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Enhancing the Performance of a Stator and Rotor Combined-Controlled Wind-Driven Induction Generator

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Abstract. All experts have expected the rapid exhaust of the conventional energy resources. Therefore, the utilization of wind energy is very important and finds nowadays great interest. The present research Paper aims at enhancing the performance of wind-driven induction generators at the different expected wind speeds employing control techniques from both the stator side and the rotor side. The control from the stator is done via cycloconverter, while the control from the rotor side is done through the simple method of adding resistances in the rotor circuit.

The combined-controlled induction generator has been modelled at steady-state conditions using frequency domain equivalent circuit. Computer-programs have been developed to compute the performance characteristics of the combined-controlled induction generator (CCIG) and the uncontrolled induction generator (UCIG). The computed performance characteristics of the combined-controlled induction generator and the uncontrolled induction generator have revealed that the control of the induction generator through the stator cycloconverter and the rotor added-resistance has enabled capturing more energy from the wind.

Keywords: Wind-driven induction generator, Solid-state controlled induction generator, Cycloconverters, Grid-connected induction generator.

List of Symbols:

C_T, C_Q and C_P	: Thrust, torque and power coefficients, respectively
I	: Current, A
L	: Inductance, H
F_T	: Thrust force, newton
S	: p.u slip
T	: Torque, N.m
V_1 and E_1	: Applied and induced stator voltage, respectively

V	: Wind speed, m/s
P_r	: Wind-turbine power, W
P_V	: The power in the wind passing through an area with speed V, watts
R_1, R_2, R_c	: Stator, rotor and core resistances respectively, ohm
R	: Turbine blades radius, m
X_1, X_2 and X_m	: Stator, rotor and excitation reactances respectively, ohm
β	: Pitch angle
λ	: Tip-speed ratio
ρ	: Air density, kg/m^3
Ω_r	: Mechanical angular speed of the turbine, rad/s

1. Introduction

The utilization of wind energy is very important and finds nowadays great interest. This interest has become vital as all experts have expected the rapid exhaust of the conventional energy resources. Therefore, generation of electrical energy from the renewable wind energy has found increasing applications.

Use of wind-turbines as prime movers has the problem of being of variable and unexpected velocities. As the frequency of the generated voltage of the synchronous generators is tied to the prime mover speed there is need to other generator types or unconventional solutions. Use of induction generators may solve the problem of the variable speed turbine as the frequency of the generated voltage of the induction generator is not tied to the prime-mover speed, but it always matches the frequency of the network to which the generator is connected [1-3].

Many research works investigating the performance of grid-connected induction generator with solid state control has been performed. Abdel-halim[4] and others [5-7] presented an analysis of the performance of induction generators connected to the network through different ac voltage controllers. Complete electrical performance characteristics have been presented. Other authors [8-14] analyzed the performance of the doubly-fed induction generators. Holdworth *et al.* [10] have presented a comparison between fixed-speed induction- generators (FSIG) and variable speed doubly-fed induction generators (DFIG). They showed that the FSIG during short circuits induces voltage sags at the terminal busbars which may cause voltage instability, while the DFIG improves the terminal bus voltage profiles thus increasing the stability margins. Fernandez *et al.* [11] developed a new way of aggregation of

DFIGs under different wind speeds by an equivalent wind turbine to approximate the active and reactive powers of aggregated wind turbines. This technique is useful in modeling wind farms with high number of wind turbines as it reduces the model order, and consequently the simulation time. de Almeidam and Pecas Lopes [12] developed a control approach to provide a frequency regulation capability integrated into a DFIG active power control loop using the frequency deviation. Such an approach could contribute to enhancing the system robustness, reducing frequency changes associated with disturbances. Shaltout and El-Ramahi [13] proposed a simple control strategy of DFIG to trace the maximum power available at different wind speeds. This strategy is based on controlling the slip power through a rotor rectifier-inverter set. Abdel-halim and Almarshoud [14] proposed a technique for the rotor injected voltage such that the wind turbine traces the maximum wind energy, and at the same time the generator current is kept at unity power factor.

Boumassata, *et al.* [15] proposed a system constituting of a DFIG with the stator connected directly to the grid while the rotor is supplied by a three phase cycloconverter. The performance of the system was with a control aiming at improving the maximum power point tracking. The control was independent of the active and reactive powers using stator-flux oriented control technique. Devabhaktuni, *et al.* [16] dealt with the stator flux oriented vector control of wind driven self-excited induction generator through the cycloconverter at the point of common coupling. The control strategy of supplying the firing pulses is based on the stator flux oriented vector control of self-excited induction generator.

The present paper aims at improving the performance of the induction generators at different expected wind speeds employing combined control techniques from both the stator side and the rotor side (CCIG). The control from the stator side will be done via cycloconverter, while the control from the rotor sides is done through the simple method of adding resistances in the rotor circuit. This work will add to the efforts made to develop usage of wind energy. The paper presents complete modelling of the CCIG, computes the performance characteristics, and compares the characteristics with those of the uncontrolled induction generator (UCIG).

2. System Description and Control Objectives

2.1 Induction Generator System

The system under study comprises a variable-speed induction generator linked to the grid through a cycloconverter in the stator side, while fine control may be achieved through added resistances in the rotor side (Fig. 1).

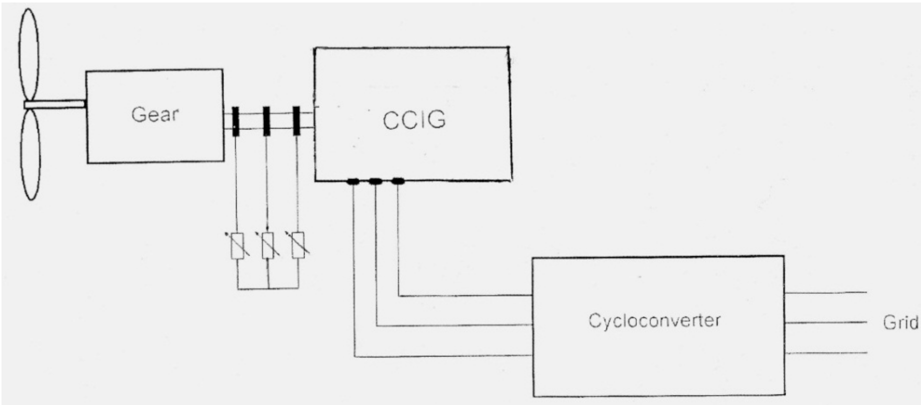

Fig. 1. Schematic diagram of the CCIG system.

2.2 Wind Energy and Wind Turbines

Wind turbines are mechanical devices specifically designed to convert part of the kinetic energy of the wind into useful mechanical energy. Depending on the position of the rotor axis, wind turbines are classified into vertical-axis and horizontal-axis ones [17]. Nowadays, almost all commercial wind turbines connected to grid have horizontal-axis two-bladed or three-bladed rotors.

Commonly, thrust force, torque and power are expressed in terms of non-dimensional thrust (C_T), torque (C_Q) and power (C_P) coefficients as follows [18, 19].

$$F_T = \frac{1}{2}\rho\pi R^2 C_T(\lambda,\beta)V^2, \tag{2.1}$$

$$T_r = \frac{1}{2}\rho\pi R^3 C_Q(\lambda,\beta)V^2, \tag{2.2}$$

$$P_r = C_P(\lambda,\beta)P_V = \frac{1}{2}\rho\pi R^2 C_P(\lambda,\beta)V^3, \tag{2.3}$$

$$C_Q = C_P/\lambda. \tag{2.4}$$

Note that the three coefficients are written in terms of the pitch angle and the so-called tip-speed-ratio; λ, defined as

$$\lambda = \frac{\Omega_r R}{V}. \tag{2.5}$$

Figure 2 shows typical variations of C_Q and C_p for a fixed-pitch wind turbine [16, 17].

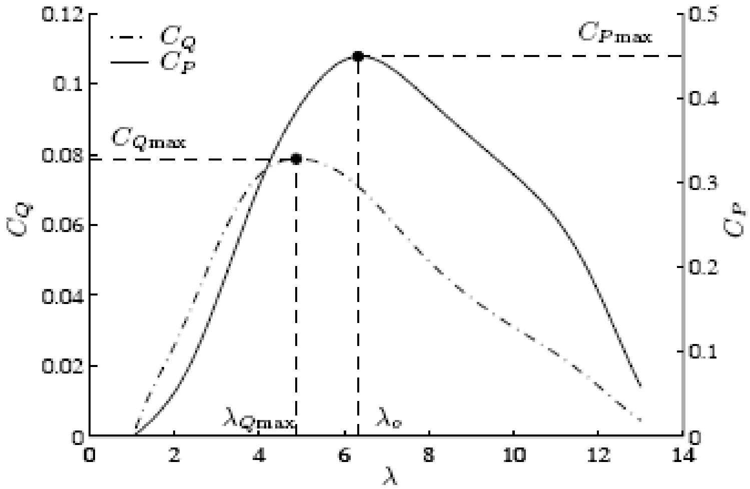

Fig. 2. Typical variations of (a) C_Q and (b) C_P for a fixed-pitch wind turbine.

2.3. Control Strategy

The system under study enables either control from the stator cycloconverter only (SCIG) or combined control from the stator side through the cycloconverter in addition to adding resistances in the rotor side when necessary. The objective of the control strategy is to regulate the speed of the generator to force the turbine to operate as follows:

At high wind speeds, the turbine is operated such that the generator works slightly higher than its nominal speed. In this case, the power extracted will be maximum at a certain wind speed (power base speed), and not over the whole range. At the power base wind speed, the output frequency of the cycloconverter is adjusted to be the nominal generator frequency. As the wind speed increases above the power base speed the frequency is kept constant at the rated value. The power extracted from the wind is not the available maximum power. At a certain wind speed higher than the power base speed, it happens that the torque extracted from the wind becomes the maximum available torque. This speed will be called the torque base speed (V_{wQ}). As the wind speed exceeds the torque base speed, resistances may be added to the rotor of the generator to keep tracing the available maximum torque.

i- As the wind speed decreases below the power base speed, the frequency is kept at its rated value. This is the case until the wind speed reaches a value such that the torque extracted from the wind at generator-speed near the nominal speed becomes half or less than the maximum torque that can be extracted from the wind, the output frequency of the cycloconverter is adjusted to be half the generator nominal frequency. Rotor resistances may be added over the range starting from the wind speed of frequency switching down to a torque sub-base speed. At this speed the torque extracted is the maximum available torque without added rotor resistance. At wind speeds lower than the torque sub-base wind speed, operation continues at half the rated frequency without added resistances.

ii- When the wind speed gets lower such that the torque extracted from the wind at generator speed near half the nominal value becomes two-thirds the possible maximum extracted torque value, the output frequency of the cycloconverter is adjusted to be one-third the generator nominal frequency. The control strategy followed at lower wind speed is similar, then, to that followed before.

3. Steady-State Modelling

3.1 Circuit Model

Figure 3 shows a frequency-domain per-phase circuit model of the 3-phase combined-controlled induction generator [3]. The generator is linked to the grid through a cycloconverter, with a possible-rotor added resistance.

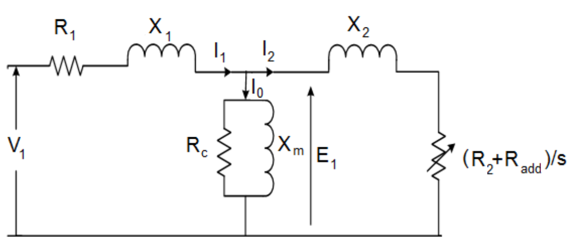

Fig. 3. Per-phase equivalent circuit of the combined-controlled induction generator.

R_{add} represents the possible added rotor resistance. X_1, X_2 and X_m are functions of the output frequency of the cycloconverter and are given by:

$$X = \frac{\omega_o}{n} L$$

where, ω_o is the generator rated angular frequency which is the input frequency to the cycloconverter, and n takes the values 1, 2, 3, .. to determine the cycloconverter output frequency ω_o/n.

For constant flux operation the output voltage of the cycloconverter is adjusted to keep constant voltage to frequency ratio. Thus, V_1 is given by V_r/n.

3.2 Mathematical Model

The iduced torque of the induction generator is related to applied voltage, slip and the equivalent circuit parameters as follows [3]:

$$\tau = \frac{3\, V_T^2\, R_{2a}/S}{\omega_s[(R_T + R_{2a}/S)^2 + (X_T + X_2)^2]} \qquad (3.1)$$

where R_{2a} is the total rotor resistance; $R_{2a} = R_2 + R_{add}$, V_T, R_T and X_T are the Thevenin's equivalent circuit parameters of the stator. Neglecting R_c, these are given by

$$V_T = \frac{V_1 X_m}{\sqrt{{R_1}^2 + (X_1 + X_m)^2}} \qquad (3.2)$$

$$R_T + jX_T = (R_1 + jX_1)//\, jX_m \qquad (3.3)$$

In case of adding resistances in the rotor circuit, the speed of the generator and hence its slip is related to the wind speed such that the tip speed ratio; λ, corresponds to the maximum torque coefficient; $C_{Qmax.}$ This means that

$$n_a/n_{so} \cong V_w/V_{wQ} \qquad (3.4)$$

The output current, active power, reactive power at a specified slip; S, and terminal voltage; V_1, can be determined as usually done for the ac circuit analysis using the equivalent circuit.

4. Results

The mathematical model given in Section 3 has been used to develop an M code program to enable the computation of the uncontrolled and the controlled induction generator performance characteristics. The program has been used to compute the characteristics of an induction generator having the parameters given in Tables 1 and 2 [14, 18]. The generator performance characteristics have been determined over a wind-range of wind speed (2 m/s up to 10 m/s).

Table 1. Main Characteristics of the Generator.

Nominal stator active power	2.5 MW
Nominal torque	15915 Nm
Nominal stator voltage, V_r	690 V
Nominal stator current	2330 A
Nominal rotor current	2459 A
Nominal speed	1500 rpm
Speed range	900–2000 rpm
Pole pairs	2

Table 2. Equivalent Model of the Generator.

Magnetizing inductance; Lm	2.3 mH
Rotor leakage inductance; L_2	0.085 mH
Stator leakage inductance; L_1	0.085 mH
Rotor resistance; R_2	0.022 ohm
Stator resistance; R_1	0.024 ohm

To evaluate the performance characteristics of the controlled induction generator, it will be helpful to compare it with the uncontrolled one. At a base wind speed (6.5 m/s in our case), the turbine extracts the maximum power from the wind, while the generator is normally driven without any control. λ (the tip speed ratio) at this wind speed corresponds to the maximum power coefficient ($C_{pmax.}$). From the typical turbine curve, λ and C_{pmax} are found to be 0.63 and 0.455, respectively. The wind extracted power at this base wind speed is found to be 1.1 MW. This meant that at the highest expected wind-speed (10 m/sec in our case), the wind extracted power will be limited at the most to about 2.5 MW. Thus, the turbine and the generator will not be over-loaded. The performance characteristics for the uncontrolled induction generator (UCIG) are, then, determined using the following algorithm:

a – The calculations started from the highest assumed wind speed going down in steps

b – λ is calculated assuming that the generator runs at a speed slightly higher than the rated synchronous speed. C_Q is then obtained from the typical turbine curves. The induced torque is calculated at each wind speed using Eq. 2.2.

c – Once the torque is calculated, the slip is calculated using Eq. 3.1.

d – The output current, power factor, active power, reactive power and the efficiency are then calculated using the equivalent circuit (Fig. 3).

The algorithm used for the stator-cycloconverter controlled induction generator (SCIG) is similar to that for the UCIG except that while the wind speed goes down, we keep watching C_Q, and once it happens that C_Q becomes half its maximum value (C_{Qmax}), the input frequency and voltage applied to the generator by the cycloconverter are halved. The tip speed ratio (λ) is recalculated to correspond to half the rated synchronous speed. The calculations of C_Q and the induced torque continue as before until C_Q reaches two-thirds the maximum value. Then, the frequency and voltage applied to the generator are changed to one-third the rated value. Then after, the calculations continue, and the frequency is reduced again, and so on until the lowest wind speed is reached.

The algorithm used for the combined controlled induction generator (CCIG) is similar to that of the SCIG except that at wind speeds higher than the torque base speed at the nominal frequency or the torque sub-base speed at the other frequencies, the extracted wind torque is assumed to be the maximum available value. This is achieved through adding resistances in the rotor circuit. The slip at these wind speeds is calculated such that it realizes the tip speed ratio that gives maximum extracted torque using Eq. 3.4. The performance characteristics of the UCIG, SCIG and the CCIG are shown in Fig. 4-16.

Comparing the performance characteristics of the UCIG and the CCIG reveals the following:

i- The power factor curves for the UCIG and the SCIG (Fig. 4 & 5) show that the power factor is enhanced by controlling the frequency such that when the frequency is changed at low wind speeds to 25 Hz, the power factor is improved and approximately ranges from 0.62 to 0.25 instead of approximately 0.45 to 0.02 at 50 Hz. When the frequency is changed to 16.67 (50/3) Hz at lower wind speed, the power factor is improved, and approximately ranges from 0.3 to 0.22 instead of approximately 0.02 to about 0.01 at 50 Hz. The effect of adding resistance on the power factor is negligible.

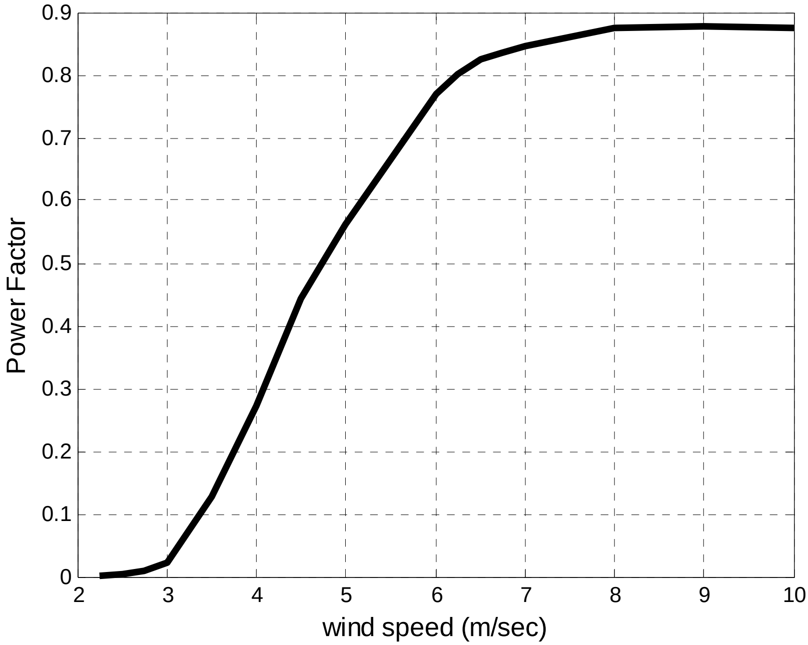

Fig. 4. Power factor versus the wind speed for UCIG.

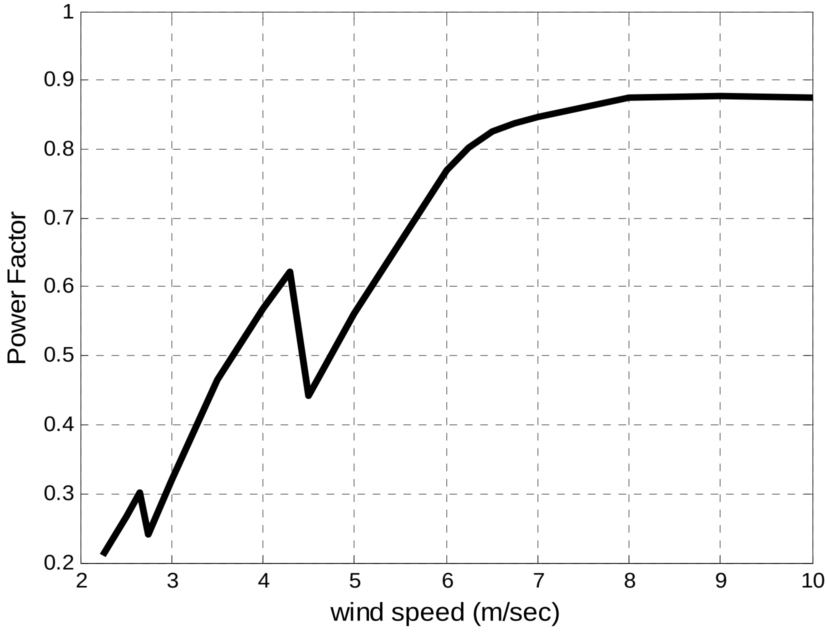

Fig. 5. Power factor versus the wind speed for SCIG.

(f=50 Hz for $V \geq 4.5$ m/s, f=50/2 Hz for 4.5 m/s $> V >$ 2.74 m/s, f=50/3 for $V \leq 2.74$ m/s)

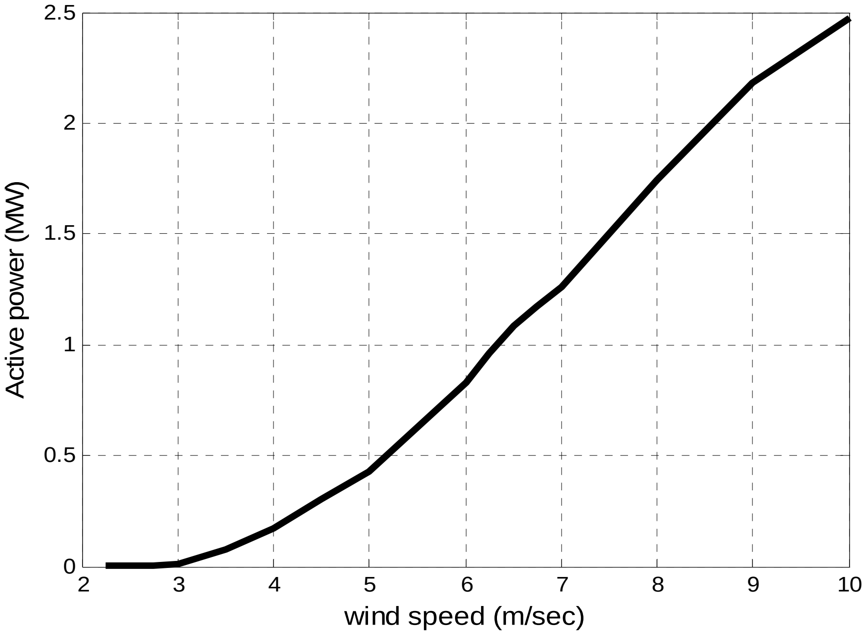

Fig. 6. Active power versus the wind speed for UCIG.

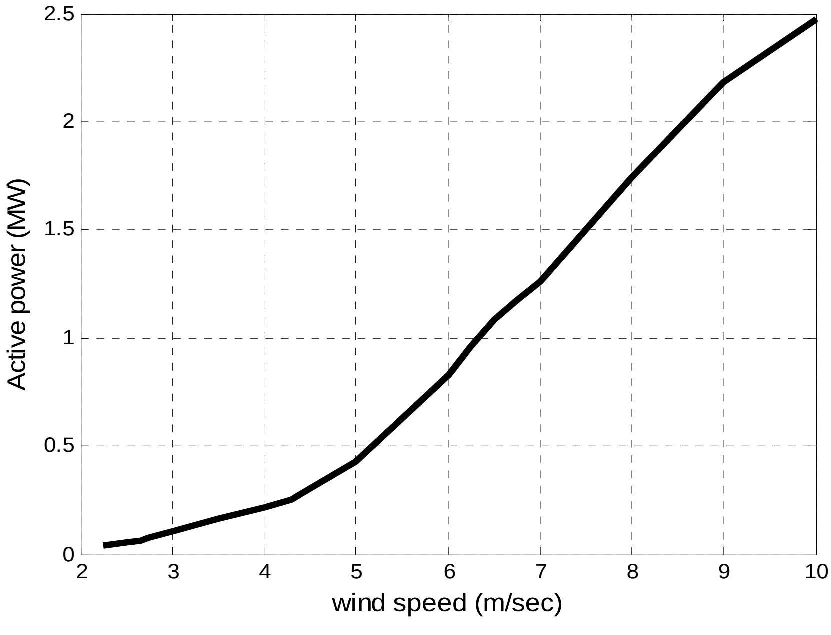

Fig. 7.Active power versus the wind speed for SCIG.

(f=50 Hz for $V \geq 4.5$ m/s, f=50/2 Hz for 4.5 m/s > V > 2.74 m/s, f=50/3 for $V \leq 2.74$ m/s)

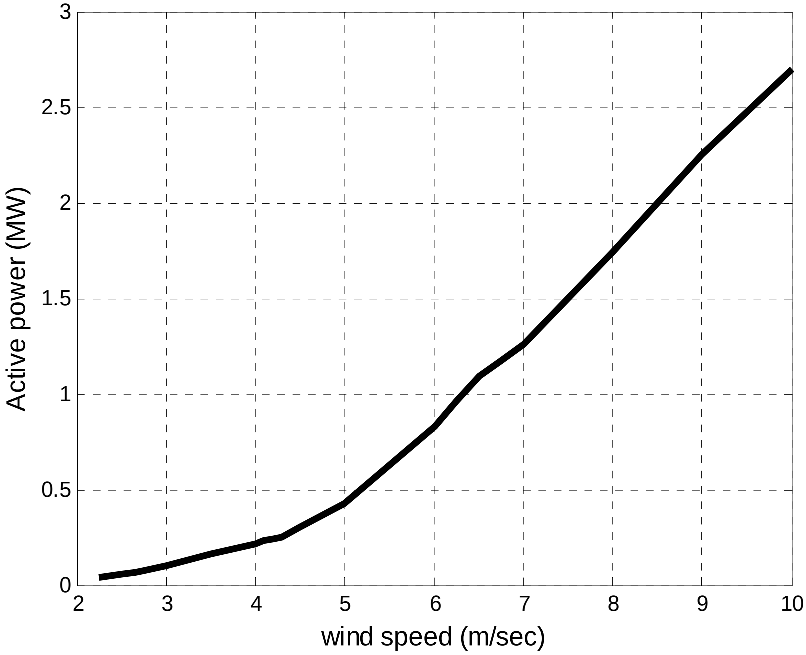

Fig. 8. Active power versus the wind speed for CCIG.

(f=50 Hz for $V \geq 4.5$ m/s, f=50/2 Hz for 4.5 m/s > V > 2.74 m/s, f=50/3 for $V \leq 2.74$ m/s)

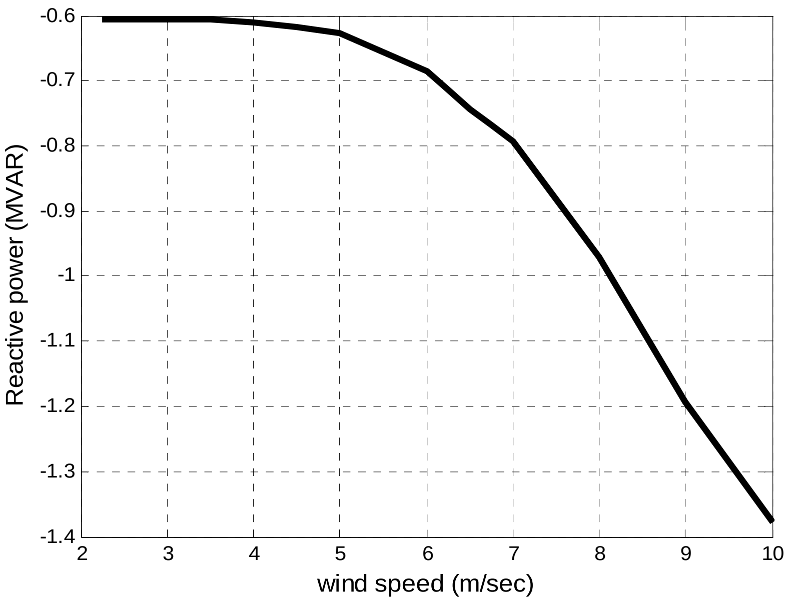

Fig. 9. Reactive power versus the wind speed for UCIG.

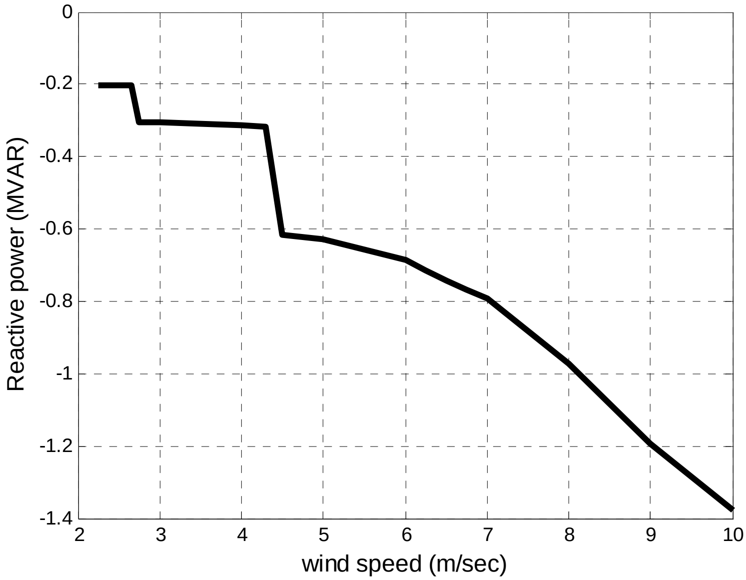

Fig. 10. Reactive power versus the wind speed for SCIG.

(f=50 Hz for $V \geq 4.5$ m/s, f=50/2 Hz for 4.5 m/s > V > 2.74 m/s, f=50/3 for $V \leq 2.74$ m/s)

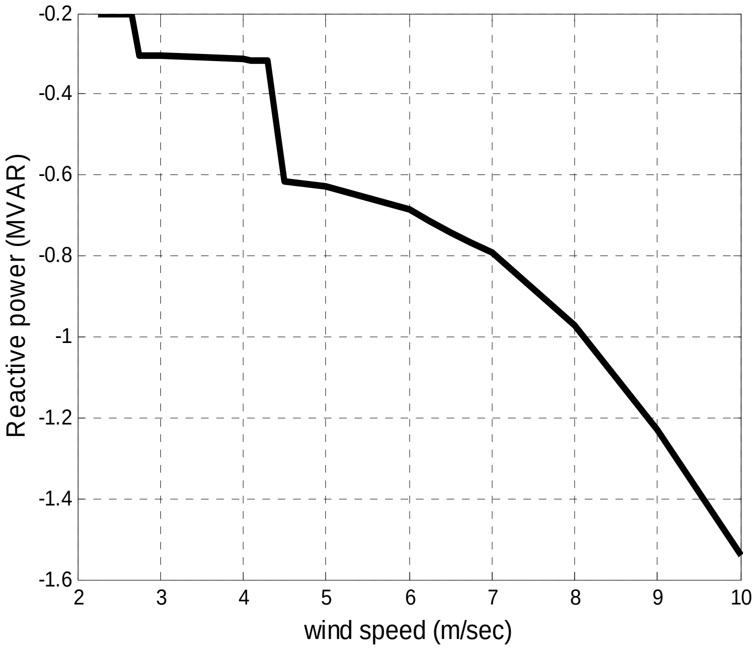

Fig. 11. Reactive power versus the wind speed for CCIG.

(f=50 Hz for $V \geq 4.5$ m/s, f=50/2 Hz for 4.5 m/s > V > 2.74 m/s, f=50/3 for $V \leq 2.74$ m/s)

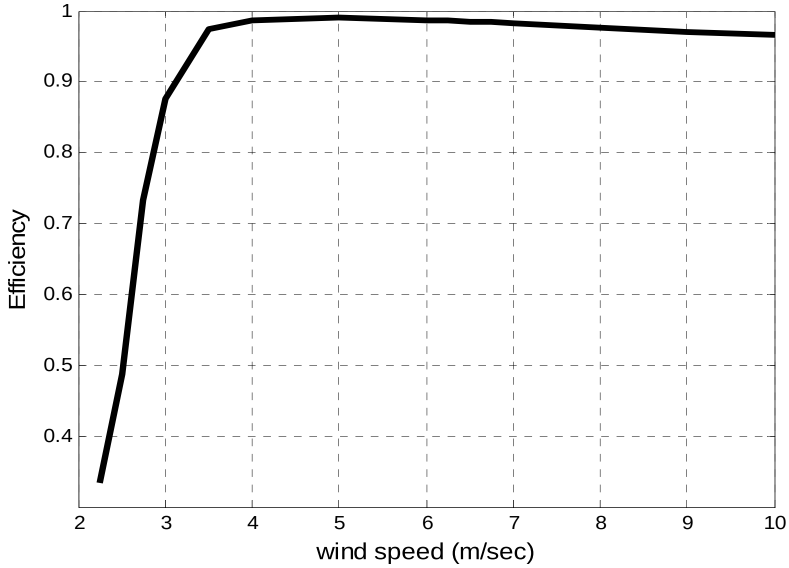

Fig. 12. The generator efficiency versus the wind speed for UCIG.

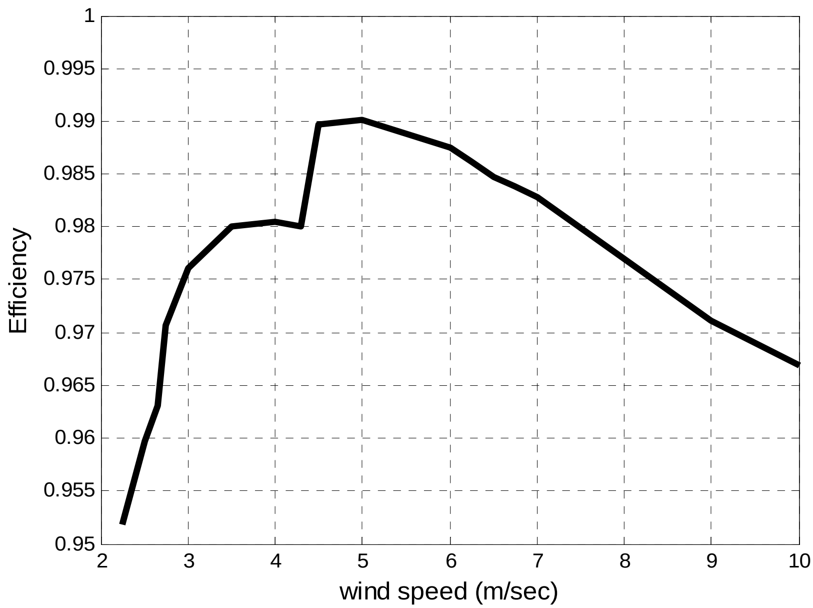

Fig. 13. The generator efficiency versus the wind speed for SCIG.

(f=50 Hz for $V \geq 4.5$ m/s, f=50/2 Hz for 4.5 m/s $> V > 2.74$ m/s, f=50/3 for $V \leq 2.74$ m/s)

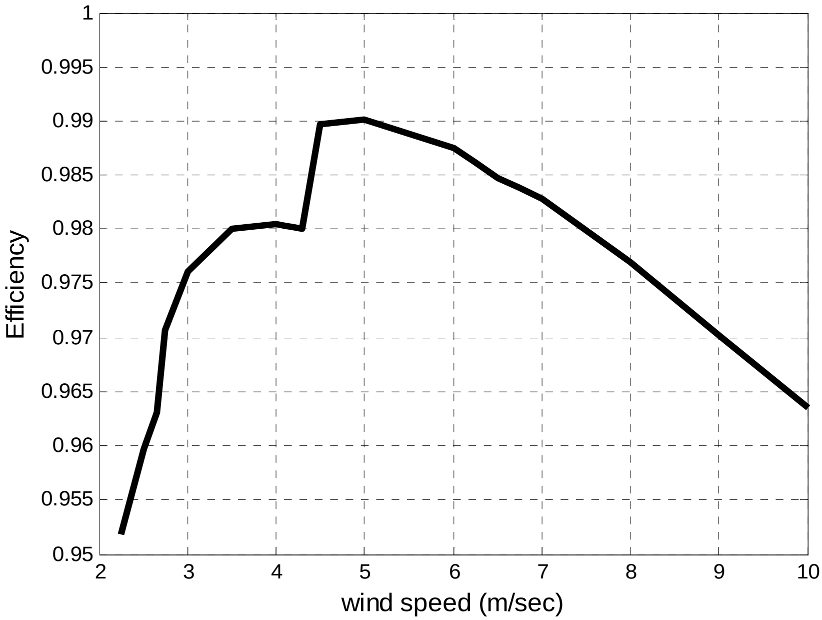

Fig. 14. The generator efficiency versus the wind speed for CCIG.

(f=50 Hz for $V \geq 4.5$ m/s, f=50/2 Hz for 4.5 m/s > V > 2.74 m/s, f=50/3 for $V \leq 2.74$ m/s)

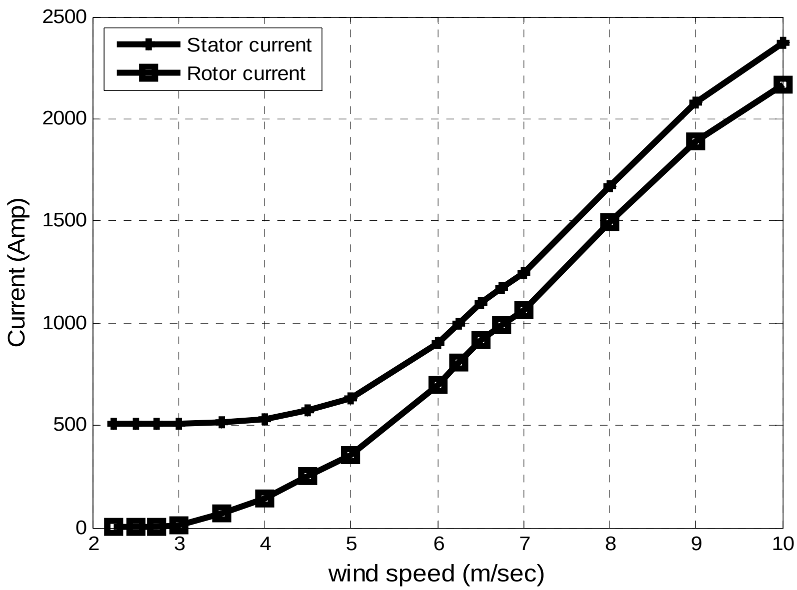

Fig. 15. Terminal current versus the wind speed for UCIG.

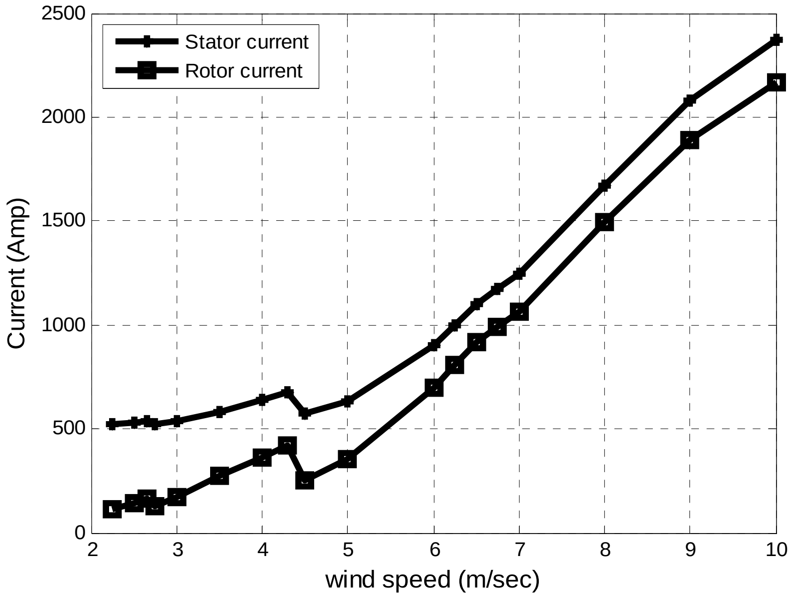

Fig. 16. Terminal current versus the wind speed for SCIG.

(f=50 Hz for $V \geq 4.5$ m/s, f=50/2 Hz for 4.5 m/s > V > 2.74 m/s, f=50/3 for $V \leq 2.74$ m/s)

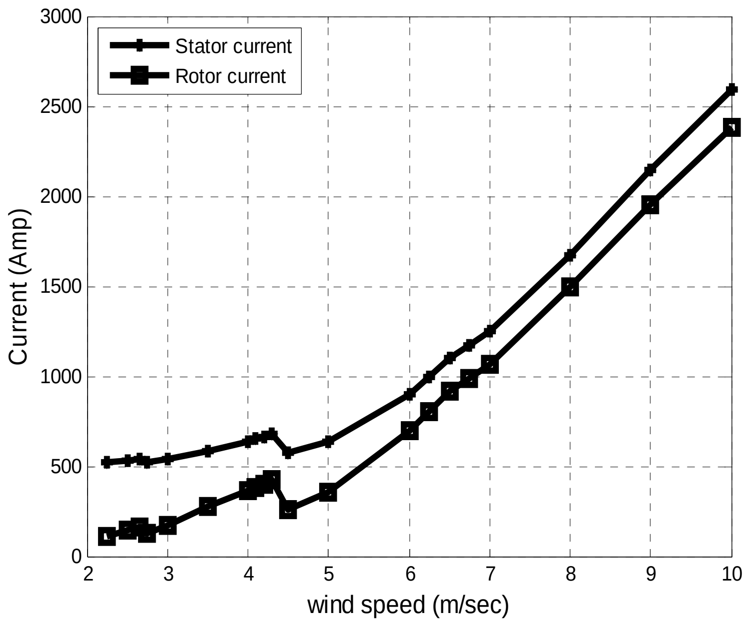

Fig. 17. Terminal current versus the wind speed for CCIG.

(f=50 Hz for $V \geq 4.5$ m/s, f=50/2 Hz for 4.5 m/s > V > 2.74 m/s, f=50/3 for $V \leq 2.74$ m/s)

ii- The output active power is increased when the frequency is changed to 25 Hz at low wind speeds such that it ranges from 0.25 MW to 0.1 MW, while the range was about 0.26 MW to 0.07 MW at 50 Hz. At lower wind speeds the output active power nearly vanishes if the frequency is kept at 50 Hz, while by changing the frequency to 16.67 (50/3) Hz, the output power ranges from about 0.1 MW to about 0.08 MW (Fig. 6 & 7). Again the effect of adding resistances in the rotor is negligible at 25 Hz and lower frequencies, while it gives noticeable effect at 50 Hz at high wind speeds. For example, the active power increases from about 2.45 MW to about 2.75 MW at wind speed of 10 m/s (Fig. 7 & 8).

iii- The reactive power consumed by the generator is decreased by halving the frequency to nearly half its value at 50 Hz, and it is again decreased to one-third its value at 50 Hz (Fig. 9 and 10). Adding resistances in the rotor increases the consumed reactive power by about 10% (Fig. 10 & 11).

iv- The generator efficiency drops as the frequency is lowered by the cycloconverter (Fig. 12 & 13). However, this is unimportant as irrespective of the decreased efficiency the output power increases due to the increase of the captured mechanical power. Adding resistances in the rotor circuit somewhat reduces the generator efficiency (Fig. 14).

v- The terminal current jumps when the frequency and the voltage is lowered (Fig. 15 & 16). Adding resistances has little effect at low frequency, however, it increases the current at high wind speed when the generator works at its nominal frequency (Fig. 15 & 17).

In the case of CCIG, the calculated values of the added resistance in each rotor phase is given in Table 3.

Table 3. Values of the added resistances in the rotor.

Wind speed, m/s	10	9.0	8.0	7.0	6.75	6.5	6.25	6	5	4.5
Frequency, Hz	50	50	50	50	50	50	50	50	50	50
R_a/phase, ohm	0.2822	0.1669	0	0	0	0	0	0	0	0
Wind speed, m/s	4.3	4.2	4.1	4.0	3.5	3.0	2.74	2.67	2.5	2.25
Frequency, Hz	25	25	25	25	25	25	25	50/3	50/3	50/3
R_a/phase, ohm	0.2476	0.1664	0.0769	0	0	0	0	0	0	0

5. Conclusion

The present paper aimes at optimizing the performance of a wind-driven induction generator at different expected wind speeds employing control techniques from both the stator side and the rotor side. The control from the stator is done via cycloconverter, while the control from the rotor side is done through the simple method of adding resistances in the rotor circuit. The combined-controlled induction generator has been modelled at steady-state conditions using frequency domain equivalent circuit. Computer-programs have been developed to compute the performance characteristics of the combined-controlled induction generator (CCIG) and the uncontrolled induction generator (UCIG). Comparing the performance characteristics of the UCIG and the SCIG reveals the following:

i- The power factor is enhanced by controlling the frequency at low wind speeds.

ii- The output active power is increased when the frequency is lowered at low wind speeds.

iii- The reactive power consumed by the induction generator almost decreases in proportion to the frequency of the generator applied frequency.

iv- The generator efficiency drops as the frequency is lowered by the cycloconverter. However, this is unimportant as irrespective of the decreased efficiency, the output power increases due to the increase of the captured mechanical power.

Adding rotor resistances has negligible effect at low wind speed. The effect at high wind speeds appears on the delivered active power which somewhat increases, and on the consumed reactive power which somewhat increases. The power factor is almost unaffected.

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تحسين أداء مولد الحث ذي التحكم المزدوج من جهتي العضو الثابت والعضو الدوار

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المستخلص. توقع كل الخبراء النفاد السريع لمصادر الطاقة التقليدية، ولذا كان استخدام طاقة الرياح هذه الأيام من الأهمية بمكان، ويهدف البحث الحالي إلى تحسين أداء المولدات الحثية والمدارة بطاقة الرياح، وذلك عند سرعات الرياح المختلفة والمتوقعة باستخدام تقنية تحكم من جهتي العضو الثابت والعضو الدوار. ويتم التحكم من جهة العضو الثابت من خلال مغير تردد الدوار، بينما يتم التحكم من جهة العضو الدوار من خلال إضافة مقاومات.

ولقد تم تمثيل مولد الحث ذي التحكم المزدوج في حالة الاستقرار باستخدام دائرة مكافئة في نطاق التردد، وتم تطوير برامج لحساب خواص الأداء للمولد ذي التحكم المزدوج وأيضا مولد الحث غير المحكوم. لقد بينت خواص الأداء هذه أن التحكم في المولدات الحثية عن طريق مغير التردد من جهة العضو الثابت وإضافة مقاومة إلى العضو الدوار قد مكننا من استخلاص المزيد من طاقة الرياح.