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Experimental evaluation of optimal tuning for PID parameters in an AVR system

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Transient step response.

Abstract. Automatic Voltage Regulator (AVR) is employed to stabilize the output voltage of generators at electric power plants. However, reliable performance of AVR depends on professional tuning of its PID controller parameters. Therefore, different optimization algorithms are used to determine those parameters. The objective of the optimization is defined as minimizing the characteristics of transient step response such as settling time, rise time, overshoot, and steady state error. Then, to verify the optimization results, a simulator is built experimentally for AVR and PID system which can also be used for other studies on AVR systems. Experimental results are compared with those of MATLAB and Pspice software. Close agreement between the simulation and experimental results confirms the success of the optimization.

1. Introduction

Automatic Voltage Regulator (AVR) is essential equipment used in power systems. The main role of the AVR system is to control the output voltage of a synchronous generator at power plants by applying fast and transient changes to its exciter. However, the generator's responses to these changes are usually slow because it has high inductance and also its load varies quickly [1]. In order to increase the AVR efficiency and improve its dynamic behavior, a Proportional-Integral-Derivative (PID) controller is added to the AVR system due to its easy implementation, robust performance, and simple physical principle [2].

To achieve an appropriate closed-loop performance of the whole system, three parameters of the PID controller (K_p, K_i, and K_d) must be accurately tuned. Tuning methods of PID controller include trial-and-error as well as traditional and artificial methods. Trial-and-error and traditional approaches such as Zigeler and Nichols are not appropriate for tuning PID parameters due to their high overshoot and long-term oscillation in the step response [3]. Moreover, finding the best PID parameters using the two approaches is a time-consuming process due to massive calculations and the results are not always optimal [2]. To overcome the mentioned drawbacks, Artificial Intelligence (AI) methods are proposed. The objective function of this optimization process is usually defined as a combination of step response characteristics including minimizing the overshoot, rise time, settling time, and steady state error [4].

There are various AI methods for optimizing PID parameters in an AVR system and each one has its own merits and demerits [5]. Neural network, fuzzy system, and neural-fuzzy logic were three famous AI techniques

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[6–8]. These methods suffer from the problems of convergence time, training process, and tuning the membership function [9]. Therefore, heuristic methods are welcomed to achieve higher performance. Among different heuristic algorithms, Genetic Algorithm (GA) [10] and Particle Swarm Optimization (PSO) [11] are widely used for tuning the parameters of PID controller. However, they suffer from significant computational burden [12], especially when there is a correlation among optimization parameters [13]. Therefore, many authors have attempted to modify these algorithms or combine them with other algorithms to improve their efficiency and obtain minimum step response characteristics (including overshoot, rise time, settling time, and steady state error) and convergence time. For example, authors in [14] combined Taguchi with PSO and revealed that this new algorithm could tune PID parameters faster and better than PSO and Taguchi combined with GA in order to achieve the best AVR step response. Furthermore, a new Modified PSO (MPSO) algorithm was developed in [15] for a PID controller, leading to a better AVR step response than conventional PSO algorithms in terms of improving computational efficiency and time complexity. In addition, multi-objective non-dominated shorting genetic algorithm [16,17], MPSO algorithms so-called Velocity Update Relaxation Particle Swarm Optimization (VURPSO), and Craziness based Particle Swarm Optimization (CRPSO) [18], combined Taguchi with GA [19], Chaotic Particle Swarm Optimization (CPSO) [20], Particle Swarm Optimization with the Gravitational Search Algorithm (PSOGSA) [21], simplified Particle Swarm Optimization (PSO) also called Many Optimizing Liaisons (MOL) algorithm [22], and Adaptive PSO (APSO) [23] are other suggestions having faster and more efficient optimized AVR step responses than conventional optimization algorithms.

Some other researchers have proposed using newly developed heuristic optimization methods to overcome the above-mentioned limitations of conventional methods. They claimed to have found a more optimum response by comparing the step response characteristics with those of GA and PSO in faster optimization. Those algorithms include Monarch Butterfly Optimization Algorithm (MBO) [24], Taguchi method [25], Slap Swarm Algorithm (SSA) [26], Artificial Bee Colony (ABC) [27], Bacterial Foraging Technique (BFT) [28], Memetic Algorithm (MA) [29], Firefly Optimization Technique (FOT) [30], Shuffled Frog Leaping (SFL) [31], Continuous Action Reinforcement Learning Automata (CARLA) [32], Differential Evolution (DE) and Teaching-Learning-Based Optimization (TLBO) algorithms [33,34], Pattern Search Algorithm (PSA) [35], Simulated Annealing (SA) [36], finite gradient [37], Global Neighborhood Algorithm (GNA) [38], Imperialist Competitive Algorithm (ICA) [39], gravitational search algorithm [40], Vector-Based Swarm Optimization (VBSO) [41], Continuous Human Learning Optimizer (CHLO) [42], Artificial Electric Field (AEF) [43], Whale Optimization Algorithm (WOA) [44], Cuckoo Search (CS) [45,46], Jaya Optimization Algorithm (JOA) [45], Ant Colony Optimization (ACO) [21], Chaotic Ant Swarm (CAS) algorithm [47], chaotic optimization algorithm [48], and Grey Wolf Optimizer (GWO) [49].

Although there are a large number of research studies on the application of different optimization methods for tuning parameters of PID controller for AVR system, it remains to be seen which of the proposed algorithms has the best performance considering the fast convergence time and the best tuning of PID parameters for AVR step response. Also, based on our literature review, there are few article papers that have compared a number of optimization algorithms to each other. They have only chosen one or two algorithms and made a comparison with one conventional method. However, in this paper, eight of the best population-based optimization methods are competing to establish the superiority of one over others. The studied optimization algorithms are Whale Optimization Algorithm (WOA), Ant Lion Optimizer (ALO), Slap Swarm Algorithm (SSA), and Dragonfly Algorithm (DA), and the results are compared with four conventional algorithms including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Artificial Bee Colony (ABC) which are used to improve the quality of the step response of the AVR system. Furthermore, in this paper, an electronic dual simulator is built for AVR system which has not been done before. The prototype AVR simulator can be regarded as preliminary linear modeling to analyze the dynamic behavior of a real AVR system. Finally, the electronic model of the PID controller is also built and the optimum parameters are experimentally tuned. The experimental test results verify the success of the employed optimizations.

2. System description

There are various AVR mathematical models and the latest developed nonlinear models are more accurate than linear models. However, given that this paper attempts to take preliminary steps towards dual electrical modeling of the AVR, the basic linear model is considered. Figure 1 shows the AVR system with its PID controller. As can be seen, the AVR system has four main components including amplifier, exciter, generator, and sensor. All components are modeled linearly with a gain of K and a time constant of τ. The amplifier is modeled with a gain of $K_A = 10$ and a time constant of $\tau_A = 0.1$ sec. The linear model of the exciter includes a gain of $K_E = 1$ and a time constant

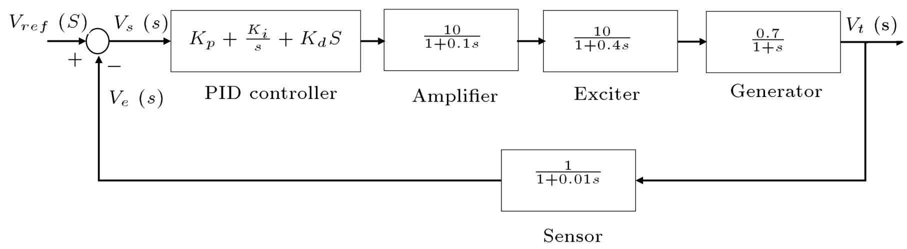

Figure 1. Block diagram of an AVR system with a PID controller.

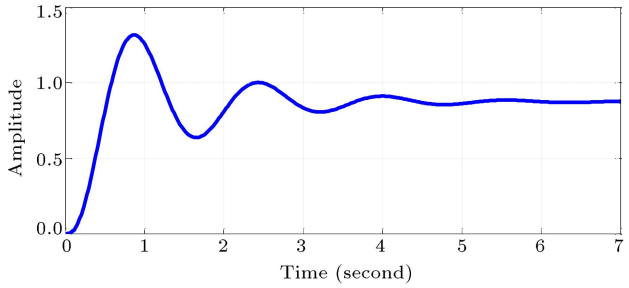

Figure 2. The AVR step response without a PID controller.

$\tau_E = 0.4$ sec. The generator gain can be changed from 0.7 to 1 and its time constant varies between 1 and 2 seconds. In this paper, $K_G = 0.7$ and $\tau_G = 1$ sec. The last component of the AVR is sensor. The gain of the sensor model (K_R) is equal to 1 and its time constant (τ_R) is assumed to be 0.01 seconds [2].

The step response of the mentioned AVR system is given in Figure 2. According to Figure 2, it has large amplitude oscillations with high overshoot. Such a response is not suitable for AVR's step response. The characteristics of the studied step response indicate that the performance of AVR system is not suitable. It means that the amplitude of the overshoot is 50.46%, the rise time is 0.3174 seconds, the settling time is 4.90 seconds, and the steady state value is 0.873. Therefore, a PID controller must be added to improve the dynamic response of the AVR and decrease its steady state error. The model of PID controller can be defined as follows:

$$G_{PID}(\mathrm{s}) = K_p + \frac{K_i}{s} + K_d \mathrm{s}, \quad (1)$$

where K_p, K_i, and K_d denote the coefficients for the proportional, integral, and derivative terms, respectively, and must be tuned simultaneously to improve both transient and steady state response.

3. Optimization

In this section, the objective function of the optimization, the studied optimization techniques, and the optimization results are discussed.

3.1. Problem formulation

K_p, K_i, and K_d are three parameters of PID controller that need to be tuned. Moreover, an ideal step response has no overshoot, no steady state error, fast rise time, and fast settling time. Therefore, the proposed objective function should include rise time, settling time, overshoot, and steady state error and the variables of the optimization are the parameters of the PID controller.

Integrated Absolute Error (IAE), Integral of Squared-Error (ISE), or Integrated of Time-weighted-Squared-Error (ITSE) are the usual forms of the objective function for tuning the PID parameters. However, they are time-consuming and inaccurate in the improvement of settling time and rise time. Therefore, a multi-objective optimization problem is defined as [50]:

$$F_{obj} = \left(1 - e^{-\beta}\right) \times (M_p + ESS) + e^{-\beta} \times (t_s - t_r), \quad (2)$$

where ESS is steady-state error, M_p amplitude of overshoot, t_s settling time, t_r rise time, and β a weighting factor that reflects the optimization performance. In case β is chosen to be higher than 0.7, overshoot and steady state error are reduced. However, when β is set under 0.7, one can reduce the rise time and settling time. Thus, according to the results achieved by the reference paper [50], the range of β is between 0.8 and 1.5. Since the objective function of Eq. (2) is able to consider all the required factors of the ideal step response, it is recommended for optimization in this paper.

3.2. Optimization methods

As mentioned earlier, eight different optimization methods are competing in this paper to minimize the objective function of Eq. (2). The studied optimization algorithms are Whale Optimization Algorithm (WOA) [51], Ant Lion Optimizer (ALO) [52], Slap Swarm Algorithm (SSA) [53,54], Dragonfly Algorithm (DA) [55], Genetic Algorithm (GA) [56], Particle Swarm Optimization (PSO) [11,57], Simulated Annealing (SA) [36], and Artificial Bee Colony (ABC) [27,58]. It is worth mentioning that the optimization variables are the parameters of PID controller (K_p, K_i, and K_d).

3.3. Optimization results

Figure 3 shows the variation of objective function versus different iterations using the studied optimization

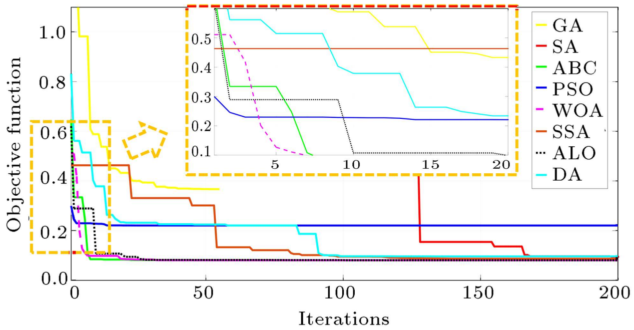

Figure 3. The optimization trend of population-based optimization algorithms.

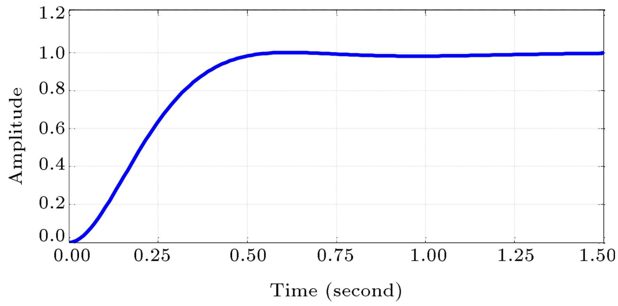

Figure 4. The step response of the AVR with optimum parameters of PID controller based on the results of ALO algorithm.

algorithms. The maximum iteration is set to 200 for all algorithms except GA and SA. GA termination criterion varied from other algorithms based on MATLAB Optimtool and it could achieve its optimum response at maximum 60 iterations. Moreover, SA could not optimize the objective function in less than four digits after the decimal point after 457 iterations, but we set the maximum iterations at 2000 to evaluate its behavior. Among the studied algorithms, PSO and WOA are faster than other algorithms in getting the final optimum point. However, ALO has the lowest value of objective function ($F_{obj} = 0.0806$) by tuning K_p, K_i, and K_d equal to 0.8593, 0.6076, and 0.2919, respectively, and it is regarded as the best response for tuning PID controller parameters. Although ALO has the optimum value of objective function, the shortest amount of settling time, 0.4962 sec, lies in ABC and the shortest amount of rise time, 0.3113 sec, is devoted to the results of GA optimization method.

The optimal value of PID parameters, optimal value of objective function, and characteristics of the step response are presented in Table 1 for different optimization methods. According to Table 1, GA and PSO are the worst optimization techniques with the highest value of the objective function. It is implied that the recent population-based optimization algorithms are more efficient than conventional ones.

Furthermore, Table 1 shows that all algorithms can remove maximum overshoot from the step response of the AVR system. It is implied that the competition for the best results includes such elements as achieving the shortest rise time and settling time and fast convergence of the method.

The step response of the AVR system with tuned parameters of PID controller based on ALO results is shown in Figure 4.

3.4. Experimental evaluation

Experimental measurement is always the best verification method. However, the AVR system of power plants is not easily available for such measurements. Therefore, a simulator is developed in this section for AVR and its PID controller. The proposed simulator is designed and simulated using ORCAD family software and then, is built experimentally.

3.5. Developing a simulator

In order to develop a simulator for AVR system and its PID controller, it is required to find the best electronic circuit of them. Regarding the transfer function of the AVR system in Figure 1, it is obvious that this function is the product of multiplying several first-degree Resistor-Capacitor (RC) circuits. The product of RCs represents time constant (τ) for each component and all gains can be produced by a multiplier comprising an operational amplifier (OP AMP).

The proposed electronic model of the AVR with PID controller is given in Figure 5. The employed OP

Table 1. PID parameters and step response characteristic for the AVR system using different optimization techniques.

	GA	SA	ABC	PSO	WOA	SSA	ALO	DA
K_p	0.8679	0.8254	0.8611	0.8648	0.8258	0.8403	0.8593	0.7787
K_i	0.6055	0.5715	0.6014	0.6026	0.6325	0.5539	0.6076	0.5219
K_d	0.3050	0.2685	0.2916	0.2924	0.2811	0.2714	0.2919	0.2398
Objective function	0.3669	0.0869	0.0811	0.2206	0.0807	0.0871	**0.0806**	0.0963
Percentage overshoot (%)	0	0	0	0	0	0	0	0
Rise time (sec)	**0.3113**	0.3415	0.3119	0.3254	0.3326	0.3366	0.3193	0.3740
Settling time (sec)	1.1283	0.5330	**0.4962**	0.5095	0.5201	0.5236	0.4965	0.5863
Required iteration	55	457	79	26	136	166	151	142

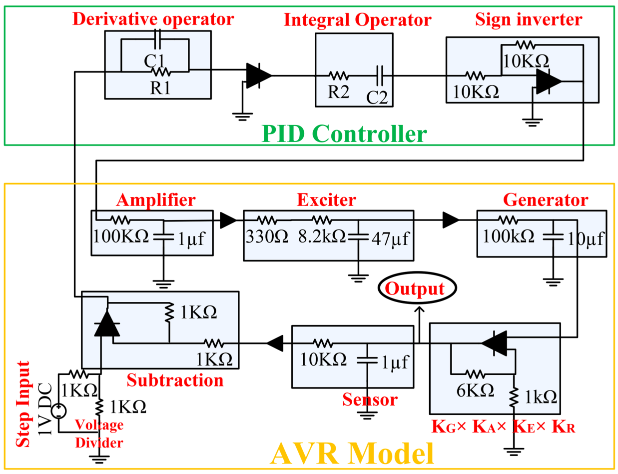

Figure 5. Proposed electronic model of the AVR with the PID controller.

AMP is LM324, which is easy to access in the electronic market.

The transfer function of PID controller, as the ratio of its output voltage to input voltage, is defined as follows:

$$\frac{V_o(s)}{V_i(s)} = \frac{R_2}{R_1}\frac{(R_1C_1s+1)(R_2C_2s+1)}{R_2C_2s}, \quad (3)$$

where V_o (s) is the output voltage of the PID controller, V_i (s) the input voltage of the PID controller, R_1/C_1 the resistor/capacitor of the derivative term, and R_2/C_2 the resistor/capacitor of the integral term. Since the transfer function of PID controller includes a derivative operator, an integral operator and a sign inverter, K_p, K_i, and K_d, could be derived from Eq. (3) as follows:

$$K_p = \frac{R_2}{R_1}\left(\frac{R_1C_1}{R_2C_2}+1\right), \quad (4)$$

$$K_i = \frac{1}{R_1C_2}, \quad (5)$$

$$K_d = R_2C_1. \quad (6)$$

Substituting the optimal values of K_p, K_i, and K_d from Table 1 into Eqs. (4)-(6) and supposing $C_1 = 10$ μF, R_2 is determined equal to 29.19 kΩ. Then, considering the known parameters and the fact that $\Delta = K_p^2 - 4 \times K_i \times K_d$ must be positive to get real numbers, R_1 and C_2 can be determined. It should be mentioned that there are two acceptable values for R_1 and C_2 because they are the result of solving a second-degree equation, which has two valid answers. Considering $R_1 = 84.71$ kΩ, C_2 will be calculated equal to 19.42 μF and for $R_1 = 56.71$ kΩ, $C_2 = 29.02$ μF.

The PSpice step response of the proposed AVR system with and without PID controller is presented in Figures 6 and 7, respectively.

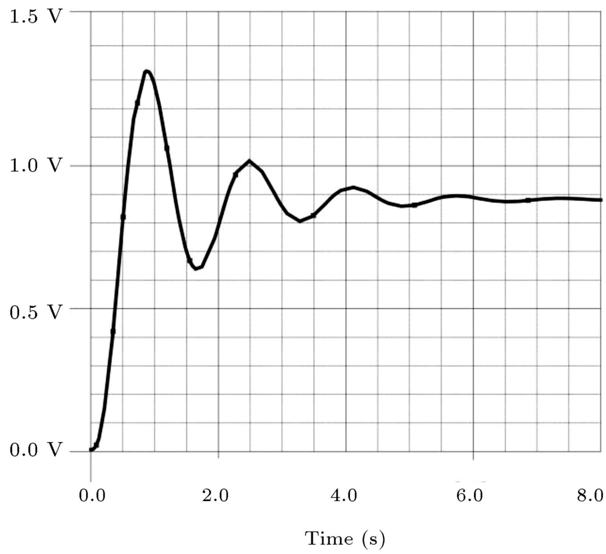

Figure 6. Step response of the AVR electronic model in PSpice.

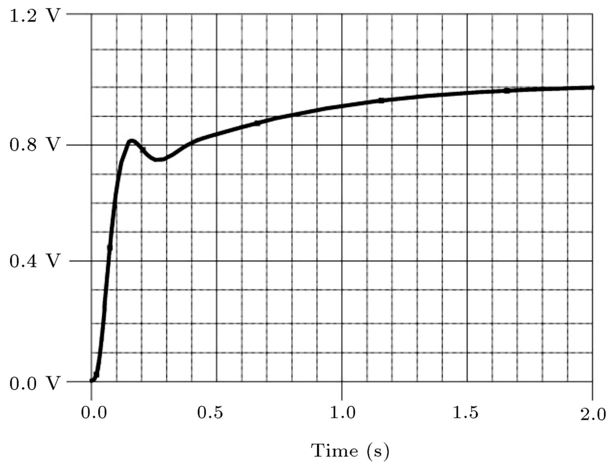

Figure 7. Step response of the AVR with the PID electronic model in PSpice.

3.6. Experimental implementation of simulator

The developed simulator is experimentally built, as shown in Figure 8. A digital oscilloscope is used to capture and save the step response of the simulator. Considering a step DC input voltage of 1 V, the measured step response of the simulator without and with PID controller is given in Figures 9 and 10, respectively.

Table 2 shows a comparison of step response characteristics of the experimental results with those of PSpice and MATLAB. According to Table 2, the developed simulator is a suitable representative for an AVR with PID controller at power plants. Before using a PID controller, the maximum peak/steady state value of the step response is measured equal to 1.32 V/0.8 V equal to the predictions of simulation results. After adding the PID controller, the rise time

Table 2. Comparing the step response of the AVR and PID controller among experiment, MATLAB, and PSpice.

	Performance characteristics	Experimental test	Simulation results using MATLAB	Simulation results using PSpice
AVR without PID	First peak voltage (V)	1.32	1.32	1.32
	First peak time (sec)	0.84	0.877	0.926
	First valley voltage (V)	0.64	0.638	0.644
	First valley time (sec)	1.56	1.64	1.62
	Steady state voltage (V)	0.89	0.875	0.880
AVR with PID	Rise time (sec)	0.36	0.3193	0.46
	Settling time (sec)	0.69	0.4965	1.5
	Steady state value (V)	1	1	1

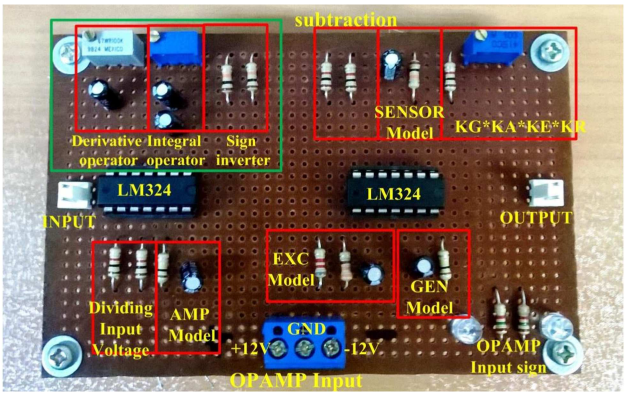

Figure 8. The experimentally built simulator of the AVR system and its PID controller.

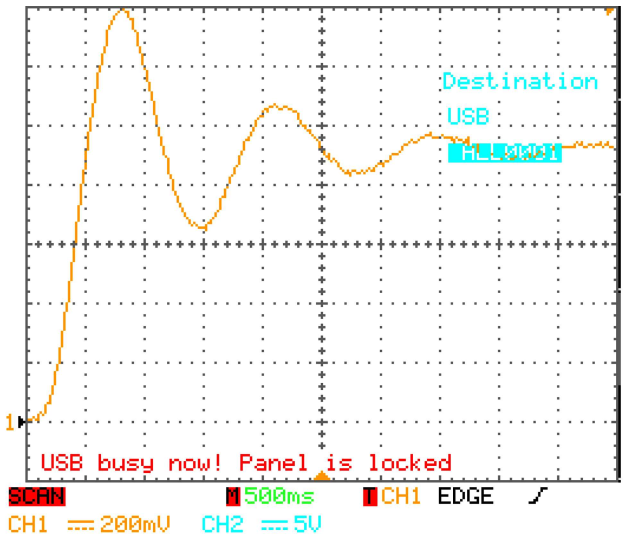

Figure 9. The measured step response of the AVR system's simulator without PID controller.

and the settling time of the measured response are in agreement with simulation results. The difference between the results of PSpice and those of experimental test and MATLAB lies in the tolerance of the employed capacitors and resistance.

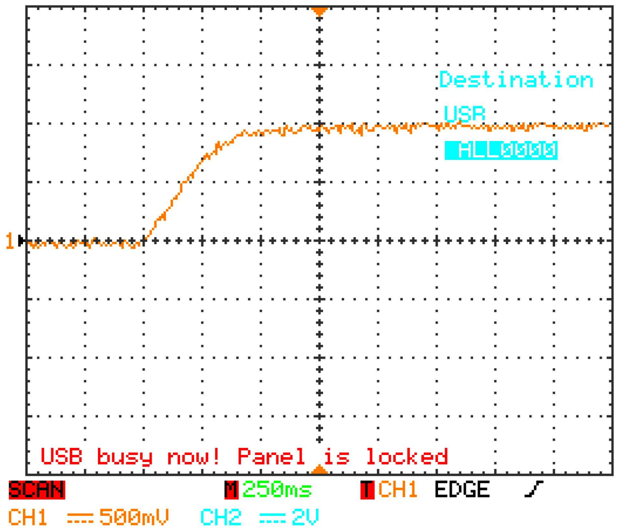

Figure 10. The measured step response of the AVR system's simulator with PID controller.

4. Conclusion

In this paper, parameters of Proportional Integral Derivative (PID) controller for an Automatic Voltage Regulator (AVR) were optimally tuned. The objective function of the optimization was defined such that all the performance characteristics of the step response were considered to ensure minimum rise and settling time, minimum overshoot amplitude, and steady state error along with fast convergence time. The abilities of well-known optimization methods including Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) were compared with those of newly proposed evolutionary algorithms including Whale Optimization Algorithm (WOA), Ant Lion Optimizer (ALO), Slap Swarm Algorithm (SSA), Dragonfly Algorithm (DA), Simulated Annealing (SA), and Artificial Bee Colony (ABC). Then, to experimentally evaluate the success of the best optimization results, a simulator was developed and experimentally built for the AVR system and its PID controller. Comparison of the experimental results with those of simulation by MATLAB and ORCAD family software confirmed the success of the proposed optimization and developed simulator.

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