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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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A B S T R A C T

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].

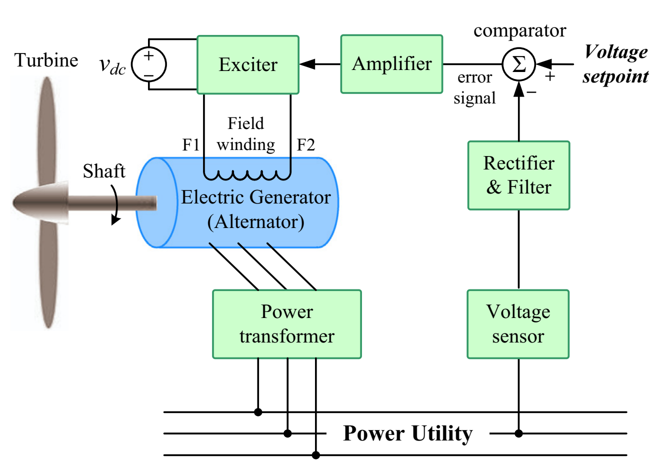

Fig. 1. Schematic diagram of an AVR system.

A. Amplifier model: The amplifier model is given by a gain K_A and a time constant τ_A, as below.

$$G_{Amplifier}(s) = \frac{K_A}{1+\tau_A s} \tag{2}$$

where K_A can vary in the range of 10–40 while τ_A ranges between 0.02 s and 0.1 s.

B. Exciter model: Like amplifier, transfer function model of an exciter may be represented by a gain K_E and a time constant τ_E and is given by

$$G_{Exciter}(s) = \frac{K_E}{1+\tau_E s} \tag{3}$$

Standard values of K_E are in the range of 1–10 and τ_E in the range of 0.4–1.0 s.

C. Generator model: The generator is modelled by a gain K_G and a time constant τ_G, as presented in Eq. (4).

$$G_{Generator}(s) = \frac{K_G}{1+\tau_G s} \tag{4}$$

Herein, K_G and τ_G are the constants dependent on generator loading conditions. K_G ranges from 0.7 to 1.0 and τ_G is between 1.0 s and 2.0 s.

D. Sensor model: The sensor circuit which is responsible for measuring, rectifying and smoothing the system voltage is often modelled by a gain K_S and a time constant τ_S, as given in Eq. (5).

$$G_{Sensor}(s) = \frac{K_S}{1+\tau_S s} \tag{5}$$

where τ_S normally takes small values ranging over 0.001–0.06 s and K_S is in the neighborhood of 1.0.

In this article, to lead a fair comparison with [1,2,5], the same parameter values have been used as $K_A = 10$, $\tau_A = 0.1$, $K_E = 1.0$, $\tau_E = 0.4$, $K_G = 1.0$, $\tau_G = 1.0$, $K_S = 1.0$ and $\tau_S = 0.01$. Adopting the above parameter values of the model, the entire AVR transfer function block diagram is given in Fig. 2.

From Fig. 2, the system transfer function $G_{AVR}(s)$ could be extracted as in Eq. (6).

$$G_{AVR}(s) = \frac{\Delta V_t(s)}{\Delta V_{ref}(s)} = \frac{0.1s+10}{0.0004s^4+0.0454s^3+0.555s^2+1.51s+11} \tag{6}$$

Notice that the input $\Delta V_{ref}(s)$ and output $\Delta V_t(s)$of this system are not current values of the reference input and terminal voltage quantities, but stand for the incremental changes of the corresponding variables. Using Eq. (6), the original terminal voltage step response change of the above AVR system is depicted in Fig. 3, from which the system is observed to be severely oscillating in the beginning and has remarkable error at steady-state. In power systems, such a response is completely unacceptable and cannot be allowed to emerge when considering the operating voltage in the order of kilo-volts.

To improve the transient response of the AVR system and eliminate the steady-state error, a controller such as a PID is required to be installed in the concerned system. Block diagram of PID controller-based AVR design which also adds a disturbance signal to $\Delta V_t(s)$ is shown in Fig. 4.

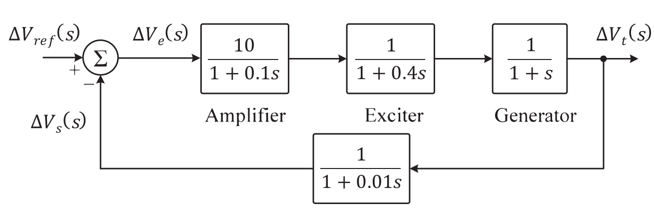

Fig. 2. Transfer function block diagram of the AVR system.

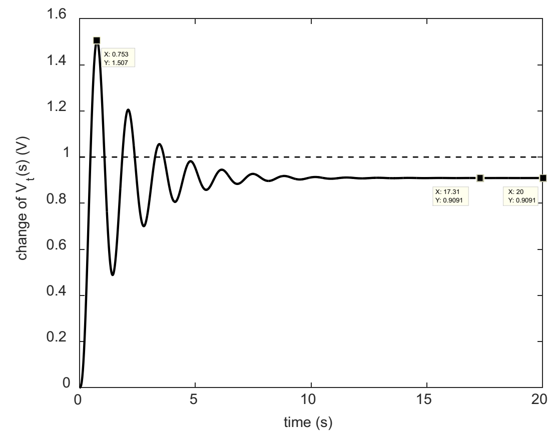

Fig. 3. Original terminal voltage step response change of an AVR system.

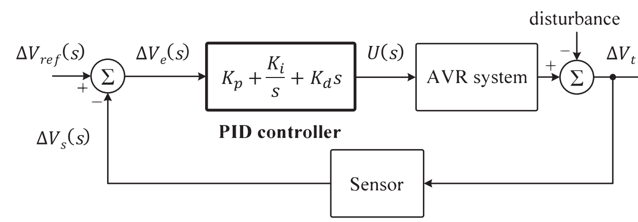

Fig. 4. Transfer function block diagram of the PID controller-based AVR design including a disturbance.

Eventually, assuming the disturbance value in Fig. 4 is zero, the final transfer function model of the AVR system employing a PID $G_{AVR_{P}ID}(s)$ can be represented by

$$G_{AVR_{P}ID}(s) = \frac{G_{PID}(s)\cdot G_{Amplifier}(s)\cdot G_{Exciter}(s)\cdot G_{Generator}(s)}{1+G_{PID}(s)\cdot G_{Amplifier}(s)\cdot G_{Exciter}(s)\cdot G_{Generator}(s)} \tag{7}$$

While we recognize that the system model is not very complex, it has been used popularly in its current state for many years to introduce incremental improvements. As a result of our literature review, it is noticed that there may be still a research gap in improving the system performance further. In this regard, the contribution of this article is not to propose a more realistic AVR model nor to verify a novel scheme for controlling AVR, but to effectively bridge that research gap in the hoping of enhancing the time-domain and frequency-domain performance of the existing AVR system using similar PID controller except that its design parameters are tuned with the guidance of a new cost function which is to be minimized by the employment of SOS algorithm.

3. Design of PID employing SOS

In this part, an efficient PID controller design employing the SOS algorithm, which can be shortly referred to as SOS-PID controller, is realized to enhance the voltage response profile of the AVR system while maintaining satisfactory stability margin. The incorporation of SOS in such a problem is primarily owing to the desire of attaining three controller coefficients K_p, K_i and K_d, so that the controlled system can have the desired performance. SOS is a relatively new algorithm proved to be powerful and robust over different kinds of optimization problems [8]. It operates on the basis of three common symbiotic strategies such as mutualism, commensalism, and parasitism developed by organisms. The property of the interaction characterizes the basis of each phase. Mutualism is the symbiotic interaction in which each organism benefits from the other's activity. Commensalism evolves when one organism receives benefits, while the other organism is neutral, and parasitism evolves when an organism gains benefits from a certain interaction at the cost of degrading the other [16]. Through all phases, each organism interacts randomly with other organisms in the ecosystem. After completion of these three symbiotic strategies, SOS tries another generation and is iterated recursively until pre-defined termination criteria are satisfied. The following outline summarizes the afore-said explanations.

Initialization
REPEAT
i = 1;
while *i* is different from *eco_size*
–Mutualism phase
–Commensalism phase
–Parasitism phase
–*i* = *i* + 1;
end while
UNTIL (termination criteria are met)

For further insight into the SOS algorithm procedures, readers are referred to the original study given by [8].

In order to implement SOS algorithm for optimizing the PID controller gains, three design parameters are initially defined to form an individual organism K by $K = [K_p, K_i, K_d]$, where each member is represented by a real number. Thus, there are three members in an individual to be optimized and each individual may be treated as a PID controller with different gains. To assess the performance of distinct PID controllers in the ecosystem, a suitable cost function complying with the requirements and necessities in a control system design must be defined properly. In literature, there exist various performance measures for design of controllers such as integral of absolute error (IAE), integral of squared error (ISE) and integral of time weighted squared error (ITSE) [17]. An important deficiency of IAE and ISE is that they lead to sluggish response due to the accumulated errors regardless of the time. On the other hand, ITSE can solve this problem and increase the dynamic response, but this is not desirable as far as stability margin is concerned as in [3]. Instead, integral of time weighted absolute error (ITAE) has been demonstrated in several studies to exhibit better system performance as compared to its integral-based counterparts [18]. In order to make this study compete with [1,2,5], two more parameters obtained from the frequency-domain response of the system are considered and combined with the ITAE criterion by weighting each term as shown in Eq. (8).

$$J = \omega_1 \int_0^{t_{sim}} t|\Delta V_e(t)|dt + \omega_2 \alpha + \omega_3 \frac{1.0}{\beta} \quad (8)$$

The first term on the right side of Eq. (8) relates to ITAE which accumulates the product of the current time t and absolute error in terminal voltage $|\Delta V_e(t)|$ up to the sufficiently chosen simulation time t_{sim}. α is the number of complex poles computed from the characteristic equation of the system while β is the sum of the damping ratios of the complex poles. Importance of each term in J is set by a weight factor ω_j. Recommended values of the weight factors are $\omega_1 = 0.71$, $\omega_2 = 0.2$ and $\omega_3 = 0.09$. It is worth highlighting that better performance is got when the value of J is minimum which requires that the values of ITAE and α are minimized and that of β is maximized. For increased stability margin, a less number of complex poles and their associated damping ratios closer to one are more preferred.

In the presented technique visualized in Fig. 5, initial ecosystem including a number of organisms is generated randomly; each

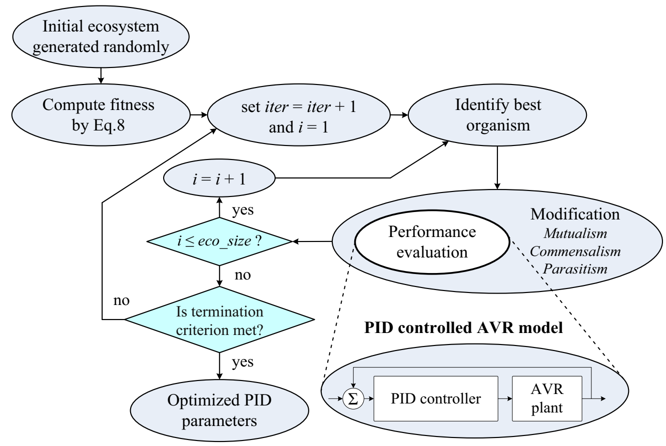

Fig. 5. SOS program implementation for optimizing PID controller gains in AVR control application.

organism has K_p, K_i and K_d gains ranging from 0.01 to2.0. After the best organism is identified, organisms are used in the PID control law in order to simulate the system behavior by means of the PID controlled AVR model. As predicted, each organism exhibits different terminal voltage curve with its own time-domain response and frequency-domain response. Then, using Eq. (8), a fitness value is computed for each organism. Later on, the organisms are modified using the particular SOS phases for the next iterations.

This process of identifying best organism, performance evaluation and employing SOS strategies is iterated until *i* is equal to the number of organisms in the ecosystem. Otherwise, unless termination criterion is met, iteration number is increased and *i* is set back to 1 again, and the whole process is repeated. The PID parameters obtained at the end of the program are used in the subsequent simulations.

4. Numerical results

In this section, simulation results obtained after applying the presented technique to the AVR system are provided, and a fair comparison from perspective of transient response analysis, root locus analysis and bode analysis is also presented in comparison with ABC [1], MOL [2] and BBO [5], which have been published in esteemed journals. In SOS algorithm, only two parameters are set as *ecosystem size* = 30 and *maximum iteration number* = 30. Simulations were implemented in the Matlab 8.5.0 (R2015a) software installed on a computer with an Intel core (TM) i5 3.3 GHz processor and 8 GB memory.

One of the major observations of the present study for analyzing the voltage response curve is given in Fig. 6, where the disturbance value in Fig. 4 is considered zero. In this figure, the change of output voltage response of proposed PID-controlled AVR system to a step command is portrayed comparatively with other indicated approaches. From Fig. 6, it is apparently viewed that the systems are poorly damped with ABC- and BBO-tuned PID controllers. It is also noticed that as compared to MOL-based response, the designed controller offers less peak overshoot (black trace) while maintaining nearly the same settling time, which is a prior indicator for improvement of stability degree of the concerned control application. Also notice that the responses with ABC and BBO cannot be hold at 1.0 pu for the considered simulation time. This is attributed to the use of ITSE cost function in those studies, which leads to unrealistic evaluations owing to squaring error. As a result, a better setpoint tracking performance is achieved with the presented technique than other techniques.

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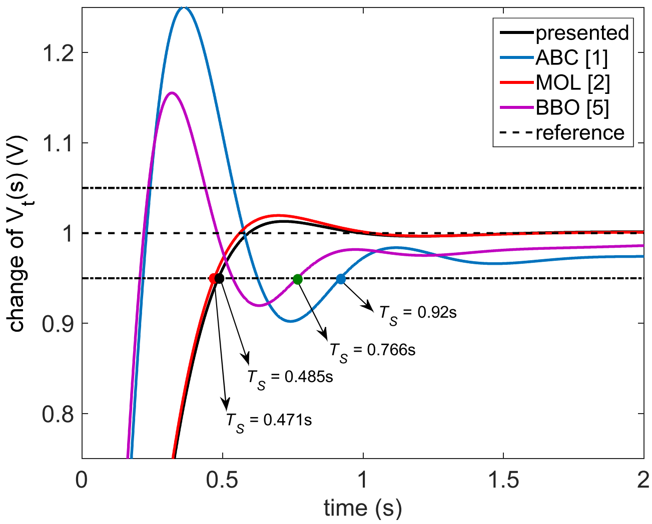

Fig. 6. Comparative terminal voltage changing profiles.

The transient response and steady-state performances regarding the time responses are measured from Fig. 6 and reported in Table 1. Transient response analysis covers the time domain performance characteristics such as peak overshoot (M_P), settling time (T_S, 5% band) and rise time (T_R) whereas steady-state performance is with the error value at steady-state (E_{SS}). In addition, optimized PID controller parameters are also given in their respective sections of Table 1. In the reported results, **bold** text indicates comparatively the best result.

It is noticeable From Table 1 that SOS-based PID control offers the best value of peak overshoot and comparable settling time with only 2.9% less than MOL-based result. On the other hand, steady-state error values of SOS- and MOL-based results are the same, and both are significantly better that those of ABC and BBO. The best result concerning rise time belongs to BBO algorithm.

For the stability concern of the studied AVR system optimized by the proposed technique, root locus analysis is performed and the respective root locus curve is depicted in Fig. 7. As shown, all the closed-loop poles are located at the left side of the *s*-plane, meaning that the proposed control application is stable.

The closed-loop poles and their respective damping ratios in Fig. 7 are also computed and gathered in Table 2 in comparison with the other indicated studies. It is clear that the conjugate poles of the presented AVR system are farther away from the imaginary axis, which makes the system be controlled with the biggest damp-

Table 1
Comparative controller parameters and corresponding system performance specifications.

Controller parameters/ performance/techniques	Presented	ABC [1]	MOL [2]	BBO [5]
K_p	0.5693	1.6524	0.5857	1.2464
K_i	0.4097	0.4083	0.4189	0.5893
K_d	0.1750	0.3654	0.1772	0.4596
M_P	**1.013**	1.250	1.020	1.160
T_S	0.485	0.920	**0.471**	0.766
T_R	0.353	0.156	0.343	**0.149**
E_{SS}	**0.002**	0.026	**0.002**	0.014

Table 2
Closed-loop poles and their respective damping ratios of the AVR system optimized by SOS, ABC, MOL and BBO algorithm.

Algorithm	Closed-loop pole	Damping ratio
Presented	−100.48	1
	−1.98	1
	−1.10	1
	−4.97 + 4.69i	**0.727**
	−4.97 − 4.69i	**0.727**
ABC [1]	−100.98	1
	−4.74	1
	−0.25	1
	−3.75 + 8.40i	0.40
	−3.75 − 8.40i	0.40
MOL [2]	−100	1
	−2.11	1
	−1.06	1
	−4.92 + 4.72i	0.721
	−4.92 − 4.72i	0.721
BBO [5]	−100.0	1
	−2.1	1
	−0585	1
	−4.8 + 10.2i	0.427
	−4.8−10.2i	0.427

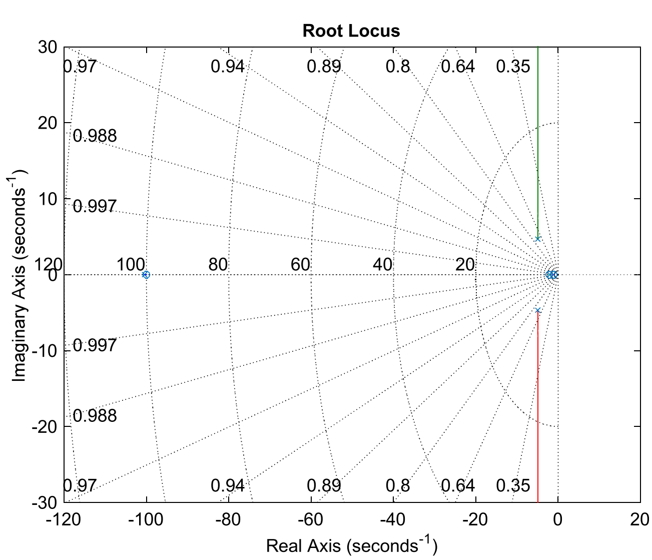

Fig. 7. Root locus curve of the studied AVR system.

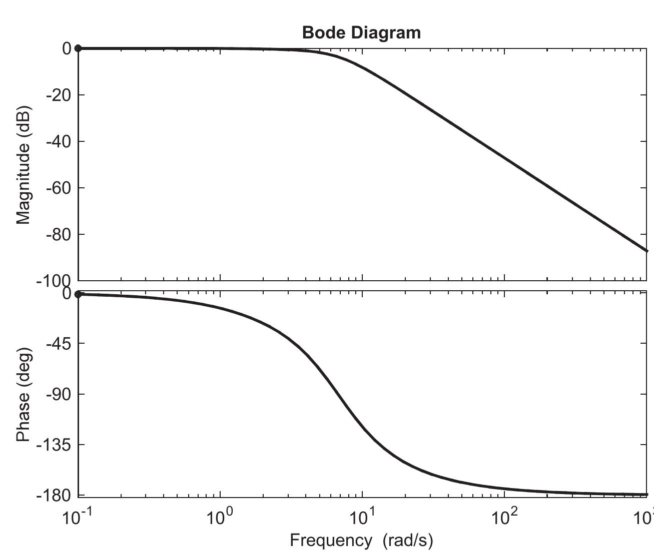

Fig. 8. Bode diagram of the proposed AVR system.

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ing ratio value of 0.727, which is 45% more than ABC, 0.83% more than MOL and 41% more than BBO.

So as to investigate the stability of the proposed AVR through another point of view, frequency response or bode analysis of the control system is conducted, and the resulting bode diagram is depicted in Fig. 8. The peak gain, phase margin, delay margin and bandwidth parameter corresponding to this bode plot are tabulated in Table 3.

From Table 3, it is seen that the minimum peak gain, maximum phase margin and maximum delay margin, which are essential factors required for enhanced stability, are provided by both our proposal and that based on MOL algorithm. With regard to bandwidth, its maximum value is offered by using BBO algorithm. As a consequence, as far as peak gain, phase margin and delay margin measures of the bode analysis are concerned, the same performance is achieved by deploying SOS and MOL, and they are the pioneers over the remaining techniques.

Table 3
Peak gains, phase margins, delay margins and bandwidths of different AVR systems using SOS, ABC, MOL and BBO algorithm.

	Presented	ABC [1]	MOL [2]	BBO [5]
Peak gain (dB)	**0.0**	2.87	**0.0**	1.56
Phase margin (deg.)	**180**	69.4	**180**	81.6
Delay margin (s)	**Inf.**	0.111	**Inf.**	0.122
Bandwidth	6.15	12.88	6.34	**14.28**

Now that the presented AVR system arguably performs better than the existing studies, the paper is extended by only focusing on the robustness of SOS optimized PID controller in presence of model uncertainty and external disturbances. Such a robustness analysis, which is previously missing in the conference version of this article, is indispensable as the final stage to validate any novel control scheme. To bridge this gap, first, time constants of the system elements such as amplifier, exciter, generator and sensor are changed separately in the range ±50% of the nominal value in steps of 25% while the controller parameters in Table 1 remain the same. The resulting responses to sudden changes in τ_A, τ_E, τ_G and τ_S are shown by four subplots in Fig. 9 along with the nominal response and the reference input signal.

Numerical results of the robustness analysis obtained from transient response analysis applied to the plots in Fig. 9 are also computed and tabulated in Table 4 for each time constant parameter.

Moreover, the range of total deviation between the maximum and minimum value of a time-domain performance parameter, and the percentage of maximum deviation relative to the corresponding nominal value are also reported in Table 5 in order to give a better picture of the robustness analysis. It is clear from Table 5 that the deviations from the nominal values are generally small. As we can see at first glance, variation of the sensor time

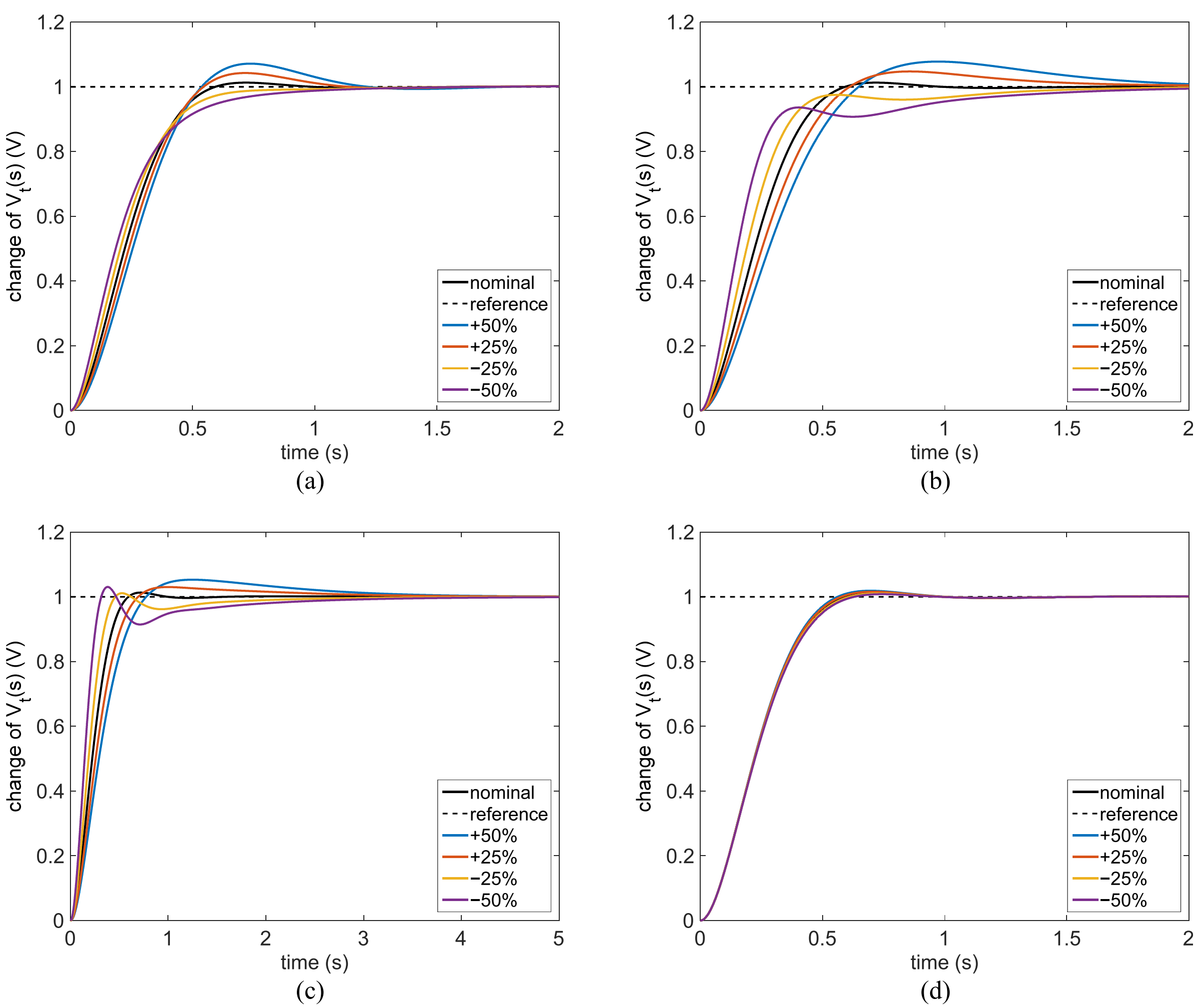

Fig. 9. Step responses of the studied AVR system under the variation of time constants (a) τ_A (b) τ_E (c) τ_G (d) τ_S.

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Table 4
Numerical results of robustness analysis of the AVR system controlled by SOS optimized PID controller.

Parameter	Rate of variation (%)	Peak Overshoot (V)	Settling Time (s)	Rise Time (s)
τ_A	+50	1.072	0.905	0.355
	+25	1.043	0.481	0.351
	−25	1.001	0.519	0.367
	−50	1.001	0.607	0.408
τ_E	+50	1.078	1.336	0.431
	+25	1.047	0.534	0.393
	−25	0.998	0.438	0.307
	−50	0.994	0.958	0.258
τ_G	+50	1.053	1.434	0.489
	+25	1.030	0.578	0.423
	−25	1.000	0.384	0.278
	−50	0.999	1.017	0.202
τ_S	+50	1.019	0.472	0.345
	+25	1.016	0.479	0.348
	−25	1.010	0.492	0.357
	−50	1.008	0.499	0.362

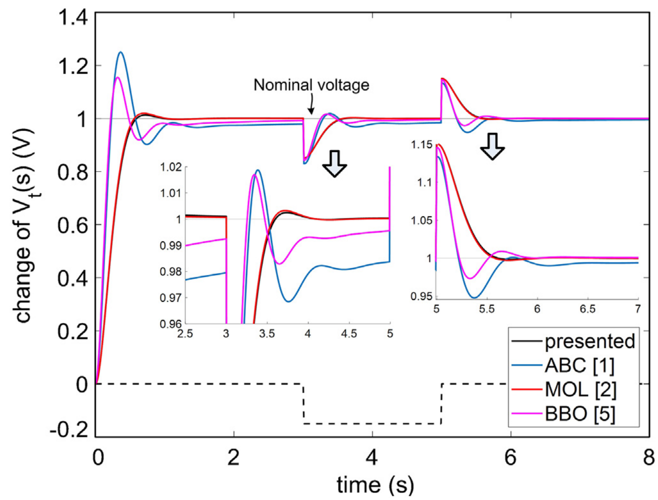

Fig. 10. Step responses of different controllers under external disturbance.

Table 5
Range of total deviations and percentage of maximum deviations (%) under parameter uncertainty.

Time constant	Parameter	Range of total deviations	Percentage of maximum deviations (%)
τ_A	Peak overshoot (V)	0.071	5.82
	Settling time (s)	0.424	86.6
	Rise time (s)	0.057	15.6
τ_E	Peak overshoot (V)	0.084	6.4
	Settling time (s)	0.898	175.5
	Rise time (s)	0.173	26.9
τ_G	Peak overshoot (V)	0.054	3.9
	Settling time (s)	1.050	195.7
	Rise time (s)	0.287	42.8
τ_S	Peak overshoot (V)	0.011	0.6
	Settling time (s)	0.027	2.89
	Rise time (s)	0.017	2.5

constant τ_S has almost negligible impact over the system response compared to that of other time constants. Given an example, following a change in τ_A in the specified interval, peak overshoot deviates from its nominal value in the range 0.071 V, settling time in the range 0.424 s and rise time in the range 0.057 s, which lead to maximum deviations of 5.82%, 86.6% and 15.6% with respect to the nominal values, respectively. Considering all the time constants, the average deviation of the peak overshoot, settling time and rise time are 4.2%, 115.2% and 22%, respectively. The fact that all the ranges of total deviations are approximately below 0.5 proves that the SOS-PID controller is robust and preserves the desired transient response regardless of the variation in any of the time constants in the considered change interval.

Finally, in order to verify disturbance rejection capability of our contribution against other techniques, an external disturbance is introduced between $t = 3$ and $t = 5$ s by setting the disturbance value in Fig. 4 as 0.15. As is observed in Fig. 10, in all cases the terminal voltage changing curve settles to the reference value after each perturbation; however, responses to external disturbance using ABC and BBO exhibit some oscillations and longer settling time. On the other hand, SOS- and MOL-PID controllers gain a similar level of disturbance rejection where the disturbances owing to the unknown changes in the system output are rejected well, but with a slightly faster sense in the case of our proposal.

5. Conclusion

Tuning problem of control parameters of a PID controller working in an AVR control application is addressed and tried to be solved in a better fashion by introducing a new cost function which is optimized employing SOS algorithm. After the cost function definition is realized with regard to both time-domain and frequency-domain performance criteria, SOS is invoked subsequently as the powerful optimization technique to tune controller gains in a sense that minimum cost function value could be achieved. In order to appraise the effectiveness of presented approach, three popular studies are chosen from the literature as a benchmark, then the results are compared under identical conditions from the perspective of diverse analysis techniques such as transient response analysis, root locus analysis and bode analysis. Simulation results show that the cooperation of the developed cost function and SOS algorithm improves the trade-off between the dynamic response and the stability margin of the system. In this context, the presented approach is able to effectively improve the stability degree of the considered AVR system by further reducing the peak overshoot of the system time response compared to existing approaches. Moreover, depending upon the results evolved from the robustness analysis, it is found that the proposed AVR system is well capable to maintain the desired response when exposed to the applied parameter uncertainties and external disturbance. Finally, according to the various tests performed by the authors, it has been seen that if desired, stability margin of the system can be further improved by increasing ω_3 in Eq. (8). However, this will degrade the transient-time characteristics such as rise time and settling time. For interested researchers, it would be of interest to use any other powerful optimization algorithms along with the cost function defined in this paper in the hope of improving the AVR performance further.

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