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Modeling of Induction Generator for Wind-Turbine Systems

Ulas Eminoglu

***Abstract*-- In this study, an analytical model is proposed for induction generator that is generally used in Wind-Turbine Systems (WTSs). The model is developed by using the steady-state model of induction machine. It is validated on an induction machine and results are compared with the results of the other models reported in the literature It is found that the developed model is comparable with the existing ones. The main advantage of the model is that it facilitates the computation of real and reactive power outputs for a specified mechanical power input and terminal voltages, in a simple way such that it does not require computation of any system parameters (i.e., rotor slip and/or current), which causes computational complexity.**

***Index Terms*--Distributed energy, induction generator, wind-turbine systems.**

I. Introduction

Distributed Energy (DE) is an approach to electricity generation that offers environmental benefits by siting generators closer to where the energy is used. DE could be produced from wind power, solar panels and other renewable energy sources, connected directly into the local distribution network. In fact, power system operation may be adversely impacted by the introduction of DE sources if certain minimum standards for control, installation and placement are not maintained. For the proper installation and placement, realistic load flow analysis has to be performed. Hence, DE sources must be included to the power flow analysis with their representative features [1].

The usage of Wind Turbine Systems (WTSs) have been gaining popularity worldwide for electricity generation since it is clean, environmentally friendly and a free source. Its most important feature is that it removes dependency to other countries in energy sector since it's locally available. It is also acknowledged that it's competitive with conventional bulk electricity generation systems on cost account. It converts the turbine's mechanical energy obtained from the wind into electrical energy through a generator. Energy conversion from the wind is described by a cubic relation of the wind speed as

$$P_m = \frac{1}{2}\rho A C_p(\lambda, v)u^3 \quad \text{(1-a)}$$

$$C_p(\lambda, v) = c_1\left(c_2\frac{1}{\Lambda} - c_3 v - c_4 v^x - c_5\right)e^{\left(\frac{-c_6}{\Lambda}\right)} \quad \text{(1-b)}$$

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08v} - \frac{0.035}{1+v^3} \quad \text{(1-c)}$$

$$\lambda = \frac{R\eta w_r}{u} \quad \text{(1-d)}$$

Where ρ is the density of air (kg/m^3), A is area swept by the rotor (m^2), C_p is the power coefficient, u is the wind speed (m/s), R is the turbine rotor radius (m), η is the gear ratio, w_r is the angular velocity (rpm), and c_1 to c_6 and x are constant. Due to its importance and advantages amongst various distributed generation sources, the effects of the wind farms on the grid should be properly investigated. Accordingly, these types of energy sources must be modeled with adequate details without causing any computational burden for the analysis. Recently, several models have been developed for WTSs in the literature [2-5]. Consequently, they are generally modeled by a five- or six-element circuit that is closely related to the physical system and whose values remain constant by ignoring magnetic saturation and thermal nonlinearity. In addition, their utilization is problematic in terms of accuracy, convergence ability and most importantly on the complexity in load flow analysis [6].

Although the most favorite type of the generators sold today for WTSs is the doubly-fed induction generator type of machines, the installed capacity of the WTSs is overwhelmingly based on the traditional fixed speed induction generators [7]. Therefore, modeling of this type of generators and their application into distribution systems are still important. For this reason, in this study, an analytical model for induction generator, which is generally used for WTSs, is developed by using a steady-state model of the induction machine. The validity of developed model is then tested for an induction machine by comparing with the results of the existing models, proposed in [2-4]. Results suggested that developed model is reliable and more usable when compared with the existing models.

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II. Development of a New Model for Induction Machine

As summarized above, the induction generators are generally used in wind turbine for electricity generation and modeled with standard equivalent circuit from using the concept of a rotating transformer. Accordingly, they are not more suitable for the implementation to the distribution systems' load flow analysis due to the computational complexity [6].

Let us consider an induction motor equivalent circuit referred to the stator side as given in Figure 1. In the figure, V_s and V_r stand for the magnitude of the stator voltage and referred rotor voltage, respectively. R_{sc} and X_{sc} show short-circuit equivalent resistance and reactance, respectively. R_m resistance represents core losses and X_m shows magnetizing reactance. P_s and Q_s stand for the terminal active and reactive power of the machine, respectively.

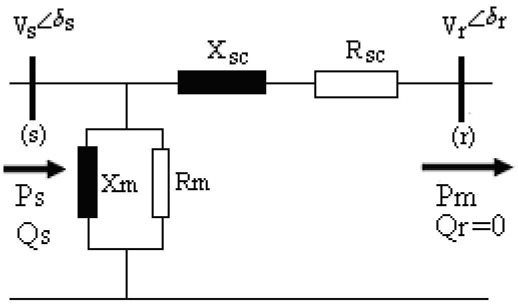

Figure 1. Induction machine equivalent circuit

From the equivalent circuit, given in Figure 1, reactive and active power balance can be written as follows

$$Q_s = X_{sc}\frac{P_m^2}{V_r^2} + \frac{V_s^2}{X_m} \tag{1-a}$$

$$P_s = P_m + R_{sc}\frac{P_m^2}{V_r^2} + \frac{V_s^2}{R_m} \tag{1-b}$$

From figure, the referred rotor voltage of the machine (V_r) can be obtained by using modified bi-quadratic equation given in [8] as follows

$$\phi_r = \tan^{-1}\left(\frac{Q_r}{P_r}\right) \tag{2-a}$$

$$K = V_s^2 - 2P_r\left(R + X\tan\phi_r\right) \tag{2-b}$$

$$V_r = \sqrt{\frac{K \pm \sqrt{K^2 - 4(R^2 + X^2)P_r^2\sec^2\phi_r}}{2}} \tag{2-c}$$

By recognizing the fact that $Q_r = 0$, the referred rotor voltage can be rewritten as follows

$$\phi_r = 0 \tag{3-a}$$

$$K = V_s^2 - 2P_r R \tag{3-b}$$

$$V_r = \sqrt{\frac{K \pm \sqrt{K^2 - 4(R^2 + X^2)P_r^2}}{2}} \tag{3-c}$$

Substituting the voltage equation, (3-c), into (1-a), one can get

$$Q_s = \frac{V_s^2}{X_m} + \frac{2X_{sc}P_m^2}{V_s^2 - 2P_mR_{sc} - \sqrt{V_s^4 - 4P_mR_{sc}V_s^2 - 4X_{sc}P_m^2}} \tag{4-a}$$

$$Q_s = \frac{V_s^2}{X_m} + \frac{2X_{sc}P_m^2}{V_s^2 - 2P_mR_{sc} + \sqrt{V_s^4 - 4P_mR_{sc}V_s^2 - 4X_{sc}P_m^2}} \tag{4-b}$$

Similarly, substituting voltage equation, (3-c), into active power balance, (1-b), we get

$$P_s = P_m + \frac{V_s^2}{R_m} + \frac{2R_{sc}P_m^2}{V_s^2 - 2P_mR_{sc} - \sqrt{V_s^4 - 4P_mR_{sc}V_s^2 - 4X_{sc}P_m^2}} \tag{5-a}$$

$$P_s = P_m + \frac{V_s^2}{R_m} + \frac{2R_{sc}P_m^2}{V_s^2 - 2P_mR_{sc} + \sqrt{V_s^4 - 4P_mR_{sc}V_s^2 - 4X_{sc}P_m^2}} \tag{5-b}$$

Equations (4) and (5) have a straightforward solution and depend on terminal voltage magnitude, mechanical power input and equivalent circuit parameters of the induction machine. They facilitate the computation of real and reactive power outputs of the induction generator, easily without needing computation of rotor slip that increases computational complexity when compared with models developed by using standard equivalent circuit of the generator [2-4]. It must be stated that for the induction generators, the mechanical power is negative because of the change on the flow of power that is transferred from 'rotor' (bus-r) to the 'stator' (bus-s). Hence, the mechanical power input, P_m, must be taken in negative sign for developed model.

III. Test Case

Since there are two solutions of real and reactive powers, the required root of power equations, (4) and (5), must be determined. Accordingly, variation of reactive power demand of the generator with different mechanical power input are provided in Figure 2 that are computed using both expressions (Eq. 4) for a hypothetical machine for the *380 V* and *10 kVA* base values. From Figure 2, it is seen that depending on terminal voltage for each mechanical power input, there are two possible solutions for the output reactive power. One of these obtained by using (4-a) coincides with the unstable equilibrium point of the machine, and is too high when compared with the mechanical power for the each terminal voltage level. Hence, it is not feasible for the induction generator modelling. On the other hand, the solution of (4-b) remains on the feasible region for the each terminal voltage level. Likewise, variation of the generated active power of the generator with different mechanical power input are computed by using (5), and provided in Figure 3. The same observation could be made from the variation of the active power. Therefore, the solution of (4-b) and (5-b) are unique for the reactive and active power outputs of the induction generator, respectively. They can facilitate the computation of real and reactive powers of the induction generator for a specified mechanical power input (i.e., wind speed) and terminal voltage, in a simple way.

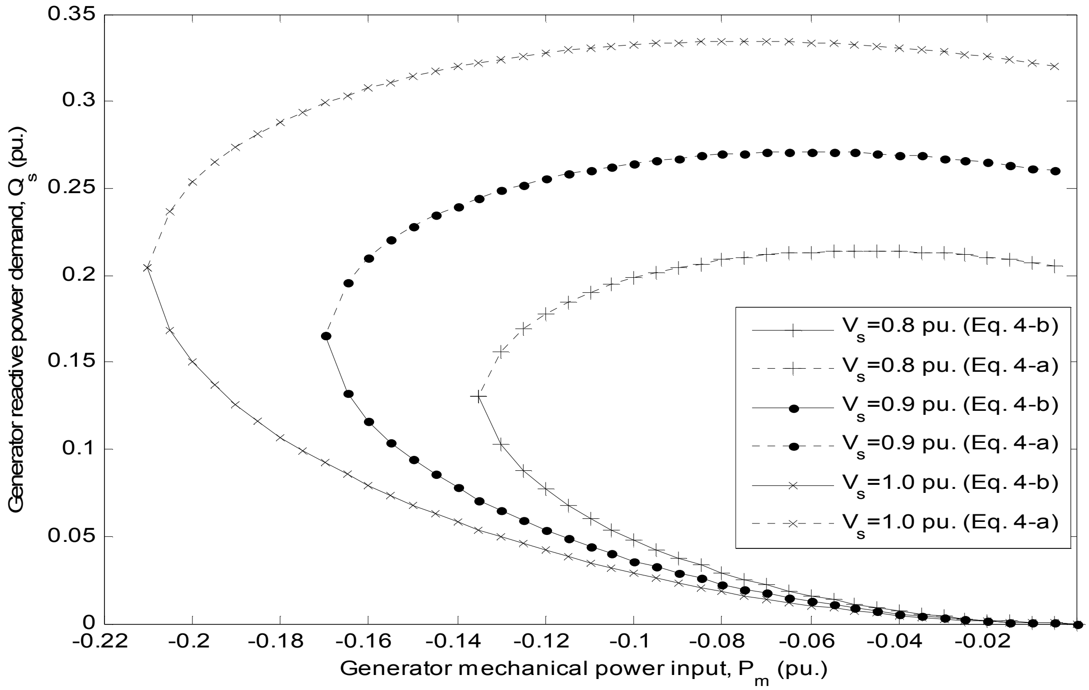

Figure 2. Generator reactive power demand (Q_s) with the mechanical power input for different terminal voltages.

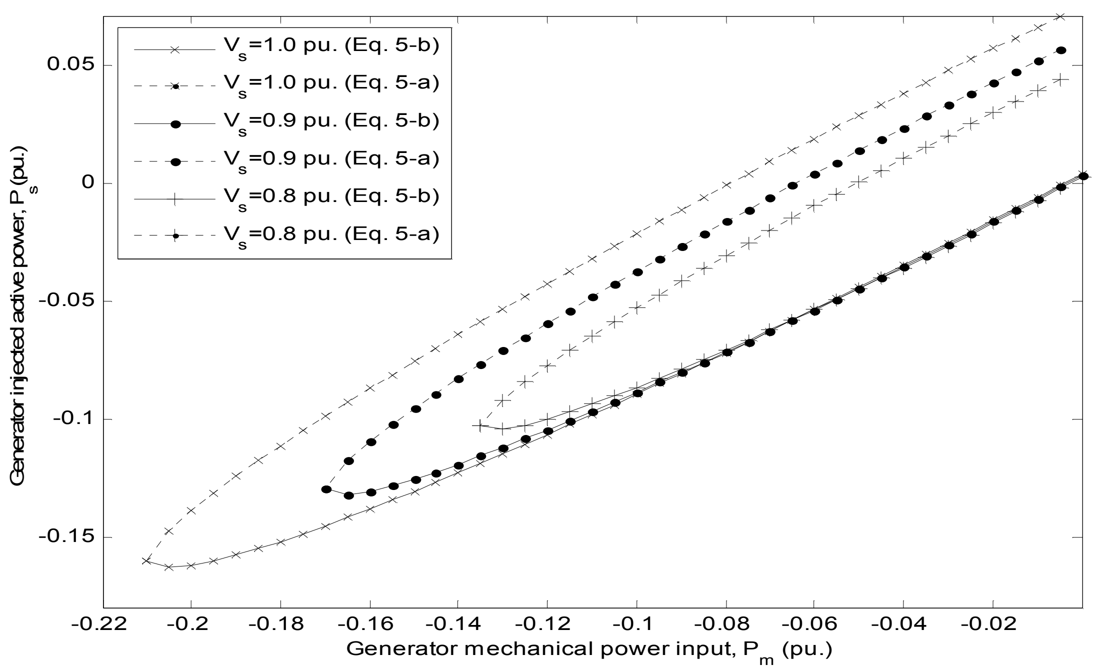

Figure 3. Generator active power (P_s) with the mechanical power input for different terminal voltages.

IV. MODEL VALIDATION

Developed analytical model is validated on an induction machine whose parameters is obtained by applying standard no-load and blocked-rotor tests, and is given in Table 1. For the different mechanical power input values, the rotor speed (W_r) as well as the generator slip are computed iteratively, starting with an initial value and then updating it so as to make the accelerating power zero as follow

$$P_a = P_g - P_m \approx 0 \tag{6}$$

where P_m is mechanical power input of the induction generator and it depends on the rotor speed as given in (1). P_g is air gap electrical power output of the induction generator and it depends on rotor slip; i.e.,

$$P_g = -|I_2|^2 R_2 \left(\frac{1-s}{s}\right) \tag{7}$$

where I_2, R_2 and s are the rotor current, resistance and slip of the generator, respectively. It must be stated that while solving (6), I_2 is defined as a function of rotor slip using generator equivalent circuit as given in [3].

Table 1. Induction machine parameters

Type of Parameters	Values
Power (kW)	1.5
Voltage (V)	380
R_{sc} (ohm)	3.312
X_{sc} (ohm)	14.76
R_m (ohm)	1230
X_m (ohm)	101.5

After computation of rotor speed and rotor slip of the generator by solving (6) for different mechanical power input iteratively, the generator output active power obtained by using developed model and the other models namely PQ model of [2], and the slip based equations of [3] and [4] are given in Figure 4. It is seen from Figure 4 that the active power output of the generator obtained by using developed model is in close agreement with the results of the other models [2-4], especially with the model proposed in [4]. This is due to that the models developed in [2-3] neglect the active power losses of the generator by equating mechanical power input with the output power of the generator. Reactive power demand of the generator is also computed by using developed model and is given in Figure 5 with the result of other models. Likewise, the same observation could be made from the reactive power variation that the results are more comparable with the results of the other models. The differences are in the minimum level for each mechanical power input values of the generator and are evidently negligible.

It can be seen from Figures 4 and 5 that the developed model is reliable, and it successfully estimates the active and reactive power outputs of WTSs when compared with the other models. It requires only wind power (mechanical power input) and terminal voltage for the computation of generator power outputs, in a simple way such that it does not require computation of any system parameters (i.e., rotor slip and/or current). On the other hand, the models proposed in [2-3] neglect the active power losses of the generator by equating mechanical power input with the output power of the generator. That introduces loss of accuracy in the produced active and consequently reactive power estimations. In addition, the model of [2] calculates reactive power with an approximate formula. Although, the authors of [2] provide an exact nonlinear equation for the reactive power that is a function of rotor slip, this system of equations increases computational complexity and is difficult to be implementation in the load flow analysis. Meanwhile, the model of [3] requires calculation of machine slip by using a second degree equation that has multiple solutions and has very complicated structure with multiple formulas which cause computational burden in load flow analysis. In addition, however, the equation given in [4] is more reliable in terms of accuracy; it requires prior knowledge of the rotor slip, which is not readily available in this type of studies. Consequently, they are not suitable for the implementation to the distribution systems' load flow analysis.

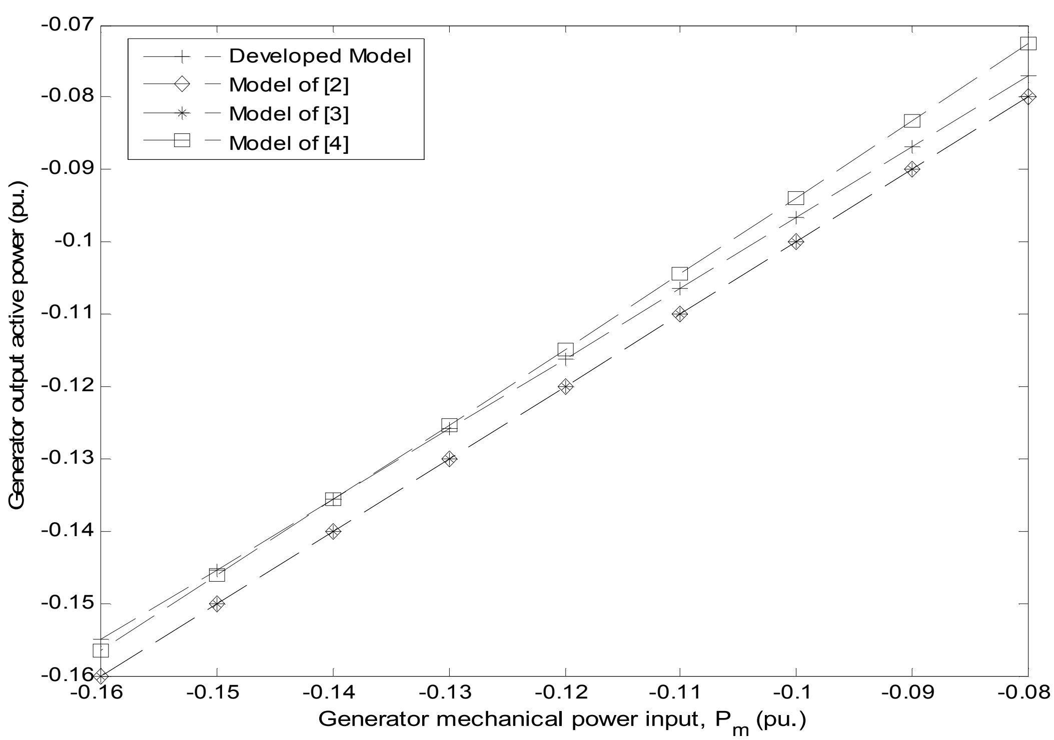

Figure 4. Variation of output active power of the generator with different mechanical power input.

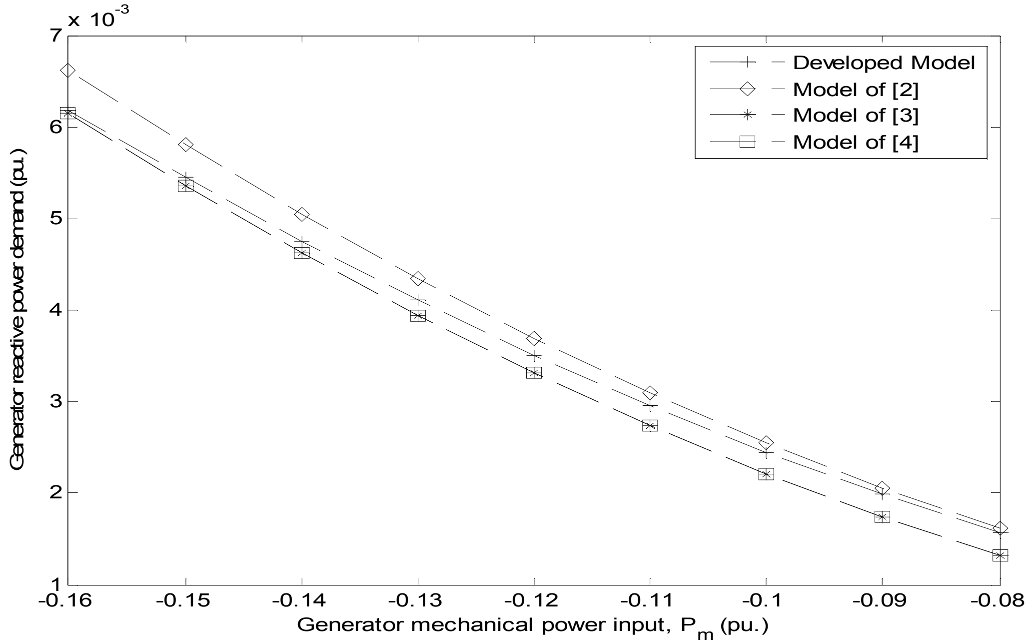

Figure 5. Variation of reactive power demand of the generator with different mechanical power input.

V. CONCLUSIONS

In this paper, a new model for induction machine, widely used for wind turbine systems, is provided. The model is developed by using the steady-state model of induction machine. It is validated for an induction generator by comparing with results of the other models reported in the literature. It is concluded that;

- The developed model is comparable with the existing models.
- It facilitate the computation of real and reactive power outputs for a specified mechanical power input and terminal voltages, in a simple way such that it does not require computation of any system parameters (i.e., rotor slip, current or Thevenin equivalent of the generator), which causes computational complexity and increases the computation time.
- The developed model can easily be incorporated into the load flow analysis. This is due to the fact that distribution system load flow algorithms, generally, take advantage of the radial network topology and consist of forward and/or backward sweep processes. They need only active and reactive power of the load in load flow calculations. Thus, the developed machine model for WTS can be modelled as a PQ-bus, and reactive and active powers can easily be computed in each iteration by using (4-b) and (5-b), respectively. Because active and reactive powers are functions of terminal voltage and mechanical power input for a specified wind speed of the WTS, and both are available during each iteration in load flow calculations.

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VII. BIOGRAPHIES

Ulas Eminoglu was born in Kars in Turkey, on November 25, 1978. He received the B. Sc and M. Sc degree in Electrical-Electronics Engineering from Inonu University in 2000 and from Nigde University, Turkey, in 2003, respectively. Then, he joined Gebze Institute of Technology as research assistant in Turkey and studied distribution systems load flow analyses. He received the Ph. D. degree at the same institute in 2007. He works in Nigde University as an assistant professor in Turkey. His research interests are distribution systems' load flow analyses, reactive power compensation, distributed energy, voltage stability and flexible AC transmission systems.