Speed Control of Wind Turbine Rotor Using Genetic Algorithm

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Abstract

In wind farms, rotor speed control of generator is essential to generate appropriate electric energy. In this study, squirrel cage induction generator (SCIG) is used and its rotor speed is controlled with Genetic Proportional-Integral (GPI) method. Determination of PI coefficients providing SCIG to operate reference rotor speed promptly is obtained with Genetic Algorithm (GA) known as an optimization method. In addition, sensorless control of rotor speed is carried out with field oriented control (FOC). To do this purpose, the transfer function of rotor speed control of induction machine is created and employed in simulation model. Used in this control, PI coefficients, firstly, are obtained with a classical method called Ziegler-Nichols Method (ZNM) and then is obtained with GA. Wind turbine (WT) model created with Matlab/Simulink are used to operate the system simulation for these different methods which determine the PI coefficients. The system simulation of the results for ZNM and GA are compared. It is clearly seen that the results which are operated with PI coefficients calculated by GA is better than the others in the respect of reaching time to reference speed and determination.

Keywords: Wind turbine, induction generator, genetic algorithm, rotor speed control

1. Introduction

WT's provide a considerable way to generate electric energy therefore studies have increasingly continued related to this topic. Turbine rotor speed is one of the important parameter for an efficient use of WT's. There are studies about keeping the turbine rotor speed in reference value with respect to ideal values [1]. Abbas et al did control of frequency and load in a system which has a self-excited induction generator depends to WT [2]. Baroudi made a detailed literature search about converter applications in several generators and comparison of their features such as their cost, efficiency and power consumption [3]. In induction machines, several different control methods are used such as scalar control, direct torque control and vector control. Besides, rotor, stator and directing controls which take air gap are applied [4]. Khalifa et al did voltage adjustment by carrying out a computer based control of self-capacitor excited induction generator [5]. Wind turbines variable speed control study carried out [6]. Jemli et al. realized mechanic non-sensored control in induction motor [7]. Johnson et al. did studies in Adaptive Torque Control of Variable speed in wind turbines [8]. Maria Oana Mora achieved a master's thesis study about sensorless Field Oriented Control (FOC) on a surface mounted permanent magnet synchronous generator (PMSG) for wind turbine applications [9]. Decio Crisol Donha made studies about keeping the power stable by Wind Turbine Controller by GA [10]. Golberg proofed that optimization problems can be solved via GA [11]. Rosmin tried to provide the rotor speed control of wind station in variable wind speeds in his study [12].

This paper begins with introduction of GA method to optimize the PI coefficients then mechanical models of WT including driver and aerodynamics model and mathematical model of induction motor are described. Finally, three different control methods, uncontrolled simulation, Ziegler-Nichols method with bode diagram and GA method, are simulated for SCIG rotor speed to compare their performance. The result of these simulations shows that GA method is the better to control SCIG rotor speed.

2. Genetic algorithm

GA is a genetic logic based method, accepted as very difficult among the optimization methods, widely used for multivariable optimization problems [11]. GA starts working by solutions compared to initial population created randomly. Then it tries to find an optimum solution by using genetic operators (selection, crossing, mutation). This method does not start the solution with only one initial point just as traditional optimization methods. It starts solving the problem by several initial points which creates initial population. Consequently, among these several solutions, the best solutions are chosen and the worst solutions are eliminated. GA starts by constructing initial population according to the pre-defined fitness function (FF) variables. Initial population is randomly created as a result of being coded of variables. Every row of population is called individual. For each individual, fitness function (FF) values are calculated. FF is occurred by adding goal function (GF) and penalty functions (PF) which include constraint function (CF). By considering FF values, a new population is constructed by calculations of elitism, selection, crossing and mutation which are the operators of GA. In GA new populations as much as generation number is constructed by considering former population. In every new population FF values are calculated. Among these results, best results are considered. Until GA termination condition is provided, these operations continue iteratively. Termination condition can be workingtime of algorithm, number of generations or giving same values of FF best values in adefined period of time. In this study the termination condition is generation number. So, by GA continuously better solutions are provided.

3. Problem description

Devices operated by electric energy are desired to work by maximum efficiency in stable voltage, current and frequency value. However, because of energy cut, sudden demand increase, harmonic, waving, spike voltage effects; there are deteriorations in frequency stability. They can occur in very low period of time such as 100-300 msec. On such as occasion, in several minutes, only field oriented control can provide wind station to work without separating from operator.

One of the purposes of this study is to determine better development strategy rules for wind turbine power control of which can be done by 3 types; Stall Control, Pitch Control and Active Stall Control and WT speed control can be done by 2 types; stable speed control and variable speed control. Stable speed control is done in the region shown by number 3 in Figure 1. Variable speed control is done in the region shown by numbers 2 and 3 in Figure 2. Because of advances in power electronics, its basic structure, maintenance easiness and having small dimensions when compared with other generators, SCIG usage is increased in WT. In this study, field oriented PI control operation is done in wind turbine 3rd region in Figure 1. In order to have maximum power in wind turbine, control is carried out by obtaining optimum top speed ratio (λ) and maximum power coefficient (Cp). These situations are shown in Figure 2.
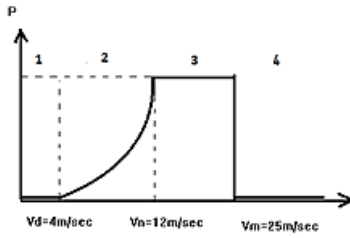

Figure 1. Ideal power setting for a WT
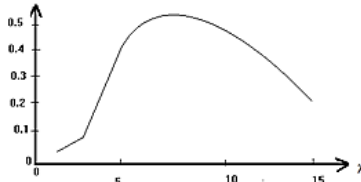

Figure 2. Variation graphic of power coefficient (CP) and top speed ratio (λ)

3.1. WT Control model

The model which is used for WT control is given in Figure 3. This WT model is occurred by 3 models called aerodynamic transfer organ, squirrel cage asynchronous generator model and back to back converter model. According to WT aerodynamic model, wind energy is converted to mechanic power via turbine wings. Mechanic power creates torque force for driver system and induction generator in order to produce electric energy. WT control basic equation is given in Equation 1,2.
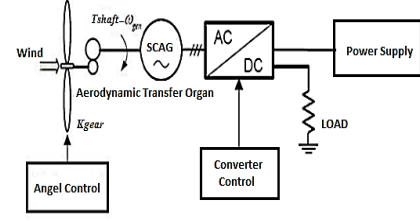

Figure 3. WT control model

3.2. WT Aerodynamic model

In Equation 1, Pw describes power generated from wind, ρ describes air mass air density, v describes wind speed and S describes surface area. In Equation 2, Cp describes power coefficient and Pm describes electric energy which is converted to the power.

$$Pw = \frac{1}{2}\rho S v^3 \qquad (1)$$

$$Cp = \frac{Pm}{Pw}, \quad Cp < 1 \qquad (2)$$

$$Tw = \frac{1}{2}\rho \pi R^3 Cq\ (\lambda, \theta)v^2 \qquad (3)$$

$$Pm = \frac{1}{2}\rho R^2 Cp(\lambda, \theta)v^3 \qquad (4)$$

$$Cq = \frac{Cp}{\lambda} \qquad (5)$$

In Equation 3-5, Tw describes turbine torque, R describes turbin blade radius Cq describes torque power coefficient λ describes top speed ratio, θ describes pitch angle.

3.3. Mathematical model of induction machine: control system is designed based on this model.

$$V'_{s\alpha\beta} = R_s{'}\dot{I}_{s\alpha\beta} + \frac{d\lambda'_{s\alpha\beta}}{dt} \qquad (6)$$

$$V'_{sdq} = R_s{'}\dot{I}_{sdq} + \frac{d\lambda'_{sdq}}{dt} + J\omega_{dq}\lambda'_{sdq} \qquad (7)$$

$$\lambda'_{rdq} = L_r{'}\dot{I}_{rdq} + L_M{'}\dot{I}_{sdq} \qquad (8)$$

$$\sigma = 1 - \frac{L_M^2}{L_r L_s} \qquad (9)$$

$$\sigma_r = \frac{R_r}{L_r} = \frac{1}{T_r} \qquad (10)$$

$\alpha\beta$ and dq describe axises in induction machine model. Induction machine space vector dq reference model equations are given in Equation 6-10. In Equation 6, $V'_{s\alpha\beta}$ describes stator $\alpha\beta$ axis voltage value, R_s describes stator resistance, ${'}\dot{I}_{s\alpha\beta}$ describes stator $\alpha\beta$ axis current value and $\lambda'_{s\alpha\beta}$ describes stator $\alpha\beta$ axis magnetic flow. In Equation 7, V'_{sdq} describes stator dq axis voltage, ${'}\dot{I}_{sdq}$ describes stator dq axes current, λ'_{sdq} describes stator dq axis magnetic flow, $J\omega_{dq}$ describes stator dq axis inertia moment. In Equation 8, L_r describes rotor inductance, ${'}\dot{I}_{rdq}$ describes stator dq axis rotor current and L_M describes mutual

inductance. In Equation 9, σ describes distribution factor, L_s describes stator inductance. In Equation 10, σ_r describes rotor distribution factor, R_r describes rotor resistance and T_r describes rotor time constant.

3.4. Current model

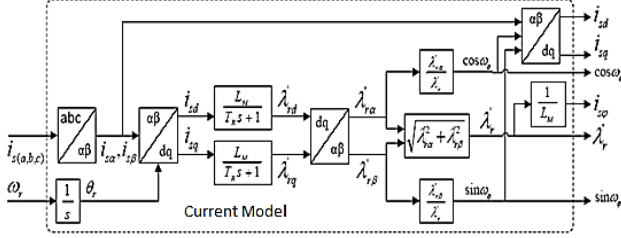Rotor flow prediction model block scheme is shown in dq rotating reference axis in Figure 4.

Figure 4. Current model (rotor flow prediction scheme)

$$\dot{I}_{sdq} = \frac{\lambda'_{rdq}}{L_M}(1 + s.T_r) \tag{11}$$

$\dot{I}_{sdq}$ current which is shown in Figure 5 is described by Equation 11. Indirect Field Oriented Control (IFOC) method speed control scheme is shown in Figure 5. d and q axis equations, based on induction machine model stator currents, are described in Equation 12-13.
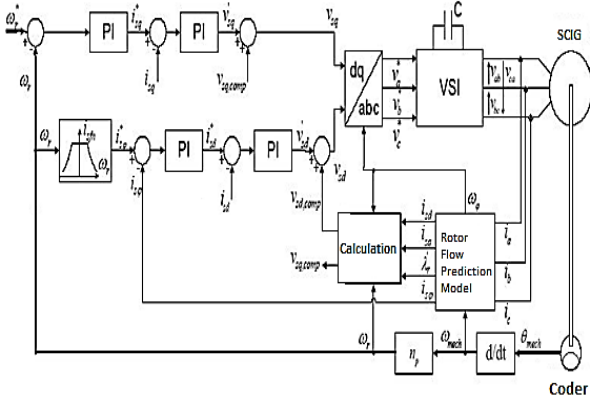

Figure 5. Indirect field oriented control (IFOC)

$$\dot{I}_{sd} = \frac{1}{R_s} \frac{1+T_r S}{T_s T_r \sigma s^2 + (\sigma T_s + T_r)s + 1}\left(V'_{sd} + \omega_\varphi \sigma L_s \dot{I}'_{sq}\right) \tag{12}$$

$$\dot{I}_{sq} = \frac{1}{R_a(1+T_a S)}\left(V'_{sq} + \omega_\varphi \sigma L_s(\dot{I}_{sd} - \dot{I}_{sq}) - \omega_r \frac{L_s}{L_M}\lambda'_r\right) \tag{13}$$

In Equation 12-13, $\lambda'_{rdq} = \lambda'_r$ is rotor magnetic flow, $\dot{I}_{sd}$ describes stator d axis current, ω_φ shows angular speed, $\dot{I}_{sq}$ shows stator q axis current, T_s is Stator time constant. R_a is equivalent resistance, T_a shows equivalent time constant.

$$P_m = \frac{3}{2}\frac{L_M}{L_r}\omega_r \lambda'_{rd} i_{sq} = \frac{3}{2}\frac{\omega_r}{p}T_m \tag{14}$$

$$T_m = \frac{2}{3}p\frac{L_M}{L_r}\lambda_r i_{sq} \tag{15}$$

Equation 14 describes induction machine mechanic power, Equation 15 describes electromagnetic torque value which is obtained by considering as $\lambda'_{rq} = 0$. In Equation 15 p shows double pole number.

4. Solution of problem

In Figure 6, speed loop is given in block scheme. In this scheme torque variable i_{sq}, depends on necessary torque i^*_{sq} reference value. I^*_{sq} reference value depends on the change between rotor reference speed w^*_r and rotor speed w_r. In Equation 16-17, dq reference generator voltage (V_{sq}) and valid q axis stator current (i_{sq}) are given. In this equation, $V_{sq,comp}$ is ignored because of not having significant effect on system.

$$V'_{sq} - V_{sq,comp} = R_a(1 + T_a.s)i_{sq} \tag{16}$$

$$V_{sq,comp} = w_\varphi \sigma L_s(i_{sd} - i_{s\varphi}) + w_r \frac{L_s}{L_M}\lambda_r \tag{17}$$

PI controllers that is used for control design is described by the Equation 18. Speed control scheme and transfer function is described in Figure 6.

$$F_{PI}(s) = K_p \frac{1 + s.\tau_i}{s.\tau_i} \tag{18}$$

P is double pole number and PI coefficients of speed transfer function Kp and Ki are calculated by Ziegler Nichols coefficient according to the Bode diagram. Kp = 1 and Ki = 5 are found, so closed loop speed transfer function is obtained in Equation 19,

$$G_\omega(s) = \frac{33.12S + 165.6}{7.998e^{-11}S^5 + 4.939e^{-7}S^4 + 0.000924S^3 + 0.486S^2 + 33.12S + 165.6} \tag{19}$$

Flow loop is described by d axis in Figure 6. Due to obtain IG rotor flow, firstly i_{sd} current is obtained by internal loop. This situation is described by Equation 20. Then external loop is designed for IG magnetization current $i_{s\varphi}$. This situation is designed by Equation 21.

$$Plant1 = \frac{1}{R_s}\frac{1+T_s S}{T_r T_s S^2 + (T_s+T_r)S+1} = \frac{0.008S + 0.4}{0.00016S^2 + 0.028S + 1} \tag{20}$$
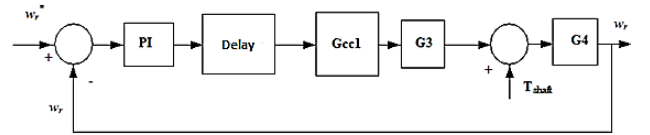

Figure 6. Speed control closed loop transfer function scheme

The Ziegler Nichols coefficients that are calculated according to Bode diagram are taken. Magnetization current PI Transfer Function $= Kp + \frac{Ki}{S}$ the PI Ziegler Nichols Control coefficients that are calculated by values taken by Bode Diagram $Kp = 1.5$, $Ki = 75$ is found.

$$G_{i_{s\varphi}}(s) = \frac{3.376.e^{11}}{S^4 + 6126 + 1.125e^7S^2 + 5.626e^9S + 3.376e^{11}} \qquad (21)$$

Speed control transfer function of analyzed system's Simulink model is given in Figure 7. This model is generated firstly by getting P parameter value as one then by bode drawings and PI coefficients that is obtained by closed loop ZNM. In solution with GA for error index, Equation 22 is used. Finally model is generated with PI coefficients that are found by GA. PI coefficients is given in Table.

$$J = IAE = \int_0^t |e(t)|.dt \qquad (22)$$
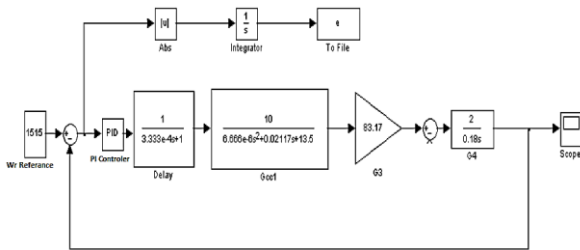
Figure 7. Control of simulink model with different PI parameters

	Proportional Gain K_p	Integral Gain K_I
Bode Ziegler – Nichols Coefficients	1	5
Genetic Algorithm Coefficients	0.799	2.1877

Table 1. PI control parameters

5. Results

The results of rotor speed control are obtained with 2 different PI controller coefficients. In Table 1, the values of PI coefficients which are calculated by 2 different methods are shown. Used these values, output curves of transfer function are simulated. The results are shown in Figure 8-10 for which are plotted uncontrolled, Bode Ziegler- Nichols Method (BZNM) and GA method, respectively. In order to compare the results for each method, in Figure 11, all curves are plotted in one figure. As figures are compared with each other, it is shown that GA method is better than the others.
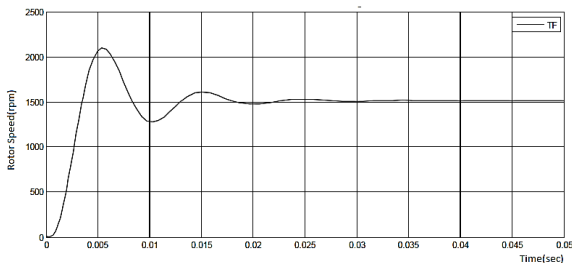

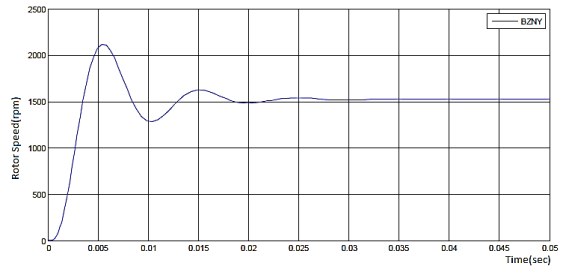**Figure 8.** Uncontrolled transfer function graphic
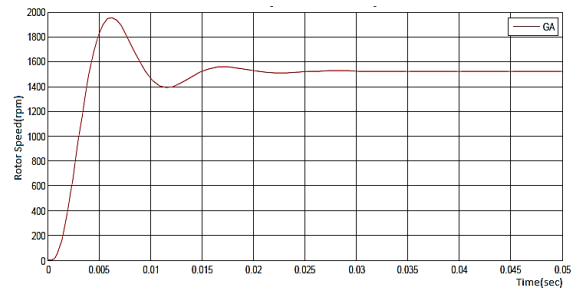

Figure 9. Ziegler-Nichols PI coefficient graphics
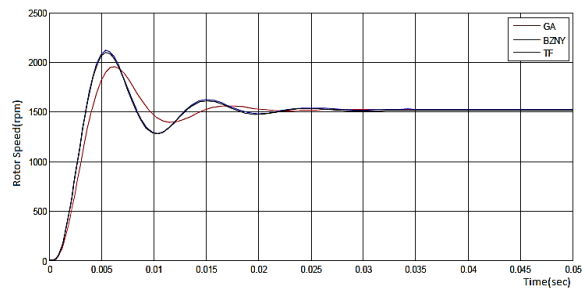

Figure 10. GA PI coefficient graphic

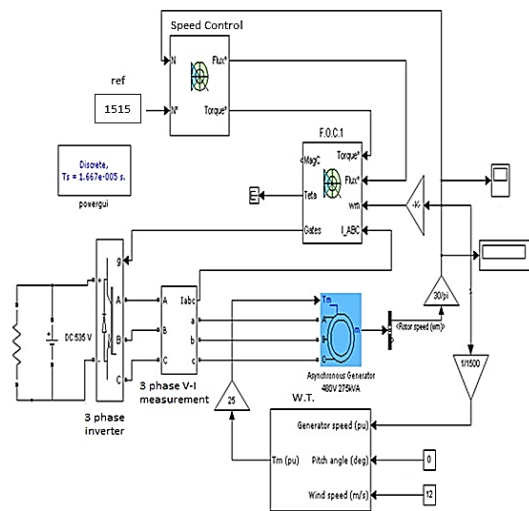**Figure 11.** Comparing all results

Figure 12: Wind turbine control system

In order to show the results of simulation, there are 2 control simulation constructed. In one of the control blocks, Ziegler

Nichols PI controller coefficients which is obtained from bode drawings is integrated and in the other control block PI coefficients that is obtained by GA is integrated. The results of simulation are given in Figure 13. It is seen that the reaching time of current obtained with GA is shorter than the others.
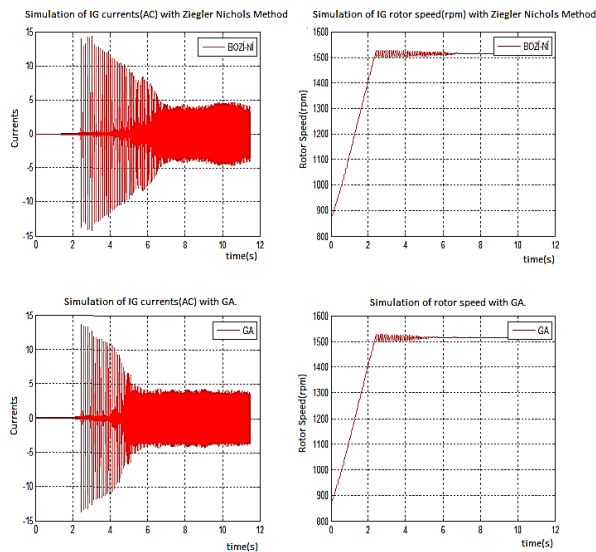

Figure 13. Comparison of result graphics

6. Conclusion

When graphics are analyzed; it is seen that the best solution is obtained by PI coefficients that are found by genetic algorithm. WT provides SCIG to operate in reference speed in a shorter period of time, as PI controller coefficients that are used for speed control in IFOC model of WT were calculated with GA. System in a short time to reach the reference speed provides that less torque variation. Therefore; it is provided that power and voltage fluctuations in network are in acceptable value. It is hown in graphics that PI coefficients optimized by GA gave better results than the PI coefficients obtained from classical Ziegler Nichols method. These results prove that GA can be applied for wind energy and turbine technology in optimization problems in future.

7. References

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