Matching a Wind Turbine with a Self-Excited Induction Generator

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ABSTRACT: This paper investigates an analytical approach for matching the characteristics of a fixed pitch angle wind turbine with that of a self-excited induction generator (SEIG). The generator feeds its stator electrical output power into an infinite bus-bar via a static power conditioner. The power conditioner used here consists of a diode bridge rectifier and an inverter bridge thyristor tied together through a d.c. link reactor of high inductance in the stator circuit. The analysis is carried out by representing the steady state performance of the self-excited induction generator mathematical model. The wind turbine's performance curve, power coefficient versus tip speed ratio, $C_p(\lambda)$, is represented by a polynomial function of both the generator speed and the wind speed. At any given generator speed the wind turbine output mechanical power is equated to the SEIG input mechanical power. From this mechanical power balance a non-linear equation for the wind speed is resulted. This equation is solved numerically using Newton-Raphson method. Knowing the wind speed the corresponding other performance characteristics can easily be obtained.

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Key Words: Wind turbine, Induction generator, Static power conditioner, Infinite bus-bar.

1. Introduction

The increasing energy demand throughout the world, the air pollution produced by fossil fuel as well as the limited reserves of this fuel and the growing doubt a bout the safety of nuclear power led to a growing demand for the wider use of renewable energy sources such as wind. Wind energy has the advantages that, it is clean and inexhaustible. Various schemes for generating electricity from wind have been proposed. One of these schemes is the SEIG connected to an infinite bus-bar using rectifier – dc link – inverter scheme in the stator circuit which is the subject of this paper. A three phase induction machine can be made to work as a self-excited induction generator (SEIG), when its rotor is driven at suitable speed and its stator terminals connected to a three phase capacitor bank to provide the necessary excitation. The induced e.m.f. and current in the stator windings will continue to rise until an equilibrium is attained due to the magnetic saturation in the machine.

The speed dependent stator voltage and frequency are interfaced with the network using a diode bridge rectifier and an inverter bridge thyristor tied together through a d.c. link reactor of high inductance. This energy conversion scheme has the following advantages:

i- It has no synchronizer and doesn't need pitch angle control. Hence, it is simple, easy to run, and cheep. Moreover, the absence of these devices reduces the weight of the turbine generator system which must be located on the top of the wind turbine tower.

ii-Because of the gust structure of the wind, and because of a cyclical variation in the turbine-blade loading caused by tower shadow and wind shear, severe mechanical and electrical stresses can be induced in the generator. Consequently, a rare or compliant damped coupling is usually interposed between the synchronous generator and the wind turbine. Johnson and Simth [1] suggested that, the use of an induction generator could be obviate the need for such coupling.

A capacitor self-excited induction generator (SEIG), has emerged as a suitable candidate of wind energy source because of its many advantages such as its small size and weight, robust construction, reduced unit and maintenance cost, brushless rotor construction, absence of a separate excitation source, and self-protection against severe over loads and short circuits [2]. It is widely known that an induction machine can self-excite when a suitable capacitance is connected across its stator terminals and the rotor is driven by a prime mover. Under such conditions, the terminal capacitance furnishes the lagging reactive power necessary for establishing the air gap flux. This phenomenon is termed the "capacitor self-excitation", which can be exploited to operate the induction machine as a generator. The induced voltages and currents would continue to rise, but for magnetic saturation in the machine which results in an equilibrium state being reached and the machine is often referred to a self-excited induction generator (SEIG) [3]. The steady state analysis and performance of the SEIG driven by regulated and unregulated turbines is discussed by Chan [4].

El-Sadek et al. [5] developed a control system for on-line simulation of wind turbine by separately excited d.c. motor and the SEIG performance with isolated load is derived. The wind electric energy conversion systems (WEECS) are classified based upon the type of turbine (fixed or variable pitch turbine) and the electric generator type. Constant speed is often obtained by using variable pitch turbines and the fixed turbines usually produce a variable speed [6]. An attempt has been made to present a simple model to control the output voltage and frequency in case of self-excited induction generator under varying wind speeds operation. [7]

Nassereddine [8] showed the advantages of using a Switched Reluctance Generator (SRG) for wind energy applications. The theoretical study of the self-excitation of a SRG and the determination of the variable parameters in a SRG design are discussed.

The power in the wind is proportional to the cube of the wind speed. The fractional power that can be extracted from the wind power by a wind turbine is usually given the symbol C_p. This symbol is called the performance or power coefficient of the turbine. The power coefficient depends on the wind speed, the rotational speed of the turbine, and turbine blade parameters such as pitch angle as well as the number of blades. In the system under study there is no need for pitch angle control [9]. The control is to be accomplished electrically by adjusting the inverter firing advance angle β. This paper presents an analytical approach for matching the steady state characteristics of a fixed pitch angle wind turbine with that of a SEIG connected to an infinite bus-bar. It is assumed here that, the machine is driven by wind energy and connected from its stator terminal to a unified network. The input mechanical power to the SEIG at any speed is computed using the equivalent circuit of the SEIG. Equating the mechanical power extracted from the wind with the input mechanical power to the SEIG results in a non-linear equation for the unknown wind speed. By solving this equation using Newton-Raphson method of iteration, we obtain the wind speed. Consequently the corresponding other performance quantities of the wind turbine such as power coefficient C_p and tip to wind speed ratio λ can easily be computed.

2. System Description

A simplified steady state analysis of a wind energy driven (SEIG) interfaced to an infinite bus bar using diode bridge - d.c. link reactor - inverter bridge scheme. Some simplifying assumptions are introduced to simplify the analysis. Concerning with the current converter, an ideally smooth current is assumed in the d.c. link. Moreover, the commutation is neglected in the inverter bridge. Also, the self-excitation capacitor reduces the commutation in the rectifier bridge to such an extent, that it can be ignored with a very minor error. Concerning with the machine side only the fundamental current component is considered. The analysis is performed assuming the magnetizing reactance is constant at its maximum value.

Similar to the procedure described by Nada [9], the minimum value for the terminal capacitor needed for self-excitation is determined using the no load steady state equivalent circuit of SEIG, in terms of the maximum saturated magnetizing reactance and the other parameters together with a chosen suitable lowest speed. This obtained capacitance is used during loading conditions. Under load, the frequency of self-excitation at any given speed is computed assuming that, the input reactive power to the diode bridge is always zero, i.e., the generator operates always at unity power factor load. Newton-Raphson method is used for solving the nonlinear equation determining the frequency of self-excitation under load. A steady state mathematical model for the system under load conditions is derived. Different modes of operations are then investigated and the required control characteristic in each case is obtained. The speed dependent generated voltage is matched with that of the supply network by appropriate adjustment of the inverter firing advance angle β.

Figure 1 shows the single line diagram of the system under study with the different constituting parts. A diode bridge rectifier is preferably used to achieve an operation of the induction generator always at nearly unity power factor. The rectified direct current I_d is smoothed by a reactor of high inductance L_d acting as an intermediate circuit to decouple the machine and the a.c. supply network.

3. System Analysis

For an induction generator to be self-excited, the machine has to operate in the saturation region. Therefore, for a given speed and load, the terminal capacitor should have a value such that the magnetizing reactance always lies in the saturated region. Let X_m be the maximum saturated magnetizing reactance of the machine, which can be experimentally determined [2]. Even though the X_{ms} of the machine varies considerably with operating conditions (owing to saturation), the assumption of a single value X_m in the analysis is acceptable, because the minimum feasible capacitor value is inevitably associated with the lowest magnetizing KVAs and magnetizing current, which in turn corresponds to the maximum X_{ms} value. In practice, the maximum saturated magnetizing reactance value corresponds to an operating point very slightly above the linear part of the machine magnetization curve (where a stable operating point is just feasible), and hence X_m will be very slightly less than the machine unsaturated magnetizing reactance [2,3].

In this paper, a suitable lowest speed is chosen. This speed should lie in the range above the generator cutoff speed. Hence, the steady state equivalent circuit of SEIG at no load is used to determine the corresponding minimum value of the terminal capacitance required for self-excitation in terms of the machine maximum saturated magnetizing reactance together with the other parameters. This obtained capacitance is used during loading conditions. The frequency of self-excitation under load is computed on the basis of assuming that the input reactive power to the rectifier bridge is always zero. This assumption is justified by the use of a diode bridge rectifier. The rectified voltage behind the d.c. reactor is equated with that of the inverter bridge to get the necessary firing advance angle β of the inverter according to the machine speed.

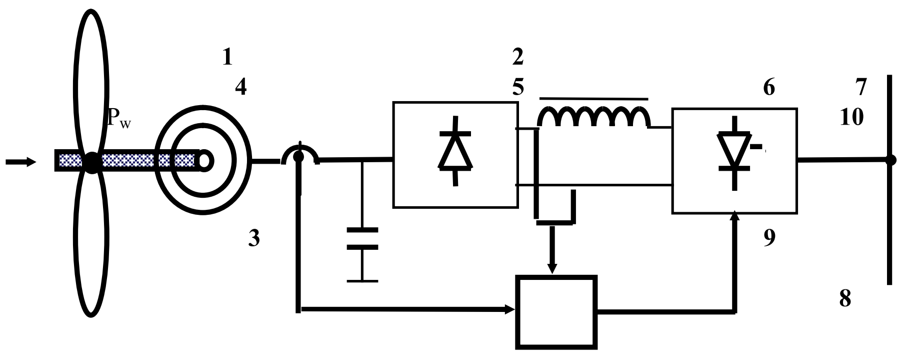

Fig. 1: Single line diagram of a wind energy driven SEIG connected to an infinite bus bar using a static power conditioner.

1 wind turbine
2 3-phase induction generator
3 3-phase capacitor bank
4 rectifier bridge
5 d.c. smoothing reactor
6 inverter bridge
7 supply network
8 control device
9 d.c. link voltage measurement
10 stator current measurement

3.1 Determination of Self-Excitation Capacitor

The per phase steady state equivalent circuit of a self-excited induction generator under no load at rated frequency f_n is shown in Fig. 2 [10,11]. Here the machine core losses and saturation effect has been ignored. As there is no externally applied voltage, the mesh equations for the stator current $\underline{I}_s$ and referred rotor current $\underline{I}'_r$ are:

$$-\left[\frac{R_s}{F}+j\left(X_{\sigma s}-X_c/F^2\right)\right]\underline{I}_s+jX_m\left(\underline{I}'_r-\underline{I}_s\right)=0 \quad (1)$$

$$-\left[R'_r/(F-\nu)+jX'_{\sigma r}\right]\underline{I}'_r-jX_m\left(\underline{I}'_r-\underline{I}_s\right)=0 \quad (2)$$

Where $F=f/f_n$ is the per unit self-excitation frequency and $\nu=n/n_s$ is the per unit speed. Eliminating $\underline{I}_s$ and $\underline{I}'_r$ from Eqs. (1) and (2) we find that:

$$\left[R'_r/(F-\nu)+jX'_r\right]\left[R_s/F+\left(X_s-X_c/F^2\right)\right]+X_m^2=0 \quad (3)$$

Where the self-reactance of the stator X_s and the referred self-reactance of the rotor X'_r are:

$$X_s=X_{\sigma s}+X_m \quad (4a)$$

$$X'_r=X'_{\sigma r}+X_m \quad (4b)$$

Equating the real and imaginary parts to zero separately, yields:

$$\frac{R_s}{F}\cdot\frac{R'_r}{(F-\nu)}-X'_r\left(X_s-X_c/F^2\right)+X_m^2=0 \quad (5a)$$

and: $$\frac{R_s}{F}\cdot X'_r+\frac{R'_r}{(F-\nu)}\cdot\left(X_s-X_c/F^2\right)=0 \quad (5b)$$

By solving Eqs. (5a) and (5b) for the per unit self-excitation frequency and the capacitive reactance X_c we obtain:

$$K_1F^2+K_2F+K_3=0 \quad (6a)$$

and:

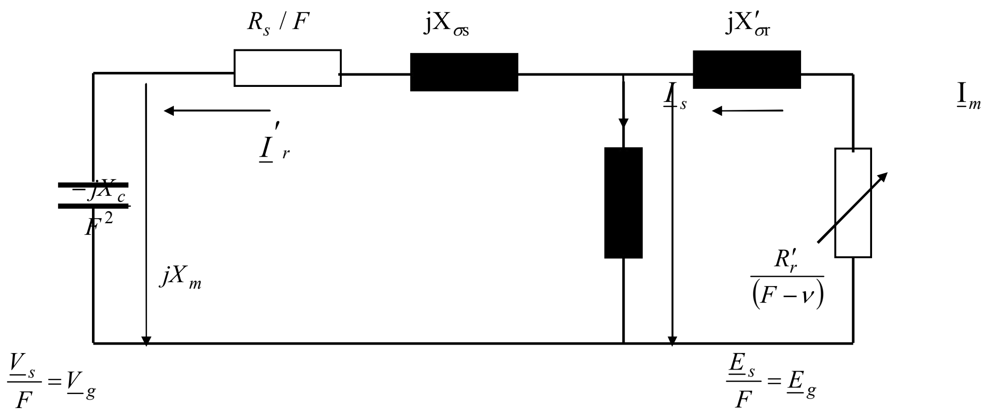

Fig. 2: Per phase steady state equivalent circuit of SEIG at no load.

$$X_c = K_4 F^2 + K_5 F \quad (6b)$$

Where the constants K_1 - K_5 are dependent on the equivalent circuit parameters and the speed of the generator. These constants are:

$$K_1 = X_m^2 + X_r'^2 R_s/R_r'$$
$$K_2 = -\nu.\left(X_m^2 + 2X_r'^2 R_s/R_r'\right)$$
$$K_3 = \nu^2.(X_r'^2 R_s/R_r') + R_s R_r'$$
$$K_4 = X_s + X_r' R_s / R_r'$$
$$K_5 = -\nu X_r' R_s / R_r' \quad (7)$$

Solving the second order Eq. (6a) we obtain the maximum per unit self-excitation frequency as:

$$F_{max} = 0.5\left[-\frac{K_2}{K_1} + \sqrt{\left(\frac{K_2}{K_1}\right)^2 - 4\frac{K_3}{K_1}}\right] \quad (8)$$

Introducing Eq. (8) into Eq. (6b), the corresponding minimum self-excitation capacitance can be found as:

$$C_{min} = \frac{1}{\omega_n.\left[K_4 F_{max}^2 + K_5 F_{max}\right]} \quad (9)$$

with the generator rated angular frequency being:

$$\omega_n = 2\pi f_n \quad (10)$$

The generator cutoff speed ν_{cutoff} below which there is no generation is attained when the quantity under the square root in Eq. (8) becomes zero. A speed below this value results in a complex root for the maximum per unit self-excitation frequency. Accordingly, we can write:

$$\left(\frac{K_2}{K_1}\right)^2 = 4\frac{K_3}{K_1} \quad (11)$$

Introducing Eqs. (7) into the above equation yields:

$$\nu_{cutoff} = \frac{2}{X_m^2}\sqrt{R_s R_r' X_m^2 + R_s^2 X_r'^2} \quad (12)$$

Thus, choosing a suitable lowest value for the per unit speed ν greater than or equal ν_{cutoff}, the corresponding F_{max} can be computed using Eq. (8). Once F_{max} is obtained, the corresponding minimum self-excitation capacitor C_{min} is determined from Eq. (9).

3.2 Determination of Self-Excitation Frequency Under Load

As stated before, the obtained C_{min} needed for self-excitation under no load, corresponding to the chosen lowest speed will be used under loading conditions. The per unit frequency F for self-excitation under load is determined by applying the assumption of unity power factor operation for the generator [3]. Combining this assumption together with the equivalent circuit of SEIG under load of Fig. 3 yields:

$$Q = \text{Imag.}\left\{\underline{V}_g . \underline{I}_L^*\right\} = 0 \quad (13)$$

where Q is the input reactive power to the rectifier bridge. Referring to the equivalent circuit of Fig. 3, the relation between the load current $\underline{I}_L$, the capacitor current $\underline{I}_c$ and the stator current $\underline{I}_s$, is obtained as:

$$\underline{I}_L = -\underline{I}_c + \underline{I}_s = \frac{-\underline{V}_g}{\frac{-jX_c}{F^2}} + \frac{-\underline{V}_g}{\frac{R_s}{F} + jX_{\sigma s} + \frac{jX_m\left[R_r'/(F-\nu) + jX_{\sigma r}'\right]}{R_r'/(F-\nu) + jX_r'}} \quad (14)$$

Where $\underline{V}_g$ is the terminal generator voltage. Introducing Eq. (14) into Eq.(13) we obtain the following relation for the per unit self-excitation frequency F:

$$C_1 F^4 + C_2 F^3 + C_3 F^2 + C_4 F + C_5 = 0 \quad (15)$$

The coefficients C_1 through C_5 are functions of the equivalent circuit parameters, the minimum self-excitation capacitor C_{min} and the generator speed. Equation (15) is solved numerically to obtain the per unit frequency F for self-excitation.

3.3 Performance Equations

As the per unit self-excitation frequency F is obtained, the complete behavior of the system under loading conditions can be determined as follows:

The load, the capacitor and the stator currents can be obtained from Eq. (14). The d.c. current I_d and the fundamental r.m.s. load current I_L are related together by the following relation [12-14]:

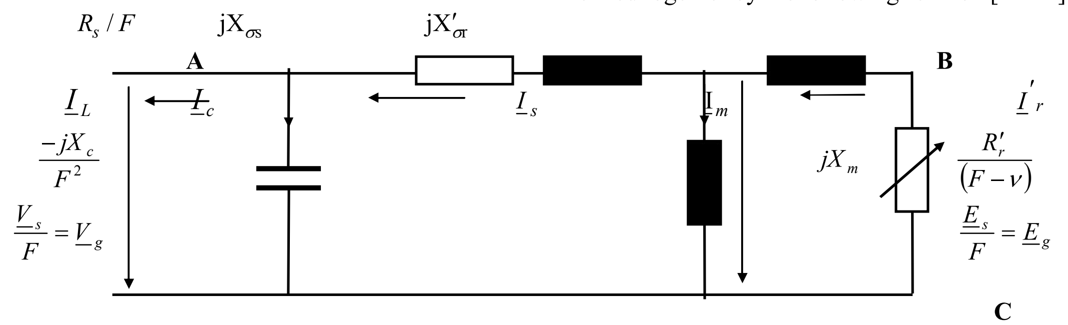

Fig. 3: Per phase steady state equivalent circuit of SEIG at load.

$$I_d = \frac{\pi}{\sqrt{6}} I_L \qquad (16)$$

The matching relation between the generated machine voltage and the supply network a.c. voltage, considering the valves as ideal switches, is given by:

$$\frac{3\sqrt{6}}{\pi}.V_g - R_{dc} I_d = \frac{3\sqrt{6}}{\pi}.V_n \cos(\beta) \qquad (17)$$

Where R_{dc} is the resistance of smoothing inductor and β is the inverter firing advance angle.

The power transferred to the supply network is given by:

$$P_g = \left[\frac{3\sqrt{6}}{\pi}.V_g - R_{dc} I_d\right].I_d = \frac{3\sqrt{6}}{\pi}.V_n \cos(\beta).I_d \quad (18)$$

The total copper losses are computed from:

$$P_{cu} = P_{cs} + P_{cr} = 3\left(R_s I_s^2 + R'_r I'^2_r\right) \qquad (19)$$

Adding Eqs. (18) and (19) yields the input internal mechanical power; thus:

$$P_{mg} = P_g + P_{cu} \qquad (20)$$

Equations (14), and (16) to (20) represent the steady state performance equations describing the complete behavior of the system under different loading conditions.

3.4 Wind Turbine

The power available in wind is proportional to the cube of the wind speed. The fraction of the wind power that can be extracted by a wind turbine P_{mt} is proportional to the air density ρ, the area swept by the turbine A, the turbine performance coefficient C_p, and the cube of the wind speed V_w, we obtain [6,9]:

$$P_w = \frac{1}{2}\rho.\mathrm{A}.V_w^3 \qquad (21)$$

with ρ is the air density and A is the area swept by the turbine blade.

The mechanical power that can be extracted from the wind and which is available at the wind-turbine shaft for driving the induction generator is given by:

$$P_{mw} = C_p.P_w = C_p.\frac{1}{2}\rho.\mathrm{A}.V_w^3 \qquad (22)$$

The wind turbine performance coefficient depends on the blades number and its pitch angle. For a certain number of blades with a certain pitch angle, the turbine performance coefficient varies with the blade tip speed V_T to the wind speed ratio λ. On the other hand the tip speed V_T is proportional to the rotor speed n, and the radius of the turbine blades R. Accordingly we can write:

$$\lambda = \frac{V_T}{V_W} = \frac{2\pi Rn}{V_W} = \frac{1-S}{v_W} \qquad (23)$$

Where the per unit wind speed v_W is given by:

$$v_W = \frac{V_W}{2\pi R n_s} \qquad (24)$$

Figure 1 shows a typical C_p (λ) curve for a two blades wind turbine having a fixed pitch angle of 1^0 which is used for analysis in this paper [6]. Using curve fitting method the curve C_p(λ) shown in this figure could be approximated by a second order polynomial of the form [9]:

$$C_p = -0.007\lambda^2 + 0.135\lambda - 0.218 \qquad (25)$$

The above approximation is shown dotted on the same Figure 4. Introducing Eq. (23) into (25) yields the power coefficient as:

$$C_p = -0.218 + 0.135\left(\frac{1-S}{v_w}\right) - 0.007\left(\frac{1-S}{v_w}\right)^2 \qquad (26)$$

Grouping Eqs. (22) to (26) the turbine output mechanical power can be expressed as:

$$P_{mw} = \mathrm{K}.v_w^3.C_p = \mathrm{K}.C_p\left(\frac{1-S}{\lambda}\right)^3 \qquad (27)$$
$$= \mathrm{K}\left[-0.218\, v_w^3 + 0.135(1-\mathrm{S}).v_w^2 - 0.007(1-\mathrm{S})^2.v_w\right]$$

with constant:

$$K = \frac{1}{2}\rho\,\mathrm{A}\,(2\pi\,\mathrm{R}\,n_s)^3 \qquad (28)$$

The constant K can be computed by considering that the turbine is designed to achieve optimum value of C_{pmax} at rated wind speed v_{Wn} corresponding to generator rated speed b_n. At this speed the generator input mechanical power is its rated value P_{mgn}. This power is calculated by solving the mathematical model of the electrical system at b_n. From Fig. 4, we have:

$C_{pmax} = 0.43$ at $\lambda_n = 9.35$ (29a)

By substituting $P_{mw} = P_{mgn}$, $C_p = C_{pmax}$, $S = S_n$ and $\lambda = \lambda_n$ into Eq. (27), the following relation for K is attained:

$$K = \frac{P_{mgn}}{C_{pmax}}\left(\frac{\lambda_n}{1-S_n}\right)^3 \quad (29b)$$

Finally, the turbine mechanical output power assumes the form:

$$P_{mw} = \frac{P_{mgn}}{C_{po}}\left(\frac{\lambda_o}{1-S_n}\right)\begin{bmatrix}-0.218\,v_w^3 + 0.135(1-S).v_w^2 \\ -0.007(1-S)^2.v_w\end{bmatrix} \quad (30)$$

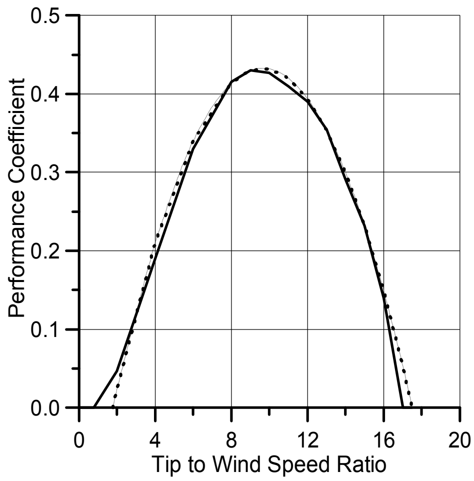

Fig. 4: Wind turbine performance curve, - - - - - curve fitting approximation.

4. Algorithm of Matching

At any given generator speed the generator input mechanical power P_{mg} is computed by solving the electrical system mathematical model during the speed range within which the given speed lies. At the same speed the determined generator input mechanical power P_{mg} is balanced by the turbine output mechanical power P_{mw} as in the equations (20) and (30).

Equation (30) represents a unified mathematical model for the wind turbine and the electrical system when they are connected together. It is solved using Newton-Raphson method of iteration for the unknown wind speed. Having obtained v_W, the corresponding required performance parameters λ and C_p of the turbine are determined using Eqs. (23) and (24).

5. Predicted Steady State Characteristics

The following computed results are obtained from a 3-phase, 4-pole, 50-Hz, Y-connected, slip-ring induction machine. The machine has the following equivalent circuit parameters:

$R_s = 2.22\ \Omega$, $R'_r = 3.1\ \Omega$, $X_{\sigma s} = X'_{\sigma r} = 5\ \Omega$, and $X_m = 74\ \Omega$.

The stator to rotor transformation ratio is 2.2 and the base values are:

Base current, $I_b = 4.5$ A, base voltage, $V_b = V_n = 220$ V, and base power $P_b = 2970$ W.

5.1 Terminal Capacitor Requirement

Using Eq. (9), the minimum self-excitation capacitance for different speeds can be obtained. As shown in figure 5, It is evident that the self-excitation capacitor sharply reduces as the speed rises. This means that a wider speed operating range is attained by using a higher capacitance value.

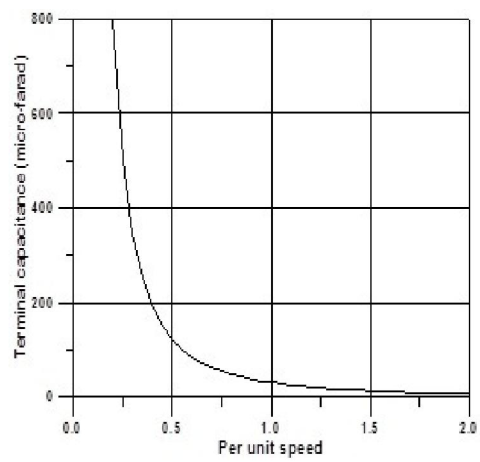

Fig. 5: Terminal capacitance versus per unit speed.

In the following results, the chosen lowest per unit speed $\nu_{min} = 0.5$, then the corresponding calculated minimum capacitance at no load $C_{min} = 122.77\ \mu F$.

5.2 Wind Turbine Requirements

The generator is driven by a wind turbine with a fixed pitch angle. Assuming the lowest per unit generator speed $\nu_{min} = 0.5$ (according to the value of self-excitation capacitor used), the system is switched on to the power system. As the wind speed rises, the generator speed rises and its stator current should consequently increase. However, the inverter firing advance angle β is controlled according to the generator speed in such a way to keep the generated voltage constant at a certain maximum value (smaller than its rated value) until the stator current reaches its rated value. After this value of wind speed, the stator current is kept constant and equal to its rated value in order to prevent overloading the machine. The stator current is kept constant until the cut-off wind speed v_{wo} is reached. The generator speed corresponding to v_{wo} is assumed here to be equal to twice its synchronous speed.

The obtained results are plotted in Figures 6 through 10. It is obvious that, there are two operating ranges:

i- The range from the cut-in wind speed v_{wi} to the rated wind speed v_{wn}:

Figure 6 shows the per unit self-excitation frequency as well as the per unit generator speed versus the per unit wind speed characteristics. The self-excitation frequency increases as the wind speed rises due to increasing the generator speed. During this range the tip to wind speed ratio λ should reduce from its largest value down to its optimum value λ_o. However, the performance coefficient C_p should rise from minimum value until its maximum value C_{po} as shown in Fig. 7. This means that the wind turbine should operate on right hand side of its characteristic as shown in Fig. 8 from the intersection point of C_p (λ) with the λ axis upwards to the point (λ_o, C_{po}). The generator input mechanical power (output mechanical power from the wind) and the generator electrical output power increase as the wind speed rises in this range as shown in Fig. 9. In this range, to maintain constant generated voltage the inverter firing advance angle β increases very slightly as shown in Fig. 10.

ii- The range from the rated wind speed to the cut-out wind speed v_{wo}:

During this range, the inverter firing advance angle β is increased to keep the stator current constant at its rated value. as shown in Fig. 10. This results in decreasing the mechanical input power as well as the output electrical power with the wind speed due to decreasing in stator voltage as shown in Fig. 9. Both the power coefficient and the tip to wind speed ratio decrease from the point (λ_o, C_{po}) downwards on the left half of the curve C_p (λ) until the cut-out wind speed is reached.

6. Conclusion

An analytical approach for matching the characteristics of a wind turbine with that of a SEIG has been presented. The analysis is carried out by representing the steady state performance of the self-excited induction generator mathematical model. The wind turbine's performance curve, power coefficient versus tip speed ratio, $C_p(\lambda)$, is represented by a polynomial function of both the generator speed and the wind speed. At any given generator speed the wind turbine output mechanical power is equated to the SEIG input mechanical power. A unified model for the electrical system and the turbine is estimated from the mechanical power balance. This model is solved numerically using Newton-Raphson method to obtain the turbine operating conditions under the specified SEIG control strategy.

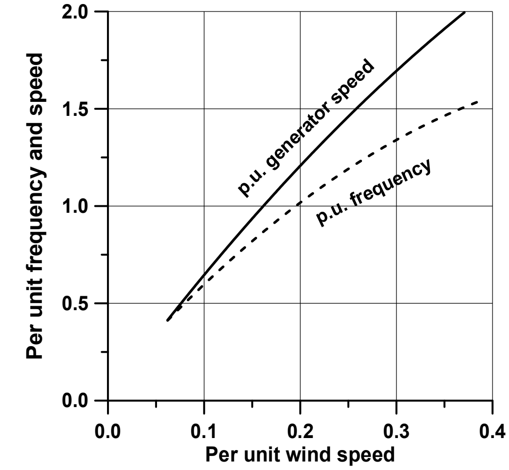

Fig. 6: Generator speed and frequency versus wind speed.

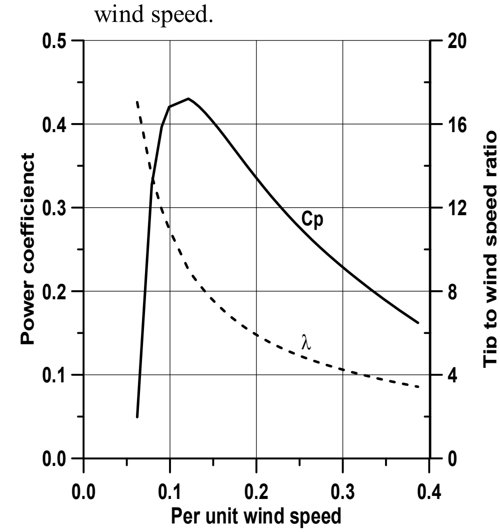

Fig. 7: Power coefficient and tip to wind speed ratio versus wind speed

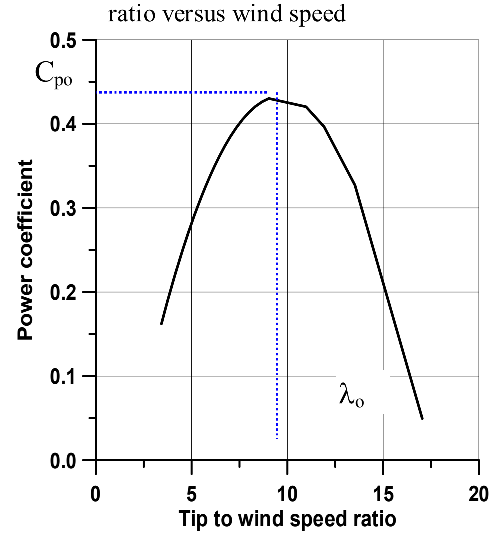

Fig. 8: Turbine operating range.

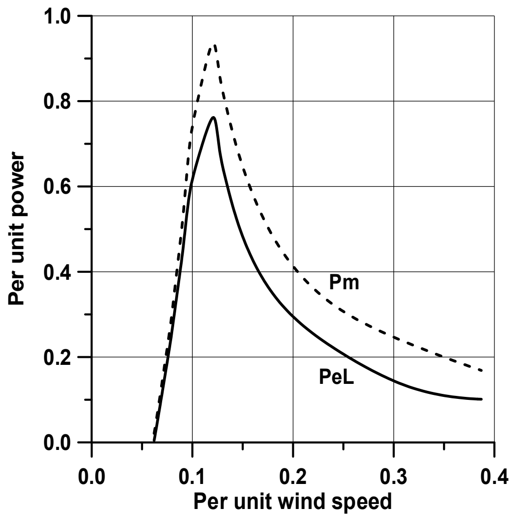

Fig. 9: Electrical and mechanical power versus wind speed.

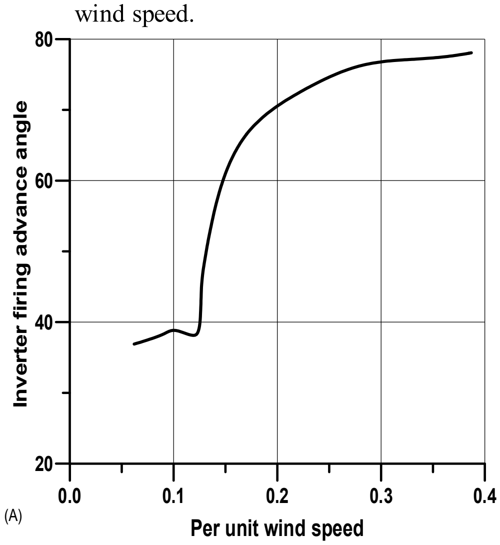

Fig. 10: Inverter firing advance angle versus wind speed

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