

WECS Based Self-Excited Squirrel-Cage Induction Generator with Reduced Voltage Source Inverter Rating

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Abstract

This paper presents the regulation of the voltage and frequency of a stand-alone fixed-pitch wind energy conversion system (WECS) based on a self-excited squirrel-cage induction machine. A shunt connected voltage source inverter (VSI) and a controllable dump load are used for regulation purposes. A battery bank is included in the dc side of the VSI so that it can absorb and inject active power thus increasing the efficiency and availability of the system. A control scheme for the VSI with self-governing control of real and reactive power allows the state of charge of the batteries to be kept in a safe range while maximizing the voltage regulating capabilities of the VSI. The characteristics of the wind turbine, self-excited generator, and the ratings of the VSI are considered in order to find out the load range for which voltage and frequency can be regulated for a given wind speed range. The possibility of the proposed system is verified by MATLAB/SIMULINK. simulations.

Keywords: Frequency control, induction generator, load management, voltage control, wind power generation.

1. Introduction

Objective wind energy conversion systems (WECSs) are constructive for powering small villages placed far from the utility grid. The squirrel-cage induction machine is very gorgeous for small and medium power generation systems for the reason that of its low cost, robustness, and high-power density (W/kg). Nevertheless, the amplitude and frequency of the generated voltage depends upon the rotor speed, the quantity of excitation, and the load (amplitude and power factor). Objective operation of a squirrel-cage induction generator based WECS with regulated output voltage and frequency requires moreover an asynchronous link (ac-dc-ac) power electronic converter [1], [2] or a matrix converter. The main drawback of the former arises from the fact that the two series connected ac-dc converters have to be rated to at least rated generator power thus requiring 2 p.u of power from the static converters. A number of lower cost schemes with a single power electronic converter have been proposed in the literature. In [3], a series connected pulse width modulated (PWM) VSI with a battery bank is used to regulate voltage and frequency. However, this scheme presents low-frequency harmonic distortion for low values of rotor speeds. The concept of terminal impedance controller for self-excited induction generators (SEIG) was proposed in [4]. A shunt connected thyristor rectifier followed by a PWM switched resistor is controlled to pick up the active and reactive power not used by a variable load. In this way, the impedance seen by the self-excited induction generator is constant and load

variations would not affect the voltage and frequency.

Since the thyristor rectifier can only absorb real and reactive power, the excitation capacitor bank is relatively large and the efficiency of the system is low. Alternatively, one can use a shunt connected VSI with a capacitor and a switched resistor in the dc bus, as proposed in [5]. This provides a reference voltage and frequency for the induction generator as if it were a virtual utility grid, without any special control schemes. The converter automatically absorbs or generates reactive power to regulate the terminal voltage. However, it can only absorb active power as the terminal impedance controller in [4] does.

This paper presents the use of a reduced rating, less than that of the generator, shunt-connected VSI with a battery bank on the dc side to regulate the voltage and frequency of the generated voltage. The replacement of the resistor used in other schemes by a battery bank increases the efficiency of the system. Besides, the VSI can now also supply active power to the load when the power produced by the induction generator is insufficient, thus increasing the availability of the system. However, a more sophisticated control scheme for the VSI is required so that the state of charge of the battery can be maintained in a safe range without compromising the voltage regulating capabilities of the VSI. A dump load is included in the system to assist the VSI when there is a surplus of active power in the ac system, which cannot be absorbed by the VSI and battery bank. This paper also presents an approach for calculating the load range that can be supplied with regulated voltage and frequency when a VSI rated at a fraction of the induction generator is used as the main compensating device. Simulation results verify the analysis of the regulation limits of a reduce-rating VSI and the response of the system to load and wind-speed variations.

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2. Study of Proposed System

Fig. 1 shows the schematic diagram of the system under consideration. The wind turbine is connected to the rotor of the induction generator through a step-up gear box. At the stator side of the generator, there is an excitation capacitor bank in parallel with a dump load, the VSI, and the consumer load. The control scheme used for the VSI is shown in Fig. 2. It is similar to that described in [6], but the active power the VSI absorbs or injects depends on the frequency error instead of the dc bus voltage error. In our case, the VSI absorbs active power that is stored in the battery bank when the system's frequency is above the reference value. The phase controlled dump load is activated when the battery bank is fully charged or when the power flowing through the VSI exceeds its rated value. It picks up the active power that the VSI cannot absorb ($i_{DL}^* = i_q^* - i_{q-VSI}^*$). Conversely, the VSI injects active power when the system's frequency decreases due to a load increase or wind speed reduction.

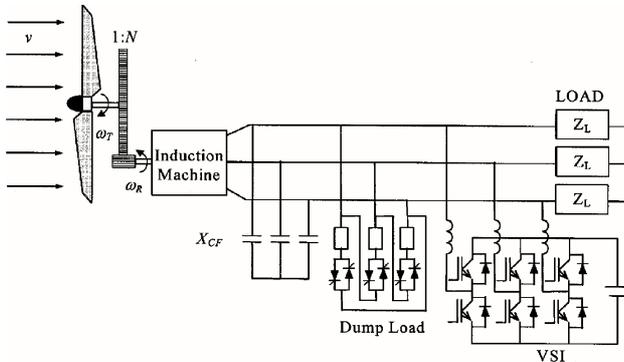


Fig. 1. The WECS regulated with a single static power converter.

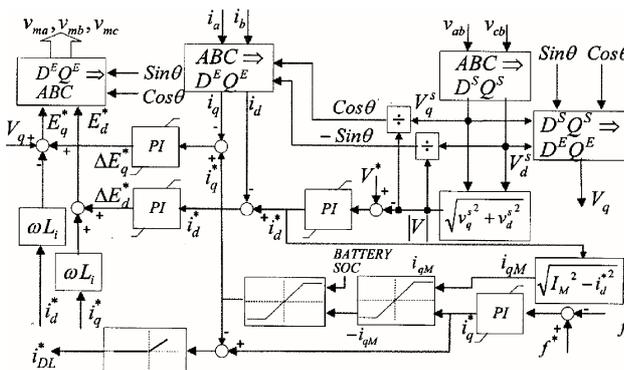


Fig. 2. Control block diagram of the proposed system

An approach for selecting the size of the excitation capacitor bank and dump load is presented in Section V. The ac inductor that connects the VSI to the induction generator is chosen so that it provides, along with the excitation capacitor, a low-pass filter for the current harmonics created by the VSI [5]. Tuned filters for the current harmonics of the dump load can be implemented by splitting the excitation capacitor bank and adding inductors in series. The size of the battery bank should be calculated according to the local wind speed and load profiles and desired reliability [7]. It should be noted that the size of the VSI defines the load range that can be supplied under varying wind-speed conditions, while the size of the battery bank (Wh) and its

state of charge define for how long that load condition can be maintained.

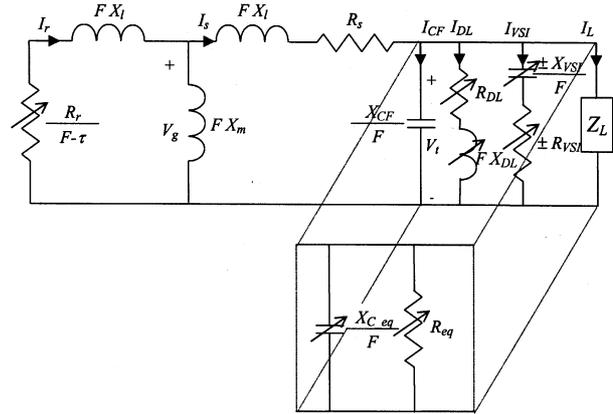


Fig. 3. Single-phase equivalent circuit of the induction generator with the shunt capacitor, dump load, VSI, and load.

3. Modelling And Analysis Of Proposed System

Fig.3 shows the per-unit per-phase steady-state equivalent circuit of the system (squirrel-cage induction generator, excitation capacitor bank, dump load, VSI, and consumer load) normalized to the base frequency. The dump load is modeled by a variable resistor (R_{DL}) and a variable inductive reactance (X_{DL}) to represent the fact that the active and reactive powers absorbed by the dump load vary with the firing angle (α) of the thyristors. The VSI, including the ac side inductance and battery bank, is modeled by a variable capacitive reactance (X_{VSI}) in series with a variable resistor (R_{VSI}). The + and - signs of X_{VSI} and R_{VSI} reflect the capability of the VSI to absorb and supply reactive and active power, respectively. The losses of the VSI are included in R_{VSI} . The load (Z_L) presents variable magnitude and power factor. It is assumed that the voltage and current harmonics in the system are reduced to acceptable values by the filters mentioned in Section II.

One of the goals of this work is to estimate the range of the load that can be supplied with regulated voltage and frequency by a VSI rated at a fraction of the induction generator power for a given wind-speed range. The approach used in this thesis is to first calculate equivalent terminal impedance (R_{eq} and X_{C-eq}) that should be present at the stator of the induction generator for a given wind speed so that the voltage magnitude and frequency are regulated at 1 p. u. Then, one can define a range for the load impedance by subtracting the active and reactive power absorbed or supplied by the other components. Alternatively, one can specify a desired load range to be fed by the system and then compute the required apparent power of the VSI, excitation capacitor, and dump load. It should be noted that all impedances external to the induction machine are lumped into the terminal impedance $R_{eq} - X_{C-eq}$ as shown in Fig. 3.

The rotor and stator resistances (R_r and R_s) of the induction generator are referred to the stator side. For a squirrel cage machine, the leakage reactance of the rotor and stator are assumed to be equal in magnitude ($X_{lr} = X_{ls} = X_l$). All machine parameters are assumed to be constant except the magnetizing Reactance.

The loop equation for the stator current (I_s) can be written as:

$$Z_s I_s = 0 \quad (1)$$

$$Z_s = Z_1 + \frac{Z_c R_{eq}}{Z_c + R_{eq}} + \frac{Z_2 Z_m}{Z_2 + Z_m} \quad (2)$$

$$Z_1 = R_s + jF X_l \quad (3)$$

$$Z_c = -jZ_{c.eq}/F$$

$$Z_2 = \frac{R_r F}{F - \tau} + jF X_l$$

$$Z_m = jF X_M \quad (4)$$

Since in the steady state $I_s = 0$, the real and imaginary parts of Z_s must be zero. Rearranging them with X_m and F as unknowns yields

$$f(X_m, F) = (C_m X_1 + C_2) F^3 + (C_3 X_m + C_4) F^2 + (C_5 X_m + C_6) F + C_7 X_m + C_8 \quad (5)$$

$$g(X_m, F) = (D_1 X_m + D_2) F^2 + (D_3 X_m + D_4) F + D_5 \quad (6)$$

The C and D coefficients, defined in the Appendix-A, contain machine parameters plus the terminal impedance ($R_{eq} - X_{c-eq}$) and rotor speed (τ). The solution of Eqns. (5) and (6) requires a numerical search method and the knowledge of the magnetization Characteristics of the machine at base frequency. Initial values for X_m and F are chosen as X_{m0} and τ , respectively. Once X_m and F have been obtained, machine voltages, currents, and per-phase powers are calculated from the following equations:

$$I_s = \frac{V_g(Z_c + R_{eq})}{Z_1(Z_c + R_{eq}) + Z_c R_{eq}} \quad (7)$$

$$I_L = \frac{I_s Z_c}{R_{eq} + Z_c} \quad (8)$$

$$V_t = I_L R_{eq} \quad (9)$$

$$I_r = \frac{I_s Z_m}{Z_2 + Z_m} \quad (10)$$

$$P_{in} = \frac{I_r^2 R_r \tau}{F - \tau} \quad (11)$$

$$P_o = V_t I_L \quad (12)$$

The rotor speed depends on the gain (N) of the step-up gearbox and on the wind turbine speed. This, in turn, varies with the wind speed and operating point on the C_p versus λ curve. The mechanical power available in wind turbine to be converted into electrical by the induction machine, neglecting the losses in the gearbox, is given by

$$P_{WT} = 0.5 \rho \pi R^2 C_p v^3 \quad (13)$$

Where

- ρ Air density (kg/m³);
- R radius of the wind turbine (m);
- C_p Power coefficient of the wind turbine;
- v Wind speed (m/s).

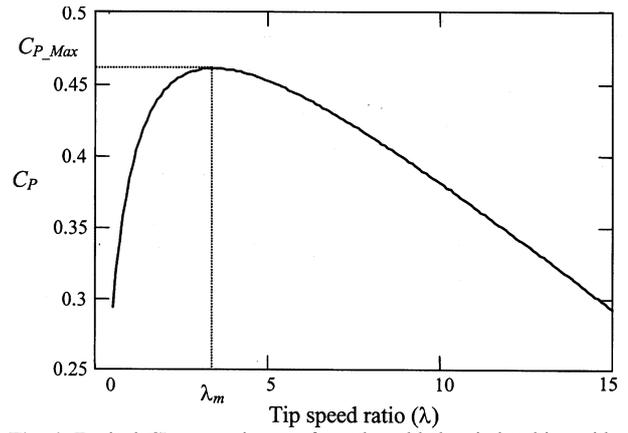


Fig. 4. Typical C_p versus λ curve for a three-blade wind turbine with a lift to drag ratio of 30.

The power coefficient of the wind turbine (C_p) varies non linearly with tip speed ratio (λ) and is a characteristic of the turbine. The tip speed ratio is defined as the ratio of the linear speed at the tip of the blade ($w_T R$) and the wind speed, w_T being the rotational speed of the wind turbine. Fig.4 depicts the C_p versus λ curve for the three-blade wind turbine [8]. It shows that C_p reaches a maximum value (C_{p-max}) for a tip speed ratio λ_m , which in turn yields the maximum mechanical power available in the wind turbine for a given wind speed. In fact, the steady-state turbine speed is determined by the power balance at the wind turbine. That is, for a given wind speed and a required input mechanical power in the induction machine to supply a given load, the steady-state values of λ are obtained from the C_p versus λ curve with the C_p that results $P_{WT} = P_{in}$. This value of λ must be larger than λ_m for a stable operation.

4. The Ideal Variable Terminal Impedance

The objective of this section is to identify the ideal values for the terminal impedance ($R_{eq} - X_{c-eq}$) so that the voltage and frequency at the load are equal to 1 p. u for wind speeds between 3 and 9 m/s. It is worth mentioning that these values are not used for controlling the VSI. They will be used to calculate the load range for regulated operation with a reduced rating VSI or the rating of the VSI for a desired load range. The main parameters of the three-blade wind turbine (R and C_p versus λ curve) and induction machine used in this analysis are shown in the Appendix-A. The step-up gear box is assumed to be lossless and is represented by a simple gain (N). This was selected as 31 so that the induction generator can supply approximately rated turbine power with rated voltage and rated frequency at a wind speed of 9 m/s and maximum power transfer from the wind turbine.

For operation with the rated frequency, the wind turbine has to operate with an approximately constant speed. For rated wind speed (9 m/s), the wind turbine operates with $\lambda = \lambda_m$ and $C_p = C_{pmax} = 0.461$. For the minimum wind speed (3 m/s), the tip speed ratio has to increase by a factor of 3 and $C_p = 0.376$ for the wind turbine under consideration. Thus, the efficiency of the wind turbine is reduced to 81.5% of its maximum value at this wind speed. This factor is primarily a function of the shape of the C_p versus λ curve of

the wind turbine. The steeper the curve at the right-hand side, the higher is the power loss.

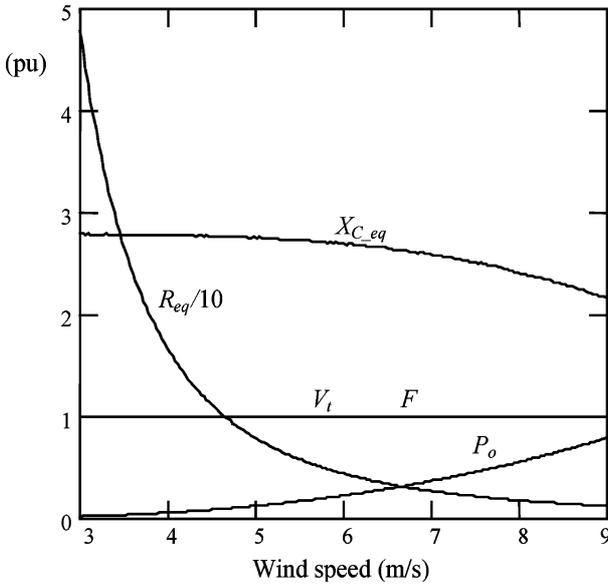


Fig. 5. Variation of the ideal equivalent excitation reactance and resistive load with the wind speed which yield voltage and frequency regulation.

The calculation of the ideal values for the terminal impedance (R_{eq}, X_{C-eq}) was carried out starting with a rated wind speed of 9 m/s and then decreasing it. At this wind speed, the turbine is expected to operate with maximum efficiency (C_{pMAX} and λ_m). Neglecting the losses in the gear box, the input power for the induction generator is obtained from Eqn. 13. Then turbine speed and the generator shaft speed ($\tau = N \omega_T$) are obtained. Next, using the initial guess values for the terminal impedance ($R_{eq0} = R_{rated}$ and $X_{C-eq0} = X_{mo}$) the equations presented in Section III and an incremental search procedure [9], one can obtain the desired values for R_{eq} and X_{C-eq} . $F = 1$ p. u is sought first by varying the λ . Then, one attempts to impose $V_t = 1$ p. u and $P_{WT} = P_{in}$ by varying R_{eq} and X_{C-eq} . If this causes a variation in F , λ is varied again. After the ideal values of R_{eq} and X_{C-eq} are obtained for this wind speed, the procedure is repeated for a lower wind speed, using the previous values of R_{eq} and X_{C-eq} as initial guesses.

The ideal values for the terminal impedance for which the voltage and frequency at the output of the induction generator equal 1 p. u for the given range of wind speeds are presented in Fig. 5. The output power is lower than 1 p. u at rated wind speed (9 m/s) because the calculations were carried out in a per-phase basis, using the phase values of the induction machine as base values. That is, the per-phase base power is 6350 VA, while the wind turbine supplies 15 kW at 9 m/s. The capacitive reactance should be varied between 2.17 and 2.79 p. u that is a relatively narrow interval. The capacitive reactance increases as the wind speed decreases. This is because the voltage drops in the stator of the generator decreases as the active output power decreases, and less reactive power is required to keep the output voltage at the rated value [10].

5. Load Range With the VSI Regulating Voltage and Frequency

The procedure discussed in Section IV resulted in the calculation of ideal steady-state values for the equivalent excitation reactance and resistive load so that the voltage and frequency are regulated for the wind speed in a given range. Hence, there is an ideal stator current (I_s) for each wind speed that should be drawn from the generator by the fixed capacitor bank, dump load, VSI, and load. The fundamental currents in Fig. 3 in phasor notation are related by [11]

$$I_s = I_{CF} + I_{DL} + I_{VSI} + I_L \quad (14)$$

Considering that the voltage magnitude and frequency at the generator terminals are regulated at 1 p. u, the current at the fixed capacitor bank (I_{CF}) is constant. Assuming that the load is variable in magnitude and power factor, the VSI should be able to adjust I_s to the appropriate value, by controlling the active and reactive power it exchanges with the system, to attain voltage and frequency regulation. The dump load would only be activated to prevent overcharge of the battery bank or overload of the VSI during light load conditions.

In the upcoming steady-state analysis, the VSI can be characterized by its apparent power (S_{VSI}), rated at a fraction of the generator's base power. Then one can calculate the load range for which voltage and frequency are regulated, given a fixed capacitor bank and a VSI rated at S_{VSI} p. u (<1).

Separating the real and imaginary parts of Eqn. (14)

$$Re(I_s) = Re(I_{DL}) + Re(I_{VSI}) + Re(I_L) \quad (15)$$

$$Im(I_s) = |I_{CF}| + Im(I_{DL}) + Im(I_{VSI}) + Im(I_L) \quad (16)$$

Where $Im(I_s) > 0$, $Im(I_{DL}) < 0$, and $|I_{CF}| > 0$. $Im(I_{VSI})$ and $Im(I_L)$ can be either smaller or greater than zero.

The real and imaginary parts of the load current are

$$Re(I_L) = PF|I_L| \quad (17)$$

$$Im(I_L) = k\sqrt{1 - PF^2}|I_L| \quad (18)$$

Where PF is the load power factor, and $k = -1$ for inductive load and 1 for capacitive. To meet power limitations, the real and imaginary parts of the VSI input current in p. u should be such that

$$Re(I_{VSI}^2) + Im(I_{VSI}^2) \leq S_{VSI}^2 \quad (19)$$

Substituting Eqns. (17) and (18) in Eqns. (15) and (3.16) one obtains the terms relative to the VSI current, which are then substituted in Eqn. (19). Solving for the magnitude of the load current, one gets

$$|I_L|^2 - 2[A.PF + B k\sqrt{1 - PF^2}]|I_L| + A^2 + B^2 - S_{VSI}^2 \leq 0 \quad (20)$$

Where $A = Re(I_s) - Re(I_{DL})$ and $B = Im(I_s) - |I_{CF}| - Im(I_{DL})$.

For the calculation of the regulated load range for a given power factor, one needs to specify the apparent power of the VSI and choose the reactance of the fixed capacitor bank and rated power of the dump load. A criterion used in this paper is that the reactive power generated and absorbed by the VSI be the same for v_{min} (3 m/s) and v_{max} (9 m/s) with a resistive load. It can be shown that this reactance is given by,

$$X_{CF} = 2 \frac{X_{C-eq-Min} X_{C-eq-Max}}{X_{C-eq-Min} + X_{C-eq-Max}} \quad (21)$$

Using the values obtained in Section IV, the reactance of the fixed capacitor bank is selected as 2.443 p. u. The dump load is designed for the worst-case condition: The induction generator supplies maximum power while the load is null and the VSI cannot absorb any active power because the battery bank is fully charged. Thus,

$$|I_{DL-rated}| = Re(I_s)_{Max} = \frac{1}{R_{eq-Min}} p.u \quad (22)$$

For the system under consideration, the rated power of the dump load is calculated as 0.734 p. u. It is worth mentioning that as the firing angle of the ac controller increases, it starts absorbing reactive power that must come from the fixed capacitor and VSI. Thus, to achieve voltage regulation at no load it is necessary that,

$$|Im(I_{DL})| < S_{V_{\square I}} + |I_{CF}| - Im(I_s). \quad (23)$$

With the battery fully charged and for medium values of wind speed, the firing angle of the ac controller is relatively large so that the active power absorbed by the dump load matches the small active power supplied by the generator. As a result, the reactive power demanded by the ac controller increases. It can be shown that the maximum reactive power absorbed by the ac controller is equal to 0.246 p. u and takes place when $v = 7.1$ m/s. For the no-load condition, the apparent power of the VSI has to be at least 0.23 p. u to achieve voltage regulation.

6. Simulation Results

The effectiveness of the VSI for regulating the magnitude and frequency of the generated voltage was verified by means of digital simulations with MATLAB/SIMULINK. A model for a wind turbine based on the C_p versus λ curve and that also includes the moment of inertia was developed in house. The gear box, considered lossless, was modeled by a gain. The main parameters of the mechanical system are listed in the Appendix-B. The reactance of the Δ connected fixed capacitor bank was selected as 2.443 p. u to comply with the analysis presented in Section 3.4, The inductance of the VSI is 2 mH. The PI controllers of the i_d^* and i_q^* loops present again of 4.34 and a time constant of 0.022 s. Those for the $|V|$ and f loops present gains of 0.5 and 2 and time constants of 0.1 and 0.06 s, respectively. No dump load was used in these tests.

Figs. 6 and 7 shows the voltage magnitude and shaft speed of the generator during the start up of the system. The load and the VSI are disconnected and the wind speed is 8 m/s. A Y-connected 3.4Ω load ($R_L = 1.33$ p.u) is switched

in at $t=2$ s when the voltage magnitude is 167V and the shaft speed is 1200 rpm. The steady-state values for these quantities are 151V and 1202 rpm, respectively.

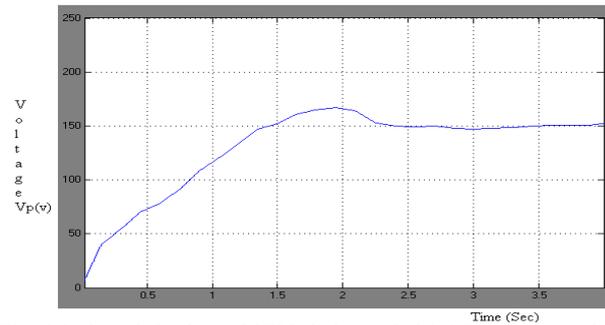


Fig. 6. Voltage behaviour of SEIG during period 0-4 Sec with capacitor bank.

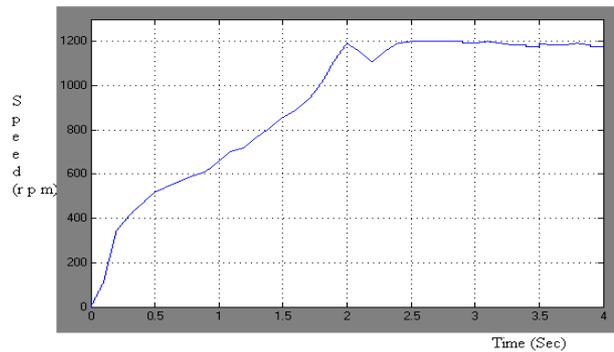


Fig. 7. Speed behaviour of SEIG during period 0-4 Sec with capacitor bank

Figs. 8 to 11, shows the effect of the VSI on the regulation of the magnitude and frequency of the generated voltage. The VSI is enabled at $t=4.2$ s, increasing the magnitude and frequency of the generated voltage to their rated values. According to Fig.5, the equivalent resistance and capacitive reactance required at the terminals of the generator should be 1.834 and 2.42 p. u, respectively to achieve regulated voltage and frequency for a wind speed of 8 m/s. Since the values of the actual resistive load and fixed excitation reactance are below these values, $R_L=1.33$ p.u and $X_C =2.433$ p. u, the VSI should supply a lot of active power and a bit of reactive power. This is observed in the waveforms of i_d^* and i_q^* in Figs. 10 and 11. Note that the direction of the VSI current in the schematics of the simulation files is from VSI to the load and generator.

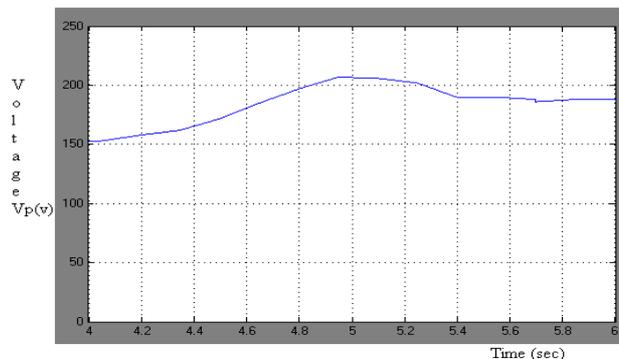


Fig. 8. Impact of the VSI on the regulation of voltage during period 4-6 Sec

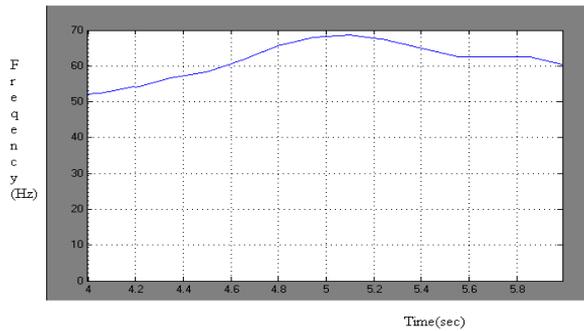


Fig. 9. Impact of the VSI on the regulation of frequency during the period 4-6 Sec

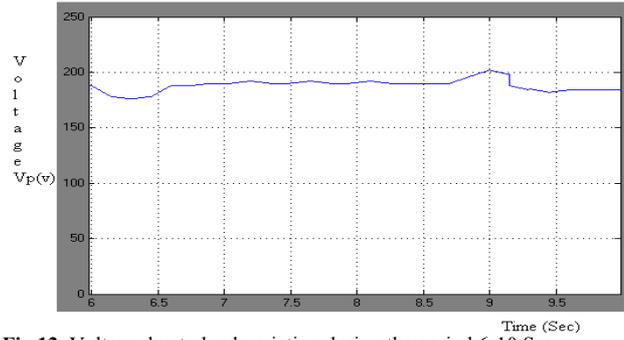


Fig.12. Voltage due to load variation during the period 6-10 Sec

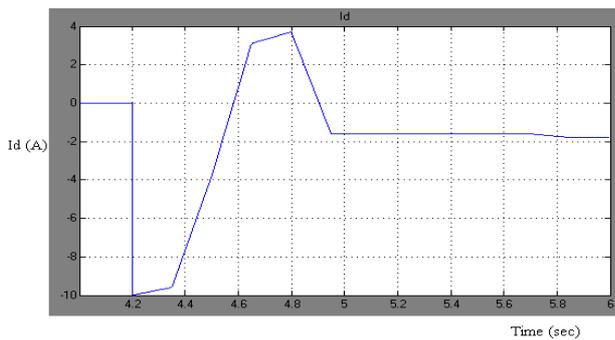


Fig. 10. Impact of the VSI on the regulation of Direct axis current (I_d) during the period 4-6 Sec

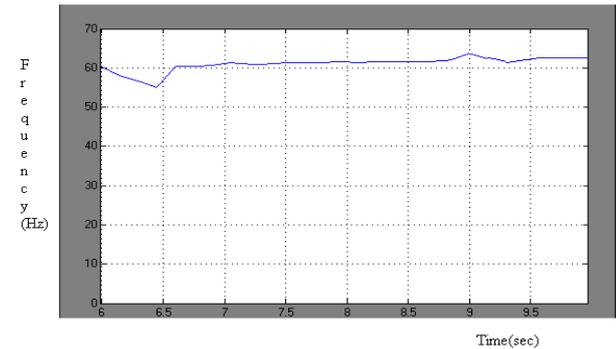


Fig.13. Frequency due to load variation during the period 6-10 Sec



Fig. 11. Impact of the VSI on the regulation of Quadrature axis current (I_q) during the period 4-6 Sec

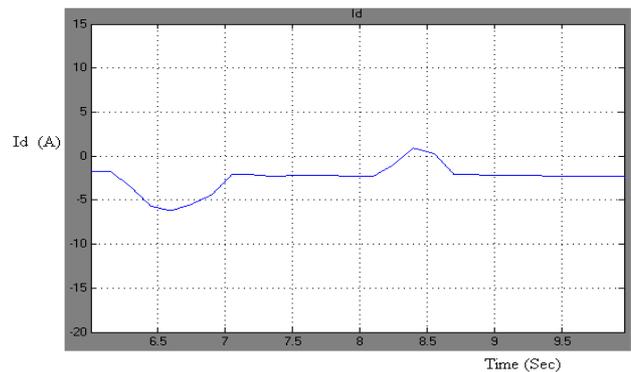


Fig. 14. Direct axis Current (I_d) due to load variation during the period 6-10 Sec

Figs. 12 to 15, shows the response of the system to a load variation. A resistive load of 16.9Ω is switched in a $t=6.2$ sec and switched out at 8.2 sec. After a transient period the magnitude and frequency of the voltage return to their rated values in the both cases. Which demonstrates the good regulating features of the system, with both loads connected, the active power consumed by them is 17.16 kW or 0.9 p. u. The wind turbine supplies around 10.5 kW of mechanical power. In steady-state, the VSI operates with $i_q = 28.5$ A, $i_d = -1.53$ A, $V_q = V_p = 183$ V, and $V_d = 0$ V, supplying 7678 W and 412 Var. The overall power required from the VSI for regulation purpose is 7689 VA or 0.4p.u. The 0.9 p. u resistive load was chosen because, it is close to the maximum value of the load that can be supplied with regulated voltage and frequency with a reduced rating (0.5 p. u) VSI when the wind speed is 8 m/s. Thus, the analysis presented in Section 3.4 is validated.

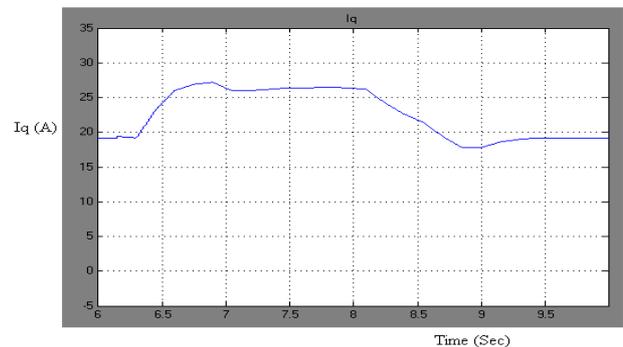


Fig. 15. Quadrature axis current (I_q) due to load variation during the period 6-10 Sec

The transient response of the system to wind variation is shown in Figs.16 to 19. The wind speed ramps down to 7 m/s at $t= 8.2$ s and up to 9 m/s at 12.2 s. Again, after transient periods, the voltage magnitude and frequency return to their rated values as a result of the variation of the active and reactive power dealt by the VSI. It is worth noting that for a

wind speed of 9 m/s, the amount of active power dealt by the VSI is very small ($I_q = 0.8$ A). The actual 3.4 ohms load ($R_L = 1.33$ p.u) is very close to that of the equivalent terminal resistance ($R_{eq} = 1.293$ p.u) required for the voltage and frequency regulation, as shown in Fig.5.

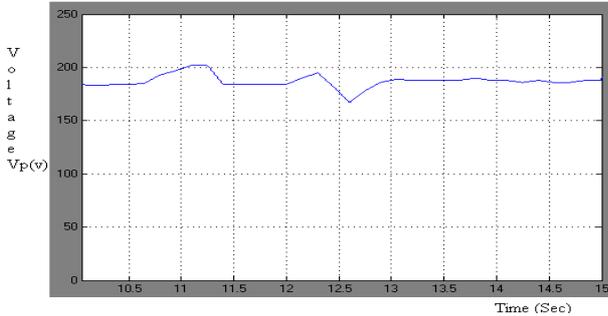


Fig. 16 Voltage due to wind speed variation during the period 10-15 Sec.

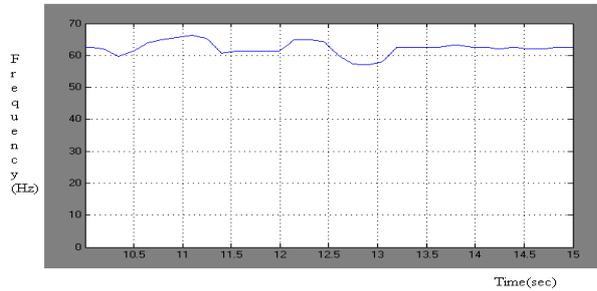


Fig. 17 Frequency due to wind speed variation during the period 10-15 Sec.

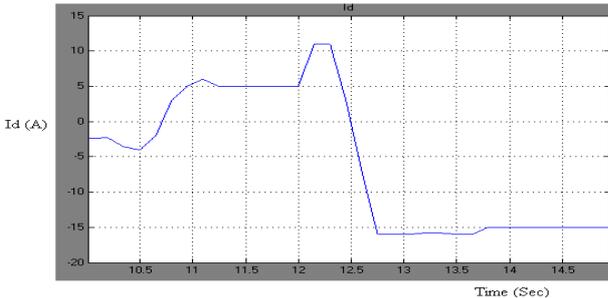


Fig. 18 Direct axis Current (I_d) due to wind speed variation during the period 10-15 Sec

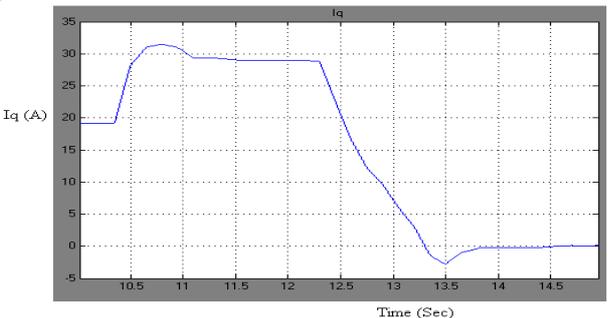


Fig. 19 Quadrature axis current (I_q) due to wind speed variation during the period 10-15 Sec

7. Conclusion

In this paper a objective constant-speed constant-frequency WECS based on self-excited squirrel-cage induction generator without mechanical turbine control has been presented. With constant speed, the maximum turbine power transfer only at rated condition, the power loss at other operating point is not significant when a wind turbine with a relatively flat C_p versus λ characteristic curve is used.

Here a reduced rating VSI with an energy storage device in the dc side and in parallel with a fixed excitation capacitor bank and dump load can be successfully employed for frequency and voltage magnitude regulation under varying load and wind speed conditions.

An approach for calculating the load range for which voltage magnitude and frequency can be regulated by a reduced-rating VSI for a given range of wind speeds has been presented. It can be easily extended for calculating a minimum-rating VSI required to regulate the voltage and frequency for a given load range. A control scheme for the VSI with independent control of its active and reactive powers is proposed as a means for preventing battery over charge and undercharge while still regulating the system voltage. And also, it allows the VSI to use most of its power capability to regulate the system voltage, while a controllable dump load limits the frequency when there is a surplus of active power in the ac system.

Finally, simulation results were presented to verify the response of the system under variable load and wind speed conditions. The feasibility of the system is verified by MATLAB/SIMULINK.

APPENDIX-A

Coefficients of $f(X_m, F)$ and $g(X_m, F)$

$$\begin{aligned}
 C_1 &= -2X_1 R_{eq} \\
 C_2 &= -X_1^2 R_{eq} \\
 C_3 &= -C_{1T} \\
 C_4 &= -C_{2T} \\
 C_5 &= (R_{eq} + R_s + R_r)X_{C-eq} \\
 C_6 &= (R_{eq} + R_s + R_r)X_{C-eq}X_1 + R_s R_{eq} R_r \\
 C_7 &= -(R_{eq} + R_s)X_{C-eq}\tau \\
 C_8 &= C_7 X_1 \\
 D_1 &= 2X_1 X_{C-eq} + R_s R_{eq} + R_r R_{eq} \\
 D_2 &= X_1^2 X_{C-eq} + (R_s R_{eq} + R_r R_{eq})X_1 \\
 D_3 &= -(2X_1 X_{C-eq}\tau + R_s R_{eq}\tau) \\
 D_4 &= -(X_1 X_{C-eq} + R_s R_{eq})X_1\tau \\
 D_5 &= -R_r(R_{eq} + R_s)X_{C-eq}
 \end{aligned}$$

References

1. R. M. Hillowala and A. M. Sharaf, "A utility interactive wind energy conversion scheme with an asynchronous DC link using a supplementary control loop," *IEEE Trans. Energy Convers.*, vol. 9, no. 3, Sep. 1994, pp. 558–563.
2. M. G. Simões, B. K. Bose, and R. J. Spiegel, "Fuzzy logic based intelligent control of a variable speed cage machine wind generation system," *IEEE Trans. Power Electron.*, vol. 12, no. 1, Jan. 1997, pp. 87–95.
3. E. Muljadi and T. Lipo, "Series compensated PWM inverter with battery supply applied to an isolated induction generator," *IEEE Trans. Ind. Appl.*, vol. 30, no. 4, Jul–Aug. 1994, pp.1073–1082.
4. R. Bonert and G. Hoops, "Stand alone induction generator with terminal impedance controller and no turbine controls," *IEEE Trans. Energy Convers.*, vol. 5, no. 1, Mar. 1990. pp. 28–31
5. E.G.Marra and J.A. Pomilio, "Self-excited induction generator controlled by a VS-PWM bidirectional converter for rural

- applications,” *IEEE Trans. Ind. Appl.*, vol. 35, no. 4, Jul.–Aug. 1999, pp. 877–883.
6. G. C. D. Souza, F. N. Martins, J. P. Rey, and J. A. Bruinsma, “An autonomous induction generator system with voltage regulations,” in *Proc 4th IEEE Int. Conf. PEDS 2001*, vol. 1, Indonesia, Oct. 22–25, 2001, pp. 94–98.
 7. A.G.Bakirtzis, “Aprobabilistic method for the evaluation of the reliability of stand alone wind energy systems,” *IEEE Trans. Energy Convers.*, vol. 7, no. 1, Mar. 1992. pp. 99–107
 8. G. S. Stavrakakis and G. N. Kariniotakis, “A general simulation algorithm for the accurate assessment of isolated diesel—wind turbines system interaction: Part I: General multimachine power system model,” *IEEE Trans. Energy Convers.*, vol. 10, no. 3, Sep. 1995, pp. 577–583.
 9. S. P. Singh, B. Singh, and M. P. Jain, “Performance characteristics and optimum utilization of a cage machine as capacitor excited induction generator,” *IEEE Trans. Energy Convers.*, vol. 5, no. 4, Dec. 1990, pp. 679–685.
 10. L. A. C. Lopes and R. G. Almeida, “Operation aspects of an isolated wind driven induction generator regulated by a shunt voltage source,” in *Proc. 35th IEEE Ind. Appl. Soc. Annual Meeting*, vol. 4, Oct. 8–12, 2000, pp. 2277–2282.
 11. Luiz A. C. Lopes and Rogerio G. Almeida, “Wind-driven self-excited induction generator with voltage and frequency regulated by a reduced-rating voltage source inverter” *IEEE Trans. on Energy Conversion*, vol. 21, no.2, Jun 2006, pp:297-304.
 12. Paul C. Krause, *Analysis of Electric Machinery*, McGraw Hill, 1987.
 13. Mohan, Undeland and Robbins, “*Power Electronics*”, Wiley India, Third edition, 2007.
 14. Luiz A. C. Lopes and Rog´erio G. Almeida ” Wind-Driven Self-Excited Induction Generator With Voltage and Frequency Regulated by a Reduced-Rating Voltage Source Inverter” *IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 21, NO. 2, JUNE 2006.*