efforts in control engineering field, PID controller or its cousins have been still widely used in various types of control systems [10]. The reason of this wide usage comes from its easily understandable nature, ease of design and robust performance irrespective to model uncertainties with proper tuning of controller parameters [11]. In s-domain, the transfer function of a PID controller is expressed by

$$G_{PID}(s) = P + I + D = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \tag{1}$$

where $E(s)$ is the error variable between the desired and real process output which produces the control signal $U(s)$ by computing the sum of proportional term P, integral term I and derivative term D. The three design parameters of this controller, i.e. proportional gain K_p, integral gain K_i and derivative gain K_d, must be tuned jointly by the operator depending upon the plant's dynamics. The resulting response against a unit step input should engage with the given reference with minimal settling time and no sustained oscillation.

In an electric power grid, there are more than one generator connected to similar busbar and each has its own AVR. As previously mentioned, the design objective of an AVR is to sustain the output voltage of a SG at a certain level. As pictured in Fig. 1, an AVR includes mainly four essential components, such as amplifier, exciter, generator and sensor. In this system, as the aim is to control the voltage of power utility that the generator is connected to via power transformer, the voltage level is continuously measured as feedback signal using a voltage sensor. After being rectified and filtered out, this signal is compared to the voltage setpoint in the comparator in order to obtain voltage error signal. The error signal is amplified, then is fed to exciter to adjust the generator field winding voltage/current so that any deviation in generator terminal voltage resulting from new operating conditions could be compensated in a quick and stable behavior.

In order to investigate the AVR dynamic performance mathematically, the following transfer function modelling is assumed, where the major time constants are used and saturation or other nonlinearities are avoided in the way similar to the literature studies [1–7,10,12–15].

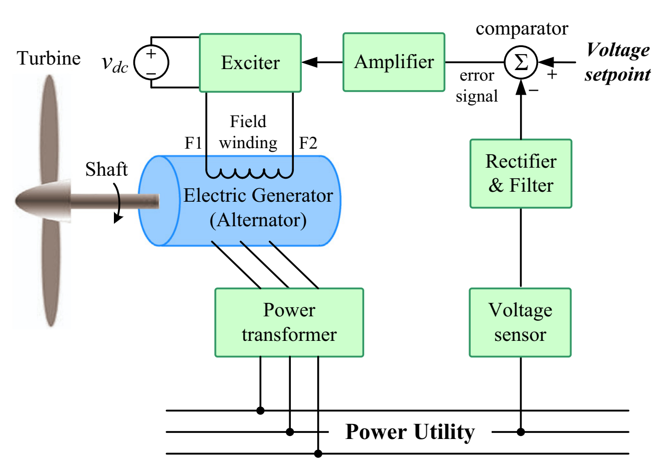

Fig. 1. Schematic diagram of an AVR system.

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