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Transient Response Enhancement of High Order Synchronous Machine based on Evolutionary PID controller

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Abstract

An efficient controller based on joint between original proportional-integral-derivative (PID) controller and fast genetic algorithm (FGA) is proposed to enhance the transient response of high order synchronous machine. PID controller has several advantages in practical design of synchronous machine compared with another controller。The transient response parameters with PID controller of synchronous machine are reasonable, but they susceptible to the local minima problem and not adequate. Therefore, FGA is used to overcome this problem and to enhance the transient response. Performance of the proposed controller is tested through a high order synchronous machine model and then compared with the original PID controller. In this paper the weak coupling relationship between the automatic voltage controller (AVR) and automatic generation control (AGC) in the synchronous machine has been proved to simplify the overall model. The results demonstrate that, the proposed controller is an efficiency and better than a conventional PID controller.

***Keywords**: Synchronous Machine, PID controller, Fast Genetic Algorithm, AVR, AGC*

1. Introduction

The simulation of the power system is based on the test of the synchronous machine response during the transient state. The accuracy of power system stability is founded over a wide range of conditions such as the modeling of the synchronous machines. Most of research used low order model (first and second-order) of synchronous generator to simulate the response of the machine, but really this model is insufficient for transient study. Therefore high order model (third and fourth-order) is adequate and will be got improved results specially when insert a controller with the system [1]. Early useful studies in this field explain some of important issues should be taken during the simulate of the machine, such as in [2] shows that, the stability analysis of the machine is based on the accurate data model. Kundur [3] and Anderson [4] offer an extensive theory and modelling analysis of the synchronous machines. Saadat [5] focuses on the transient analysis, balanced and unbalanced faults in the synchronous generator. Recently, the proposed computing power studies made possible to work with modern power system which decidedly complex and non-linear. Law [1] introduce an interesting design and simulation model of operation of the synchronous machine. A review paper is introduced in [6] for synchronous generator parameter estimation and model identification, and show that, the valid model is important for stability analysis also explain the modeling of synchronous machine is still a challenging research topic.

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Many research used PID controller to enhance the response of the synchronous machine. PID controller is certainly the most accepted controller in various industrial processes, due to its simplicity and comforts satisfactory performances for a wide range of processes [7]. Unfortunately, the power system is dynamic and varying with time therefore, the conventional PID controller is insufficient to obtain good response for the system due to the difficult to optimize the gains of the controllers. Also the tuning of the PID parameters by conventional methods is not covering all the steady and transient cases that pass over the powers system. So the intelligent techniques such as genetic algorithms (GAs) are powerful optimized algorithms to solve this problem [8]. GA is a stochastic global search technique that mimics the process of natural evolution and capable of locating high performance areas in complex domains [8, 9]. GA is used to tune the controller until the optimum controller being evaluated for the system. Many research papers provide an improvement search performance of the GA to find the optimum three coefficients (proportional K_p, differential K_d, and integral K_i) in the PID controller [10, 11].

In this paper, the synchronous machine with high order model has been simplified and then tuned the parameters of PID by fast genetic algorithm (FGA) to enhance the terminal voltages. The remnant of the paper is organized as follows: section 2 explain the modeling of the synchronous machine, section 3 provides the proposed controller design, section 4 provides the simulation results, and finally the conclusions are explained in section 5.

2. Synchronous Machine Model

The performance of the simulated power system is mainly obvious by how correctly model of the synchronous machines within the system. Figure 1 shows the schematic diagram of the governor and automatic voltage regulator (AVR) of the synchronous machine [1]. In order to produce a closely simulate model of the synchronous machine operation the range of transfer functions in Matlab are used to build the model and to define the transient response for any synchronous machine. Where, the correct model gives an understanding view of the machine work. In this paper, the parameters of machine model are based on Walton[12] and Law [1].

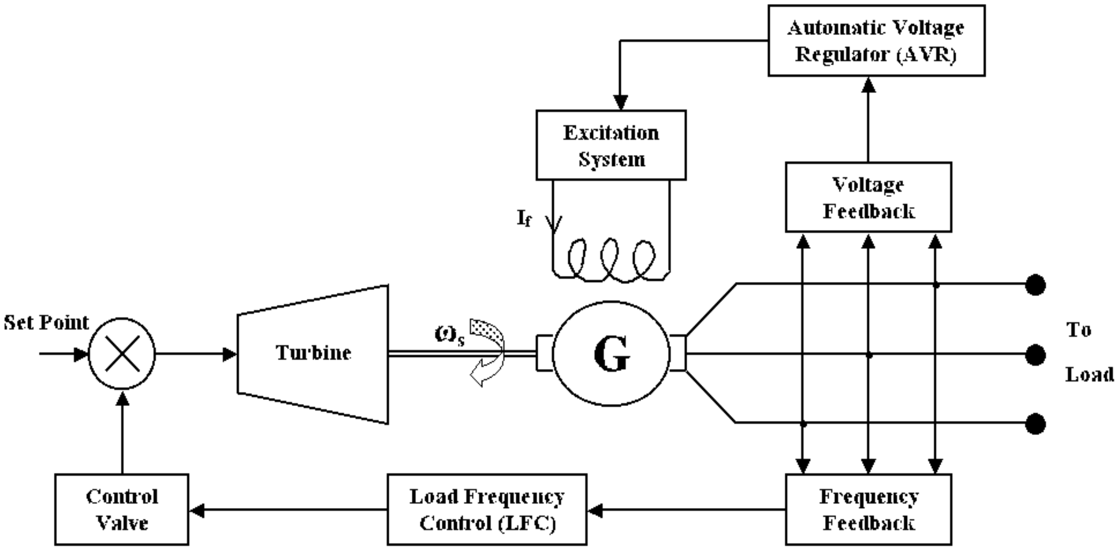


Figure 1. Schematic Diagram of Governor and AVR of the Synchronous Machine

The block diagram representation of the synchronous machine model is shown in Figure 2 [1].

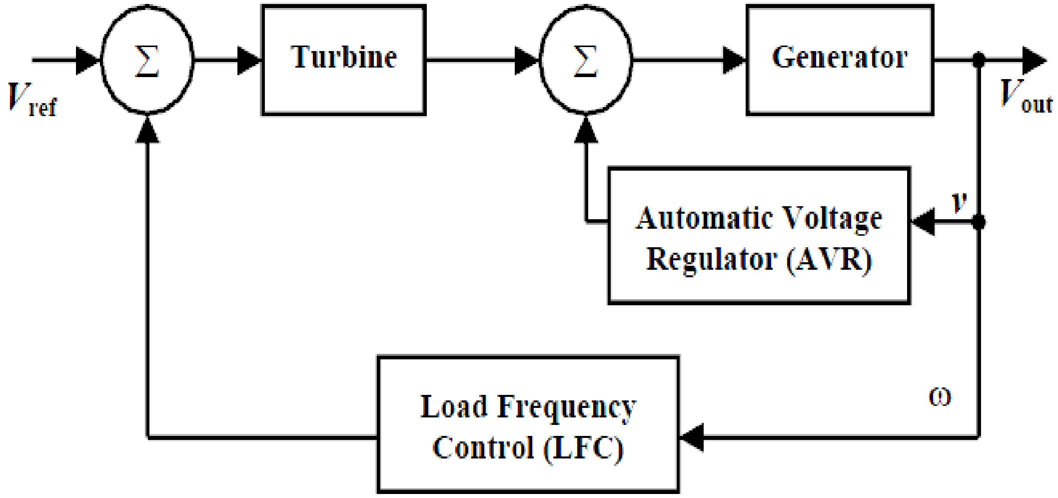


Figure 2. Block Diagram of Governor and AVR of the Synchronous Machine

Final model for high order synchronous machine time constants with PID controller based on Walton [12] and Law [1] is shown in Figure 3.

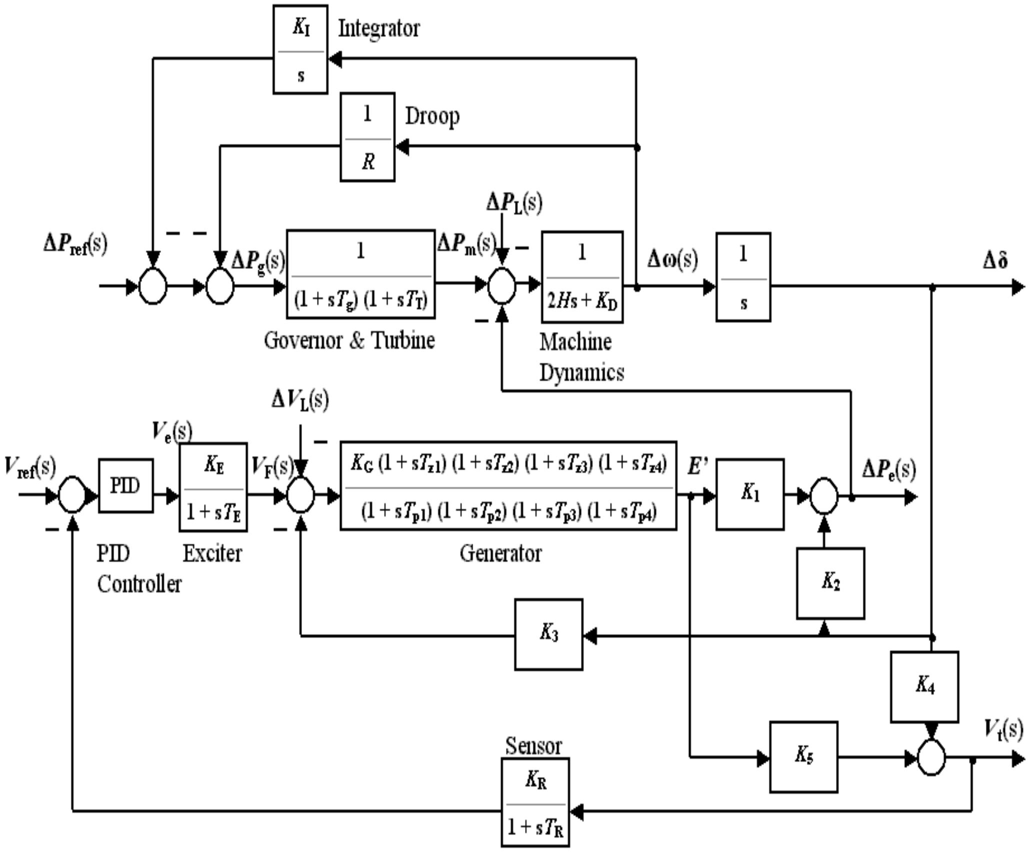


Figure 3. High Order Synchronous Machine Model with PID Controller

Where

ΔP_{ref} is a power change reference
V_{ref} is an input reference voltage
V_e is a control action from PID controller
V_F is an exciter output signal
ΔV_L is a load change in voltage
ΔP_L is a load change in power
$\Delta\delta$ is a frequency deviation step response
V_t is a terminal voltage response

The functions and gains of Figure 3 are summarized in Table 1. These values are chosen based on [1, 3, 5, 12-16] (all values are in per unit).

Table 1. Summary of Functions and Variables of Synchronous Machine (Figure3)

Block	Function /value	Variable with its value
PID	$G_{PID}(s) = K_P + \frac{K_i}{S} + K_d S$	K_p is a proportional gain K_i is an integrator gain K_d is a derivative gain
Exciter	$G_{Exc} = \frac{K_E}{1+sT_E}$	K_E =200 (Gain) T_E=0.05 (Time constant)
Generator	$G_{Gen} = \frac{K_G(1+sT_{z1})(1+sT_{z2})(1+sT_{z3})(1+sT_z}{(1+sT_{p1})(1+sT_{p2})(1+sT_{p3})(1+sT_{p4}}$	K_G =1 (Gain) T_{p1}=3.9517 (Time constant) T_{p2}=0.1481 (Time constant) T_{p3}=8.38e^{-3} (Time constant) T_{p4}=9.37e^{-4} (Time constant) T_{z1}=0.9087 (Time constant) T_{z2}=0.1257 (Time constant) T_{z3}=6.88e^{-3} (Time constant) T_{z4}=7.75e^{-4} (Time constant)
Sensor	$G_{sen} = \frac{K_R}{1+sT_R}$	K_R =1 (Gain) T_R=0.05 (Time constant)
Governor and Turbine	$G_{Gov} = \frac{1}{(1+sT_g)(1+sT_T)}$	T_g=0.2 (Time constant) T_T=0.5 (Time constant)
Machine Dynamics	$G_{Mach} = \frac{1}{2Hs+K_D}$	H= 10 K_D =0.8
Integrator	$G_{Int} = \frac{K_I}{s}$	K_I = adjusting according in order to satisfy the transient response of the machine
Droop	$G_{Droop} = \frac{1}{R}$	R=0.05
K_1	0.2	Constant
K_2	1.5	Constant
K_3	1.4	Constant
K_4	-0.1	Constant
K_5	0.5	Constant

In this paper the PID gains (K_p, K_i, and K_d) are changed and tuned by fast genetic algorithm to obtain the best and optimum machine responses. One of the most important components in the power system is the excitation system, which expressed by a gain K_E and time constant T_E (Table 1). There are many excitation system amplifier such as rotating amplifier, magnetic amplifier and modern electronic amplifier. The amplifier block is represented by gain K_A and time constant T_A. But T_A is very small therefore is almost neglected. For this reason the amplifier is merged with exciter in Figure 3. The generator block is a linearized model and similar to the exciter block based on the gain K_G and time constant T_G. K_G and T_G are loading dependent, therefore K_G (0.7 to 1) and TG (1 to 2 seconds) from full load to no-load. The high order generator model such as fourth order consists of a generator gain plus four pairs of pole-zero time constants. The sensor block is also a linearized model and similar to the exciter model.

3. Controller Design

The PID controller is used to correct the system response by correct the error between a measured process signal and the desired input signal. The general form of PID controller is:

$$U(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \tag{1}$$

Where
K_p is proportional gain
K_i is the integral gain
K_d is the derivative gain.
e(t) is the error signal (error=desired input-actual output)

Desired output is of the PID controller produced by weighted sum of the PID actions as shown in Figure 4 [7] :

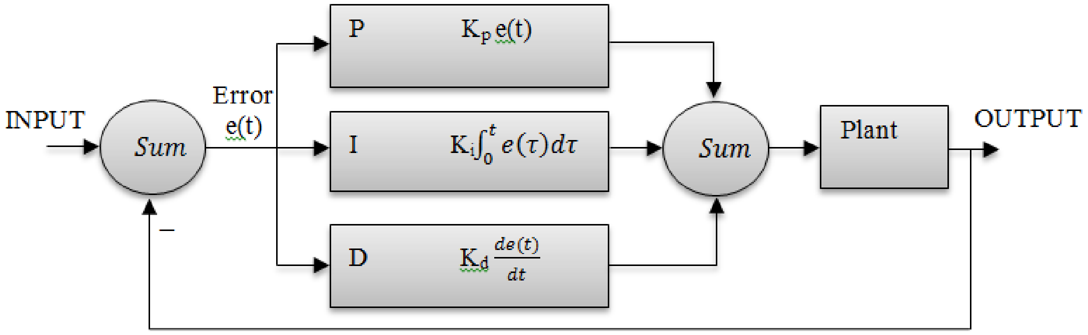


Figure 4. Block Diagram of Feedback Control System with a PID Controller

Genetic algorithms are stochastic global search methods that are based on natural biological evolution and these algorithms are very effective at finding optimal solutions to a variety of problems. Genetic algorithms operate on an initial population of search solutions applying the principle of survival of the fittest to produce better solutions [17]. At each generation a new set of solutions is created which will ideally have greater fitness values than the previous solutions. Fitness refers to how well a solution acts in the problem domain. This process leads to the evolution of populations of individuals that are better suited to the environment they are in. GA is a powerful global search, but the long computation times represent one of the shortcomings for solving large scale optimization problems. Fast GA

(FGA) is used to overcome this, by reduces the computational burden and number of generations to converge [18]. FGA is a simple yet powerful implementation of GA. FGA is used generate and optimize the PID parameters to improve the transient response of the system. Usually the optimization process is continuing until the optimum PID coefficients of the system have been obtained or until satisfy some of conditions. The optimum coefficients produced when maximize the objective function which provides the best individual. When applied FGA to PID design, the chromosome consist of three genes, each gene represents the controller gain. Usually the error criterion such as integral square error (ISE) is used as a fitness function [17].

GA parameters are:

- Maximum number of Generation = 50
- Population Size (pop) = 40
- Length of chromosome =3
- Probability of Crossover = 0.95
- Probability of Mutation = 0.05
- Fitness function:

$$\mathbf{Fit}(\mathbf{y}) = \frac{\mathbf{1}}{\mathbf{ISE}+\boldsymbol{\varepsilon}} \tag{2}$$

The fitness is chosen depending on the problem in hand such that the individuals having high fitness values are the good solution candidates for the optimization. The Optimization criterion which is applied in the present algorithm is Integral of square error (ISE). The epsilon (ε) is a constant small value (0.0001) added to ISE in the denominator of the fitness function to avoid the infinity case. The chromosome representation of the proposed algorithm is shown in Figure 5.

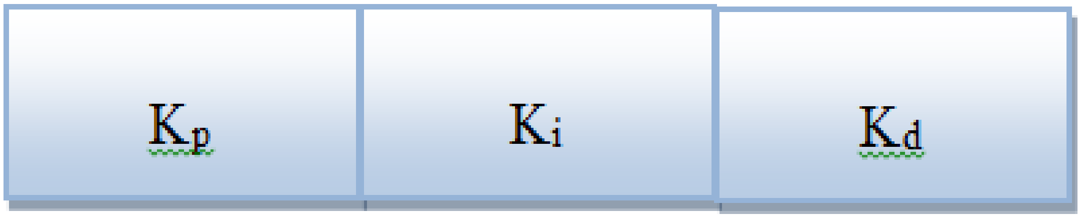


Figure 5. Chromosome Representation

The optimal tuning of the PID parameters is used to regulate and enhance the terminal voltage transient response. Overall use of GA in the field of PID optimization is expected to overcome weaknesses of other conventional approaches in non-linear situations with a particular reference of optimization criterion (performance index Eq. (3)). This innovative technique performs well when solving complex problems because it does not impose many limitations of traditional techniques. GA will search for solutions without regard to the inner workings of the problem in question.

For more details and explanation the flowchart of the proposed controller is illustrated in Figure 6.

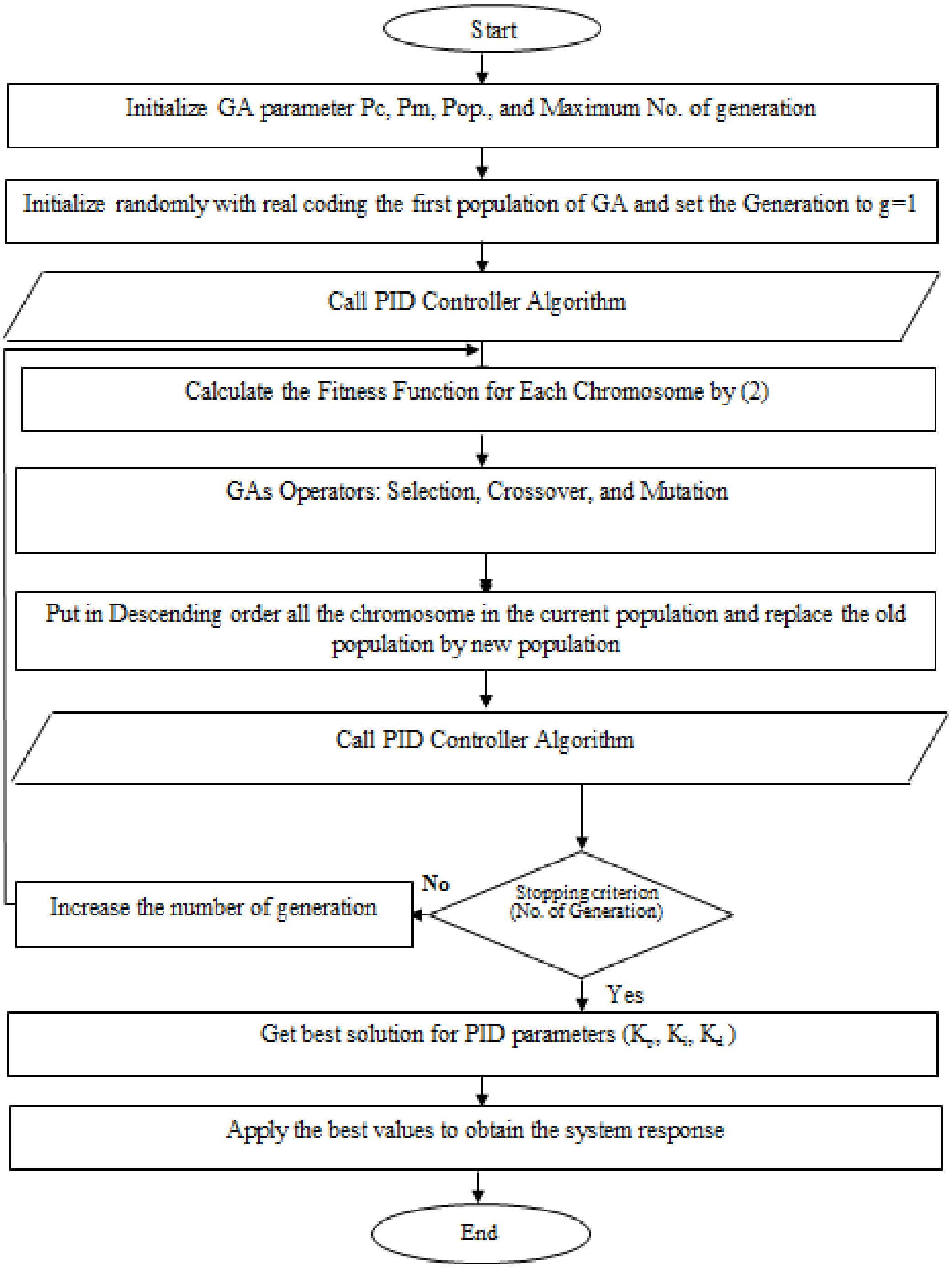


Figure 6. Flowchart of the Proposed Controller

4. Simulation Results

This section provides the simulation of high order synchronous machine model in MATLAB program as shown in Figure 7, based on Table 1 and Figure 3, then simplify this model based on the notes in Kundur [3] and Anderson [4]. Finally, the proposed controller is tested to enhance the terminal transient response.

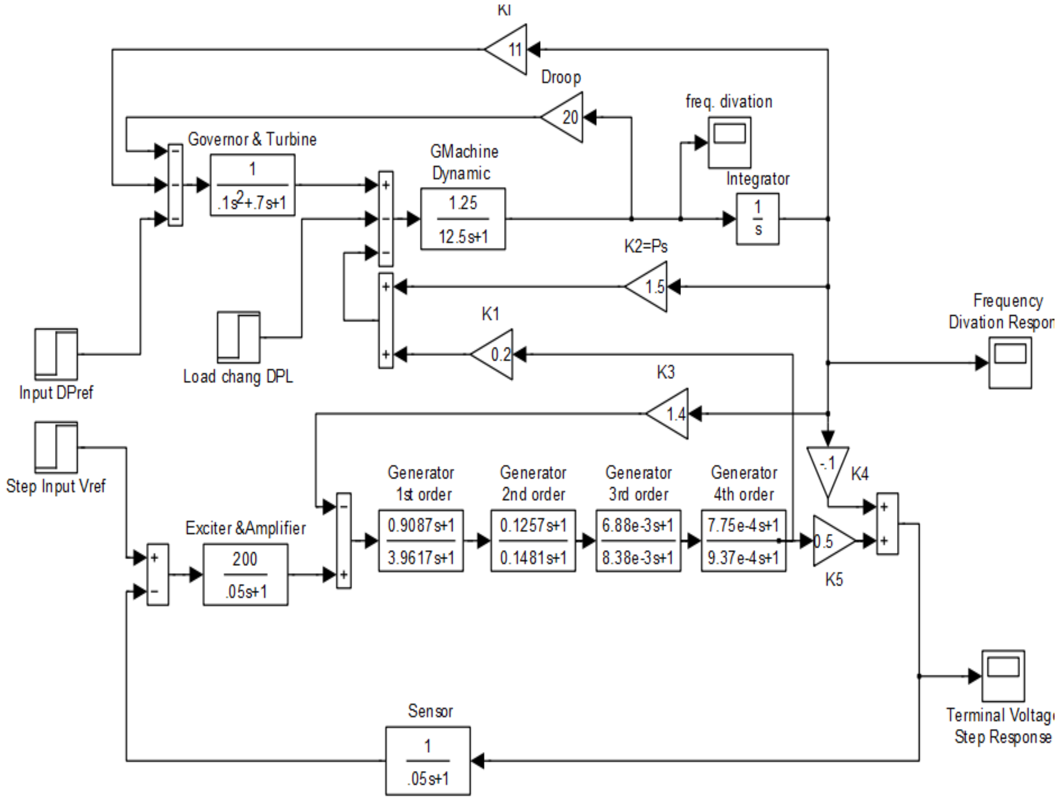


Figure 7. Simulated of High Order Synchronous Machine Model in MATLAB without Controller

First step: Simplification

Two control systems (LFC & AVR) in Figure 7 are decoupled at the points appears in Figure 8. The simulation results illustrate and prove that the obtained results of the terminal voltage transient response before and after separation are nearly matching as shown in Figure 9. This means that, each of the two control systems can be processed separately as mentioned in Kundur [3] and Anderson [4]. Therefore, the model in Figure 10 will be taken to study the transient voltage response of fourth order synchronous machine.

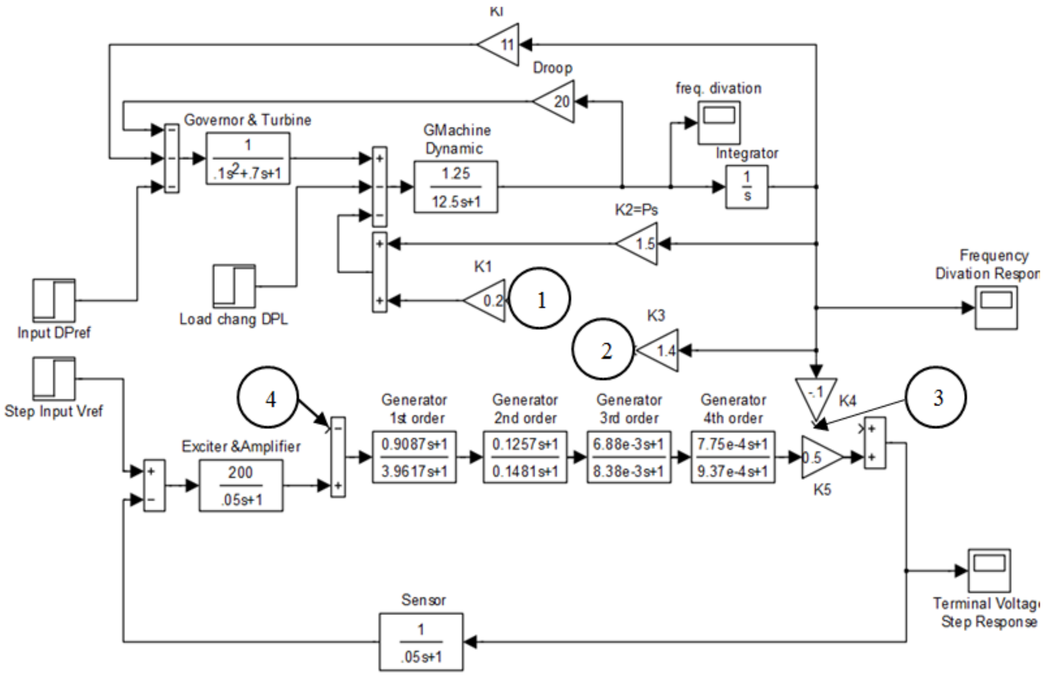
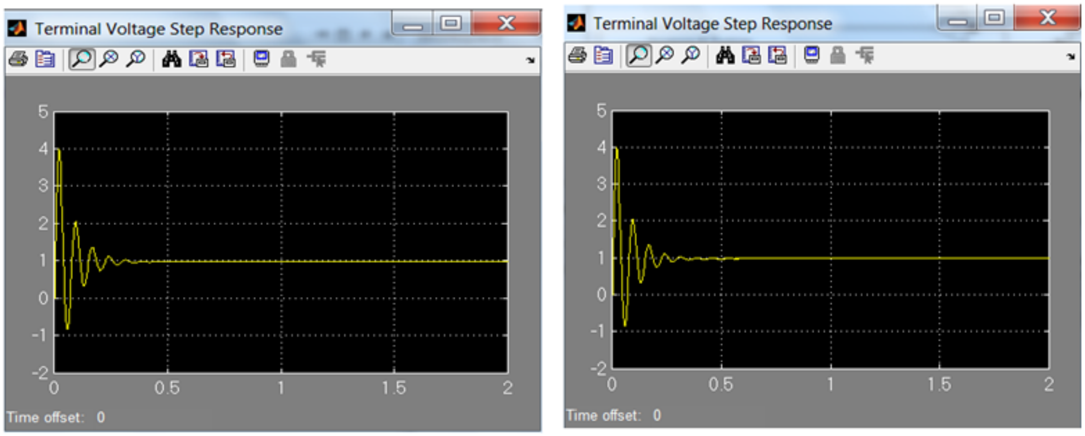


Figure 8. Separation between LFC and AVR of Synchronous Machine



(a) Before separation

(b) After separation

Figure 9. Terminal Voltage Responses

There is no visual inspection of the output signals (before and after separation) confirms that both systems produce the same signals.

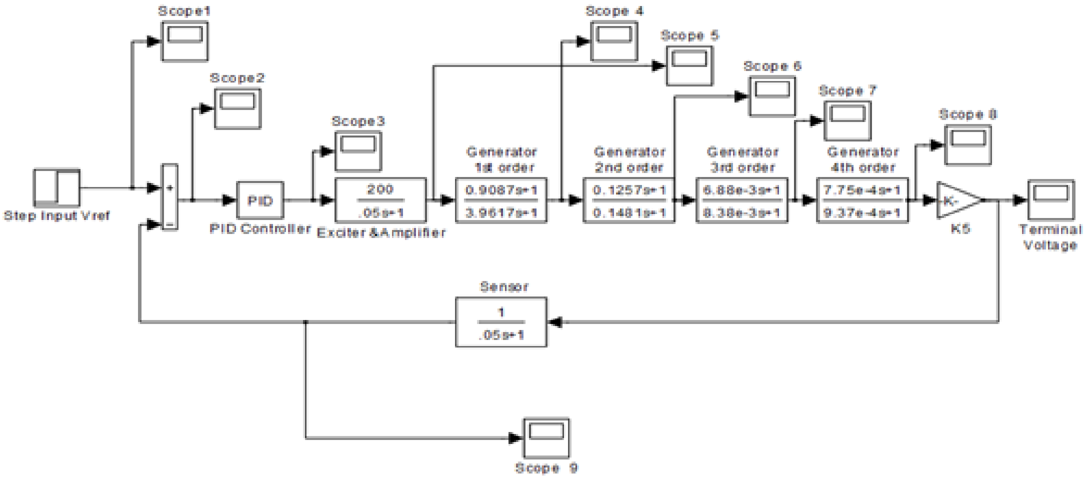


Figure 10. Fourth Order Simulation Model of SG–AVR with PID Controller

Step 2: Test the Proposed Controller

The obtained simulation model for the automatic voltage regulator (AVR) will be examined without controller, with conventional PID controller, and with evolutionary PID controller to make a good comparison for power system transient voltage stability enhancement. In AVR model (Figure 10) the input is a unite step signal of 1 (p.u) as a voltage reference, indicates the desired output response that one would like to obtain from the system output as a terminal voltage. In a lot of real processes it is not possible to obtain the correct output from a specified input, as the output may drift away from the set point for a variety of reasons or may respond too slowly to changes. A controller is therefore used, which compares the system output to the desired set point. It then uses this information to find a new control action to the system, so the system output can be adjusted correctly. All Figures with a simulation time of 2 second coincide with the X–axis, while the terminal voltage in each figure is in per unit and coincide with Y–axis of 5 p.u (the range of this axis had been chosen within this value, since the first overshot of the SG terminal voltage reach less than this value for the simulation without controller as shown in Figure 9). The conventional PID controller tuned by Ziegler – Nichols method [19] to find the output terminal voltage response as shown in Figure 11.

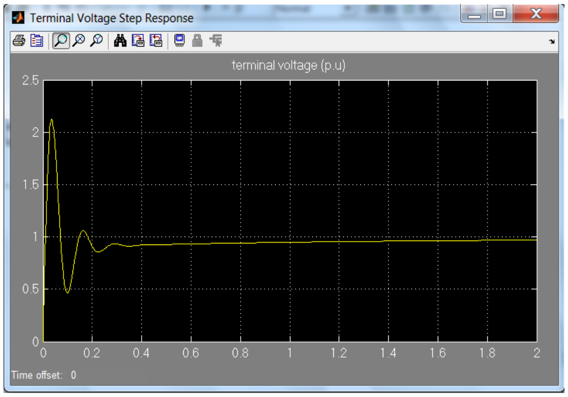


Figure 11. Terminal Voltage Response with PID Controller

The system have been subjected to a sudden large disturbance (symmetrical three phase short circuit to ground) at the terminal of the synchronous generator for a very short period (0.1 second) after a delay of 0.6 second as shown in Figure 12 . Figure 12 illustrate the voltage control system (AVR), with a monitoring scope at each point to monitor the control signal and the voltage response of each unit in this model. Through applying the same parameters (gains) values of the PID controller that optimized by using Ziegler-Nicholas tuning method, The response signals are illustrated at different points through the simulation system as shown in Figures 13-15.

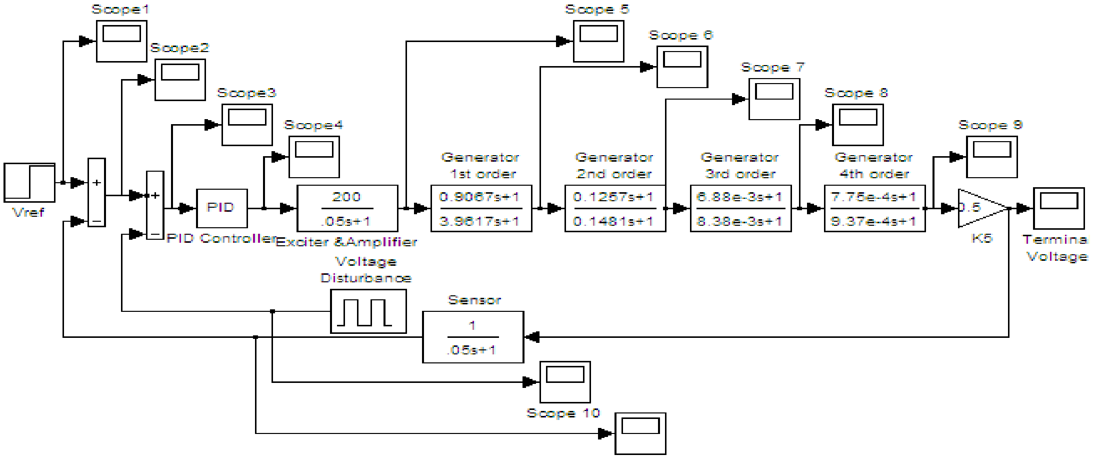


Figure 12. Simulation System (AVR) of 4th SG Model Subjected to a Disturbance

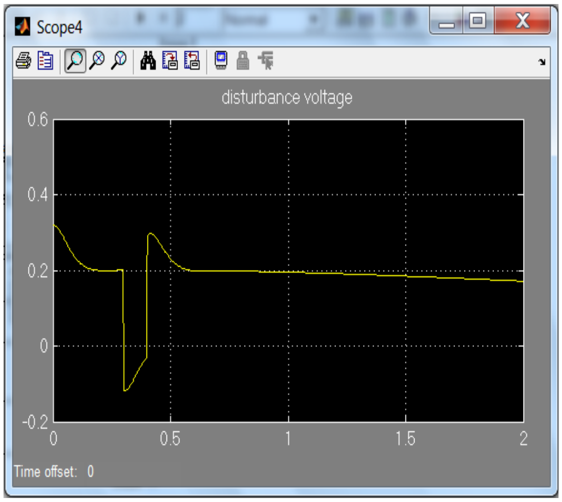


Figure 13. Scope 4: PID Control Action Signal

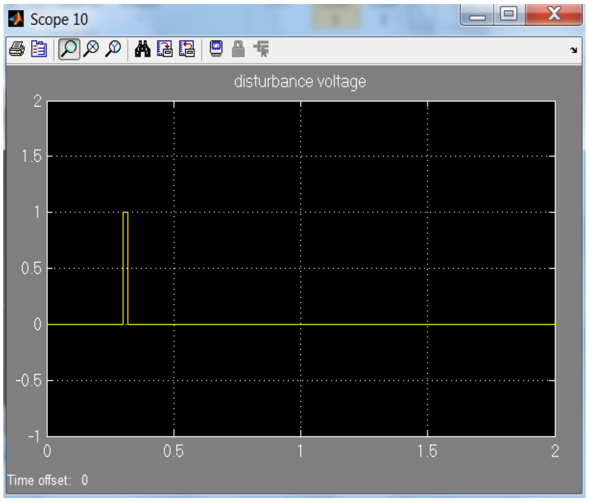


Figure 14. Scope 10 Disturbance Signal

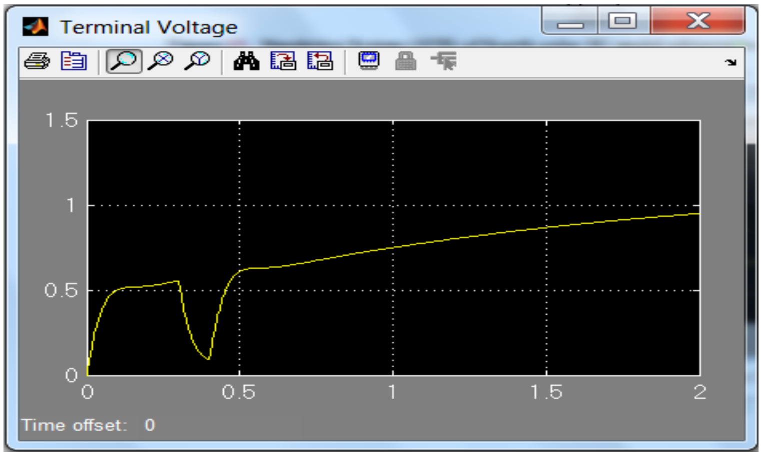


Figure 15. Scope Terminal Voltage System Response for Sudden Change with Conventional PID

The proposed controller is putted instead of the conventional PID controller to enhance the terminal voltage response. Where the obtained PID parameters through using the proposed algorithm are: K_p =3, K_i =0.7, and K_d =0.2. These values are obtained randomly by fast genetic algorithm. The results when using evolutionary PID controller are illustrated in Figures 16 and 17.

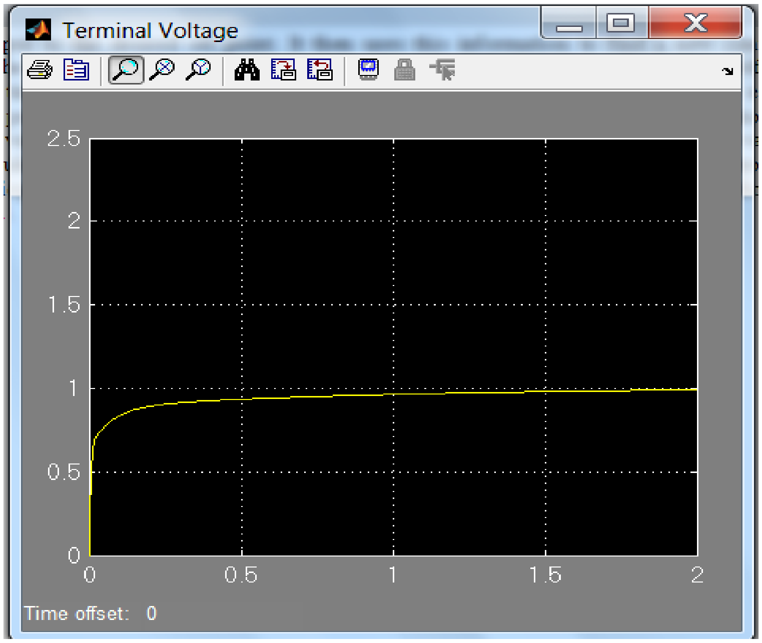


Figure 16. Terminal Voltage with Evolutionary PID Controller (without Disturbance)

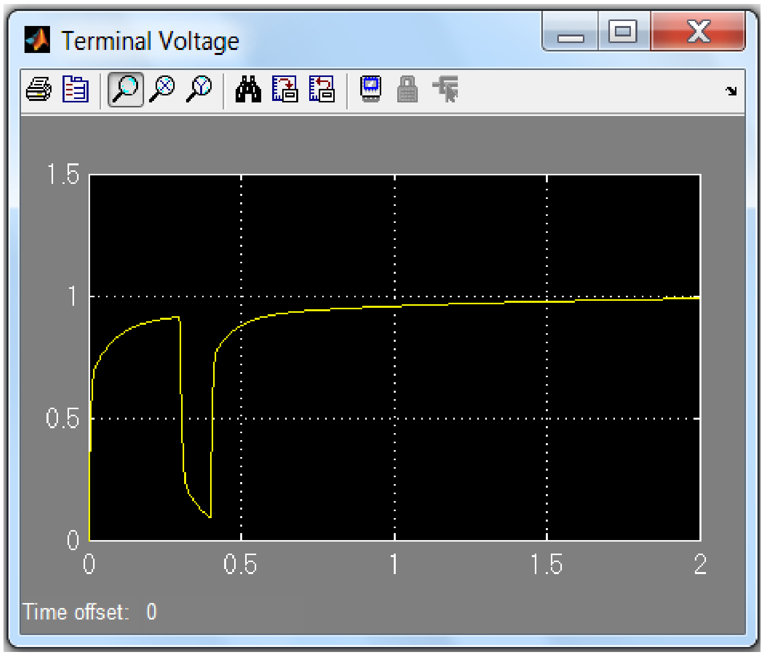


Figure 17. Terminal Voltage with Disturbance Controlled by Evolutionary PID Controller

Table 2 illustrates the Performance Index (ISEs) for high-order models of synchronous generator without Controller, with conventional PID conventional, and with evolutionary PID.

Table 2. Performance Indexes of the Terminal Voltage Response

Generator order	Controller type	ISE
3rd order	Without controller	26.1148
	PID controller	2.6946
	Evolutionary PID controller	**1.7716**
4th order	Without controller	27.2391
	PID controller	6.1151
	Evolutionary PID controller	**2.6061**

5. Conclusion

The proposed controller is an evolutionary PID controller based on hybridization between classical PID controller and fast genetic algorithm. It is a powerful controller to enhance the transient response parameters compared with original PID and other types of controllers as shown in the simulation results. Evolutionary PID controller solves many problems by connect the original PID controller with fast genetic algorithms. But it is a little complicated in computation like. The fitness function based on integral square error is very efficient choose. The Changing in the PID parameters have a significant effect on the system response therefore the best choose is generated and tuned randomly by FGA. The results obtained by the proposed controller are encouraged.

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