PID Control Design Based on Genetic Algorithm with Integrator Anti-Windup for Automatic Voltage Regulator and Speed Governor of Brushless Synchronous Generator

O. S. Ebrahim, M. A. Badr, Kh. H. Gharib, H. K. Temraz

***Abstract*—**This paper presents a methodology based on genetic algorithm (GA) to tune the parameters of proportional-integral-differential (PID) controllers utilized in the automatic voltage regulator (AVR) and speed governor of a brushless synchronous generator driven by three-stage steam turbine. The parameter tuning is represented as a nonlinear optimization problem solved by GA to minimize the integral of absolute error (IAE). The problem of integral windup due to physical system limitations is solved using simple anti-windup scheme. The obtained controllers are compared to those designed using classical Ziegler-Nichols technique and constrained optimization. Results show distinct superiority of the proposed method.

***Keywords*—**Brushless synchronous generator, Genetic Algorithm, GA, Proportional-Integral-Differential control, PID control, automatic voltage regulator, AVR.

I. Introduction

In an ideal AC power plant, voltage and frequency at every supply point should be constant irrespective of the type and characteristic of the load. The quality of the supply can be measured by how nearly constant the voltage and frequency are [1]. In reality, constant voltage and frequency do not exist since the electric power is never in equilibrium for very long time. Frequent changes disturb the equilibrium so that the system is always in transition between steady state and transient conditions. Two of the major means to attenuate such disturbances and improve the performance are the AVR and speed governor [2]-[4]. The AVR controls the magnitude of the generator terminal voltage, while the governor regulates the output power and system frequency.

The PID control is normally employed for both controllers due to its simplicity and ease of realization. In addition, robust design of the controller is possible in order to cope with variations of system parameters. Unlike, switching mode control [4], the proposed PID architecture does not require complex online computations to avoid chattering and actuator saturation problems. Besides, use of rotating bidirectional power converter or external rotor resistance to realize very fast AVR de-excitation is not suitable for normal brushless field construction [2], [5]. However, optimizing the PID controller's coefficients for the AVR and speed governor is difficult due to system nonlinearity and uncertainties in the linearized model parameters. Various methods exist in the literature to overcome such design difficulty including neural network, fuzzy logic, adaptive control, Zeigler-Nichols method and GA based automatic tuning [6]-[11]. The Zeigler-Nichols routine is particularly characterized with less accuracy than other competitive methods [10]. The GA based optimization has been recently used to design the PID controller parameters, utilizing its high capability in solving nonlinear optimization problems. Furthermore, GA has a shorter calculation time and better convergence characteristics when compared to other stochastic optimization algorithms [11].

Another practical problem of PID control is the integral windup, also known as integrator windup, which refers to the situation in the PID controller where a large change in the set-point (or disturbance) occurs and the integral term accumulates a significant error that is unwound (i.e., offset by errors in the other direction) [12], [13]. This specific problem leads to excessive overshooting and might instability as a result of breaking the feedback loop. The integral windup particularly occurs due to limitation of physical systems, compared with ideal one, as the ideal output being physically impossible (process saturation). For example, the position valve of the speed governor, shown in Fig. 1 (b), cannot be more than fully open or less than fully closed. In this case, anti-windup can actually involve the integrator being turned off for periods of time until the control input becomes feasible [14]. Within modern digital control systems, integral windup can be prevented by either limiting the controller output, limiting the integral to produce feasible output, or by using external reset feedback [12]-[14].

This paper presents an optimal design of PID controllers for AVR and governor systems of synchronous generators using GA. The models of three-stage steam turbine and brushless excitation system are considered. The traditional Ziegler-Nichols tuning method is first used to design PID controllers.

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Then, GA is employed to obtain the controller parameters which minimize the IAE. Further, an integrator anti-windup scheme is presented during actuators saturation. Fig. 1 (a) shows digital realization for the proposed PID control with anti-windup scheme where the comparator output (flag) is used to stop updating the integral term in case of actuator saturation. This has the potential to obtain larger solution set for the optimization problem than constrained GA and hence better controller tuning. Finally, time-domain analysis is carried out to evaluate the controller design and compare the proposed methodology to traditional routines.

II. System Modeling

A. Steam Turbine

In the 3-stage steam power plant, shown in Fig. 1 (b), the primary energy is converted into thermal energy by a boiler. The boiler generates the steam, which enters the three-stage turbine at the high-pressure turbine section (HPT) after passing a high-pressure control valve (HPCV). The partly expanded steam is transferred to the reheater passing the intermediate-pressure control valve (IPCV), and reaches the intermediate-pressure turbine section (IPT). Then, the steam is expanded into the low-pressure turbine section (LPT). The exhaust steam of the LPT part condenses in the following condenser. Finally, feed-water pumps supply the accumulating condensate to the boiler. The output power passes on to the electrical grid by the generator, while the control deviation of actual and reference speed is carried out by the speed controller. The resulting controller output acts on the control valves by using position actuators. Single-mass, linearized model for 3-stage steam turbine is shown in Fig. 2, where it is assumed proper mechanical coupler and choice of the shaft stiffness and turbine inertia are used to provide drive train isolation and damping of torque pulsations [15], [16]. The output power is the result of the mass flow rate, thermal gradient and internal efficiency. Each stage of the turbine blades is shown as a first order system with time constants THP, TIP, and TLP. The outputs of the three turbine sections are summed up to the turbine power corresponding to the power proportions KHP, KIP and KLP. Every change of the turbine power, PT, and the generator power, PG, is transferred to speed change with acceleration time constant Ta. The transfer function representing each element could be depicted as in the block diagram of Fig. 2.

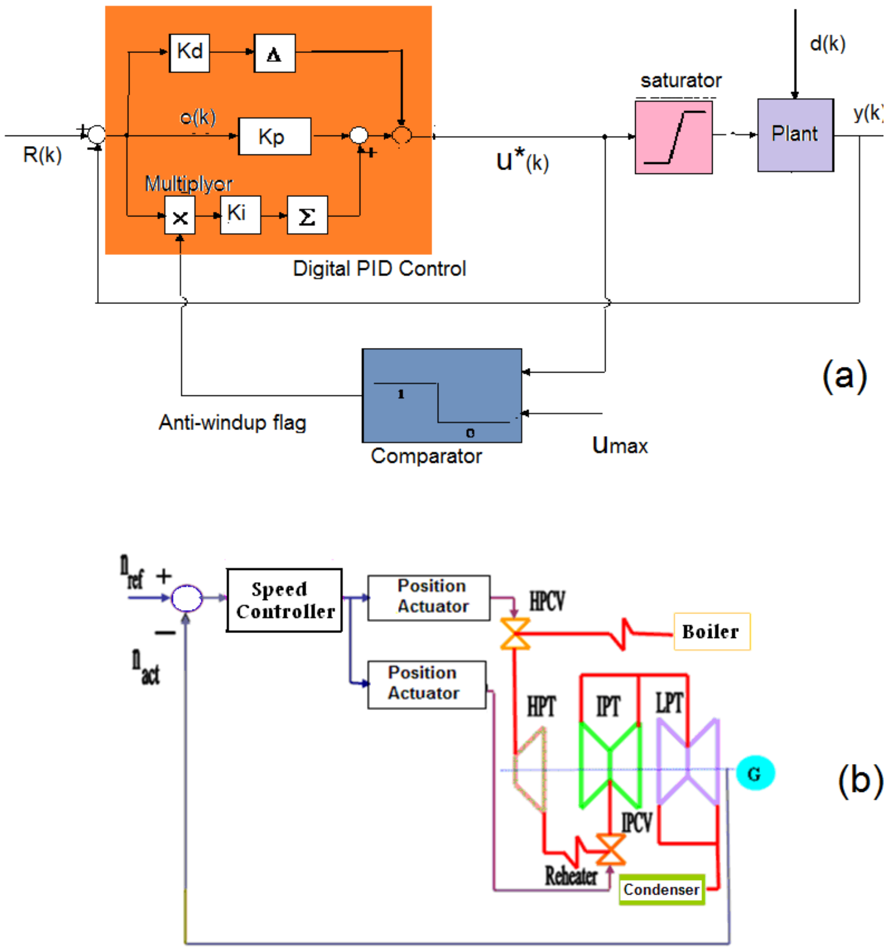

Fig. 1 Digital PID control with anti-windup (a) and (b) block diagram of a 3-stage steam turbine

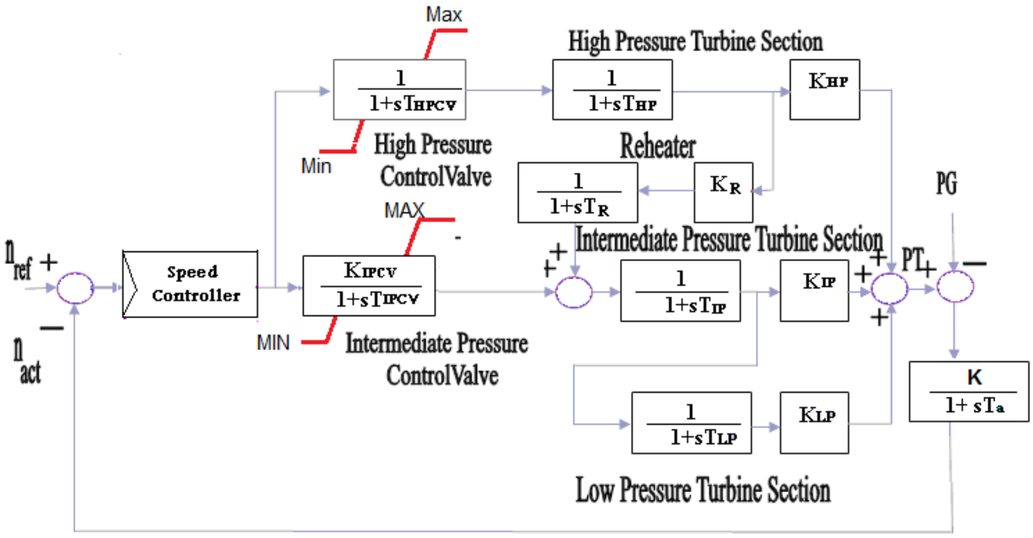

Fig. 2 Modeling of a three-stage steam turbine

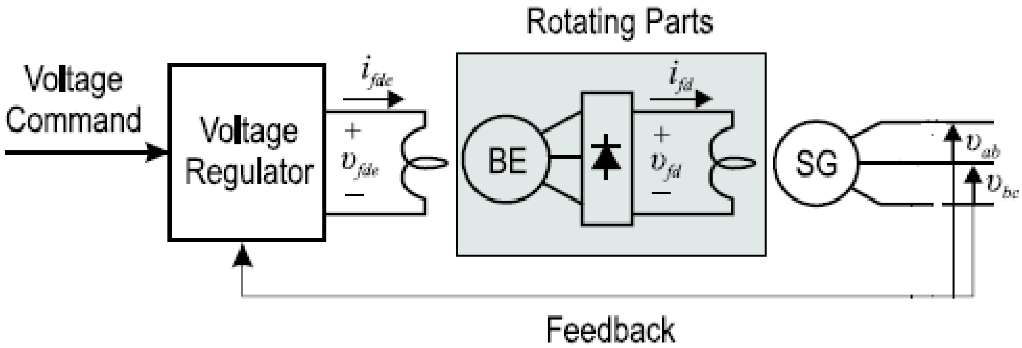

Fig. 3 The brushless excitation system in turbo-generators

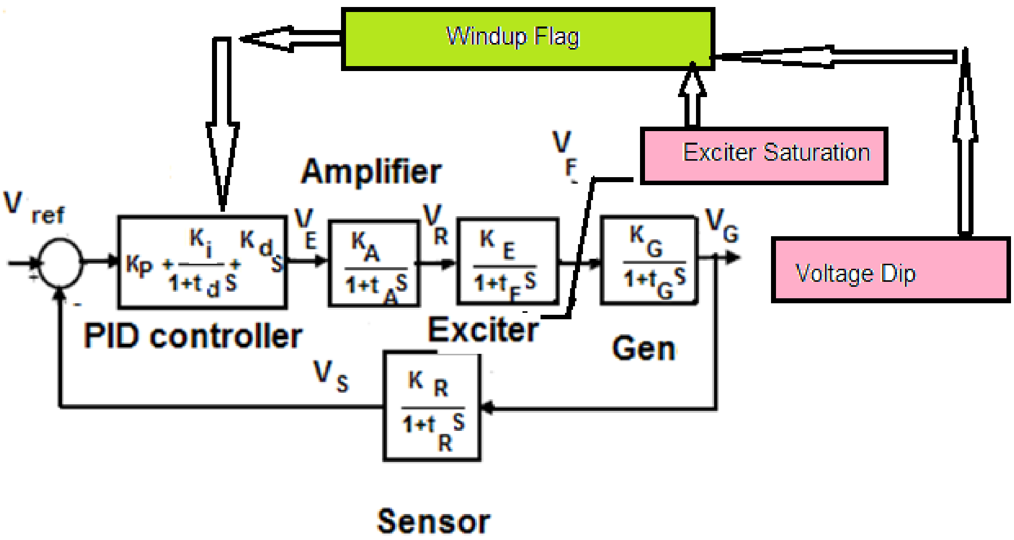

Fig. 4 An AVR block diagram

B. Automatic Voltage Regulator

To ensure a stable terminal voltage of the synchronous generators at the generating stations, AVRs are used to adjust the field voltage depending upon the load variations. In conventional schemes, the field voltage control is achieved by means of a thyristor-based rectifier. The firing angle of the rectifier is adjusted depending upon the field voltage requirement, which in turn controls the terminal voltage of the synchronous generator.

Nowadays, the brushless excitation system is commonly used for synchronous machines due to absence of slip rings and lower maintenance cost. It employs a three-phase pilot (sub)exciter having a revolving field with permanent-magnet poles. The three-phase AC generated by the pilot exciter is rectified through a controlled rectifier before being applied to the stator field winding of the main exciter. The three-phase AC induced in the rotary armature of the main exciter is rectified by a rotating diode bridge and fed to the field winding of the main generator rotor through a DC lead. The system is shown schematically in Fig. 3. It is worth mentioning that the brushless structure is often considered more complicated for control since the exciter adds considerable phase lag during de-excitation state. This is because the brushless excitation has only positive field forcing capability [21]. The role of an AVR is to keep constant the output voltage of the generator in a specified range. Basically, the AVR consists of amplifier, exciter, generator, and sensor (potential transformer + transducer). Fig. 4 shows a linearized model for AVR controller's tuning where the transfer function of each system component is assumed to have bounded uncertainty limits [4], [17], [21]. To design the parameters of the PID controller, the system response is modeled in the MATLAB/Simulink platform. The controller parameters are determined using the traditional Ziegler-Nicholas method and proposed GA routine.

III. Tuning Methods for PID Controller

The PID controller represents one of the most common structures due to the inherent simplicity and ease of implementation. There are many tuning formulas for PID control for processes with transient responses. The Ziegler-Nichols step response method is based on the basic features of the step response, and is investigated from the view point of robust loop shaping [10]. The results are insight into the properties of PID control and simple tuning rules that give robust performance for processes with essentially monotone step responses. On the other hand, GA is an effective method for nonlinear optimization, which could be used to optimize the set point and load disturbance response for a batch of test processes controlled by PID controllers [18], [19].

A. Ziegler-Nichols Method

The proportional control action is first computed in order to obtain a critical value (K_{cr}) for the proportional gain (K_p); the gain is increased till the output first exhausts sustained oscillations. Then, the critical gain (K_{cr}) and the corresponding period (P_{cr}) are used to set values of the PID gains (K_p, K_i, and K_d) according to the following formulae [10], [13]:

$$K_p = 0.6K_{cr},\ K_i = \frac{0.6K_{cr}}{0.5P_{cr}},\ K_d = \frac{0.6K_{cr}}{0.125P_{cr}} \tag{1}$$

Compared to GA, the Zeigler-Nichols method is regarded as an aggressive tuning method with low accuracy.

B. The GA Algorithm

The GA routine determines the controller parameters based on minimizing some error function according to the following algorithm. Let the PID controller be implemented as follows [18], [19]:

$$u = K_p\, e + K_i \int e\ dt + K_d \frac{de}{dt} \tag{2}$$

$$e = y_r - y \tag{3}$$

where, u = controller output, y_r = set point, y = process output, K_p = proportional gain, K_i = integral gain, K_d = derivative gain, and e = error, $U_{min} < u < U_{max}$ given that, $U_{min} = 0$ and $U_{max} = 1$ pu.

In case of actuator saturation, an anti-windup flag is activated and used to stop updating the integral part. The controller output is modified according to the following selection scheme

$$u = \begin{cases} u = u_{max} & if \quad u > u_{max} \\ u = u_{min} & if \quad u < u_{min} \\ K_p e + K_i \int edt + K_d \frac{de}{dt} & \text{otherwise} \end{cases} \tag{4}$$

The closed-loop transfer function is given by

$$\frac{U}{e} = \frac{1}{K_p + \frac{K_i}{s} + K_d s} \tag{5}$$

There are various performance indices that could be optimized such as; integral square of error (ISE), integral of absolute error (IAE), integral time of absolute error (ITAE), and integral time of square error (ITSE). The IAE is given as follows:

$$J = \int |e(t)|\ dt \tag{6}$$

Such index is commonly used for computer simulation studies since it is simple to be computed and yields moderate performance between ISE and ITAE in terms of maximum overshoot, rise-time, and settling-time [20]. The PID controller parameters are designed using GA such that J is minimized. The objective is to search (K_P, K_i, K_d) globally such that J is minimized. Thus, an individual that has lower J should be assigned a large fitness value. Then, the GA inherently generates better offspring to improve the fitness and avoids local minima. Therefore, a better PID controller could be obtained by better fitness. Finally, the fitness function is defined in (7). The one added to the denominator of the function is obviously to avoid division by zero.

$$F = \frac{1}{1 + J(K_p, K_i, K_d)} \tag{7}$$

By considering different system parameters in accordance with the bounded-uncertainty limits during GA search routine, the system sensitivity constraint will be included inherently in the solution without additional complex computations. In [19], the optimization problem is solved with a measure in the fitness function to exclude cases of actuator saturation. Here, the occurrence of actuator saturation is permitted by using integral anti-windup scheme, as shown in Fig. 4, under either excitation system saturation or large voltage disturbances. Also, anti-windup measure is applied to the speed governor control as shown in Fig. 2. This has the potential to obtain larger solution set for the optimization problem and better controller tuning. Hence, enhanced dynamic response could be realized while maintaining good robustness against parameters variations.

IV. Simulation Results

Comparisons of the two design approaches are carried out with respect to step change in the reference input command. Evaluation of the control performance under system parameters variation is also performed.

A. Speed Governor Results

TABLE I
PARAMETERS OF THE STEAM TURBINES USED IN SIMULATION

Parameter	System1	System2
THPCV	0.3	0.35
KHP	19.3	23.16
THP	0.3	0.3
TR	6.5	7
KR	2	2.5
KIPCV	0.2	0.26
TIPCV	0.2	0.3
TIP	0.4	0.5
KIP	34.929	28
TLP	0.45	0.5
KLP	60	72
Ta	100	50
K	0.2	0.3

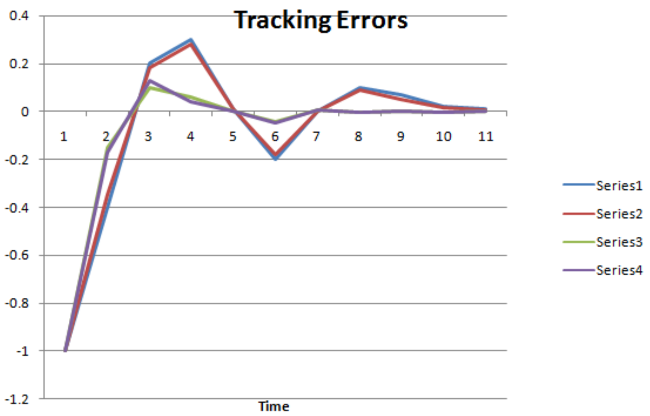

Fig. 5 Turbine Power tracking errors using different controllers: Ziegler Nichols: System1 (series1) and System2 (series2). Proposed GA: System1 (series3) and System2 (series4)

In order to compare the quality of the proposed GA routine with the traditional method, two sets of system parameters are assumed as given in Table I. To reduce simulation time, step response of the turbine power is considered and the tracking errors are shown in Fig. 5 for different controllers. The plots signify much better response for both systems using the proposed controller in terms of the damping ratio, maximum overshoot, and settling time. Such conclusion is supported by the results given in Table II. The findings of the comparison study indicate that the proposed controller always outperforms the traditional controller.

B. AVR Results

For the purpose of comparing the two PID controllers developed for AVR, parameters for two different systems are described in Table III. The step responses of the generator output voltage of the two systems are shown in Fig. 6 with both traditional and proposed controllers. The simulation test represents a voltage recovery after severe short circuit fault and depicts an improved response for both systems upon using the proposed controller. Results of the comparison process are quantified in Table IV, which shows much better performance for the GA-based controller on both systems than the Zeigler-Nichols controller. Further, the proposed control design is compared to constrained GA as in [19], where the actuator saturation is prohibited via fitness function, and the AVR results are depicted in Table V for both cases. It is evident that considering the proposed anti-windup scheme in case of actuator saturation as a feasible solution for the optimization problem can yield faster dynamic response in terms of settling and rise times meanwhile obtaining acceptable overshoot and steady-state errors. The effectiveness of the proposed integrator anti-windup is tested in case of AVR step response. Fig. 7 shows the AVR tracking errors with (blue curve) and without (red curve) integrator anti-windup. The proposed measure can maintain the closed loop stability with a fast positive field forcing capability.

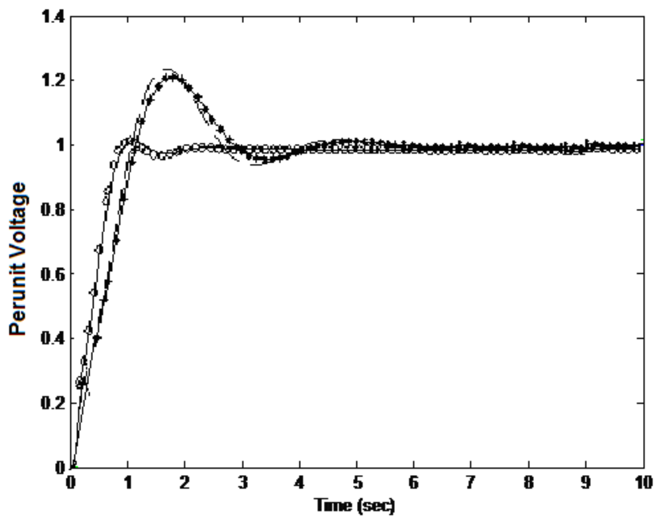

Fig. 6 Step response of the AVR using different controllers: Ziegler-Nichols: System1 (--) and System2 (*-). Proposed GA: System1 (o) and System2 (-)

TABLE II
RESPONSE COMPARISON OF THE TWO SYSTEMS USING DIFFERENT CONTROLLERS

Index	System1		System2	
	Zeigler	GA	Zeigler	GA
% Max. overshoot	29	4	32	4
Settling time (S)	6 Sec.	3.9	8.7	2.4
Rise time (S)	1.7	1.3	1.4	1.25
%Abs. error	1.3	0.21	1.4	0.27

TABLE III
PARAMETERS OF THE TWO AVR SYSTEMS USED IN SIMULATION

Parameter	System1	System2
KA	10	40
TA	0.1	0.01
KE	1	2
TE	0.1	0.4
KG	0.7	1
TG	1	2
KR	0.9	1.1
TR	0.1	0.01

TABLE IV
RESPONSE COMPARISON OF THE AVR SYSTEMS USING ZEIGLER AND PROPOSED CONTROLLER

Index	System1		System2	
	Zeigler	GA	Zeigler	GA
% Max. overshoot	20	2.7	21	2.8
Settling time (S)	4.2	1	4.4	1
Rise-time (S)	0.94	0.46	1	0.45
% Abs. error	0.9	0.08	0.95	0.08

TABLE V
RESPONSE COMPARISON OF AVR SYSTEMS USING CONSTRAINED GA [19] AND PROPOSED CONTROLLER

Index	System1		System2	
	GA	GA [19]	GA	GA [19]
% Max. overshoot	2.7	-	2.8	-
Settling time (S)	1	1.81	1	1.89
Rise-time (S)	0.46	0.628	0.45	0.71
% Abs. error	0.08	0.07	0.08	0.065

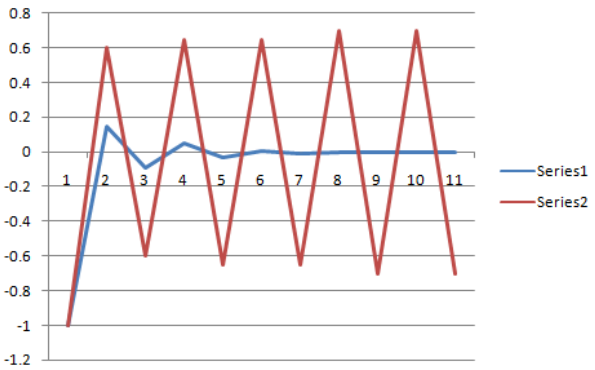

Fig. 7 AVR tracking error with (series1) and without (series2) integrator anti-windup

V. CONCLUSION

The paper presents a robust design technique for the PID controllers employed in steam turbines and AVRs of the brushless synchronous generator. The technique is based on GA, which determines the controller parameters to minimize ITAE and employs a simple measure against integrator windup. The technique is successfully applied to 3-stage turbine and brushless AVR systems. The obtained controllers are compared to those obtained through the traditional Zeigler-Nichols method and constrained GA optimization. Comparisons show better dynamic performance and indicate the effectiveness of the developed algorithm in terms of robustness against changes in system parameters, actuator physical limitations, and large disturbances while achieving enhanced dynamic response.

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CONFLICT OF INTEREST STATEMENT

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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