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Performance of a Pole-Amplitude-Modulated Self-Excited Wind-Driven Cage Induction Generator

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Abstract. The renewable wind energy encountering a globally rapid growth to become an important electricity source, which replaces the polluting and exhaustible fossil fuel. The induction generators are commonly used to convert the mechanical power of the wind-turbine prime-mover to electrical power. Many control techniques are used to track maximum point of wind energy. The present research aims at enhancing the performance of the self-excited wind-driven cage induction generator at the different wind speeds employing control technique by changing the number of poles of induction generator and adjusting the shunt capacitor. The control aims to track the wind maximum power and to improve the generator electrical performance when the generator feeds a static load, and when it feeds an induction motor as a dynamic load. A complete mathematical model and computer simulation has been performed, and control protocols have been reached. 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 are highly recommended.

***Keywords*:** Wind energy, Self-Excited, Pole-Amplitude Modulation, Cage Induction Generator.

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_L: Current of load.
I_{m2} : 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_{Cg}: Iron loss resistance of generator.
R_{Cm}: Iron loss resistance of motor.
S_g: Generator slip
S_m: Motor slip.
V_t: Terminal voltage.
WS: Wind speed.
X_{1g} , X_{2g}: Generator stator-side and rotor-side leakage reactance, respectively.
X_{1m}, X_{2m}: Motor stator and rotor leakage reactance of motor, respectively.
$X_{\Phi g}$, $X_{\Phi m}$: Generator and motor magnetizing reactances, respectively.
Z_L: Load impedance.
β: Blade pitch angle.
λ: Tip-speed-ratio.
τ: Generator induced torque.
ω_{syn}: Angular synchronous speed.

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 [1, 2]. 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 [1].Wind-driven self-excited induction generators (SEIG) [1, 2] 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 [3, 4]. 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 [5-7] besides a developed model for the pole-controlled generator. The built voltage and its frequency of the self-excited induction generator (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 Fig.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.

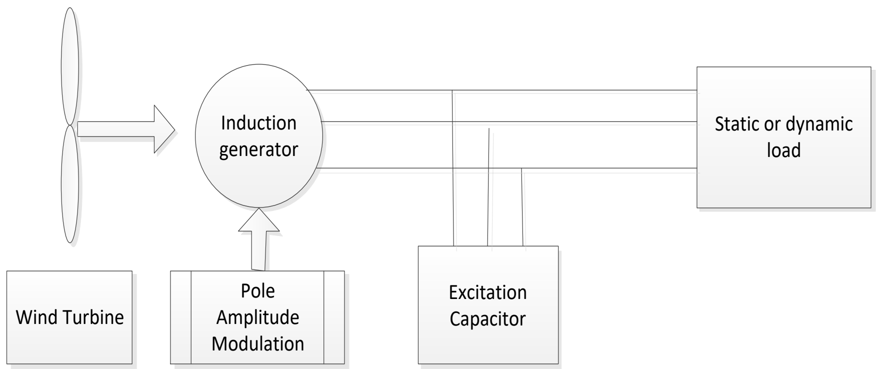

Fig. (1). Layout of the system under study

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 [3].

In two-sets of poles using pole amplitude modulation (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 [4]. 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 [3]. With the aid of the circuit displayed in Fig.2, Table 1 explains how the terminals are connected to obtain certain number of pole which gives the required specific speed.

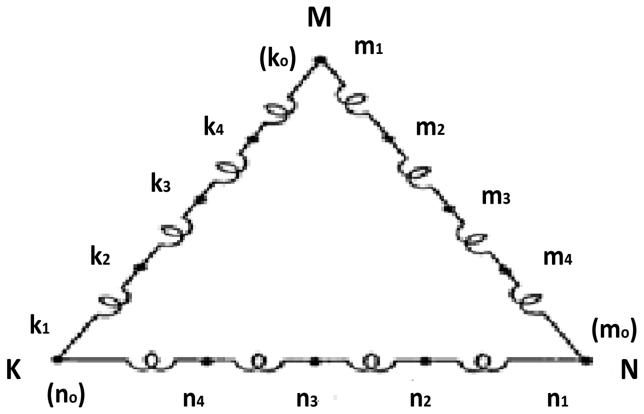

Fig. (2). Circuit connection for the pole-amplitude modulation technique in case of three-speed settings

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 k_1 m_1 n_1 Connect k_3 m_3 n_3 Connect k_2 k_4; m_2 m_4; n_2 n_4 Feed k_2 k_4; m_2 m_4; n_2 n_4	Connect k_1 m_1 n_1 Disconnect k_2 k_4 m_2 m_4 n_2 n_4 Feed k_3 m_3 n_3	Disconnect k_2 k_3 k_4 m_2 m_3 m_4 n_2 n_3 n_4 Feed k_1 m_1 n_1

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 [5]. 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 [6, 7].

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

$$P_T = \frac{1}{2}\rho\pi R^2 C_P(\lambda.\beta)WS^3 \quad (2)$$

$C_Q = C_P / \lambda$ (3)

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

$\lambda = (\omega_T R_T) / WS)$ (4)

R_T and ω_T are the turbine blade radius and angular speed, respectively. *WS* is the wind stream velocity. Fig.3 shows typical variations of C_Q and C_p for a fixed-pitch wind turbine [5-7].

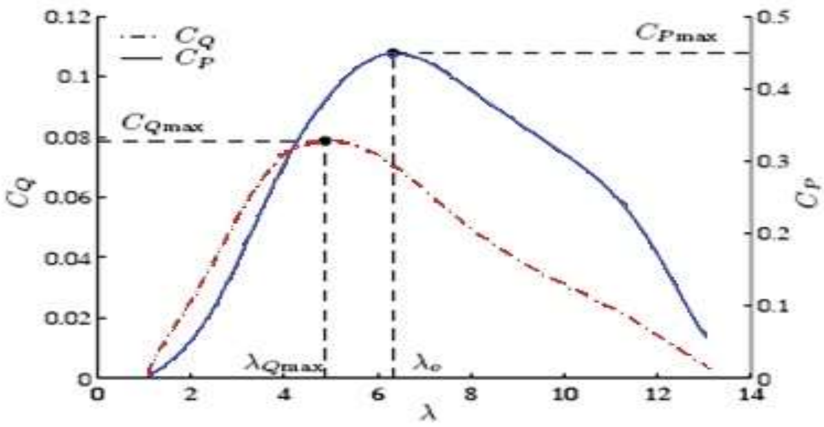

Fig. (3). Typical variations of C_Q and C_P for a wind turbine assuming fixed-pitch

4.2 Induction Generator Model

An induction generator when steadily stands alone may be represented by the frequency-dependent circuit shown in Fig. 4 [1]. 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 [3].

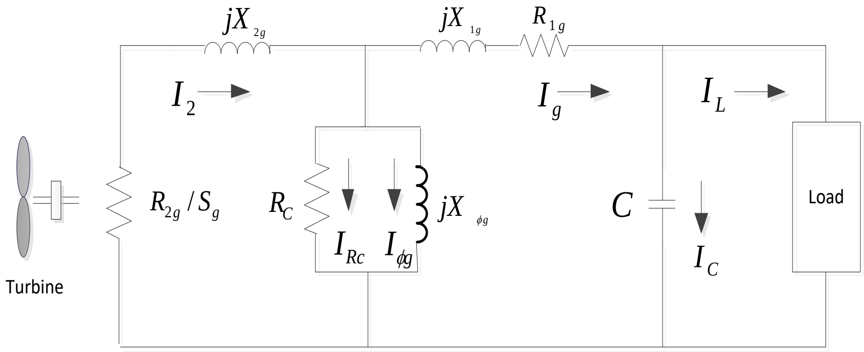

Fig. (4). Induction generator pole and frequency dependent equivalent circuit

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 (Fig. 5), such that.

$$R_g = [(R_{18} + R_{2g}/S_g)^2 + (X_{1g} + X_{2g})^2 * \left(\frac{f}{f_o}\right)^2]/(R_{1g} + R_{2g}/S_g) \quad (5)$$

$$X_g = [(R_{1g} + R_{2g}/S_g)^2 + (X_{1g} + X_{2g})^2 * \left(\frac{f}{f_o}\right)^2]/[(X_{1g} + X_{2g}) * (\frac{f}{f_o})] \quad (6)$$

$X_{\Phi g}$ depends on the saturation condition and the frequency, it is represented as given in Appendix 1.

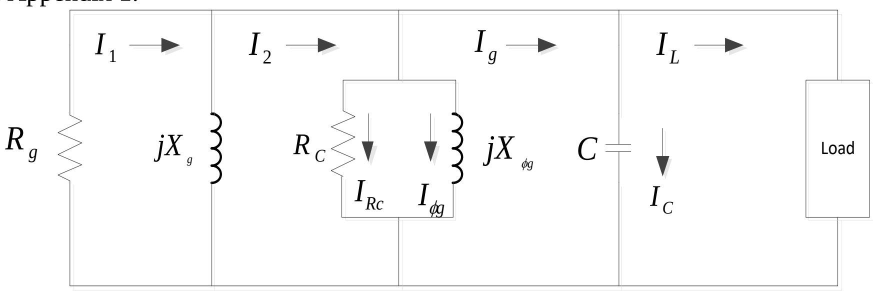

Fig. (5). Parallel representation of the induction generator

The generator current can be express by:

$$I_g = I_L + I_C \quad (7)$$

$$I_2 = I_g + (I_{X\emptyset g} + I_{RC}) \quad (8)$$

$$P_{AG} = 3 * (I_2)^2 * (R_{2g}/S_g) \quad (9)$$

$$P_m = P_{AG} * (1 - S_g) \quad (10)$$

The condition to attain wind maximum power is realized when:

$$P_m = P_T \quad (11)$$

Which can be solve with Eq. 5 to obtain the generator slipS_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 Fig. 5, and replacing the load with a series resistance and reactance as show in Fig.6.
The static load impedance can be express by:

$ZL = R_L + j\, L_L 2\pi\left(\frac{f}{f_o}\right)$ (12)

$I_L = V_t / ZL$ (13)

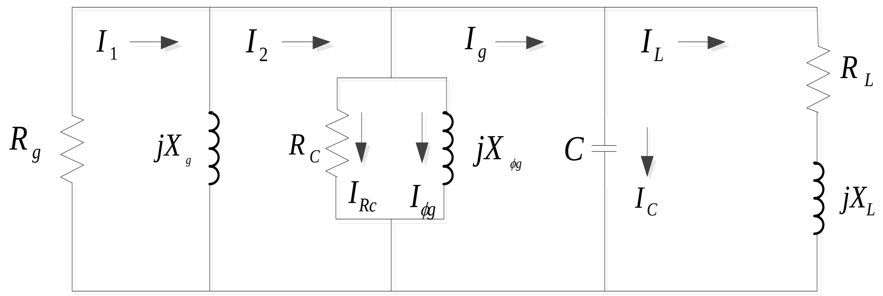

Fig.6: Circuit Model of isolated induction generator supplying an R-L static load

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 show in Fig.7.
The motor current can be express by:

$I_{m2} = I_g - (I_{\o m} + I_{R_C m})$ (14)

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

$$\tau = \frac{3 V_t^2 (R_{2m}/S_m)}{\omega_{syn}[(R_{1m}+R_{2m}/S_m)^2+(X_{1m}+X_{2m})^2]} \quad (15)$$

At equilibrium,

$\tau = \mathrm{Cpp}\ \boldsymbol{\omega}_{\mathbf{syn}}^2 (1 - S_m)^2$ (16)

where C_{pp} is the pump torque constant. Solving the above equation, we can find the motor slip and obtain the desired operation points.

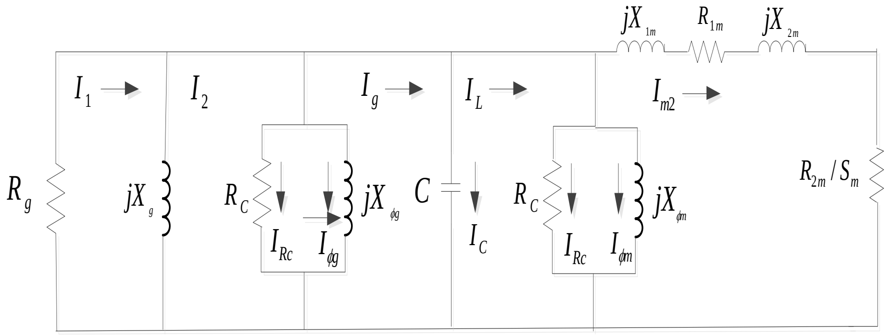

Fig.7: Circuit model of isolated induction generator supplying a dynamic motor load,

5. Computational Algorithms

The flow chart given in Fig.8 and Fig.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.

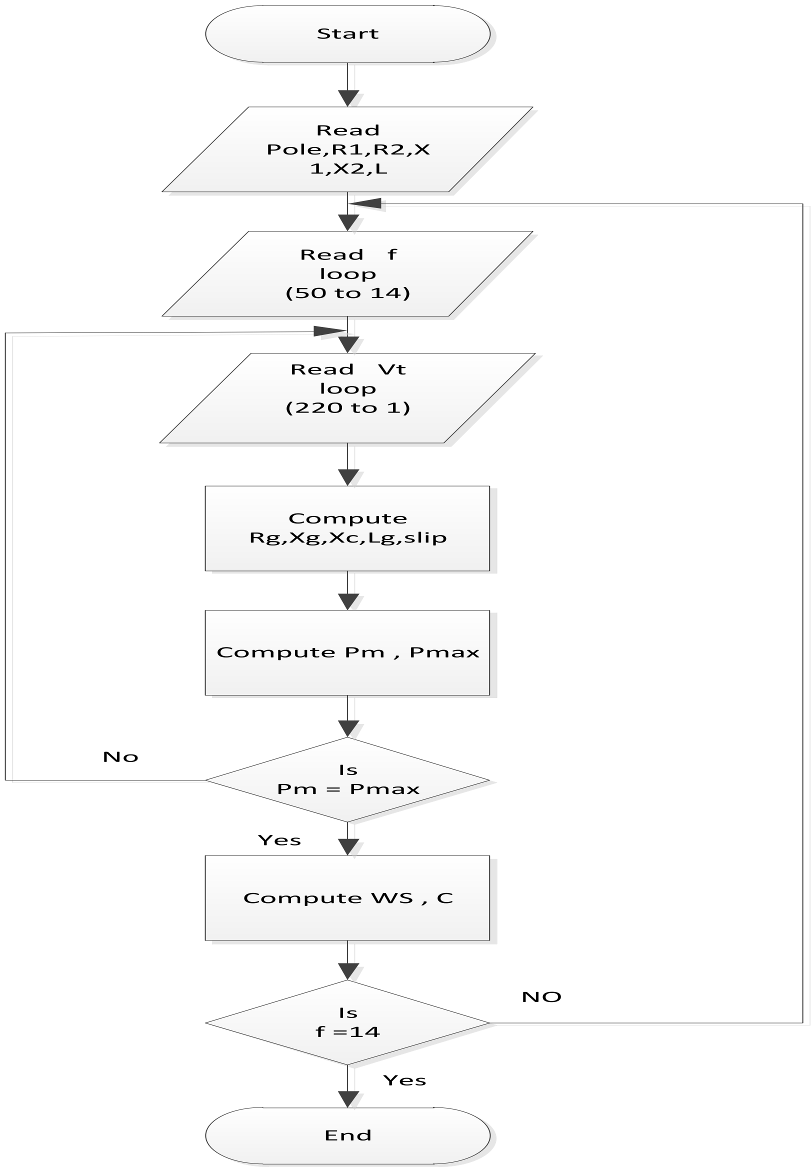

Fig. (8). Flowchart for the steps of computing the operation characteristics of induction generator loaded by a static (R-L) load

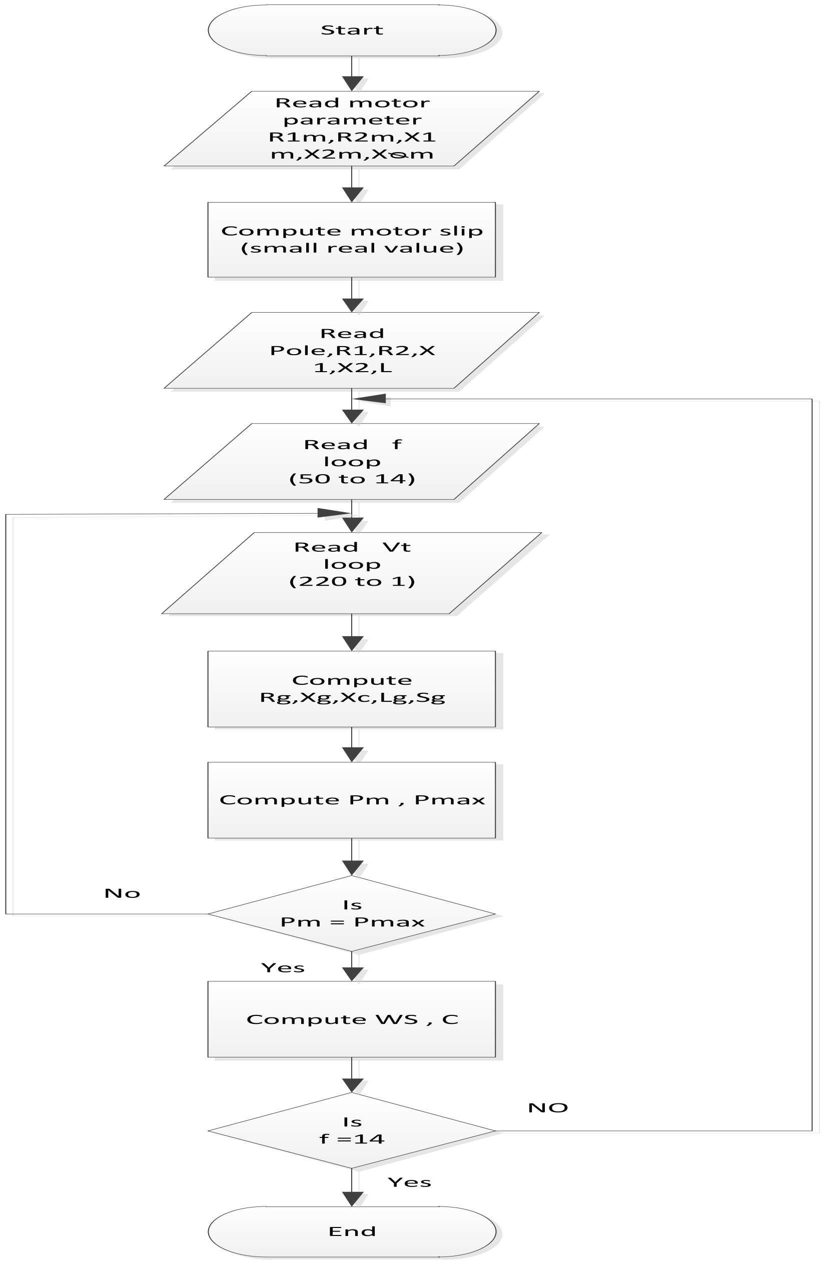

Fig.9: Flowchart for the calculation of the performance characteristics of induction generator with dynamic load

6. Results and Discussion

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

6.1 Static R-L load

6.1.1 Results

The induction generator characteristics at static load for various number of poles are shown in Figs 10-15. The mechanical input power extracted from the wind happened to be the possible maximum power that can be obtained (Fig.10). This could be obtained at frequency depending on the number of poles, and of course it varies with the wind speed (Fig. 11).

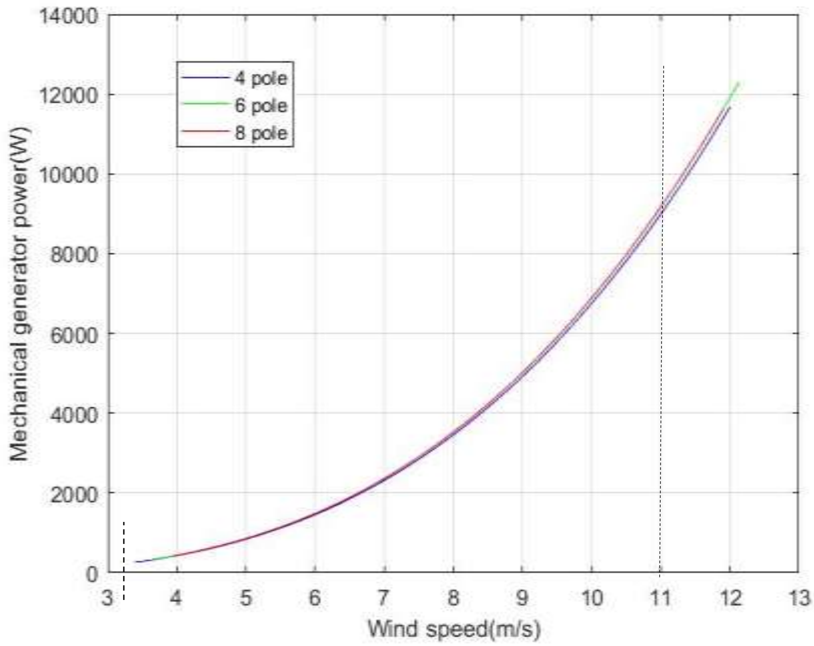

Fig. (10). Variation of the input mechanical power with wind stream speed in case of a static load at the various pole settings

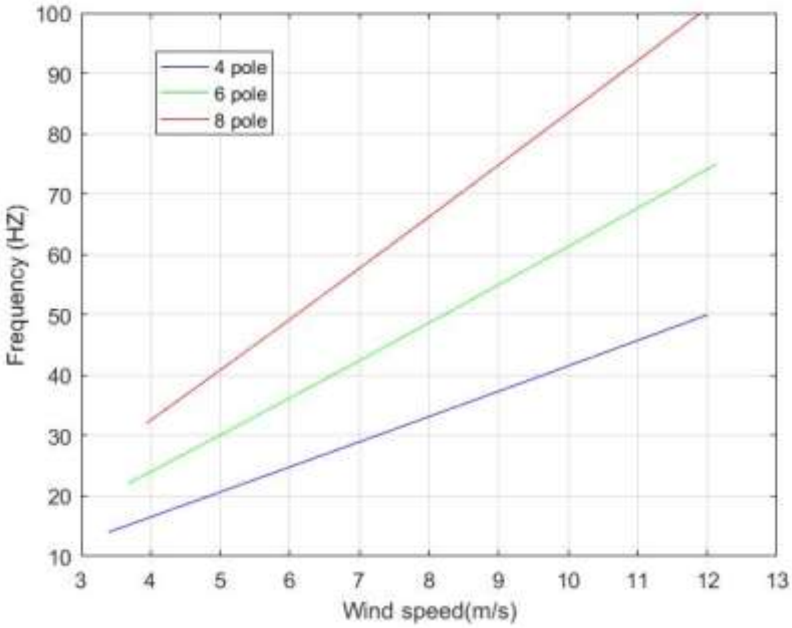

Fig. (11). Frequency variation for the different number of poles versus wind stream speed for a generator having a static load at the various pole settings

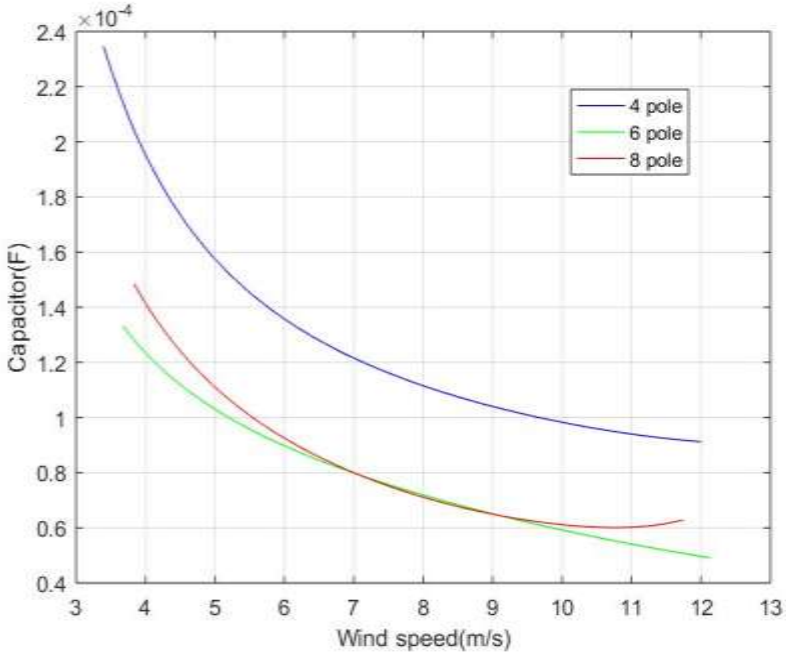

Fig. (12). Capacitor for the different number of poles versus wind speed in case of static load

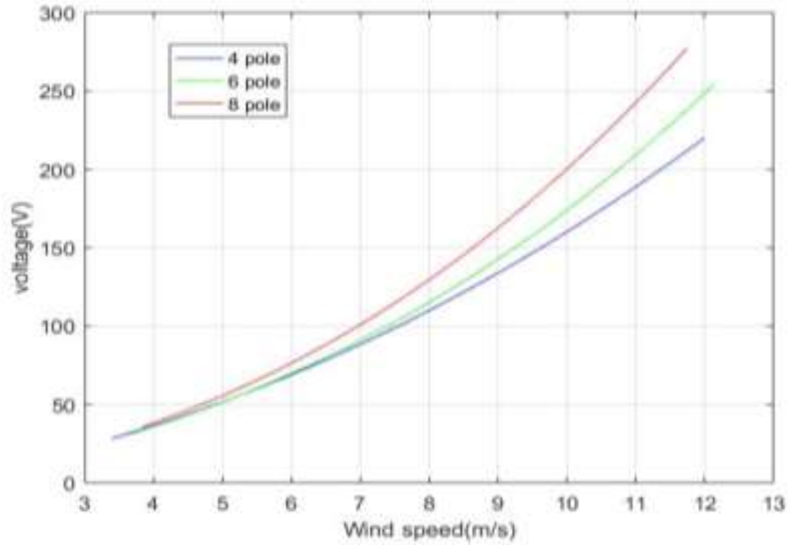

Fig. 913). Terminal voltage variation with the wind stream speed for a generator having a static load at the various pole settings

Variation of the frequency have been obtained through variation of the capacitor size as depicted in Fig. 12. The variation of the capacitor size resulted in variation of the voltage (Fig. 13).The variation of the generator output current and power as a result to the variation of the voltage and frequency are shown in Figs 14 and 15.

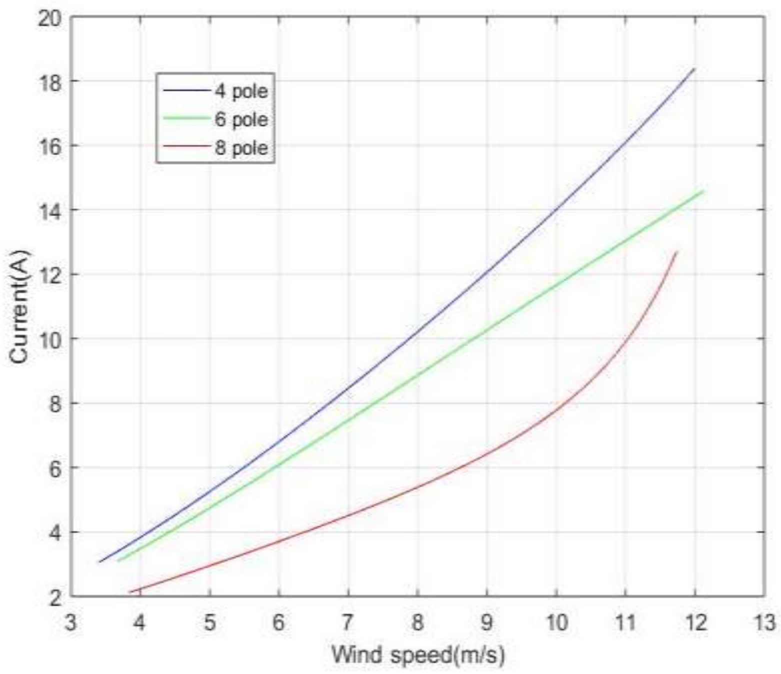

Fig. (14). Variation of the generator output current with the wind stream speed for a generator having a static load at the various pole settings

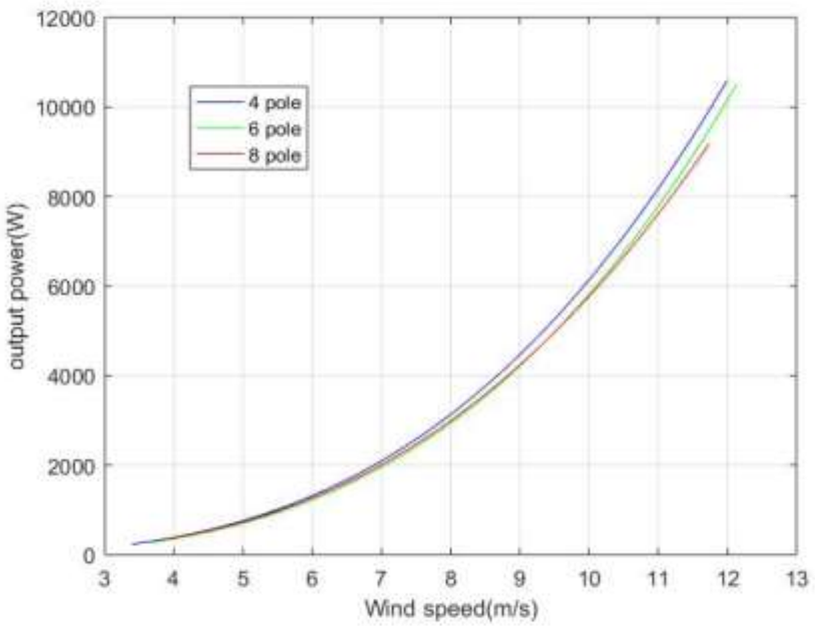

Fig. (15). Variation of the generator output electrical power with wind stream speed for a generator having a static load at the various pole settings

6.1.2 Control Protocol

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 (Fig. 10), and in case of static load, pole control is recommended 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 7.81m/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 7.81m/s, the pole setting should switched to that corresponding to 8 poles (Fig.16-18).

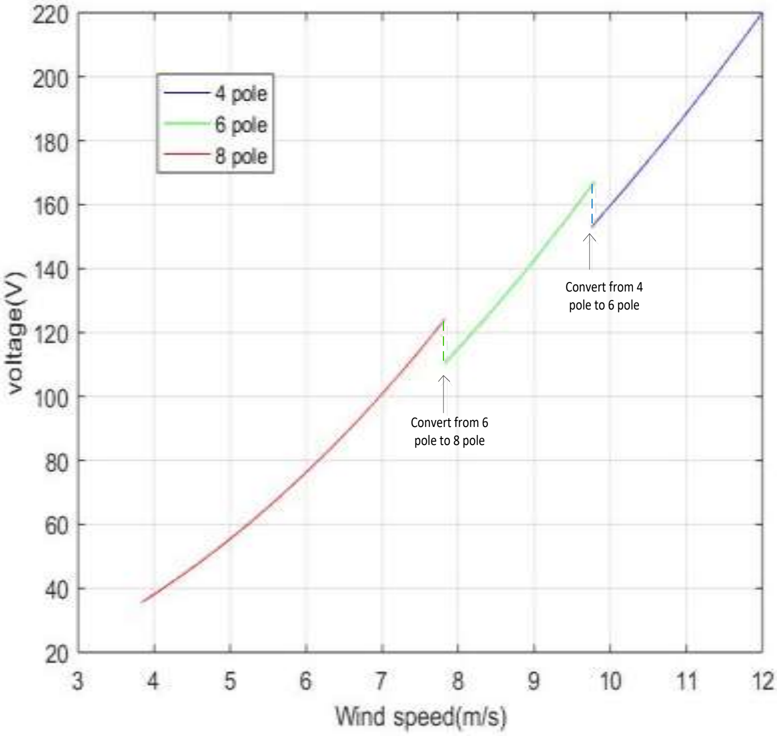

Fig. (16). Voltage control strategy through changing the number of poles

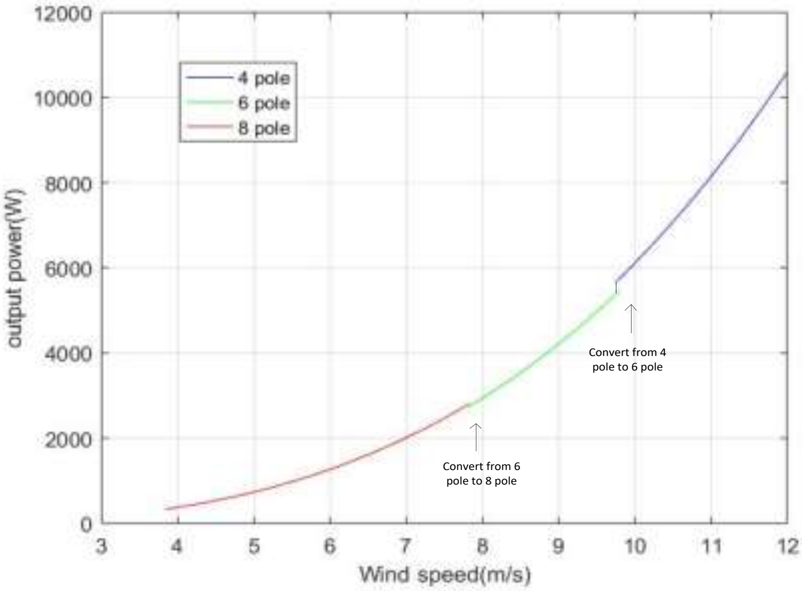

Fig.17: Effect of change of the number of poles on the output electrical power

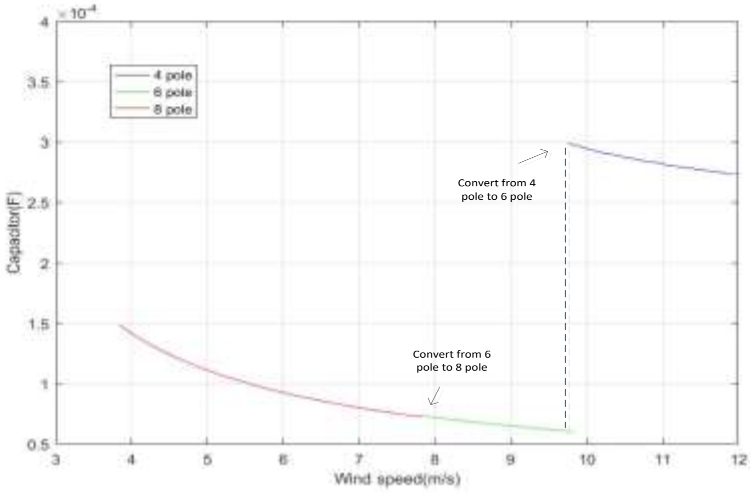

Fig.18: Effect of change of the number of poles on the capacitor size

6.2 Dynamic load

6.2.1 Results

The characteristics of the operation of the turbine-generator-load system when energizing an induction motor as a dynamic load- having the particulars given in Appendix 2- are shown in Figs. 19-24. The input mechanical power to the generator is controlled to be the maximum possible extractable power from the wind (Fig. 19) for all pole settings. This necessitated frequency variation (Fig. 20) through capacitor size adjustment (Fig. 21).

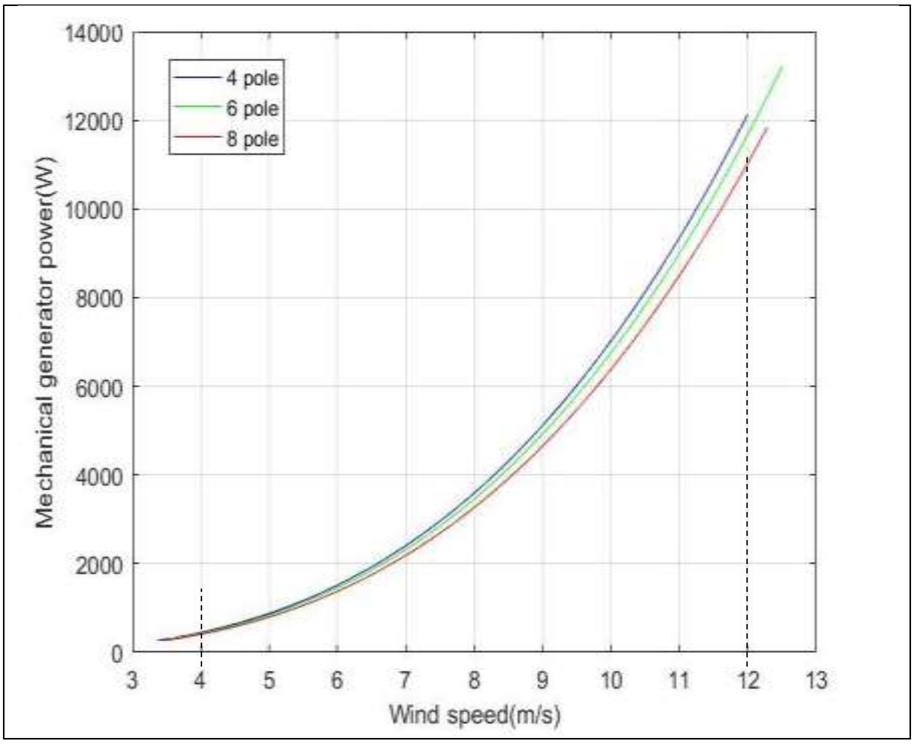

Fig. (19). Variation of input mechanical power to the generator with wind stream speed when feeding dynamic load for various pole settings

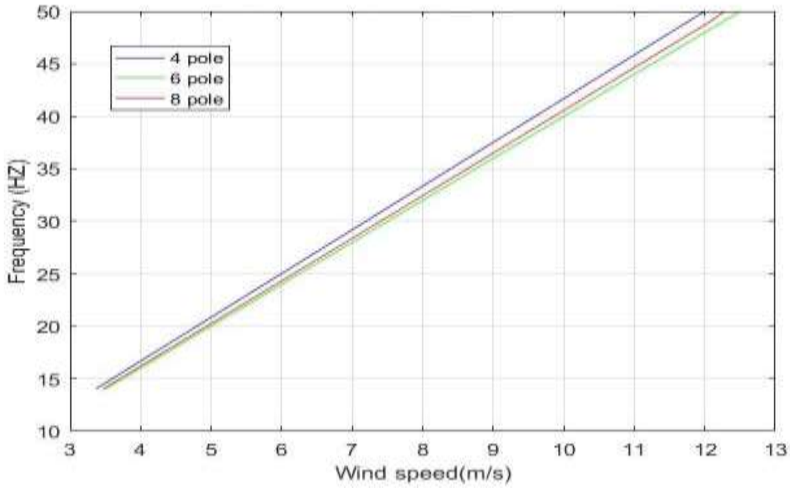

Fig. (20). Frequency for the different number of poles versus wind speed in case of dynamic load

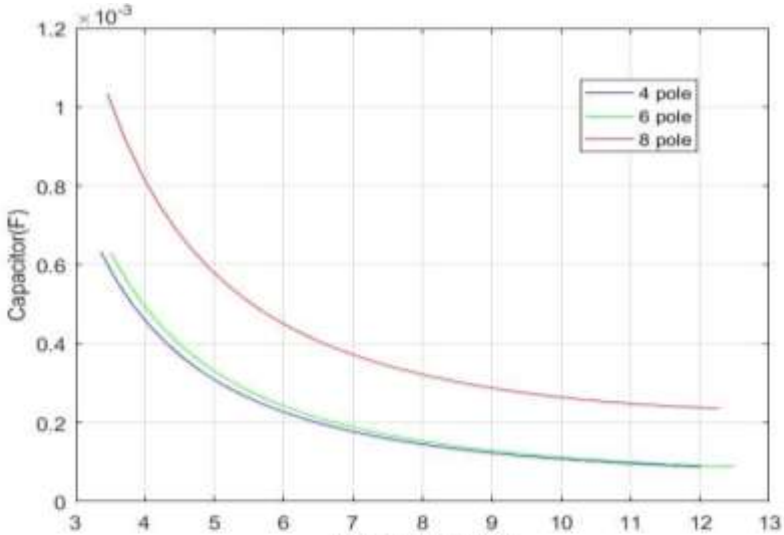

Fig. (21). Capacitor size for the different number of poles versus wind speed in case of dynamic load

The terminal voltage has been controlled through the variation of the capacitor size such that V/f is nearly kept constant (Figs. 20 and 22). This guarantees good performance of both the generator and motor as it results in constant magetic loading.

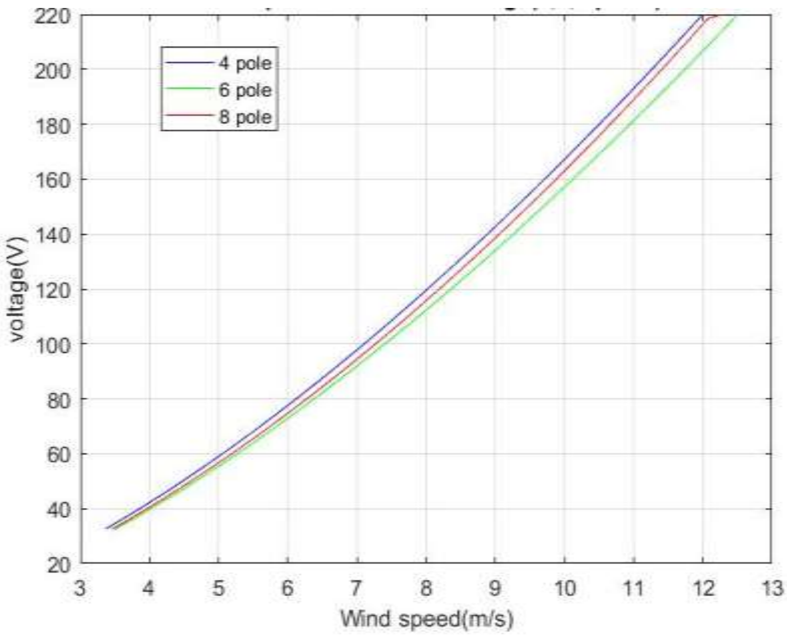

Fig. (22). Variation of the terminal voltage with wind stream speed when feeding dynamic load for various pole settings

The output electrical power changes slightly as the number of poles changes (Fig.23). The variation of the output current with the wind speed for the three sets of poles is shown in Fig. 24.

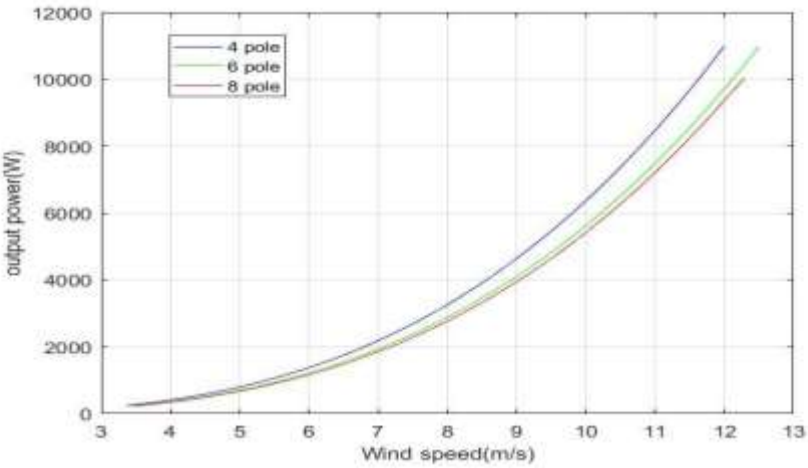

Fig. (23). Output electrical power for the different number of poles versus wind speed in case of dynamic load

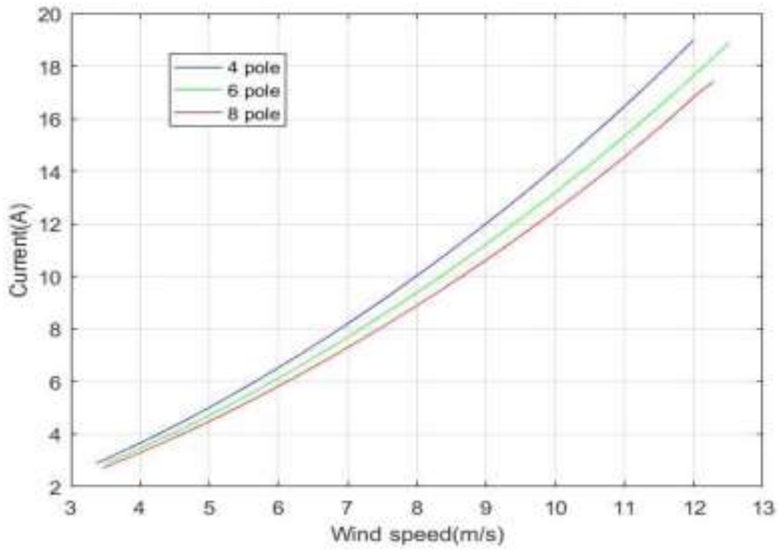

Fig. (24). Generator current for the different number of poles versus wind speed in case of dynamic load

6.2.1 Control Protocol

If the load is dynamic, the number of generator magnetic poles should be kept at 4 poles at different wind speed, because it gives the highest possible power and less capacitor size.

Ac voltage controllers [10] can be used in future work to control the load voltage more flexibly, as have been sometimes employed in case of grid-linked generators [11]. In general, adjusting the capacitor size and changing the number of magnetic poles enables operation too close to that obtained with the costly one when converter-inverter sets are used in the stator side [12] or when the generator employing double circuit with permanent magnet pole modulation [13] is used.

7. Conclusion

The paper suggests a novel method for controlling a wind-driven self-excited cage induction generator through changing the number of poles employing the pole amplitude modulation along with variation of the shunt capacitor. The control technique has been applied to different type of loads, namely; static and dynamic loads. The input power of the generator could be maximized at each wind speed by controlling the frequency through the variation of the capacitor size. In case of static load, pole control is used to adjust the load voltage to satisfy the load requirements. When the induction generator is loaded by an induction motor as a dynamic load, constant number of magnetic poles is recommended, and change of the capacitor size is enough to control the generator such that the power extracted is maximized, and at the same time the constant voltage to frequency ratio which indicates good performance for the generator and motor is realized.

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Appendices

Appendix 1: The Generator Data

3-phase, 12.2 kVA, 380 V, 50 Hz, Y/Y/Δ, 18.44/14.98/13.68 A, 4/6/8 pole amplitude modulated cage induction generator. The parameters are as follows:

Parameters	**4 poles**	**6 poles**	**8 poles**
R_{1g}, Ω	0.47	1.034	1.504
R_{2g}, Ω	0.47	0.972	1.361
X_{1g}& X_{2g} Ω	0.86	0.7568	0.86
Rc, Ω	500	409.07	522.710

$X_{\Phi g}$ depends on the number of poles [3], and due to the magnetic nonlinearity, $L_{\Phi g}$ is calculated using curve fitting [2] for each number of poles as follows for 4 poles:

$L_{\Phi g}$= - .00039 $(Vt/f)^5$ + .0056 $(Vt/f)^4$ - .027 $(Vt/f)^3$ + .04 $(Vt/f)^2$ - .038 (Vt/f) + .34

Similar formulae are used for 6 and 8 poles with different coefficients. Finally, $X_{\Phi g}$ is calculated as usual using

$X_{\Phi g} = 2\pi f\, L_{\Phi g}$

The driving wind-turbine is a 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 Fig. 3.

Appendix 2. The Load Data

Static load impedance; Z_L, is 9.8969 + j 6.1335 ohm at 50 Hz.

Dynamic load consists of 3-phase induction motor driving a pump load. The data and equivalent circuit parameters of the motor are as follows:

13.4 Hp, 380 V, 50 Hz, 6-Pole, Y-connected induction motor has the following parameters in ohm; $R_{1m} = R_{2m} = 0.47$, $X_{1m} = X_{2m} = 0.86$, $X_{Øm} = 30$, $R_{cm} = 210$.

The pump Hp is 13.4 Hp at the motor rated speed. Pump-torque constant (C_{pp}) = 0.005577 N.m.sec^2.rad^{-2}.

أداء مولد حث قفصي ذي سعة أقطاب محورة ذاتي الإثارة ومدار بطاقة الرياح

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ملخص البحث. طاقة الرياح المتجددة تشهد زيادة عالمية سريعة لتوليد الطاقة الكهربائية، وذلك كبديل للوقود الأحفوري القابل للنفاذ والملوث للبيئة. يشيع استخدام مولدات الحث لتحويل الطاقة الميكانيكية لتوربينات الرياح إلى طاقة كهربائية، وتستخدم عديد من تقنيات التحكم لتعقب نقاط أقصى طاقة رياح. ويهدف البحث الحالي إلى تحسين أداء مولد الحث القفصي ذاتي الإثارة المدار بطاقة الرياح وذلك بتغيير عدد أقطاب المولد وضبط قيمة مكثف الإثارة. وتهدف تقنية التحكم المقترحة إلى تعقب أقصى طاقة للرياح وتحسين أداء المولد عند تغذيته للأحمال الاستاتيكية والأحمال الديناميكية. وتم تقديم نموذج رياضي متكامل وخوارزميات حساب للأداء، تم تطبيقها وأسفرت عن بروتوكول تحكم للحصول على أفضل أداء عند السرعات المختلفة للرياح.

سفر الطريقة المقدمة عن طريقة رخيصة للتحكم في مولدات الحث لتوليد الطاقة الكهربائية، وذلك لتطبيقها في الأماكن البعيدة حيث لا تتوفرشبكة كهربائية، ويكون مولد الحث ذاتي الإثارة هو الحل الأنجع.