

Maximizing the Output Power of Wind-Driven Grid-Connected Cage Induction Generator through Pole and Voltage Control

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Abstract

Objectives: A new cheap wind-driven grid-connected cage induction generator has been used to generate electrical power. The performance of the generator has been ameliorated through multiple change of its number of poles using pole amplitude modulation to comply with the wind speed. The generator stator voltage has been adjusted via voltage controller for better performance. **Methodology:** Circuit and mathematical models have been developed to represent the generator system. An algorithm has been developed and implemented through computer programs to determine the performance characteristics of the turbine-generator system. The performance has been judged by comparing it by the performance when feeding the generator through a rectifier-inverter set in the stator side, which is costly but leads to a generator with ideal performance. **Findings:** Complete performance characteristics of the new proposed system have been computed. The obtained results have been used to establish a control protocol to guarantee maximizing the output electrical power. The suggested method has been with those of the case of using a rectifier-inverter set in the stator side to achieve ideal operation of the generator. The comparison has proved that the suggested method, being cheap, is very efficient as the proposed technique led to driving the generator and consequently the wind-turbine at speeds close or equal to those realizing the maximizing tip-speed ratio, which results in extracting the greatest mechanical energy from the wind. The output power applying the presented method closely approaches the output power of the generator when ideally controlled by the aid of a rectifier-inverter set inserted in the stator side. **Applications:** The very good performance obtained with the suggested control technique besides its low cost encourages its application in case of small and moderate size wind-driven grid-connected induction generator systems.

Keywords: Induction Generator, Pole Amplitude Modulation, Wind Energy

List of Symbols:

C_p : Wind power coefficient
 C_Q : Wind torque coefficient
 I_r : Rotor current
 I_s : Stator current
 V_s : Stator voltage
 V_w : Wind speed
 R_r : Rotor voltage
 R_s : Stator voltage
 R_c : Core resistance
 R_T : Thevini's equivalence resistance
 R_b : Radius of the turbine blade
 X_r : Rotor leakage reactance
 X_s : Stator leakage reactance

X_m : Magnetizing reactance
 X_T : Thevini's equivalence reactance
 s : Per-unit slip
 β : Blade pitch angle
 λ : Tip-speed ratio
 ω_T : Angular speed of the wind turbine
 τ : Torque

1. Introduction

Generation of electrical energy from the renewable wind energy has become an essential goal of energy researches nowadays. The wind-turbines as prime movers have variable and unexpected velocities. If synchronous generators are

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used, its frequency will be no-longer constant and will vary as it directly depends on the mechanical speed. Consequently, there is a need to other types of generators or unusual solutions. Use of induction generators solves the problem of this variable speed turbines¹⁻³. Most of the research works carried out in this field aimed at maximizing the utilization of the wind energy through controlling the generator system such that the turbine rotates at speed enables catching the possible maximum wind-energy at all wind speeds⁴⁻¹⁰.

In⁴ proposed a simple technique to control a Double Fed Induction Generator (DFIG) such that it will trace the maximum power available at different wind speeds. Using a rectifier-inverter set in the rotor. In⁵ proposed a technique for the rotor injected voltage of a DFIG such that the wind turbine traces the maximum wind energy and at the same time the stator current is kept at unity power factor. In⁶, proposed a system constituting of a DFIG using a controlled cycloconverter in the rotor aiming at tracing the maximum power locus. In^{7,8} suggested a method of controlling the induction generator such that the driving wind-turbine follows the point of maximum wind power. This is employed through dual control using a cycloconverter inserted between the stator and the supply besides resistances inserted in the rotor circuit. Other authors suggested controlling the IG from the stator side using rectifier-inverter set⁹ with the aim of tracing the maximum wind power points or using a cycloconverter¹⁰ to drive the generator as near as possible to these maximum points.

In general, control of the induction generators is achieved with the aid of the various power-electronics converters inserted in the rotor and/or in the stator. If power-electronics converters are inserted in the rotor side, they will be of reduced rating (about 25% of the generator rating)¹¹. But in this case, the induction generator should have a slip ring rotor, which is expensive compared to the cage one. To control the cheaper cage induction generator utilizing rectifier-inverter set, the converters - because of the inaccessible rotor circuit - have to be applied in the stator which is the only available side. In this case, if a rectifier-inverter set is used, its rating should be the same as that of the generator, which is again costly. To avoid such costly converters, different control techniques should be employed for the cage induction generators like altering the generator number of pole pairs.

The present study aims at increasing the output electrical power of the induction generators at the different wind speeds through differently setting the number of poles of the generator, besides controlling the applied

voltage via a low-rating low-cost AC voltage controller when necessary. Pole control will be achieved via changing the machine number of poles using pole amplitude modulation technique for the stator winding¹². The study will end with proposing governing strategies to get the most of the generator electrical power. The characteristics of the generator performance when employing the suggested method will be compared with these resulting if the generator is ideally controlled through rectifier-inverter set inserted in the stator side to keep continuous change of the frequency to comply with the wind speed.

The research will be performed through developing a circuit model for the controlled grid-connected cage induction generator considering pole-changing and voltage control and another one for the variable voltage and frequency input for the case of feeding the generator through a rectifier-inverter set. Then mathematical models will be developed for the complete system. Based on these models, computer programs have been developed to identify the performance characteristics of the generator system. Posteriorly, thorough analysis and discussion of the resulted performance of the controlled generator will be carried out.

2. Studied System

The system under study comprises a wind-driven grid-connected cage induction generator controlled by pole amplitude modulation technique. The generator is linked either directly to the grid or through an ac voltage controller (Figure 1).

3. Control Methods

To raise the system output power, it is obligatory to upsurge the power extracted by the turbine from the wind. This is attained by shifting the generator rotational speed to reach a turbine tip-speed ratio amounting to or

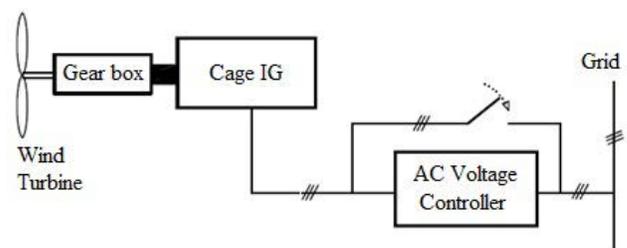


Figure 1. The wind-driven grid-connected induction generator system.

very near to the optimum value^{13,14}. ‘Pole amplitude modulation’ technique¹² will be used to adjust the generator speed at 3 levels. This is performed to enable the turbine to haul out the maximum wind power by adapting its tip-speed ratio to be close to its optimum value. Moreover, the stator terminal voltage is adjusted through an AC voltage controller¹⁵ to have a value of this tip-speed ratio very near to the optimal value.

3.1 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 windings¹².

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

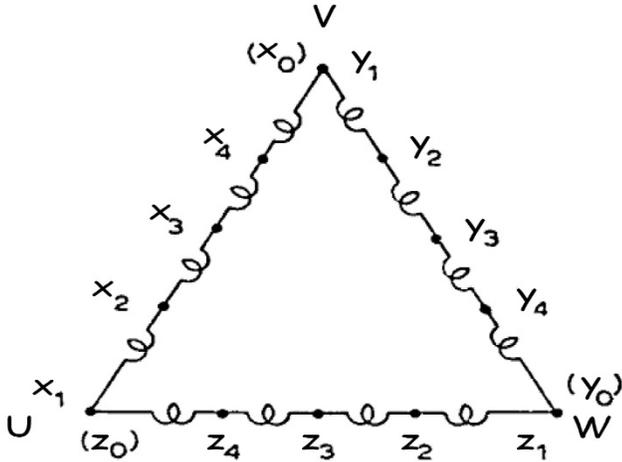


Figure 2. Circuit connection for the pole-amplitude modulation technique in case of three-speed settings.

of 2-parallel circuits per phase to delta connected phases of series circuits per phase¹².

With the aid of the circuit displayed in (Figure 2), the suggested connection of terminals is shown in (Table 1) to obtain certain number of poles which gives the required specific speed.

3.2 Stator Voltage Control

If the generator number of poles is altered, operation of the generator is shifted to a speed which is around the optimum speed. When the stator terminal voltage is decreased, a chance to adjust the speed such that λ realizes the condition of getting the maximum power point (Figure 3)^{3,17}. Maximization of the generator input is expected to increase the output electrical power. It is worth to mention here that when the terminal voltage is lowered, the current should be observed and the process of voltage reduction is performed provided that the current is kept within the rated values. In other words, voltage reduction is performed as long as it leads to increase in the output electrical power, while the generator currents are bordered by the rated values.

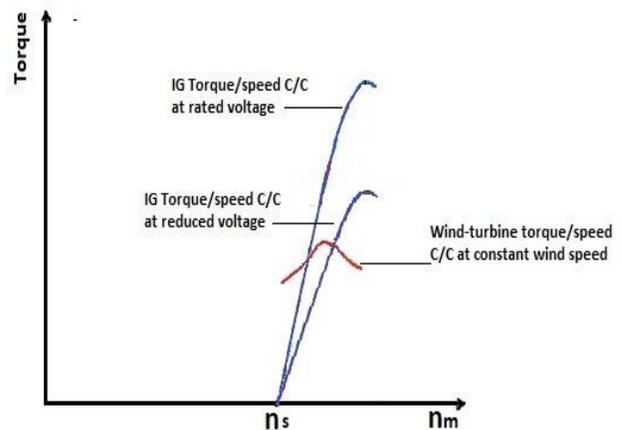


Figure 3. Tracing the maximum power point by decreasing the stator voltage.

Table 1. Connections and feeding arrangements for three-speed pole-amplitude-modulation method

First Speed: (four-Parallel phase- circuit with 3-phase Y)	Second Speed: (two-Parallel phase- circuit with 3-phases Y)	Speed 3: (Series phase circuit with 3-phase Δ)
Connect x_1, y_1 & z_1 Connect x_3, y_3 & z_3 Connect x_2, x_4, y_2, y_4, z_2 & z_4 Feed x_2, x_4, y_2, y_4, z_2 & z_4	Join x_1, y_1 and z_1 x_2, x_4, y_2, y_4, z_2 & z_4 are left open Feed x_3, y_3 and z_3	$x_2, x_3, x_4, y_2, y_3, y_4, z_2, z_3$ & z_4 are left open Feed x_1, y_1 & z_1

4. Mechanical Side Modelling

4.1 Wind Turbine Mathematical Model

Wind turbines are equipment specially designed to convert part of the wind stream energy into usable mechanical energy. Wind turbines are either vertical-axis or horizontal-axis shafts¹⁸. Nowadays, almost all commercial wind turbines used in conjunction with generators to deliver electrical power to grids have horizontal-axis two-bladed or three-bladed rotors.

The torque and power are usually expressed in terms of non-dimensional torque (C_Q) and power (C_p) coefficients as follows^{14,15}.

$$\tau_T = \frac{1}{2} \rho \pi R^3 C_Q (\lambda, \beta) V_w^2 \quad (4.1)$$

$$P_T = \frac{1}{2} \rho \pi R^2 C_p (\lambda, \beta) V_w^3 \quad (4.2)$$

$$C_Q = C_p / \lambda \quad (4.3)$$

Note that the two coefficients are functions of the blade pitch-angle in addition to the tip-speed ratio; λ , which is determined as follows:

$$\lambda = (\omega_T R_b) / V_w \quad (4.4)$$

Where ω_T is the turbine angular velocity in rad/s, R_b is the turbine blade radius in meter and V_w is the wind stream speed in m/s.

Figure 4 shows typical variations of C_Q and C_p for a fixed-pitch wind turbine¹⁵.

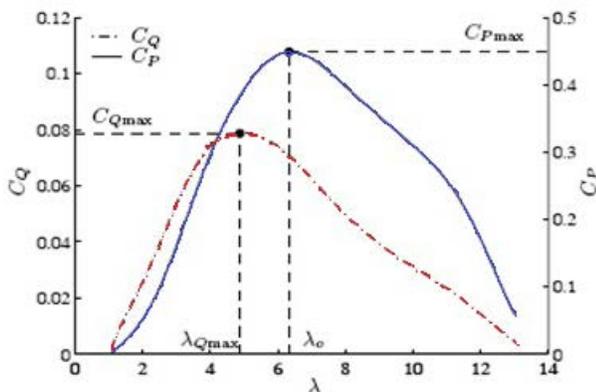


Figure 4. C_Q and C_p typical variation for a constant pitch-angle turbine.

5. Induction Generator Modelling

5.1 Pole and Voltage Controlled Generator

Figure 5 shows steady-state circuit model of the induction generator³. The parameters of this circuit model depend on the stator circuit configuration, which in our case varies according to the generator required number of poles¹².

The induced torque of the induction generator is related to applied voltage, slip and the equivalent circuit parameters as follows³:

$$\tau = \frac{3 V_T^2 R_r / s}{\dot{u}_s \left[(R_T + R_r / s)^2 + (X_T + X_r)^2 \right]} \quad (4.5)$$

Where V_T , R_T and X_T are the circuit parameters when applying Thevenin's theorem on the stator side³.

$$V_T = \frac{V_s Z_{ms}}{\sqrt{(R_s + R_{cs})^2 + (X_s + X_{ms})^2}} \quad (4.6)$$

$$R_T + jX_T = (R_s + jX_s) // jX_m // R_c \quad (4.7)$$

Where $(R_{cs} + jX_{ms})$ is equivalent series impedance of the parallel components; R_c and X_m .

5.2 Frequency Controlled Generator

The circuit model of Figure 5 is used in the case of feeding the generator from the variable source inverter where the reactance and slip are modified according to the frequency. The parameters will be taken corresponding to the constant used number of poles.

6. Computation Algorithms

A computer program has been developed to define the functioning characteristics of the studied cage induction

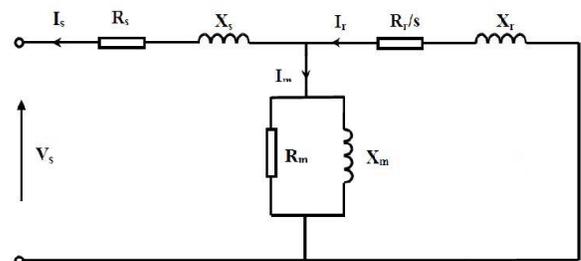


Figure 5. Per-phase equivalent circuit of the induction generator.

generator when employing pole-modulation-amplitude and stator voltage adjustment, in case of powering the generator by wind turbines which is subjected to variable wind speeds. The computations have been based on the mathematical models given in Section 4.2.

6.1 Pole and Voltage Control Case

The algorithm followed during computing the generator performance for when varying the poles is,

1. At an assumed wind stream speed and number of poles, λ is firstly calculated supposing that the generator runs at the synchronous speed using Equation 4.4. Then, the torque coefficient (C_Q) is obtained from the turbine characteristic depicted in Figure 4. Consequently, the torque developed by the wind turbine is determined from Equation 4.1.
2. The P.U slip is determined from Equation 4.5. Then, the speed of the generator is recalculated. Thereafter, λ , C_Q and the turbine torque are recalculated. The iterative technique continues till the accurate value of slip is reached.
3. The required adjusted stator voltage is calculated through the following steps:
 - At the considered wind speed, the generator speed resulting in the optimum λ_o which gives maximum extracted wind power is calculated. At this generator speed the corresponding slip is determined.
 - C_Q and the turbine driving torque is calculated at this optimum tip-speed ratio.
 - The turbine torque (referred to the generator shaft) is considered the generator driving torque. Then, the venin's voltage (V_T) and the stator voltage (V_s) are, then, calculated using Equations 4.5 and 4.6, respectively.
4. At the specified stator voltage (rated or reduced) and the value of the slip previously calculated, the equivalent circuit depicted in Figure 5 is used to calculate the generator currents, power factor, output power, losses etc.
5. The calculation is repeated for different wind speeds over the wind speed rang and for the three sets of poles.

6.2 Inverter-fed Generator

The system in this case will be adjusted such that the generator will deliver its rated VA at the maximum expected

wind speed while its voltage and frequency are the rated values. Thereafter:

- At any other wind speed the generator frequency is assumed. Hence, the voltage is determined keeping V/f constant for good performance.
- The tip-speed ratio; λ , is taken the optimum value. The generator revolving speed is determined using Equation 4.4. and the driving torque of the turbine is calculated using Equation 4.1 at the optimum C_Q .
- The slip is calculated and, by the aid of Equation 4.5, the generator torque is determined.
- The turbine torque is compared to the generator torque and according to the sign of the difference, the frequency is either incrementally increased or decreased.
- The iterative technique continues till the accurate value of frequency is reached.

7. Results and Discussion

The developed computer program has been applied on a generator of the data and parameters given in Appendix 1. The performance characteristics at different number of poles, namely; 4, 6 and 8 are depicted in Figures 6-9.

The mechanical power captured from the wind streams clearly depends on the number of poles as shown in Figure 5. As the wind speed goes down, the number of poles ought to be increased to extract more mechanical power from the wind. For the studied generator, for speeds higher than about 9.2 m/s 4-poles should be used, while when the generator number of poles is changed to 6-poles, more mechanical power is extracted when the wind speed ranges between 9.2 m/s and 6.9 m/s. To extract the highest mechanical power at wind speeds lower than 6.9 m/s, the number of poles has to be changed to 8 poles. The output electrical power of the generator has a pattern very analogous to the behavior of the input mechanical power as shown in Figure 6. When the number of poles is 4, the output electrical power is the highest compared with that of the other number of poles for the topmost wind speed value and down to about 9.2 m/s. Over the medium range of wind speed starting from about 9.2 m/s down to about 6.9 m/s, the generator output electrical power is the highest with 6-poles. At wind speeds lower than 9.6, that of the 8-poles is the highest.

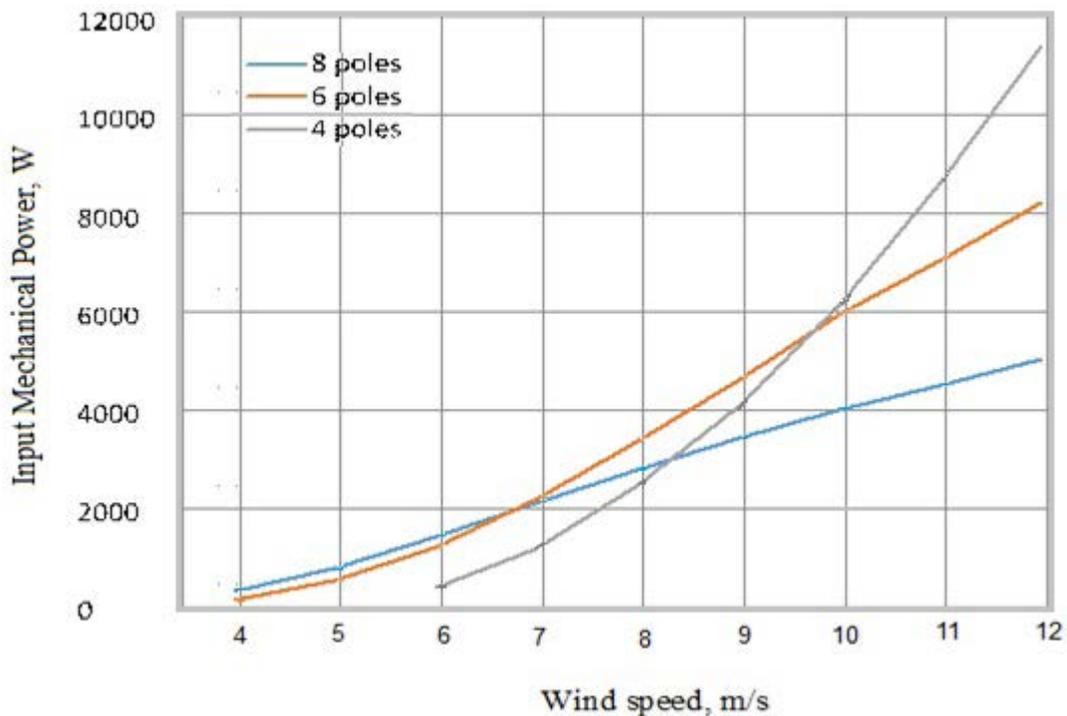


Figure 6. Variation of the input mechanical power with the wind speed for the 3 sets of poles.

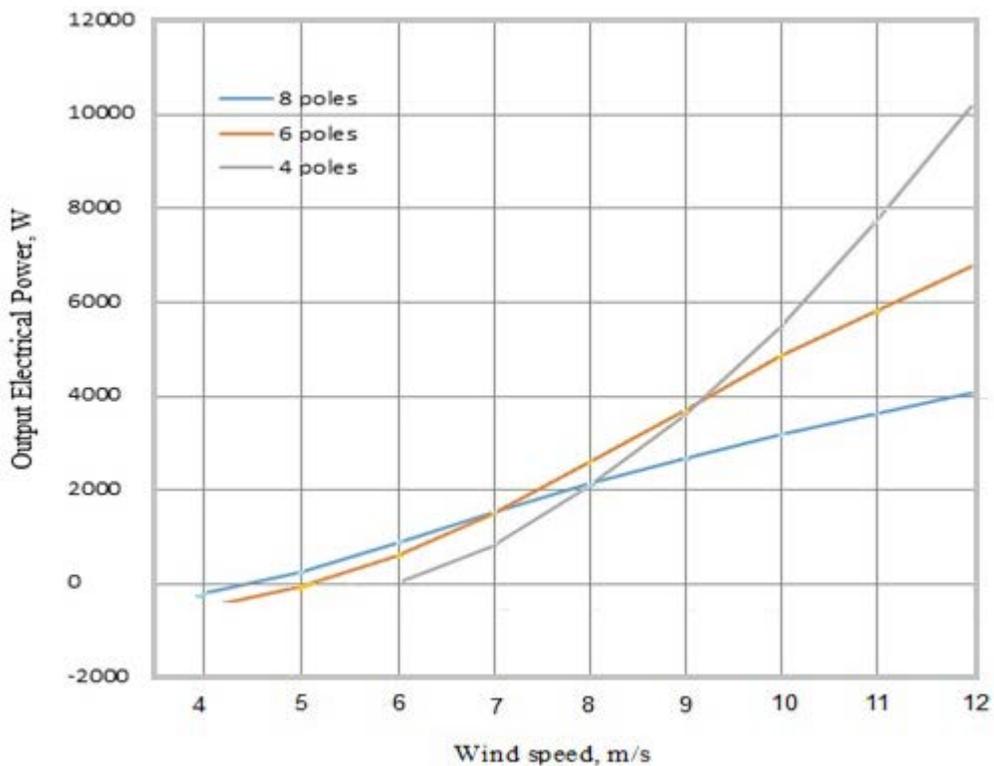


Figure 7. Variation of output electrical power with the wind speed for the 3 sets of poles.

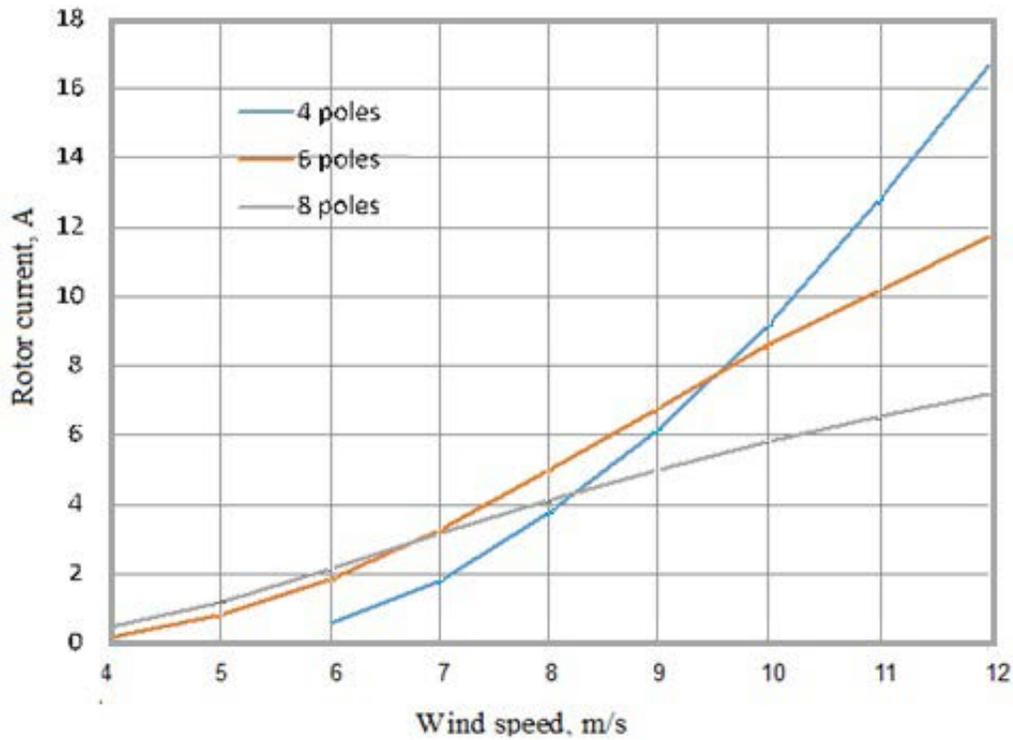


Figure 8. Variation of the rotor current with the wind speed for the 3 sets of poles.

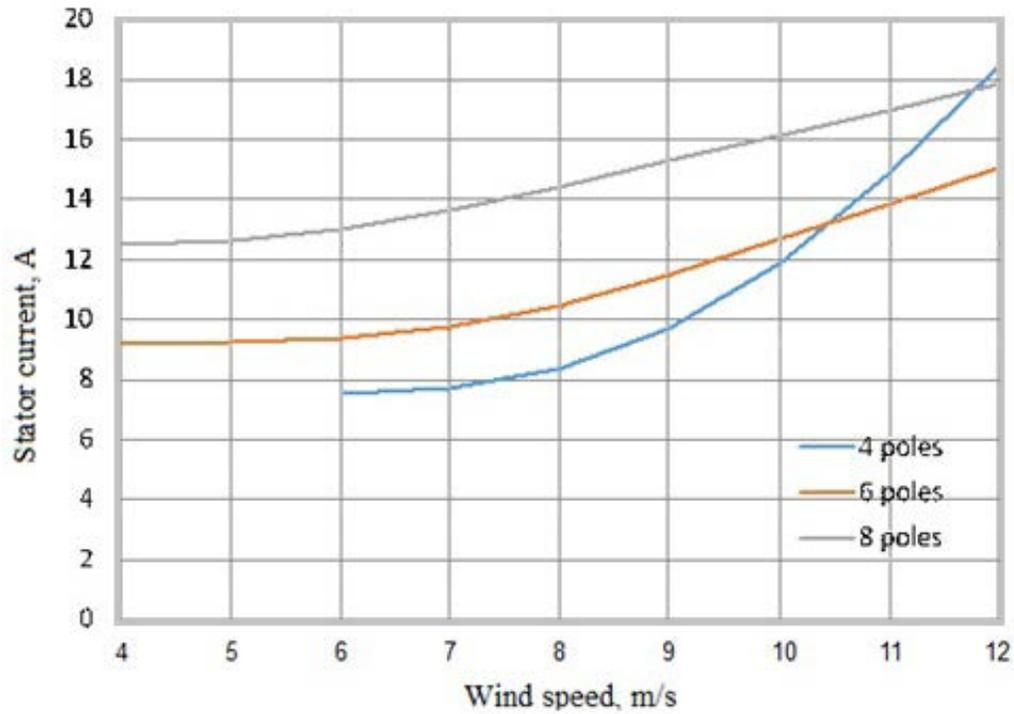


Figure 9. Variation of the stator current with the wind speed for the 3 sets of poles.

The stator and rotor currents (Figures 7 and 8) decrease generally as wind speed decreases. An eye should be kept on these currents to ensure that they are within the permissible rated values. The investigation of these figures show that if the number of poles is changed corresponding to the specified wind speeds, the currents will be kept within the rated values (see Appendix 1)

The calculated power factor curves depicted in Figure 10 show that increasing the number of poles as the wind speed decreases improves the power factor, and, thus, results in less generator reactive power demand. The results of the induction generator performance at reduced voltage are shown in Figures 11-16.

Voltage reduction results have indicated that reduction of voltage is not effective at high wind speeds where the number of poles is 4. At medium and low wind speeds somewhat increase in the output power is achieved over the lowest part of the concerned range. It can be seen from Figures 11 and 15 that the output power could be increased over specific wind speed ranges in cases of 6 and 8 poles. For 6 poles, the output power is increased over a range from about 7.9 m/s up to about 8.4 m/s without violating the current constraints (Figure 12). For 8 poles, the range is from about 5.87 m/s up to about 6.2 m/s without violating the current constraints (Figure 16). It is noted that both the stator current and voltage decrease, while the electrical power increases. This is because of the improvement of

the power factor. The terminal voltage of the generator is almost halved at the upper limit of wind speed in this considered range (Figures 12 and 15). The increase of the output electrical power resulted from stator voltage adjustment is obtained through additional cost arising from the utilization of the voltage controller. Thus, benefits of the usage of the voltage controller have to be assessed against the additional cost. It is important to mention here that the rating of the suggested voltage controller will be fraction amount of the complete rating of the induction generator. In our studied generator, the voltage controller rating is about one-third of the full generator rating, as it is only applied at medium and low wind speed levels where the power dealt with is low as shown in Figures 12 and 14. Therefore, a low-rating cheap voltage controller can be inserted at low wind speeds and bypassed at high wind speeds

For comparison purposes, performance characteristics of the ideal case are depicted in Figure 16. Operation is ideal when feeding the generator from an inverter which, at a certain wind-speed, gives frequency such that the generator operates always at speed satisfying the optimum tip-speed-ratio.

The suggested cheap method when compared with the case of inverter-fed induction generator confirms its effectiveness as the output power (Figure 7) is very close to that of the ideal control method (Figure 17). If the input mechanical power employing the suggested pole control

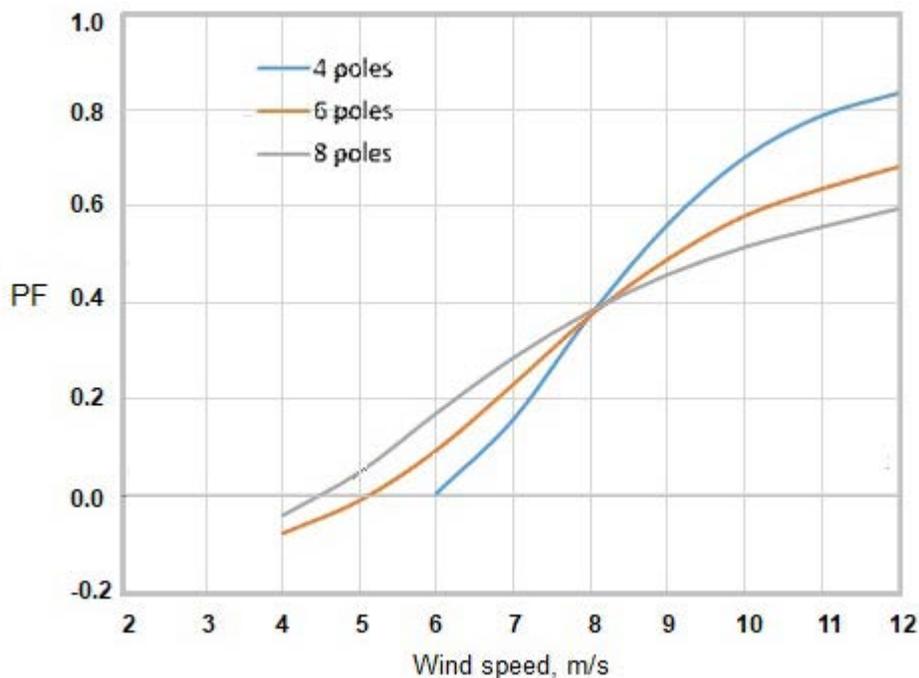


Figure 10. Variation of the power factor with the wind speed for the 3 sets of poles.

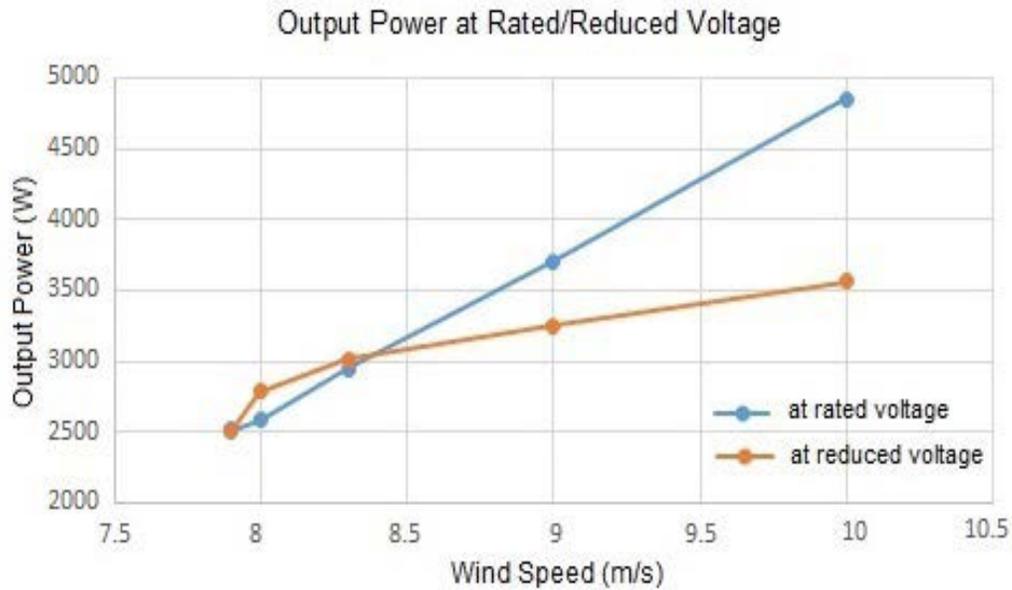


Figure 11. Effect of reducing the voltage on the output electrical power in case of 6-poles.

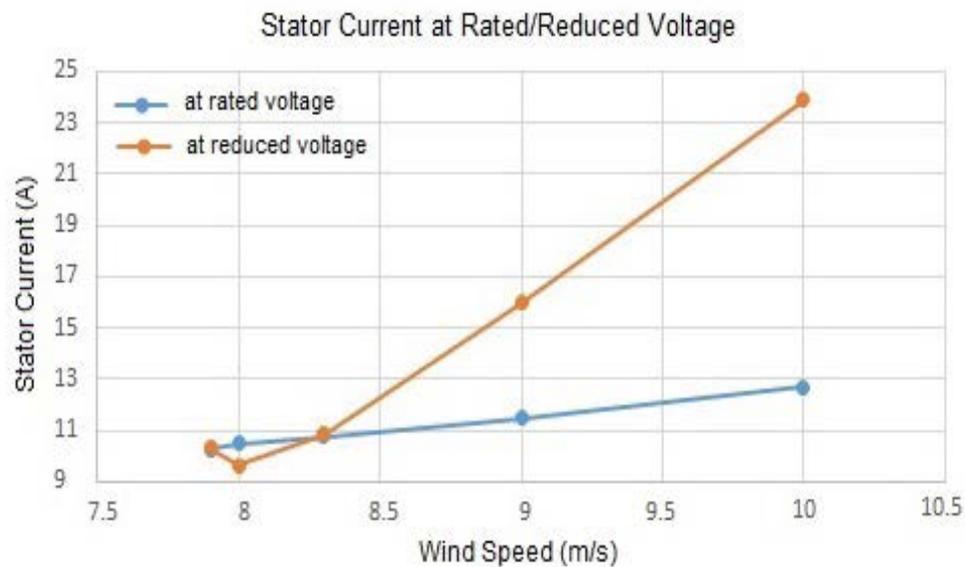


Figure 12. Effect of reducing the voltage on the stator current in case of 6-poles.

technique is compared to the ideal maximum mechanical power, it will be found that it is very close over the entire wind speed range (Figure 18).

8. Conclusions

Utilization of wind energy to generate electrical power is very vital. Cage induction generators- being cheap can

be used in wind energy conversion system to replace the costly slip ring generators. To enhance the performance of such induction generator, pole amplitude modulation technique has been applied to increase the captured wind mechanical power and hence the output electrical power.

Pole amplitude modulation method with three sets of poles has proved its effectiveness in this regard. To cope

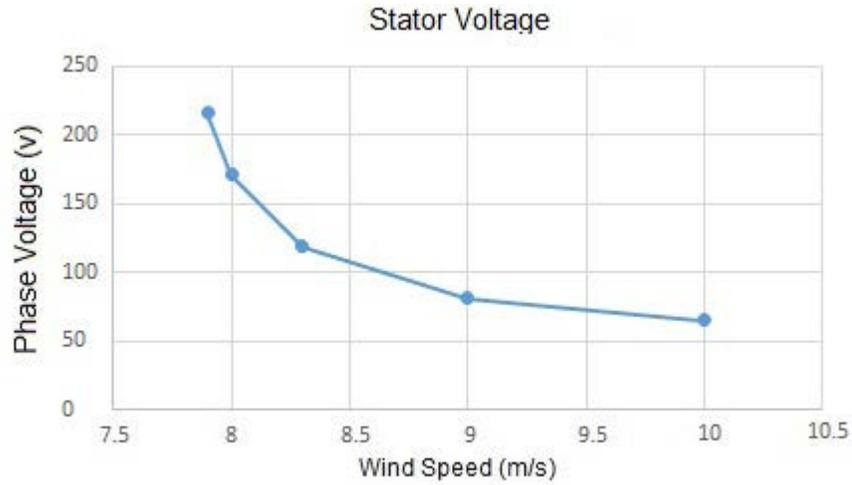


Figure 13. Stator voltage resulting in maximum input mechanical power in case of 6-poles.

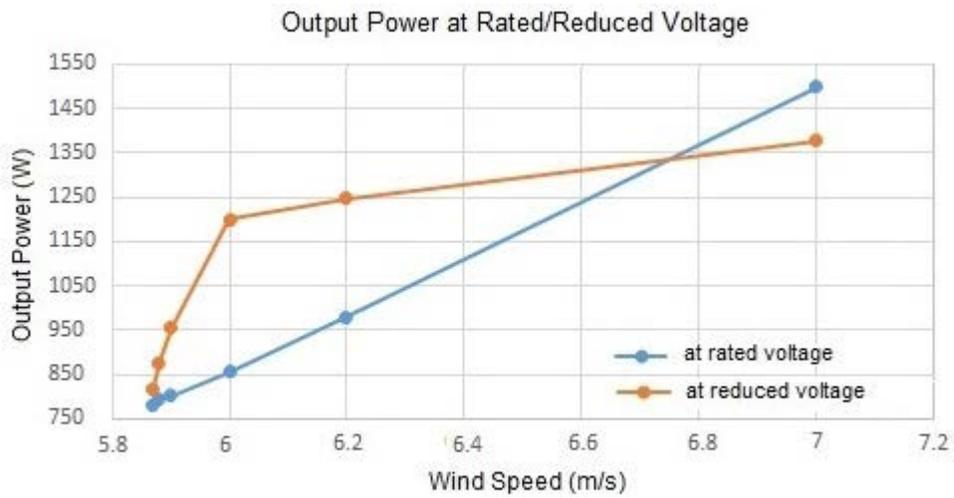


Figure 14. Effect of reducing the voltage on the output electrical power in case of 8-poles.

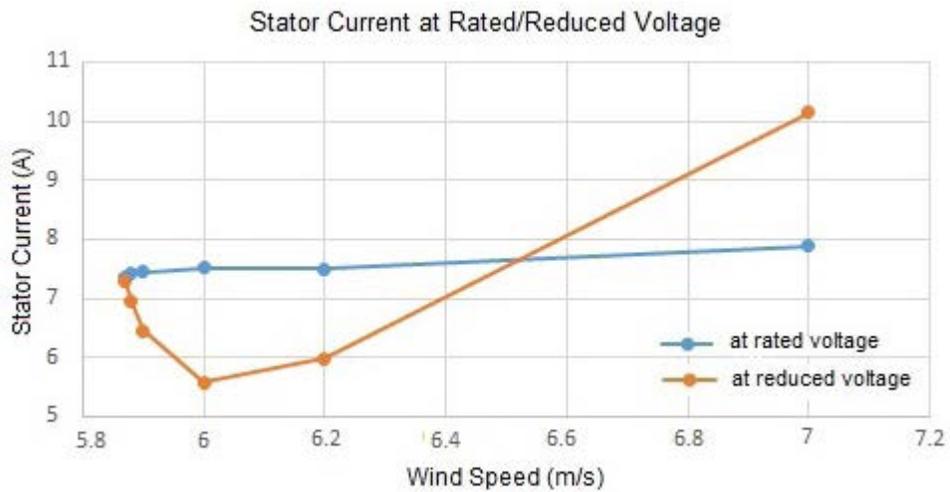


Figure 15. Effect of reducing the voltage on the stator current in case of 8-poles.

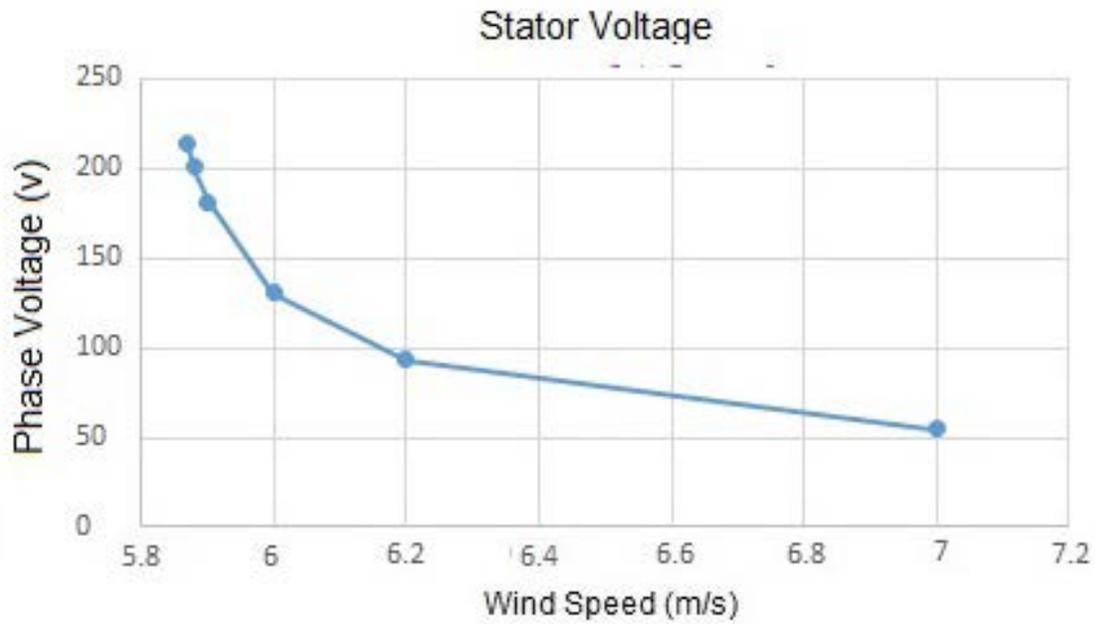


Figure 16. Stator voltage resulting in maximum input mechanical power in case of 8-poles.

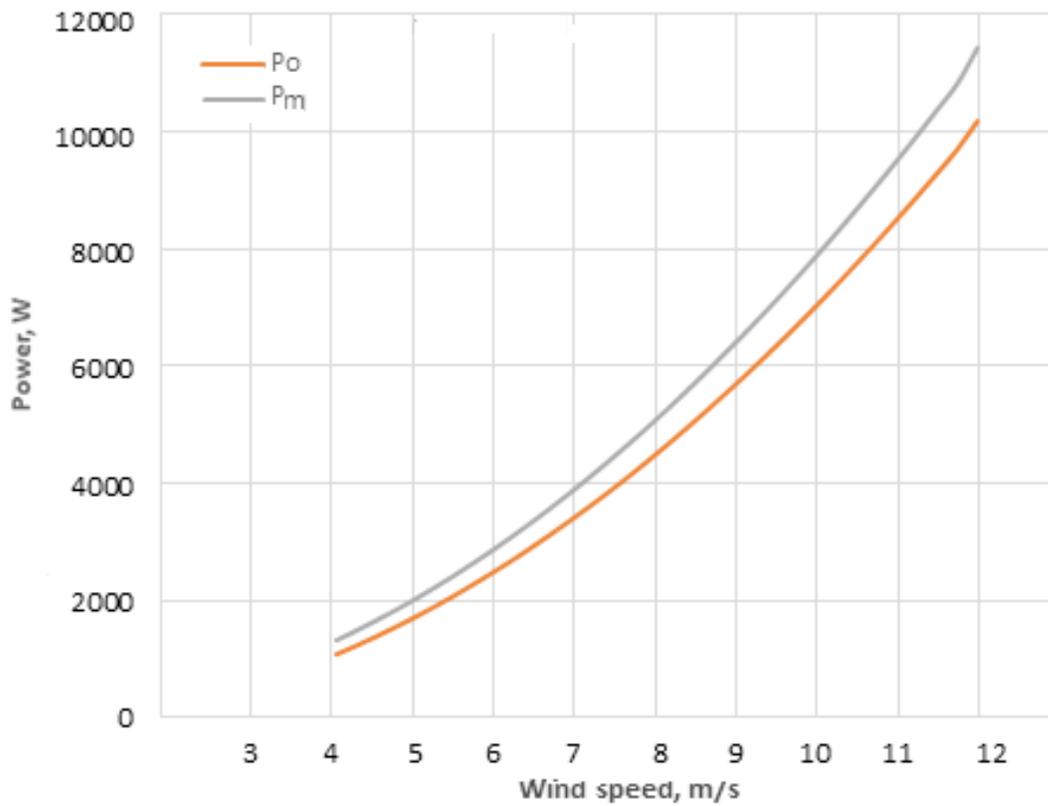


Figure 17. Input and output powers versus the wind speed.

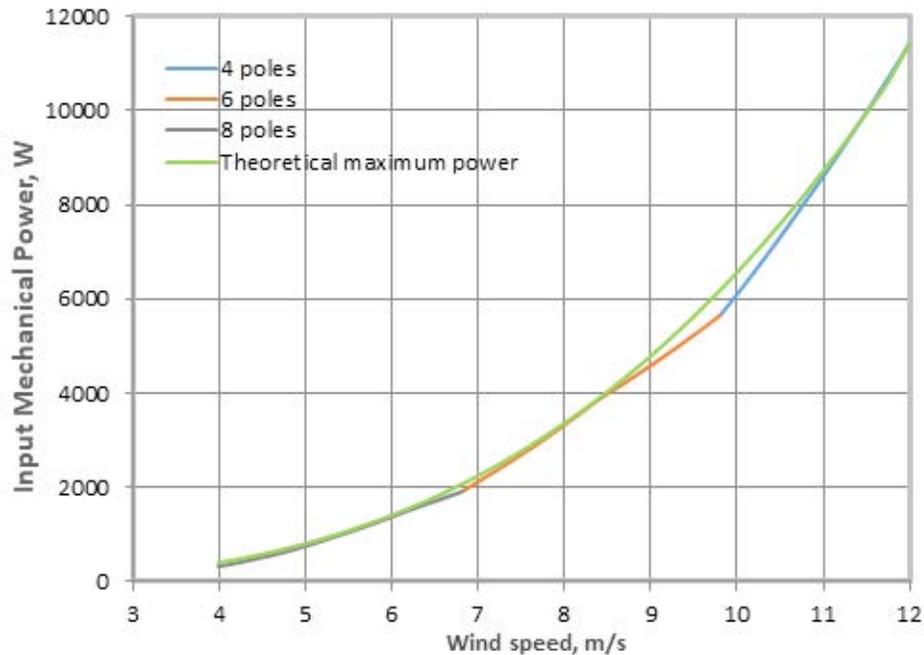


Figure 18. Input mechanical power using pole control compared with the ideal extracted maximum power.

with high wind-stream speeds, the generator stator should be switched to the least poles number. While, for medium wind-stream speeds the stator is switched to the medium poles number. For low wind-stream speeds, the stator should be switched to the highest number. Adhering to this control protocol guarantees operation of the generator and consequently, its wind turbine very near to point of maximum extracted wind-energy at all wind speeds.

In addition to altering the stator pole setting, the electrical power could be raised via stator voltage control over the low and medium ranges of wind-stream speeds. Through stator voltage reduction, the induction generator speed could be regulated so that the wind turbine follows the optimum locus of the extracted energy over divisions of the wind-stream speed range. Also, the reactive power demand of the generator has been significantly cut-down. While applying this pole and voltage control techniques, the generator currents should be observed to avoid overloading the generator. The revenue got from the more output electrical power if stator voltage is reduced should be weighed against the extra charges of the voltage controller. The previous discussion clarified that this AC voltage controller is fortunately of low rating. Thus, its low cost justifies its use.

The suggested cheap method when compared with the case of inverter-fed induction generator confirms its effectiveness as the output power is very close to that of the ideal control method.

9. Acknowledgment

The authors are grateful to the Deanship of Scientific Research in Qassim University for their financial support through this research.

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Appendix 1: The Generator Data

The studied cage generator has the following data and parameters:

3-phase, 10/6.67/5 kW, 380 V, 50 Hz, 4/6/8 pole amplitude modulated cage induction generator. The parameters of the generator are as follows:

Parameters	4 poles	6 poles	8 poles
R_1, Ω	0.47	1.034	1.504
R_2, Ω	0.47	0.972	1.361
X_1, Ω	0.86	0.7568	0.86
X_2, Ω	0.86	0.7568	0.86
X_m, Ω	28.27	23.129	29.55
R_c, Ω	500	409.07	522.710
R_T, Ω	0.444	0.968	1.412
X_p, Ω	0.8396	0.77	0.899
Stator Rated Current, A	18.44	14.98	13.68
Stator Connection	Star	Star	Delta