Fuzzy Logic Control of Squirrel Cage Induction Generator for Wind Energy Conversion

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Abstract: *This paper presents a novel direct rotor flux oriented control applied to self excited induction generator equipping a wind turbine in remote sites. The squirrel cage induction generator connected to the three non linear loads through a back-to-back converter. The fuzzy logic controller is used to ensure the DC-bus voltage a constant value when a change in speed and load condition. The proposed control strategy is validated by simulation in Matlab/Simulink.*

Key words: *Self excited induction generator, vector conrol, PWM, rectifier/inverter, fuzzy logic control.*

1. Introduction

In the last years, new energy sources have been proposed and developed due to the climate change and pollution caused by fuels. On the other hand, fossil or nuclear fuel has a huge negative impact on the environment and human health.

One in four world's population lives in rural villages and remote areas are not connected to an electrical grid. They use fossil fuels for their need of energy requirements. Its use causes ecological and economic problems.

Induction generator connected to the wind turbine has many advantages such as cost, reduced maintenance, rugged, simple construction, and brushless rotor (squirrel cage).

The control of the output voltage of the generator transmitted to the consumers is the most challenge, when change in speed and load condition.

2. Self excited induction generator modeling

The mathematical model of SEIG in stationary d-q reference frame is described by the following equations [1][2][3][4]:

$$\begin{bmatrix} L_s & 0 & L_m & 0 & 0 & 0 \\ 0 & L_s & 0 & L_m & 0 & 0 \\ L_m & 0 & L_r & 0 & 0 & 0 \\ 0 & L_m & 0 & L_r & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{di_{ds}}{dt} \\ \frac{di_{qs}}{dt} \\ \frac{di_{dr}}{dt} \\ \frac{di_{qr}}{dt} \\ \frac{dv_{ds}}{dt} \\ \frac{dv_{qs}}{dt} \end{bmatrix} =$$

$$\begin{bmatrix} R_s & 0 & L_m & 0 & -1 & 0 \\ 0 & R_s & 0 & L_m & 0 & -1 \\ 0 & -\omega L_m & -R_r & -\omega L_r & 0 & 0 \\ \omega L_m & 0 & \omega L_r & -R_r & 0 & 0 \\ \frac{1}{C} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C} & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ V_{ds} \\ V_{qs} \end{bmatrix} \quad (1)$$

Where, L_s and L_r are respectively the stator and the rotor cyclic inductances, L_m magnetizing inductance, R_r the rotor resistance and R_s the stator resistance [2].

The SEIG model can be describe by a system of six equations [3][4][5].

$$[X] = \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ V_{ds} \\ V_{qs} \end{bmatrix} ; [L]= \begin{bmatrix} L_s & 0 & L_m & 0 & 0 & 0 \\ 0 & L_s & 0 & L_m & 0 & 0 \\ L_m & 0 & L_r & 0 & 0 & 0 \\ 0 & L_m & 0 & L_r & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} ;$$

$$[B] = \begin{bmatrix} R_s & 0 & L_m & 0 & -1 & 0 \\ 0 & R_s & 0 & L_m & 0 & -1 \\ 0 & -\omega L_m & -R_r & -\omega L_r & 0 & 0 \\ \omega L_m & 0 & \omega L_r & -R_r & 0 & 0 \\ \frac{1}{C} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C} & 0 & 0 & 0 & 0 \end{bmatrix} \quad (2)$$

Also, the state space equation is:

$$[\dot{X}]=[A][B][X] \quad (3)$$

Where: $[\dot{X}]=\frac{d}{dt}[X]=sX$, et $[A]=[L]^{-1}$

- [L]: inductance matrix ;
- s: Laplace operator.

The variation of the magnetizing inductance is the main factor in the dynamic of the voltage build up and stabilization in SEIG [5][6].

It must be emphasized that the generator needs residual magnetism so that the self excitation

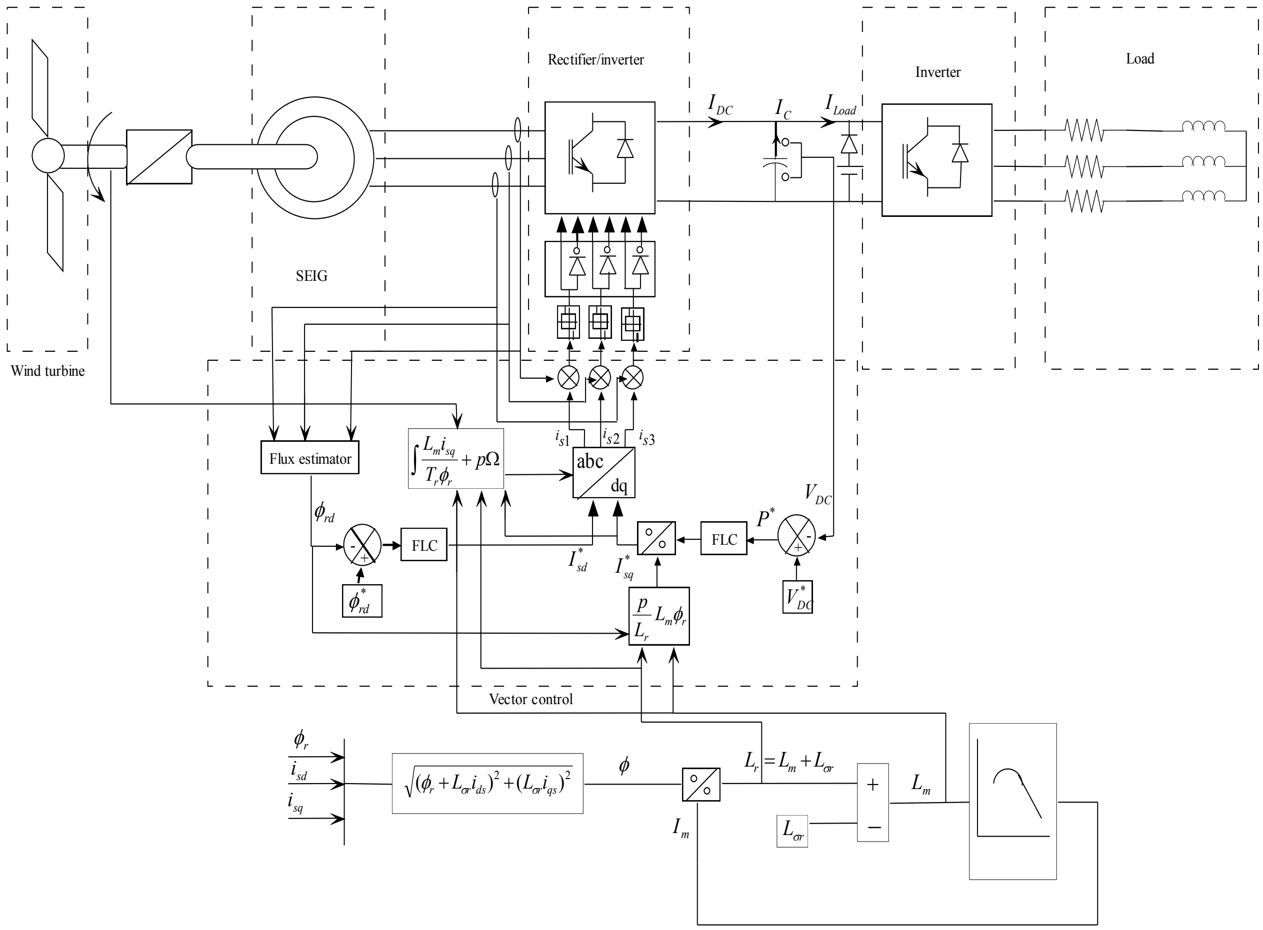

Fig. 2. Algorithm of control.

process can be started. The magnetizing inductance, L_m , used in this work is given in Fig. 1.

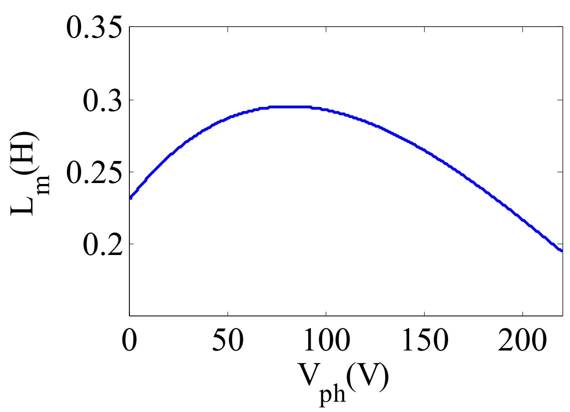

Fig. 1. Variation of magnetizing inductance with phase voltage.

The self excited induction generator needs the reactive energy for its excitation, the battery on the DC side provides the initial voltage across the capacitor during the excitation process and as soon as the load voltage rises to a value higher than the battery voltage, this one is automatically switched off by a diode.

3. Vector Control

The goal in controlling system is to ameliorate the generated energy quality by ensure DC bus voltage follow the reference value, this obtained by controlling the flux and the power transmitted by the generator.

In this designs the sinusoidal pulse width modulation (SPWM) technique has been used for controlling the inverter as it can be directly controlled the inverter output voltage and frequency according to the sine functions.

Flux and electromagnetic torque controlled independently to keep the magnitude of flux constant can be simplified the structure of the control system, the magnetic saturation should also be taken into account [4][7][8][9].

While directing rotor flux, we obtained the simplifying model of the generator:

$$\frac{di_{sd}}{dt} = \frac{1}{L_s}(V_{sd} - R_s i_{sd} + \omega L_s i_{sq} - L_m \frac{di_{rd}}{dt} + \omega_s L_m i_{rq})$$

$$\frac{di_{sq}}{dt} = \frac{1}{L_s}(V_{sq} - R_s i_{sq} + \omega L_s i_{sd} - L_m \frac{di_{rq}}{dt} + \omega_s L_m i_{rd})$$

$$\phi_r = \frac{L_m i_{sd}}{1+T_r s} \qquad (4)$$

$$T_{em} = p\frac{L_m}{L_r}\phi_r i_{sq}$$

$$\omega_s = \frac{L_m i_{sq}}{T_r \phi_r} + p\Omega$$

Where: $T_r = \frac{L_r}{R_r}$ time rotor constant.

L_r is determined by the following expression:

$$\frac{di_{sd}}{dt} L_r = \frac{\phi}{i_m} = L_{\sigma r} + L_m \qquad (5)$$

ϕ: flux linkages physically can non-existent flux (6).

$$\phi = \sqrt{\phi_d^2 + \phi_q^2}$$

$$\phi_d = \phi_r + L_{\sigma r} i_{ds} \qquad (6)$$

$$\phi_q = L_{\sigma r} i_{qs}$$

3. Algorithm of control

The objective of the vector control in this case is to maintain constant the output voltage of rectifier, what over the speed and the load in great beach of variation.

From the desired value of the voltage, it is possible to express the reference power (7) [3][7][8][10].

$$V_{DC} i_{dc} = P^* = P_{ele} = T_{em}\Omega \qquad (7)$$

Neglecting the losses, the torque expression can be written as:

$$T_{em} = \frac{P^*}{\Omega} \qquad (8)$$

Substituting equation (4) in (8), the current control i_{sq} is defined by [2][3][4][7][8][10].

$$i_{sq} = \frac{L_r}{pL_m\phi_r} T_{em} \qquad (9)$$

The flux ϕ_r is estimated from the i_{sd} current. When the flux is maintain to his reference, then torque is directly proportional to i_{sq} [3][4][7][8][10].

The expression for calculating the slip angular speed is given by:

$$\omega_s = \frac{L_m i_{sq}}{T_r \phi_r} + p\Omega \qquad (10)$$

The implementation of the control is presented in Fig. 2.

4. Fuzzy logic control

The main feature of fuzzy logic controllers (initiated by Mamdani and Assilian based on Fuzzy set theory suggested by Zadeh in 1965) is that linguistic, imprecise knowledge of human experts is used [11].

The proposed voltage and flux fuzzy PI controllers block diagram are shown in Fig. 3. They have two inputs and one output for everyone.

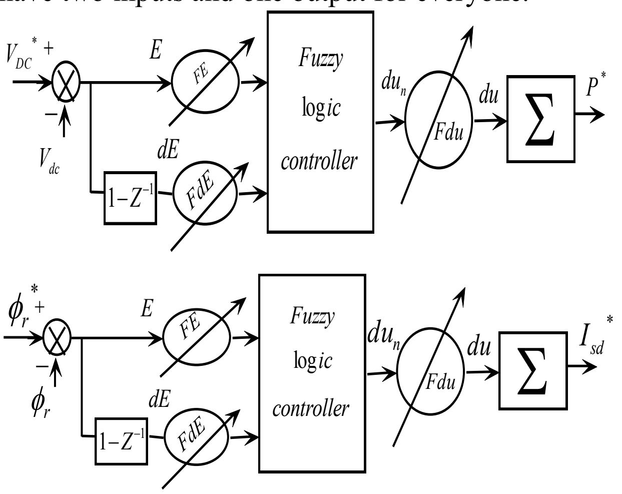

Fig. 3. Structure of fuzzy logic controller.

Where E is the error expressed by:

$$E(k) = V_{DC}^*(k) - V_{DC}(k-1) \qquad (11)$$

dE is derived from the error approximated by:

$$dE(k) = E(k) - E(k-1) \qquad (12)$$

Whit T_e is the sampling period.

The output of the regulator is given by:

$$P^*(k) = P^*(k-1) - dU(k) \qquad (13)$$

FE, FdE, FdU are gains called "scale factor". Fig. 4. shows the function of membership of each input signals (E, dE). The fuzzy subsets are as follows: NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big).

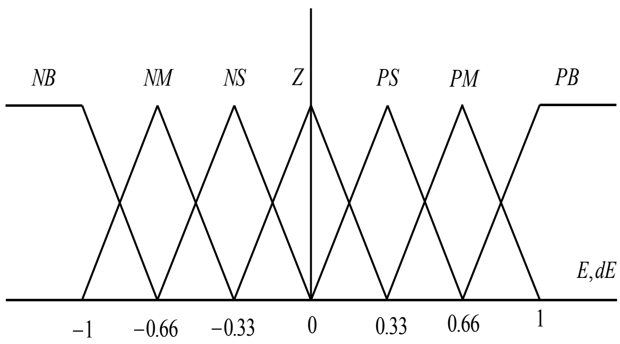

Fig. 4. Membership function.

There are 7 fuzzy subsets for each variable, which gives 7*7=49 possible rules.

dEn|En	NB	NM	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PS	NM	NS	Z	PS	PM	PB	PB
Z	NB	NM	NS	Z	PS	PM	PB
NS	NB	NB	NM	NS	Z	PS	PM
NM	NB	NB	NB	NM	NS	Z	PS
NB	NB	NB	NB	NB	NM	NS	Z

4. Interpretation of results

The simulation of the proposed control scheme has been implemented using Matlab/Simulink. The sample time used $T_s = 50\mu s$. The load is a resistance of 120Ω and inductance of $2\,mH$.

The load is changed from (120Ω-2mH) to (140Ω-4mH) at 3s on second inverter leg and on the third inverter leg from (120Ω-2mH) to (90Ω-3mH) at 7s.

Fig. 5. shows the DC bus voltage. For changes in load or rotor speed the controlled DC voltage effectively tracks the command, which is 700V.

Fig. 6. shows the speed rotation.

Fig. 7. shows that the rotor flux is constant during entire operation, and the current i_{sd} has the same pace as rotor flux Fig. 10.

The Fig. 8. shows that the amplitude and the frequency of the output voltage of the inverter adapt in spite of the speed variation.

The Fig. 9. shows the output current of the inverter and its variation when the load changed.

Fig. 10. shows the d-q axis currents, the q axis current due to changes of rotation speed and load can be seen.

Fig. 11. shows the stator currents.

In Fig. 12, the stator phase current is shown to be successfully maintained within the imposed hysteresis band limits for different load values.

Fig. 13. and Fig. 14. show the magnetizing current and magnetizing inductance within estimator.

It can be clearly seen that the proposed control scheme guarantees near-sinusoidal input current and output voltage inverter.

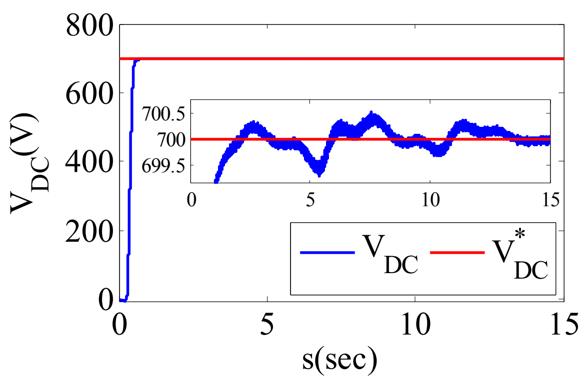

Fig. 5. The terminal voltage.

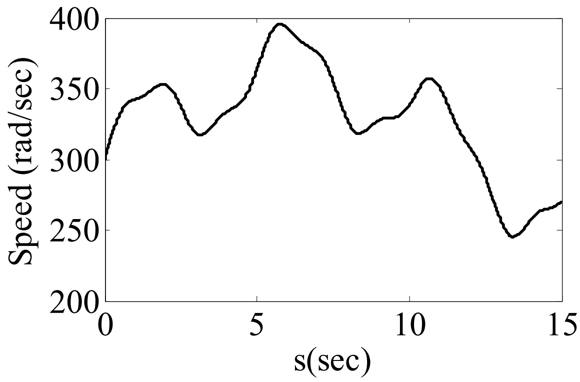

Fig. 6. The speed rotation.

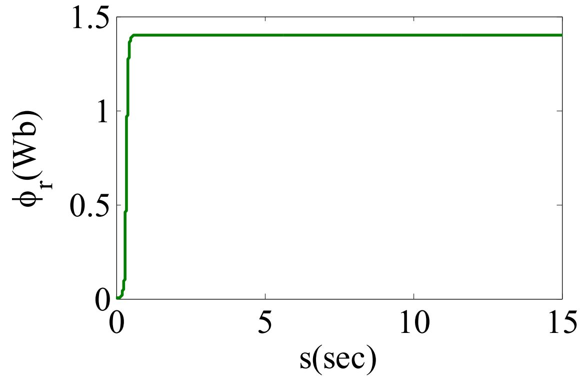

Fig. 7. Rotor flux.

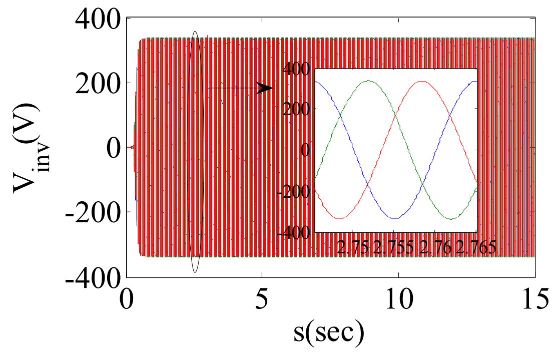

Fig. 8. The output voltage inverter.

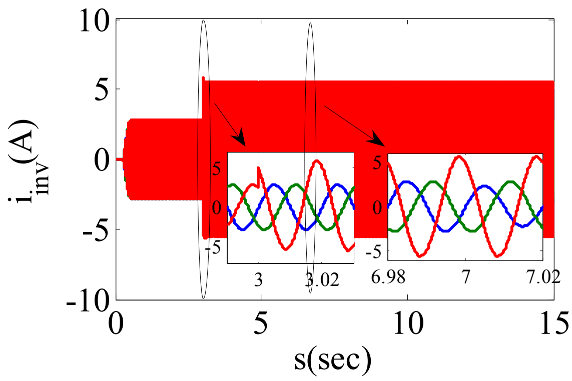

Fig. 9. The output current inverter.

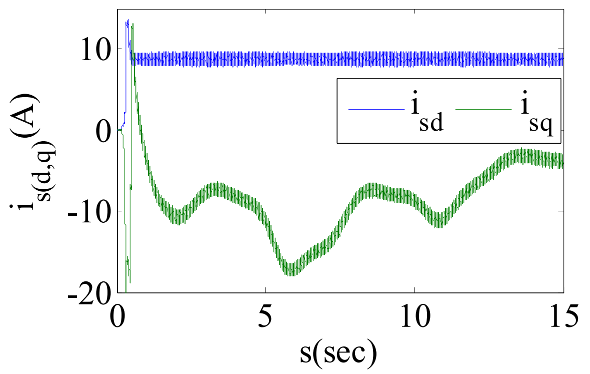

Fig. 10. The d-q axis currents .

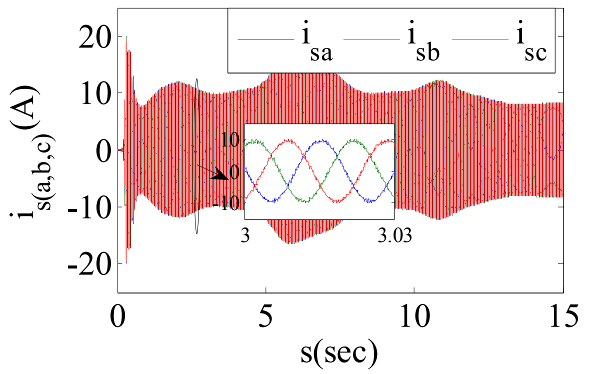

Fig. 11. The stator currents.

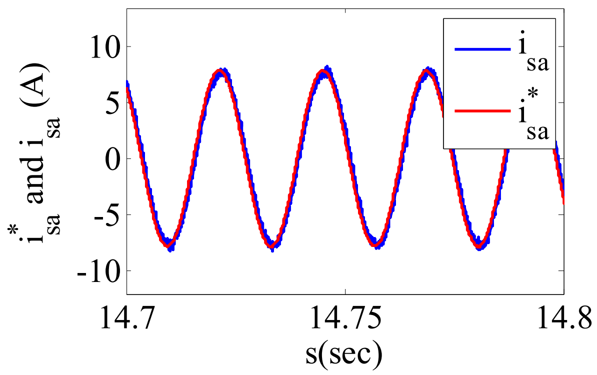

Fig. 12. The stator current and reference current.

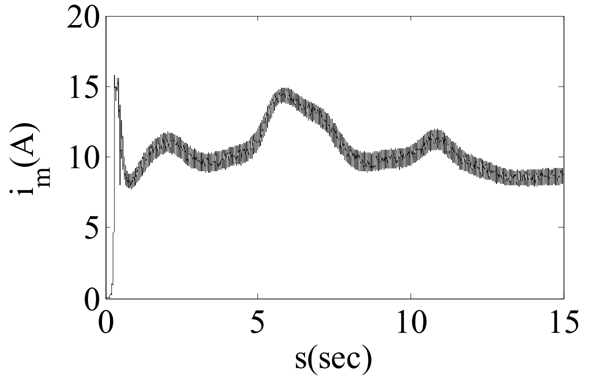

Fig. 13. The magnetizing current.

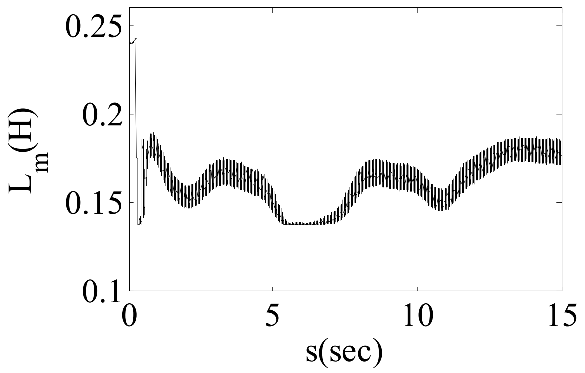

Fig. 14. The magnetizing inductance.

5. Conclusion

In this paper, a rotor flux oriented control using fuzzy logic applied to a self excited induction generator, in a variable speed wind system, has been presented and studied. The proposed scheme control offer a perfect DC bus and rotor flux magnitude tracking. The proposed system conversion control can be exploited in the wind power generation.

6. Induction generator parameters

Nominal voltage	$V_n = 415V$
Nominal current	$I_n = 15\ A$
Stator resistance	$R_s = 1.7\Omega$
Rotor resistance	$R_r = 2.7\Omega$
Inductance stator	$l_s = 0.024H$
Inductance rotor	$l_r = 0.023$
Mutual inductance	$L_m = 0.023$
Moment of inertia	J=0.038Kg. m^2
Frequency	F=50 Hz
Pair pole	P=4

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