Tuning of PID Controller Coefficients for AVR Systems by Simulated Annealing Algorithm

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ABSTRACT:
As a real time process, in tuning the coefficients of PID controllers in AVRs, accuracy vs. speed is an important issue. Considering complexity of the problem and real systems requirements, various methods, including exact methods and approximation algorithms, have been implemented for this purpose. Since the conventional methods based on meta-heuristic algorithms solving this problem, generally use population-based algorithms such as GA and PSO, this paper aims to investigate the efficiency and performance of single- solution based metaheuristics to solve this problem. So Simulated Annealing (SA) algorithm is proposed, and implemented for optimizing PID coefficients. In addition, an extension of SA is presented improving the search strategy based on neighborhood adjustment. The results indicate that the proposed algorithms as single based metaheuristics, have a good or even better performance vs. population based metaheuristics, in spite of simplicity in implementation and less computation requirements. This fact implies that the landscape complexity of these problems does not necessarily require population-based algorithms. The presented method is also applied to multiple objective functions regarding different time response criteria in output voltage and leads to better results in less time.

KEYWORDS: AVR System, PID Controller, Population based and Single-solution based Metaheuristics Algorithms, Simulated Annealing Algorithm.

1. INTRODUCTION

Types of automatic voltage control are used for voltage stabilization under variable load and frequency conditions in power plants. Different types of controllers are used to control AVR (Automatic Voltage Regulator) systems, and the most important one is the PID controller (Proportional Integrator and Derivative controller) and there are several methods for tuning the coefficients of PID controllers. In this research area, there are many articles in which population based meta-heuristics like GA (Genetic Algorithm) or PSO (Particle Swarm Optimization) have been applied to this problem.

In this article, the SA method is used as a single-solution based meta-heuristic algorithm to optimize the PID coefficients. The algorithm and simulating AVR system and PID controller are implemented using MATLAB and Simulink software. Previous works in this field generally used population based metaheuristics which are suitable for optimization problems with high complexity in the landscape of solutions.

This paper suggests single solution based metaheuristics, that generally are simpler in implementation and need less computation. So the purpose of this article is to compare the performance of population-solution based algorithms such as GA and PSO with single-solution based algorithms such as SA in the problem solving. In addition, an extended version of the simulated annealing algorithm based on neighborhood adjustment is presented improving the search strategy. Moreover, as another contribution, multiple object functions based on different response time characteristics such as overshoot, rise time and settling time, are linearly combined as a single object applied to the problem in this paper.

In the following, introducing the main concepts, we will review the methods applied to optimal PID control in the AVR system in the related literature. Then, in the next section problem modelling and formulation, also simulation method and the proposed algorithm will be explained. Finally, comparative results, conclusions, and some suggestions for further research are presented.

1.1. Automatic Voltage Regulator (AVR)

The role of the AVR system in a power grid is to

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regulate the output voltage of a synchronous generator connected to a steam turbine at a specified level. Therefore, the stability of the AVR systems is very important. The AVR is a closed-loop controller that compares the signal proportional to the output voltage of the generator with a constant base voltage and uses the voltage error obtained to control the output of the excitation system [1]. Fig. 1 shows the general scheme of the AVR.

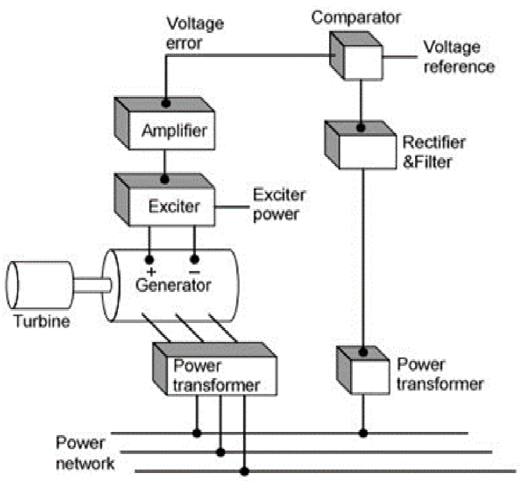

Fig. 1. General scheme of the AVR [2]

1.2. PID Controller

The PID controller, most widely used in different industries, is applied to reduce steady state error. In spite of simplicity in design and implementation, this controller provides good stability and fast response. PID controllers consisting three main parts: Proportional, Integral and Derivative, use a control loop feedback mechanism to control process variables. The PID controller conversion function is expressed in relation (1):

$$Gc(S) = Kp + Ki/S + KdS \tag{1}$$

In which, K_P is the proportional coefficient, K_i is the integral coefficient and K_d is the derivative coefficient.

1.3. Metaheuristic Algorithms

Metaheuristic algorithms provide some random search strategies in the solution space applicable to a wide range of optimization problems in various fields providing near optimal solutions, however determining the exact optimum by exact mathematical methods gets impossible due to the problem complexity or solving time or some other limitations.

These algorithms are divided into two main categories: single solution based and population based algorithms [3]. In single solution based algorithms, the search starts from a single solution and follows a solution by solution search path in the solution space till the stop condition and the algorithm terminates.

The Simulated Annealing algorithm and Tabu search belong to this category. Whereas in population-solution based algorithms, the search is based on a population of solutions in each iteration and thus the search in the solution space is more complete and can be navigated simultaneously in multiple regions. So. it would typically be harder to design and implement and generally with higher solving time. Genetic algorithm, ant colony and Particle Swarm Optimization algorithm are among this second group of algorithms. Therefore, which algorithm would be suitable for solving an optimization problem, depends on its requirements and mostly the complexity of its landscape complexity in solution space.

1.4. Simulated Annealing Algorithm

This algorithm as a single solution based metaheuristics is inspired by the method of metal cooling in order to achieve a robust structure. Main idea in this method is based on accepting the worse solutions in some conditions in order to escape the local optimum. In each iteration, a random neighbor is generated and accepted as new solution on the condition of improvement in the objective function, otherwise, with a certain probability that depends on the current temperature and worsening degree of the objective function, it would be accepted or another neighbor would be generated as the new point in the search path. A control parameter called temperature determines the probability of accepting the worse solutions. At a specified temperature level many points in the search space would be examined achieving to equilibrium condition at that temperature. Then the temperature is gradually decreased. As the algorithm progresses, the probability of accepting worse solutions decreases. This probability generally follows the Boltzmann distribution:

$$P(\Delta E, T) = e^{-\Delta E/T} \tag{2}$$

Where, T is the current temperature, ΔE is the magnitude of the difference between the objective function for the current solution and the new one.

The algorithm continues with a gradual decrease in temperature and achieving equilibrium condition in each temperature to obtain the stopping condition, which is usually the final temperature. The main parameters of the algorithm include initial temperature, final temperature, equilibrium condition at each temperature and the rate of temperature decrease.

2. LITERATURE REVIEW

Different methods are used to adjust PID controller coefficients in different applications according to the real conditions and constraints. Trial and error, neural network, fuzzy system [4], neural-fuzzy logic [5], and Ziegler-Nichols (Z-N) [6] method are mentioned here among various methods. Some of these methods apply exact mathematical methods, while considering time limitation and other constraints in real problems, many methods try to just provide approximate and near optimal solutions with an admissible accuracy.

Therefore, nowadays, the Ziegler Nichols and similar methods is no longer used due to the disadvantages including high time, conditional stability and system damage. Also, the implementation of fuzzy logic in common hardware requires multiple and time-consuming experiments, which is why it is used less often these days.

In applications such as voltage control and stabilization as a real time process, where solving time is important, approximation and meta-heuristic methods are widely used. In article [2] Three objective functions are considered and Genetic Algorithms(GA) and Particle Swarm Optimization algorithm (PSO) are used to design PID controller parameters for the AVR system in a synchronous generator.

Also in the article [7] the Imperialist Competitive Algorithm (ICA) is used to design a fuzzy-PID controller to control the AVR system.

In article [1] Three objective functions are considered and the BBO algorithm is used to adjust the parameters of the AVR system controller. Also in articles [8], [9] and [10], optimization of PID controller coefficients by PSO algorithm with different objective functions is performed.

In the article [11] using Tabu Search algorithm is used to design a PID controller for AVR system.

3. MATERIALS AND METHODS

3.1. AVR and PID Models and Parameters and Software

In this article, a typical PID controller is designed and simulated to control the output voltage in Simulink based on the model, given in Fig. 2. Tuning the PID coefficients is implemented by the proposed algorithm in order to optimize three objective functions, including: maximum overshoot, a weighted combination of maximum overshoot and settling time and finally a weighted combination of maximum overshoot and rise time.

In most of the articles, merely one of the features of Time response is considered as the objective function, but improving one of them leads to worse conditions for the others. So in this article a linearly weighted combination of overshoot, rise time and response time is considered as the objective function. Fig. 2 shows the block diagram of the AVR system with the PID controller.

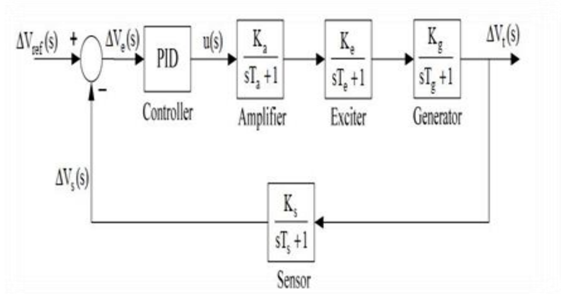

Fig. 2. AVR Diagram Block with PID [2].

The model of the AVR system in this paper is similar to the model in articles [1], [2], [4] and the parameters values is set based on the article [2].

Amplifier:

$$V=ka/(1+STa) \quad , \ 10\leq ka\leq 40 \ , \ 0.02\leq Ta\leq 0.1 \ , \quad ka=10 \ , \ Ta=0.1 \tag{3}$$

Exciter:

$$V=ke/(1+STe), \ 1\leq ke\leq 1, \ 0.4\leq Te\leq 1, \quad Ke=1 \ , \ Te=0.4 \tag{4}$$

Generator:

$$V=kg/(1+STg) \quad , \ 0.7\leq kg \leq 1 \ , \ 1\leq Tg \leq 2 \ , \quad Kg=1 \ , \ Tg=1 \tag{5}$$

Sensor:

$$V=ks/(1+STs) \ , \ 0.001\leq TS \leq 0.06 \ , \quad Ks=1 \ , \ Ts=0.01 \tag{6}$$

Fig. 3 shows the AVR block diagram with the PID controller used in the AVR block simulation.

3.1. Algorithms and Methods Applied for Tuning PID Coefficients as an Optimization Problem

In this article, we adjust the PID coefficients in order to optimize AVR performance considering different objective functions, including:

- Improving maximum overshoot
- Improving the linear combination of maximum overshoot and settling time
- Improving linear combination of maximum overshoot and rise time

It is performed by implementing three methods, based on SA algorithm:

- SA
- SA algorithm with multi start points
- an extension of SA improving search strategy by neighborhood adjustment, presented and implemented in this paper

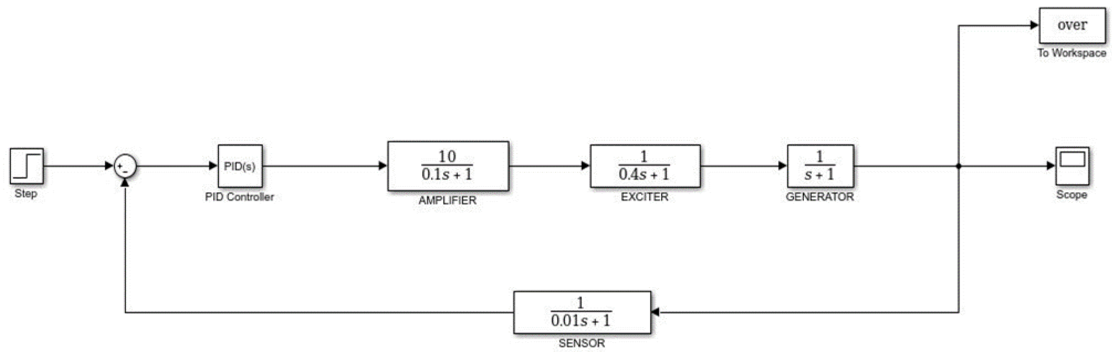

Fig.3. Simulation of AVR and PID Simulink.

3.2. Improved SA Algorithm Presented in this Paper

The SA algorithm makes it possible to escape local optimum and search more properly in the solution space by accepting the worse solutions in the certain conditions.

The modifications in the proposed algorithms are based on adjusting neighborhood distance in different conditions: in an iteration If a better solution is generated, it would be accepted as new point and the neighborhood distance for generating the next random solution would be set on a small radius. But on the condition of accepting worse solutions in order to escape the local optimum, the neighborhood distance for generating the next random solution would be set on a bigger radius. This trick makes it possible to escape from a local optimum in a larger region and improves the search diversity. So the search intensifies in the locations with probable better solutions and diverges in the condition of a local optima trapping. The flowchart of this algorithm is provided in Fig. 4.

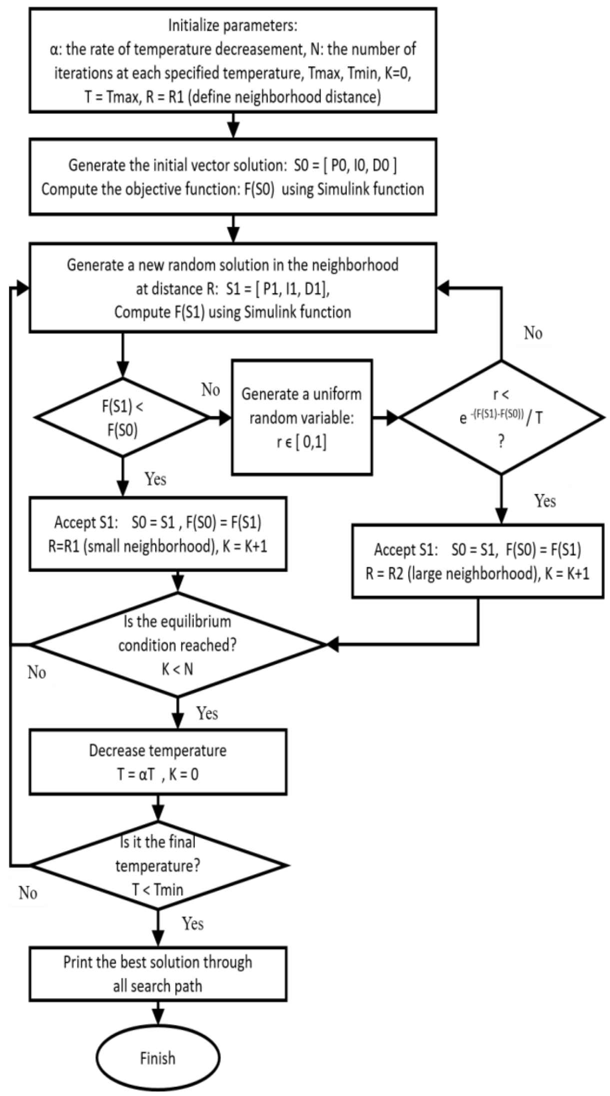

Fig. 4. Flowchart of the improved SA algorithm (R:R1,R2 are defined to adjust neighborhood distance in different situations).

4. RESULTS AND DISCUSSION

Fig. 5 shows the step voltage response of the AVR system without any specific coefficients adjustment. As it is clear, the system has high fluctuations and distortions.

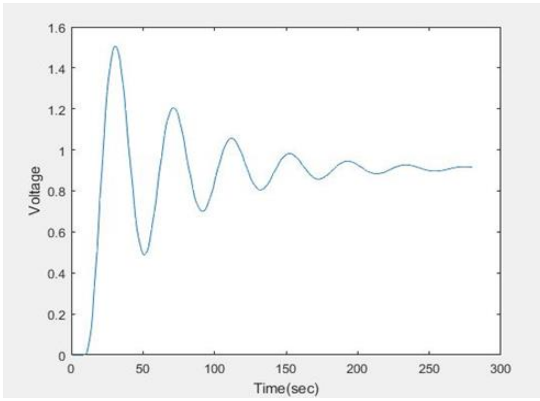

Fig. 5. Output AVR step function.

The simulation results of the system output applying the SA algorithm, SA algorithm with multi start points, and the proposed algorithm here in this paper, to improve the different objective functions, are given in Table 1.

Table 1. System output results with the developed SA algorithm (Mp: maximum overshoot, tr: rise time, ts: settling time, related to the final solution)

method	Mp	tr	ts
SA	1.0835	0.1080	1.0584
multi start SA	1.0870	0.1075	1.0652
Improved SA (presented in this paper)	1.0721	0.1017	0.9605

As can be seen, the best results are related to the proposed algorithm based on the SA development using variable neighborhood radius as shown in Figs. 6, 7 and 8.

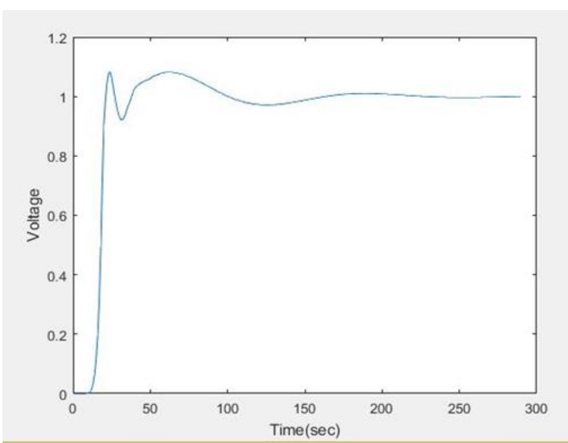

Fig. 6. System output with overshoot objective function improvement.

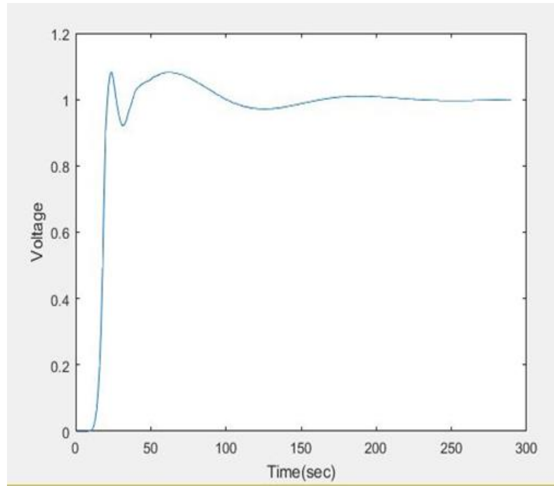

Fig. 7. System output with rise time objective function improvement.

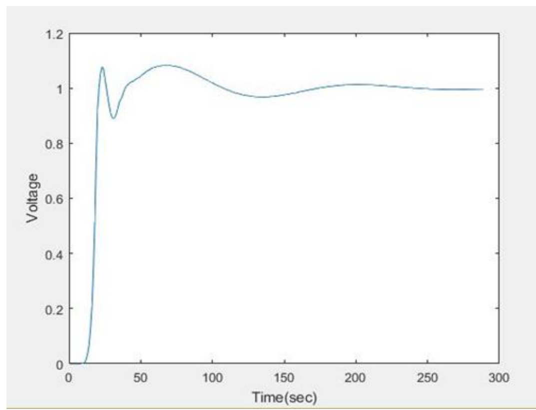

Fig. 8. System output with settling time objective function improvement.

As can be seen, by improving each parameter, the other parameters may become worse and to solve this problem, the parameters can be combined together and the objective function can be considered as linear combination of each characteristic: maximum overshoot, rise time and settling time. Some results are given in Table 2.

Table 2. System output results with specified linearly combined objective functions

method	Mp + tr	Mp	tr
Modified SA (presented in this paper)	1.2448	1.1504	0.1044

method	Mp + ts	Mp	ts
Improved SA (presented in this paper)	2.3771	1.1691	1.0322

Finally, Table 3 compares the results of the output characteristic under control by the presented method in this article with the results in the reference article [2] applying Genetic Algorithm and PSO Algorithm tuning system coefficients.

Table 3: Comparison of our modified SA algorithm results to the results by other algorithms [2].

method	Mp	tr	ts
Improved SA (presented in this paper)	1.0721	0.1017	0.9605
GNA [2]	1.124	0.215	0.808
PSO [2]	1.078	0.255	0.915

4.1. Discussion

The main purpose of this paper is proposing an appropriate metaheuristic for determining control system coefficients in order to better output stabilization as an optimization problem. In fact, there are many optimization methods and choice, the appropriate type for any range of problems is an important issue in solving optimization problem. In turn, when meta heuristics methods are suitable for an optimization problem, choosing an appropriate algorithm among various algorithms would be an important question and some concerns would be important such as required accuracy, speed, simplicity in design and implementation, etc. These issues depend on mathematical problem structure and requires landscape analysis.

The previous works used generally population based metaheuristics such as PSO and GA and ACO solving this problem. In general, implementation of the population based metaheuristics generally is more complicated and needs more time and space requirements than single solution based methods such as SA algorithm. Whereas the results of this paper show that in tuning control system coefficient in order to better output stabilization as an optimization problem, the SA algorithm and some its modified versions as singe solution based metaheuristics have even better performance vs. the method base on population based metaheuristics such as PSO and GA. This fact clarifies implicitly that the complexity degree of the search landscape in these problems does not require population based algorithms. Also an extended version of SA designed and implemented improving search strategy by neighborhood adjustment and the results indicate its better performance.

5. CONCLUSIONS AND SUGGESTIONS

Time and speed are important issues in adjusting control parameters in many systems specially in tuning the coefficients of the PID controller in the AVR system as a real time optimization problem. So among many exact and approximative methods, metaheuristics have an important role and wide applications in solving many real time optimization problems providing a near optimum solution in an admissible time. However, choosing an appropriate algorithm among various metaheuristics methods would be an important question and some concerns would be important such as required accuracy, speed, simplicity in design and implementation, etc. that depend on mathematical problem structure and real problem requirements.

However, the review of related articles shows that chiefly population-based algorithms such as GA and PSO have been used solving the problem, which can be implemented harder and need more time and space requirements, therefore are appropriate for problems with complicated search landscape with highly irregular distribution Patten of numerous local optimums.

Even so, the results of this article in designing and implementing an extended version of the SA-based algorithm as a single-solution based algorithm, show that the proposed algorithm has better performance than the genetic algorithm and PSO in solving this problem. These results implicitly show that the search landscape of this range of problems is not too complicated to apply population-based algorithms that require harder design and implementation and need more time generally. Presenting a new modification of SA based on neighborhood adjustment in order to improve search strategy and also applying a linear combination of different characteristics of desired output signal as a single objective function can be considered as the other contributions in this paper.

As direction for further research these points can be mentioned. firstly, in the presented algorithm as an extension to SA, the neighborhood distance in the search path in each iteration is chosen depending on the better or worse new solution acceptance. Modifying variable neighborhood distance in the search path depending on the temperature, also could be considered as an improvement in search strategy. The next point, the algorithm parameters and also the weights in the linear combination of criteria in the objective function could be important in the quality of the final solution and effects the system response. Investigating different parameters and the right choice may be considered in another research.

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