Enhancing the Performance of Self-excited Wind-driven Cage Induction Generator through Altering the Poles

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Abstract
Objectives: The present research aims at enhancing the performance of the self-excited wind-driven cheap cage induction generators at the different wind speeds employing control technique involving altering the number of poles of the cage generator and adjusting the shunt capacitor. The control aims to maximize the input power captured from the wind, and to improve the generator electrical performance when the generator feeds static loads, and when supplies dynamic induction motor load. Methods: The analysis of the system has been carried out utilizing a complete mathematical model presented for the driving wind-turbine, in addition to developed mathematical models derived from modernistic circuit models for the self-excited induction generator with both static and dynamic loads. A computer simulation has been performed using the models to identify the performance characteristics. Findings: Control protocols for the generator exciting capacitor and the number of magnetic poles have been reached, which governs the generator speed such that the wind turbine blades revolves at speed which is optimally proportional to the wind stream velocity. Consequently, the highest mechanical power is being taken from the wind. At the same time, the built-up voltage could be adjusted around the load rated voltage for static loads through the newly suggested pole-control technique. In case of dynamic induction motor loads, the poles it is found that good performance is possible through controlling the capacitor size only while fixing the number of magnetic poles at the minimum number. Application: The suggested method leads to cheap and efficient utilization of the wind energy in electrical power generation system, especially in the remote isolated places where usage of systems of self-excited cage induction generators is highly recommended.

Keywords: Cage Induction Generator, Pole-amplitude Modulation, Self-excited, Wind Energy

List of principal symbols:
\( C_p, C_q \): Turbine coefficient.
\( f \): Frequency.
\( f_0 \): Rated frequency.
\( I_1 \): Generator rotor current.
\( I_2 \): Generator stator current.
\( I_g \): Output generator current.
\( I_C \): Capacitor current.
\( I_\text{L} \): Current of load.
\( I_m \): Motor rotor current.
\( n_m \): Mechanical speed.
\( P_m \): Input mechanical power.
\( P_L \): Load power.
\( P_{AG} \): Air gap power.
\( P_T \): Turbine output power.
\( R_{1m}, R_{2m} \): Stator and rotor resistance of motor, respectively.
\( R_{c_g} \): Iron loss resistance of generator.
\( R_{c_m} \): Iron loss resistance of motor.
\( S_g \): Generator slip
\( S_m \): Motor slip.
\( V_T \): Terminal voltage.
\( WS \): Wind speed.

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1. Introduction

Wind is one of the major sources of renewable energies. It is non-polluting and economic source. The wind turbine driven generator system produces electricity at varying wind velocity conditions. It is the fastest growing energy technology in the world. The wind energy market has grown because of the environmental advantages of harnessing a clean and inexhaustible energy source besides economic incentives supplied by several governments. Use of wind-turbines as prime movers has the problem of being of variable and unexpected velocities. If a synchronous generator is used, the frequency of the voltage will vary depending directly on the prime mover speed. Therefore, the need to other generator types or unconventional solutions arises. Use of induction generators may solve the problem of variable speed turbines. The induction generators have been recently given increasing consideration due to its suitability to operate in connection with the electric grid or alone when necessary with the aid of various energy resources either traditional or new. These generators have advantages compared with the conventional synchronous generator, such that the SEIG has become one of the most significant renewable-energy based electrical energy sources. Wind-driven Self-Excited Induction Generators (SEIG) are widely used in remote isolated places. The advantages of using standard three-phase squirrel cage induction machine over standard synchronous alternator are the lower cost due to their simple construction, and the lower maintenance requirements due to their ruggedness and the dispensing of brushes. In addition, there is no need of a separate source for dc excitation current as in case of synchronous generator.

The present research aims at ameliorating the performance and functioning of the self-excited cage induction generators at the different likely wind speeds through changing in steps the stator-side number of magnetic poles, besides controlling the voltage-building capacitor. The generator will be controlled such that it will follow the maximum energy locus, and govern the generator electrical operation characteristics such that the voltage in case of static load is adjusted around the load rated voltage at all wind speeds or keeping. Altering of the number of magnetic poles is performed via applying the pole amplitude modulation. It is an intelligent design and pattern reconfiguration of the stator winding which allows the transformation of the machine number of magnetic poles in a wide range. The operation characteristics of the investigated SEIG will be determined utilizing the wind-turbine available models besides a developed model for the pole-controlled generator. The built voltage and its frequency of the SEIG has been found to depend entirely on the generator speed, the machine number of magnetic poles, the flux energizing capacitor and the load. There exist minimum- and maximum- capacitances for the self-excitation build up voltage at a particular speed and load.

2. The Studied System

The studied system comprises a wind turbine acting as a prime-mover, and self-excited isolated induction generator feeding different load types as shown in Figure 1. Each equipment is represented by its power-speed characteristic. The operation point of this system is then obtained by the intersection of these characteristics.

![Figure 1. Layout of the system under study.](image)

3. Pole Amplitude Modulation

The winding of the machine is apportioned to many sections in which the current is directed in one section reversely to the direction in the other. This technique adopts the principle of amplitude modulation to the...
magnetic motive force space distribution resulted by the windings.

In two-sets of poles using PAM technique, the three phase windings are altered from star connected phases, where each phase has two parallel circuits, to delta connected phases, where each phase circuits are connected in series. In case of three-sets of poles, three speeds can be obtained by switching from star connected phases having 4-parallel circuits per each phase to star connected phases of 2-parallel circuits per phase to delta connected phases of series circuits per phase. With the aid of the circuit displayed in Figure 2, Table 1 explains how the terminals are connected to obtain certain number of pole which gives the required specific speed.

![Figure 2](image)

**Figure 2.** Circuit connection for the pole-amplitude modulation technique in case of three-speed settings.

| Table 1. Different connections and supplying patterns for the 3-speeds PAM |
| --- |
| **Speed 1 (4-Parallel-star)** | **Speed 2 (2-Parallel-star)** | **Speed 3 (Series-delta)** |
| Connect k₁ m₁ c₁ | Connect k₁ m₁ n₁ | Disconnect k₅ k₆ m₃ m₄; n₃ n₄ |
| Connect k₃ m₃ n₃ | Disconnect k₅ k₆ m₃ m₄; n₃ n₄ | Feed k₁ m₁ n₁ |
| Connect k₂ k₄; m₂ m₄; n₂ n₄ | Feed k₂ k₄; m₂ m₄; n₂ n₄ |

4. System Modelling

4.1 Wind Turbine Model

Part of the energy stored in the wind is extracted and delivered to the shaft of the induction generator by the wind turbine. The wind turbines have either vertical-axis or horizontal-axis. Nowadays, almost all commercial wind turbines are of the horizontal-axis type, and have two blades or three blades rotors.

The turbine output torque and power are usually expressed in terms of non-dimensional torque ($C_Q$) and power ($C_P$) coefficients as follows:

$$r_T = \frac{1}{2} \rho \pi R^2 C_Q (\lambda \beta) WS$$

$$P_T = \frac{1}{2} \rho \pi R^2 C_P (\lambda \beta) WS$$

$$C_Q = C_P / \lambda$$

Note that the two coefficients depend on both the pitch angle and the blade tip-speed-ratio; $\lambda$, which is calculated as follows:

$$\lambda = (\omega_T R_T / WS)$$

$R_T$ and $\omega_T$ are the turbine blade radius and angular speed, respectively. WS is the wind stream velocity. Figure 3 shows typical variations of $C_Q$ and $C_P$ for a fixed-pitch wind turbine.

![Figure 3](image)

**Figure 3.** Typical variations of $C_Q$ and $C_P$ for a wind turbine assuming fixed-pitch.
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4.2 Induction Generator Model

An induction generator when steadily stands alone may be represented by the frequency-dependent circuit shown in Figure 4. The model has a closed rotor circuit, which differs from that used in case of double-fed induction generator.[8,9] The building up capacitor is shunting the generator. The circuit parameters have to be varied when the winding topology is altered to switch the poles to another setting.

The series resistance and reactance of induction generator can be represented after shifting the magnetizing reactance at the stator terminals by parallel resistance and reactance (Figure 5), such that.

\[ R_g = \left( \frac{R_{2g}}{S_g} \right)^2 + \left( X_{1g} + X_{2g} \right)^2 \left( \frac{1}{f_s} \right)^2 \left( \frac{R_{2g}}{S_g} \right) \]  
\[ X_g = \left( \frac{R_{2g}}{S_g} \right)^2 + \left( X_{1g} + X_{2g} \right)^2 \left( \frac{1}{f_s} \right)^2 \left( \frac{1}{X_{1g} + X_{2g} \left( \frac{1}{f_s} \right)} \right) \]

The generator current can be express by:

\[ I_g = I_L + I_C \]  
\[ I_2 = I_g + \left( I_{xg} + I_{xc} \right) \]  
\[ P_{Ag} = 3 \left( I_2 \right)^2 \left( \frac{R_{2g}}{S_g} \right) \]  
\[ P_m = P_{Ag} \left( 1 - S_g \right) \]

The condition to attain wind maximum power is realized when:

\[ P_m = P_T \]

Which can be solving with Eq. 5 to obtain the generator slip \( S_g \).

4.2.1 Static R-L Load

The induction generator which supplies static loads may be analyzed for the steady-state case using the circuit model shown in Figure 5, and replacing the load with a series resistance and reactance as shown in Figure 6.

The static load impedance can be express by:

\[ Z_L = R_L + jX_L \frac{2\pi f}{f_s} \]  
\[ I_L = \frac{V_L}{Z_L} \]

Figure 4. Induction generator pole and frequency dependent equivalent circuit.

Figure 5. Parallel representation of the induction generator.

Figure 6. Circuit Model of isolated induction generator supplying an R-L static load.
4.2.2 Dynamic Load

The equivalent circuit of the induction generator when feeding an induction motor as a dynamic load can be arranged as shown in Figure 7.

The motor-pump current can be expressed by:

\[ I_{m2} = I_g + (I_{im} + I_{rc}) \]  

(14)

The developed torque of the motor using the approximate equivalent circuit is given as follows:

\[ \tau = \frac{3*V^2*(R_{2m}/S_m)}{\omega_{syn} \left( \frac{R_{2m}}{S_m} \right)^2 + \left( X_{1m} + X_{2m} \right)^2} \]  

(15)

At equilibrium,

\[ \tau = C_{p} \omega \left[ 1 - S_m \right]^2 \]  

(16)

Solving the above equation, we can find the motor slip and obtain the desired operation points.

Figure 7. Circuit model of isolated induction generator supplying a dynamic motor load.

Figure 8. Flowchart for the steps of computing the operation characteristics of induction generator loaded by a static (R-L) load.

Figure 9. Flowchart for the calculation of the performance characteristics of induction generator with dynamic load.
5. Computational Algorithms

The flow chart given in Figures 8, 9 presents the steps of calculation of the terminal voltage, frequency and capacitor size of the self-excited induction generator when stands alone supplying static (R-L) and dynamic (induction motor) loads, respectively.

6. Results and Discussion

The developed computer program has been applied on a generator system of the data given in Appendices 1–2. The performance characteristics at different number of poles, namely; 4, 6 and 8 have been calculated.

Appendix 1: The Generator Data

The studied cage generator is a 3-phase, 10.6 kW, 380 V, 50 Hz, 4/6/8 pole amplitudes modulated cage induction generator. The parameters of the generator are as follows:

| Parameters | 4 poles | 6 poles | 8 poles |
|------------|---------|---------|---------|
| $R_{1g}$, $\Omega$ | 0.47 | 1.034 | 1.504 |
| $R_{2g}$, $\Omega$ | 0.47 | 0.972 | 1.361 |
| $X_{1g}$, $\Omega$ | 0.86 | 0.7568 | 0.86 |
| $X_{2g}$, $\Omega$ | 0.86 | 0.7568 | 0.86 |
| $R_c$, $\Omega$ | 500 | 409.07 | 522.710 |
| Stator Rated Current, A | 18.44 | 14.98 | 13.68 |
| Stator Connection | Star | Star | Delta |

The driving Wind-turbine is 3-blade horizontal shaft, wind turbine has 12 kw rating at wind speed of 12 m/s. The parameters and coefficients of the turbine are taken from the typical diagram of Figure 3.

6.1 Static R-L Load Result

The relationships between wind speed and induction generator characteristics at Static load as shown from Figures 10 to 15.

Figure 10. Variation of the input mechanical power with wind stream speed in case of astatic load at the various pole settings.

Figure 11. Terminal voltage variation with the wind stream speed for a generator having a static load at the various pole settings.

Figure 12. Frequency variation for the different number of poles versus wind stream speed for a generator having a static load at the various pole settings.

Figure 13. Variation of the generator output current with the wind stream speed for a generator having a static load at the various pole settings.
The computed results show that the induction generator speed could be controlled through adjusting the capacitor size such that it always extracts the maximum wind power irrespective of the number of poles (Figure 10). However, in case of static load, pole control is recommended to be performed to keep the terminal voltage around the rated value. In our case, down to wind speed of about 9.75 m/s 4-poles should be used. The generator number of poles is changed to 6-poles when the wind speed ranges between 9.75 m/s and 7.81 m/s to achieve terminal voltage around the rated value with less capacitor size. To keep the voltage closer to the rated value, at wind speeds lower than 7.81 m/s, the pole setting should have switched to that corresponding to 8 poles (Figures 16–18).
6.2 Dynamic Load

The characteristics of the operation the turbine-genera-
tor-load system when energizing an induction motor as a
dynamic load- having the particulars given in Appendix 2
are shown in Figures 19–25.

Appendix 2: The Load Data

Static load impedance: $Z_L = 9.8969 + j 6.1335$; of power
10.6 kW.

Dynamic load induction motor is a 13.6 Hp has the following
parameters:

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| $R_{1m}$, $\Omega$ | 0.47 | $X_{2m}$, $\Omega$ | 0.86 | Voltage, V | 380 |
| $R_{2m}$, $\Omega$ | 0.47 | $X_{bm}$, $\Omega$ | 30 | Frequency, Hz | 50 |
| $X_{1a}$, $\Omega$ | 0.86 | Rc, $\Omega$ | 210 | Connection | Y |

Figure 19. Variation of input mechanical power to the
generator with wind stream speed when feeding dynamic
load for various pole settings.

Figure 20. Variation of output pump power with wind
stream speed for various pole settings.

Figure 21. Variation of the terminal voltage with wind
stream speed when feeding dynamic load for various pole
settings.

Figure 22. Frequency for the different number of poles
versus wind speeding case of dynamic load.

Figure 23. Output electrical power for the different
number of poles versus wind speeding case of dynamic load.
7. Conclusion

The study suggests a method for controlling a wind-driven self-excited cage induction generator through variable shunt capacitor in addition to changing the generator number of magnetic poles. Change of the number of magnetic poles has been performed through pole amplitude modulation. The control technique has been applied for static and dynamic load conditions. The input power of generator could be maximized at each wind speed by controlling the frequency through varying the capacitor size. In case of static load, pole control is used to adjust the load voltage to satisfy the load requirements. In case an induction motor dynamic load, constant number of magnetic poles is recommended where change of the capacitor size is enough to control the generator such that the power extracted is maximized, and the constant voltage to frequency ratios of the generator and motor are realized.

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