A Reactive Power Based Reference Model for Adaptive Control Strategy in a SEIG

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***Abstract*—In this paper, a new control strategy is proposed for a three-phase squirrel-cage self-excited induction generator (SEIG) connected to a variable speed wind turbine in autonomous mode. In order to improve the dynamic performance of the mentioned vector control system, a model reference adaptive controller is used for online rotor time constant estimation. Thus, the main drawbacks of this method, which include the effects of the changes in machine parameters on rotor flux estimation, slip speed, the creation of instability problems and the system leaving vector control mode, are resolved. In this control strategy, a PI controller is used to control the dc voltage and three similar hysteresis current controllers (HCC) are used to control the switching of IGBTs. The results of the dynamic simulation indicate the desirable performance of the proposed system.**

Keywords-Self-Excited Induction Generator (SEIG); Rotor Flux Oriented (RFO) Vector Control; Model Reference Adaptive System (MRAS)

I. INTRODUCTION

Using capacitor-excited squirrel-cage induction generators in small hydropower or wind power plants in areas far from the grid has always attracted interest in order to electrify isolated areas. Some of the advantages of induction generators include the simple and sturdy structure (due to the squirrel-cage rotor), simpler operation, low price, lesser safety and measurement equipment, higher reliability, self-protection against errors, high power-to-weight ratio, adequate dynamic response, no need for synchronization and excitation adjustment. Also, the lack of rings, commutators, brushes and a separate dc source for excitation lead to reduced repair and maintenance costs. In addition, since wind speed varies in different times, the use of induction generators has attracted a lot of attention, because these generators are able to convert mechanical to electrical energy in a wider range of rotor speed changes. Poor regulation of voltage and the required reactive power are the two main drawbacks of an induction generator. In order to use an induction generator in autonomous mode, we need a proper control system to maintain a constant dc-bus voltage [1-3].

Some solutions are presented in various articles in order to control the terminal voltage of SEIGs. In [4], a rotor flux oriented vector control is proposed by taking into account the effects of core losses and magnetic saturation. But no solution is offered for the sensitivity of the system to rotor resistance changes. Authors in [5] propose a stator flux oriented (SFO) vector control. The main advantage of this control method is that it's not sensitive to the changes of the generator leakage inductance. However, the main drawback is the system's dependency on stator resistance changes which can reduce the precision of flux estimation in low voltages. In [6], SEIG steady state characteristics are proposed by series and shunt capacitors. The results show that short shunt generator has the best characteristic and is a good candidate for static power supply. A SEIG transient characteristic with series compensation that feeds a dynamic load such as induction motor has been studied in [7]. In addition, the steady state and transient behavior in different operational conditions, such as SEIG voltage generation under no load condition and sudden connection of induction motor to SEIG with and without series compensation, has been analyzed through mathematical modeling. However, series capacitor may cause sub synchronous resonance (SSR) in SEIG-IM, such that create overvoltage, over current, induction motor speed and torque unstable oscillations. In [8], a self-controlled static reactive power compensator with a fixed-capacitor thyristor-controlled reactor (FC-TCR) is used to adjust the terminal voltage and frequency of induction generators. A model predictive controller (MPC) is used in order to control the SVC's fire angle. Magnetization inductance has the main role in SEIG voltage generation and stability in no-load and under load conditions. Therefore, to have a real and accurate model for SEIG dynamic analysis, it is required to evaluate magnetization inductance. An estimation method of magnetization inductance is proposed in [9].

In [10], the authors proposed a control strategy to obtain the maximum possible energy from wind turbines and also to simultaneously adjust the terminal voltage of the generator against the original load and wind speed changes. This strategy is based on the principles of fuzzy logic control using an electronic load controller (ELC) connected to a voltage source inverter. A current controlled voltage source inverter with a suitable control algorithm could be used as a static synchronous compensator (STATCOM). STATCOM performance principle and control strategy for SEIG terminal voltage regulation is proposed in [11-15]. STATCOM could be considered as a required reactive power source for SEIG terminal voltage regulation in variable load conditions. In this strategy, SEIG supplies the required active power of the load, while the required reactive power of the load and SEIG are supplied through STATCOM. In addition to compensating reactive power, the STATCOM is employed to compensate the unbalanced currents caused by single-phase loads that are connected across the two terminals of the three-phase SEIG, and also suppresses the harmonics injected by consumer loads. However, this method is not able to regulate SEIG frequency under variable load conditions. In [16], a decoupled voltage and frequency controller (DVFC) is proposed which causes SEIG to feed linear and nonlinear loads in constant voltage and frequency by regulating them separately. Hence, the DVFC is a combination of a static synchronous compensator for regulating the voltage and an ELC [17] for controlling the power which maintains the system frequency constant. However, this procedure includes a PI controller for regulating active power in the ELC and two other PI controllers for ac and dc voltage control are also set in STATCOM controller which regulating these controllers cause practical problems in the design of DVFC.

II. STUDIED SYSTEM DESCRIPTION

The main structure regarding the execution of the vector control system is illustrated in Figure 1. The main components of the studied system are a vector control system and a three-phase induction generator. The generator's shaft is connected to the wind turbine through the gear box, its stator terminal is connected to a current-controlled voltage source inverter, and an excitation capacitor, battery and resistive load exist in its DC-link. In this paper, the dynamic model for SEIGs proposed in [18] is used to design the vector control system due to high precision and reduced amount of calculations, which needs less hardware and software requirements and lower costs. The effects of saturation and iron losses are both taken into account in this model in a way that the iron loss resistance is a function of synchronization frequency and flux, and the magnetizing inductance is a function of magnetizing current. The effects of the magnetizing flux on iron losses are expressed by the corresponding current of iron losses iRm. The equivalent circuit of the SEIG in a stationary reference frame is illustrated in Figure 2. All the variables along the q axis are similar to the variables of the d axis with a 90-degree phase shift, therefore, only the equivalent circuit of the d axis is actually illustrated. If we substitute the dashed area by its Thevenin equivalent, we will obtain the equivalent circuit of Figure 2(b), in which the iron loss resistance is included in the variable resistance of the stator. The values of the magnetizing inductance and iron loss used in the simulation are calculated online by look-up tables [4], as shown in Figure 3. The Thevenin equivalents for the stator current/voltage and resistance are calculated in the following.

$$R_{sT} = R_s \| R_m = \frac{R_s R_m}{R_s + R_m} \quad (1)$$

$$u_{sTd} = u_{sd} \frac{R_m}{R_s + R_m} \quad (2)$$

$$u_{sTq} = u_{sq} \frac{R_m}{R_s + R_m} \quad (3)$$

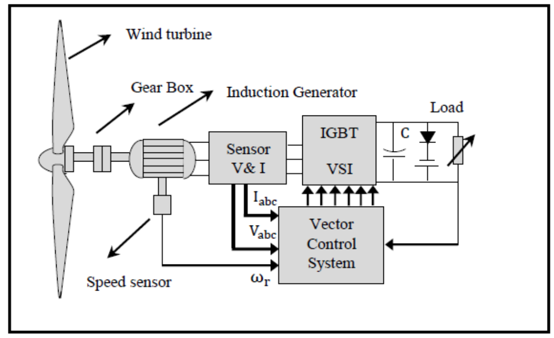

Fig. 1. System description

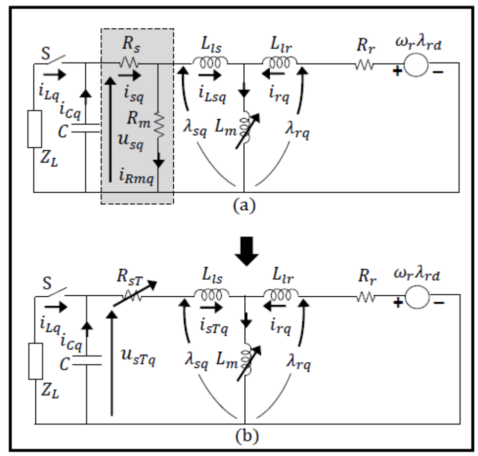

Fig. 2. The equivalent circuit of the SEIG

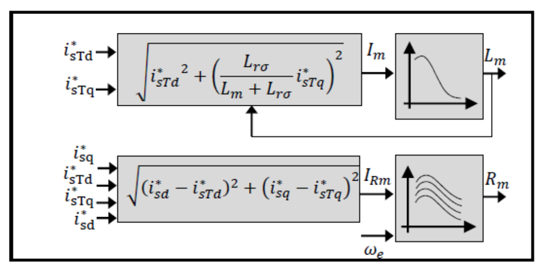

Fig. 3. The online calculation of Lm and Rm

Since the structure of the equivalent circuit shown in Figure 2 is similar to the lossless SEIG model, we can maintain the structure of the lossless model within the model with losses using the following substitution. The equations of the lossless model will also be valid and the first-order differential equations are preserved, resulting in a lower amount of calculations:

$$R_s \to R_{sT} \ , \ u_{sq} \to u_{sTq} \ , \ u_{sd} \to u_{sTd} \ , \ i_{sq} \to i_{sTq} \ , \ i_{sd} \to i_{sTd}$$

The SEIG model illustrated in Figure 2 (b) can be perfectly described through the following four first-order differential equations by choosing the rotor and stator currents as state variables.

$$i_{sTd} = i_{sd}\frac{R_s + R_m}{R_m} + \frac{u_{sd}}{R_m} \tag{4}$$

$$i_{sTq} = i_{sq}\frac{R_s + R_m}{R_m} + \frac{u_{sq}}{R_m} \tag{5}$$

$$s \cdot i_{sTd} = \frac{1}{\sigma L_s L_r}(L_m{}^2\omega_r i_{sTq} - L_r R_{sT} i_{sTd} + L_m\omega_r L_r i_{rq} + L_m R_r i_{rd} - L_r u_{sTd} - L_m K_{rd}) \tag{6}$$

$$s i_{sTq} = \frac{1}{\sigma L_s L_r}(-L_r R_{sT} i_{sTq} - L_m{}^2\omega_r i_{sTd} + L_m R_r i_{rq} - L_m\omega_r L_r i_{rd} - L_r u_{sTq} - L_m K_{rq}) \tag{7}$$

$$s i_{rd} = \frac{1}{\sigma L_s L_r}(-L_s\omega_r L_m i_{sTq} + L_m R_{sT} i_{sTd} - L_s\omega_r L_r i_{rq} - L_s R_r i_{rd} + L_m u_{sTd} - L_s K_{rd}) \tag{8}$$

$$s i_{rq} = \frac{1}{\sigma L_s L_r}(L_m R_{sT} i_{sTq} + L_s\omega_r L_m i_{sTd} - L_s R_r i_{rq} + L_s\omega_r L_r i_{rd} + L_m u_{sTq} - L_s K_{rq}) \tag{9}$$

III. Field-oriented vector control (FOC)

In a DC machine, the axes of the field and the two armature coils are perpendicular and the MMF forces caused by their currents do not interact with each other if we disregard core saturation. Therefore, the controlling variables of the machine, the vectors of the armature current I_a and the excitation current I_f, can be regarded as stationary and orthogonal in space, each of which can be controlled independently. In general however, controlling a three-phase induction machine is not as easy and simple as controlling a DC machine because the rotor and stator fields obey the operating conditions, and their spatial directions lack the 90-degree phase difference, so they interact with each other. If the equations and block diagram of an induction machine are studied in a reference frame at synchronous speed, then the stator current is expressed by two components i_{ds} and i_{qs} which can be used as controlling tools for the induction machine. In the vector control of induction machines, the i_{ds} current is similar to the I_f current and acts as the component of flux and the i_{qs} current is similar to the I_a current and acts as the component of torque. Therefore, the performance of a DC machine can be extended to an induction machine using this control strategy. In vector control, the control strategies are implemented in a two-phase reference frame fixed on the rotor or a stationary reference frame with an excitation frequency. We are looking to convert all the variables from the three-phase a-b-c system to a two-phase stationary reference frame and then convert them again from the stationary reference frame to a synchronous rotating reference frame. In this situation, all sinusoidal signals seem like DC values in the steady state (like a DC machine). After applying field-oriented vector control on the d and q components of the stator current, the variables need to be converted to the a-b-c system, which is done using inverse transformations [19]. These transformations, which are usually in series, are shown in Figure 4 [19].

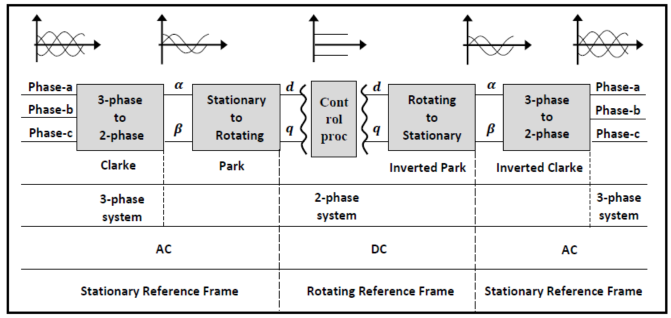

Fig. 4. Vector control transformations

Vector control is a mathematical control strategy based on space vector theory which is performed in a synchronous reference frame with current and phase angle control. In the vector control strategy, we try to put the space vectors of the stator's flux and current in the hands of the controller, so that by tracing the space vector, the d and q components of the stator current are separated and controlled properly. Direct and indirect strategies are proposed based on the calculation of the solid angle of the induction machine's flux in the vector control algorithm. In direct vector control strategy, the positioning of flux is done by measuring flux signals through the Hall effect sensor. However in the indirect strategy, parameters such as the speed signal ω_r and the slip frequency ω_{sl} are used. In vector control analysis, all vector quantities must be in the same basis and frame reference in order for a correct and significant analysis. Basically, three reference frames are considered in vector control: the magnetizing flux, rotor flux and stator flux oriented reference frames.

In this paper, an indirect rotor flux oriented vector control strategy is used. We have chosen the indirect vector control strategy because of the shortcomings of the direct technique, namely the need for a flux sensor which results in the high volume and high costs. In the stator flux oriented strategy, we need a decoupling circuit in the flux control loop due to the coupling of the variables. We also need PI controllers and more amplitude limiters at the output which results in higher complexity in comparison with the rotor flux oriented strategy. Therefore, the rotor flux reference frame is chosen among other types of reference frames due to the simplification of the equations of the induction machine and simpler performance. According to the vector control diagram illustrated in Figure 5, the de axis of the rotating reference frame overlays the rotor flux vector λ_r in the rotor flux oriented strategy. In other words, the rotor flux vector is considered as a reference of measurement for the other vectors. In this case, the q component of the rotor flux would be zero and the flux in the d axis would be equivalent to the total rotor flux in the induction machine. Therefore, the conditions of validity for the rotor flux oriented vector control can be expressed as [20]:

$$\lambda_{dr}^e = \lambda_r \tag{10}$$

$$\lambda_{qr}^e = 0 \tag{11}$$

$$\frac{d\lambda_{qr}^e}{dt} = 0 \tag{12}$$

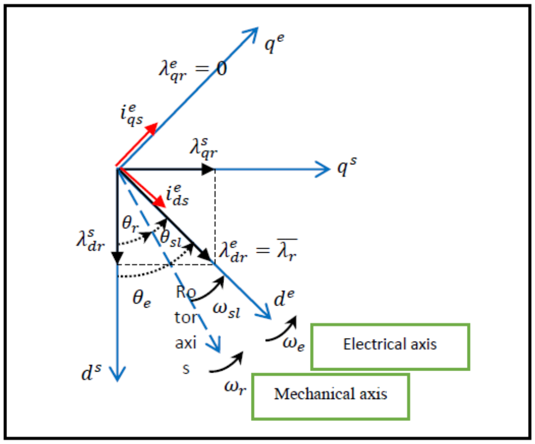

Fig. 5. The rotor flux oriented vector control diagram

The ds – qs axes are fixed and the de – qe axes rotate with the synchronous speed ω_e. The angle of the rotating de axis relative to the fixed ds axis is equivalent to θ_e which is the sum of the rotor angle θ_r and the slip angle θ_{sl}.

$$\theta_r = \int \omega_r dt \quad (13)$$

$$\theta_{sl} = \int \omega_{sl} dt \quad (14)$$

$$\theta_e = \theta_{sl} + \theta_r \quad (15)$$

The rotor voltage equations of an induction machine in a synchronous reference frame are:

$$\frac{d\lambda^e_{dr}}{dt} + R_r i^e_{dr} - (\omega_e - \omega_r)\lambda^e_{qr} = 0 \quad (16)$$

$$\frac{d\lambda^e_{qr}}{dt} + R_r i^e_{qr} + (\omega_e - \omega_r)\lambda^e_{dr} = 0 \quad (17)$$

The rotor currents are obtained from the equations of the d and q components of the rotor flux in the synchronous reference frame:

$$i^e_{dr} = \frac{\lambda^e_{dr} - L_m i^e_{ds}}{L_r} \quad (18)$$

$$i^e_{qr} = \frac{\lambda^e_{qr} - L_m i^e_{qs}}{L_r} \quad (19)$$

Substituting (18) and (19) in (16) and (17), we can obtain the rotor voltage equations in terms of rotor flux and stator currents.

$$\frac{d\lambda^e_{dr}}{dt} + \frac{R_r}{L_r}\lambda^e_{dr} - \frac{L_m}{L_r}R_r i^e_{ds} - \omega_{sl}\lambda^e_{qr} = 0 \quad (20)$$

$$\frac{d\lambda^e_{qr}}{dt} + \frac{R_r}{L_r}\lambda^e_{qr} - \frac{L_m}{L_r}R_r i^e_{qs} + \omega_{sl}\lambda^e_{dr} = 0 \quad (21)$$

Substituting (12) to (19), which describe the conditions of validity of the rotor flux oriented vector control, in (20) and (21), we obtain the following:

$$T_r \frac{d\lambda_r}{dt} + \lambda_r = L_m i^e_{ds} \quad (22)$$

$$\omega_{sl} = \frac{L_m}{\lambda_r T_r} i^e_{qs} \quad (23)$$

In which $\omega_{sl} = \omega_e - \omega_r$ and $T_r = \frac{L_r}{R_r}$ represent the slip speed and the time constant of the rotor respectively. In the steady state, the rotor flux is constant and therefore, (22) can be expressed as below:

$$\lambda_r = L_m i^e_{ds} \quad (24)$$

Substituting the above equation in (23), we obtain:

$$\omega_{sl} = \frac{1}{T_r}\frac{i^e_{qs}}{i^e_{ds}} \quad (25)$$

As seen in the above equations, the rotor flux oriented vector control strategy controls the variables separately; because the rotor flux depends only on the d axis current. However, the main drawback of this strategy is the variability of the machine parameters, because the rotor resistance may vary with temperature and the skin effect, and also the rotor inductance might vary with the level of the core magnetic saturation. This drawback leads to the presence of noise in the reference slip estimation which ultimately leads to the coupling of the variables. Thus, the system exits vector control mode. In this paper, the model reference adaptive system is proposed for the compensation and the online adjustment of the rotor resistance in order to resolve this problem.

IV. MODEL REFERENCE ADAPTIVE SYSTEM (MRAS)

So far, various programs have been presented for the online estimation of machine parameters. These programs can be classified as: the signal injection strategy, the model reference adaptive system, the observer-based strategy [21] and other strategies. The model reference adaptive system is a strategy that has attracted a lot of interest due to its relatively simple execution. The main idea of the system is based on the calculation of one quantity in two different ways. The first value is calculated by the references within the control system and the second value is obtained from the measured signals. One of these two values is independent of the studied quantity. In this paper, the model reference adaptive system is designed on the basis of the reactive power, in a way that it eliminates all demands for the estimation of stator resistance and flux in the calculation process. The main structure of the MRAS block is illustrated in Figure 6. This structure contains a reference model and an adjustable model which calculate the momentary reactive power (Q_{ref}) and the steady state reactive power (Q_{est}), respectively. The reference model is independent of the slip speed (rotor resistance or time constant) while the adjustable model is dependent on this quantity. The error signal caused by the difference between these two values $(e = Q_{ref} - Q_{est})$ implies the error in the resistance of the rotor used in the control system which is the input of the adaptation mechanism block (I or PI controller). The output of the block is the estimated slip speed $\omega_{sl,est}$ which can be used to calculate rotor resistance.

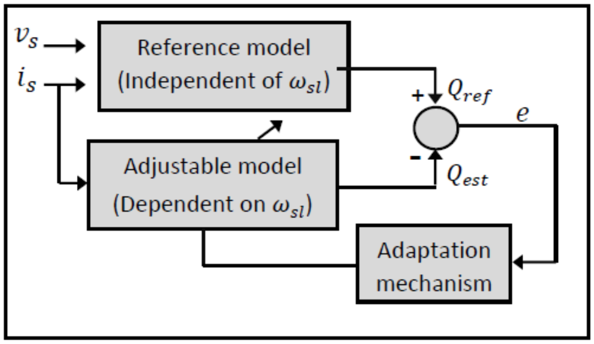

Fig. 6. The main structure of the model reference adaptive system

The d and q components of the stator voltage in the rotating synchronous reference frame ω_e can be expressed as follows:

$$V_{ds} = R_s i_{ds} - \omega_e \sigma L_s i_{qs} - \frac{\omega_e L_m}{L_r}\lambda_{qr} + \sigma L_s \frac{di_{ds}}{dt} + \frac{L_m}{L_r}\frac{d\lambda_{dr}}{dt} \quad (26)$$

$$V_{qs} = R_s i_{qs} + \omega_e \sigma L_s i_{ds} + \frac{\omega_e L_m}{L_r}\lambda_{dr} + \sigma L_s \frac{di_{qs}}{dt} + \frac{L_m}{L_r}\frac{d\lambda_{qr}}{dt} \quad (27)$$

The momentary reactive power (Q) can be expressed as below:

$$Q_1 = V_{qs} i_{ds} - V_{ds} i_{qs} \quad (28)$$

Substituting equations (26) and (27) in equation (28), we obtain a new equation for Q:

$$Q_2 = \sigma L_s \left[i_{ds}\frac{di_{qs}}{dt} - i_{qs}\frac{di_{ds}}{dt} \right] + \frac{\omega_e L_m}{L_r}\left[\lambda_{qr} i_{qs} + \lambda_{dr} i_{ds} \right] + \omega_e \sigma L_s \left[i_{ds}^2 + i_{qs}^2 \right] + \frac{L_m}{L_r}\left[i_{ds}\frac{d\lambda_{qr}}{dt} - i_{qs}\frac{d\lambda_{dr}}{dt} \right] \quad (29)$$

If we take the derivative segment to be zero in the steady state, and substitute equation (24) and the conditions of validity for rotor flux oriented vector control (equations (10) to (12)), we can simplify the (29) as:

$$Q_2 = \omega_e \sigma L_s \left[i_{ds}^2 + i_{qs}^2 \right] + \omega_e \frac{L_m^2}{L_r} i_{ds}^2 \quad (30)$$

Where $\omega_e = \omega_r + \omega_{sl}$ and the equation for Q_2, which is independent of the rotor flux and stator resistance and dependent on slip speed, can be regarded as the adjustable model and the equation for Q_1, which is independent of slip speed, can be considered as the reference model.

V. SIMULATION RESULTS

In order to use an induction machine as an autonomous generator for wind energy conversion, we need a proper control system. Figure 7 illustrates the details of the implementation of the proposed vector control strategy in an autonomous induction generator. In this article, we use the rotor flux oriented vector control strategy in order to control the flux of the induction machine and maintain a constant dc-link voltage. The vector control algorithm contains two loops that work in parallel. The first loop allows us to control the flux and also the d component of the reference current. That's how we control the flow of reactive power in the system. The second loop lets us control the DC voltage and thus the q component of the reference current. Therefore, the flow of active power from the generator to the DC circuit can be controlled. The reference current on the rotating qe axis in the rotating synchronous reference frame (i_{qs}^*) is obtained from the DC voltage controller output but the d component of the reference current in the rotating synchronous reference frame (i_{ds}^*) is obtained if we divide the rotor flux amplitude by the magnetizing inductance, according to (24). The reference slip ω_{sl} can be calculated by (25). In the next step, the value of ω_e and thus the value of θ_e, the position angle of the rotating area which is the heart of the vector control system, are calculated with high precision using the values of slip and rotor speeds. The simulation has been performed in MATLAB Simulink in order to evaluate the efficiency of the proposed vector control strategy. The rated values and parameters of the induction machine are brought in Table I.

TABLE I. MACHINE PARAMETERS

Parameter	Value
Shaft power : PN	5.5 Kw
Stator phase voltage: UN	200 V
Base speed: ΩN	690 rpm
Stator resistance: Rs	1.0713 Ω
Rotor resistance: Rr	1.2951 Ω
Rotor inertia : J	0.230 kg.m2
Rotor friction coefficient: d	0.0025 N.m/rad
Pole pairs: p	4
Frequency: f	50 Hz

At first, the rotor of the induction machine gains speed until it reaches the synchronous speed. We now investigate the performance of the proposed system with a 10% increase in rotor speed in 6 seconds using different variables. The rotor speed of the induction machine is illustrated in Figure 8 in which the machine reaches the synchronous speed in 0.5

seconds. Figure 9 displays the changes of the rotor flux. The rotor flux reaches its reference value in 1.26 seconds without overshoot. The rotor flux follows the changes of speed rapidly and therefore it passes the noise generated in the speed and returns to its reference value immediately. The DC voltage wave in the inverter output is illustrated in Figure 10 which reaches its reference value in 1.127 seconds with a poor overshoot of about 2.14%. The response of the DC voltage to the generated noise is exactly similar to that of the flux. Figure 11 shows the d and q components of the stator currents which can be controlled separately. The i_{sq} current wave is similar to the rotor flux. In other words, i_{sq} shows the changes of speed which in turn imply the changes of the electromagnetic torque in the induction generator, illustrated in Figure 12.

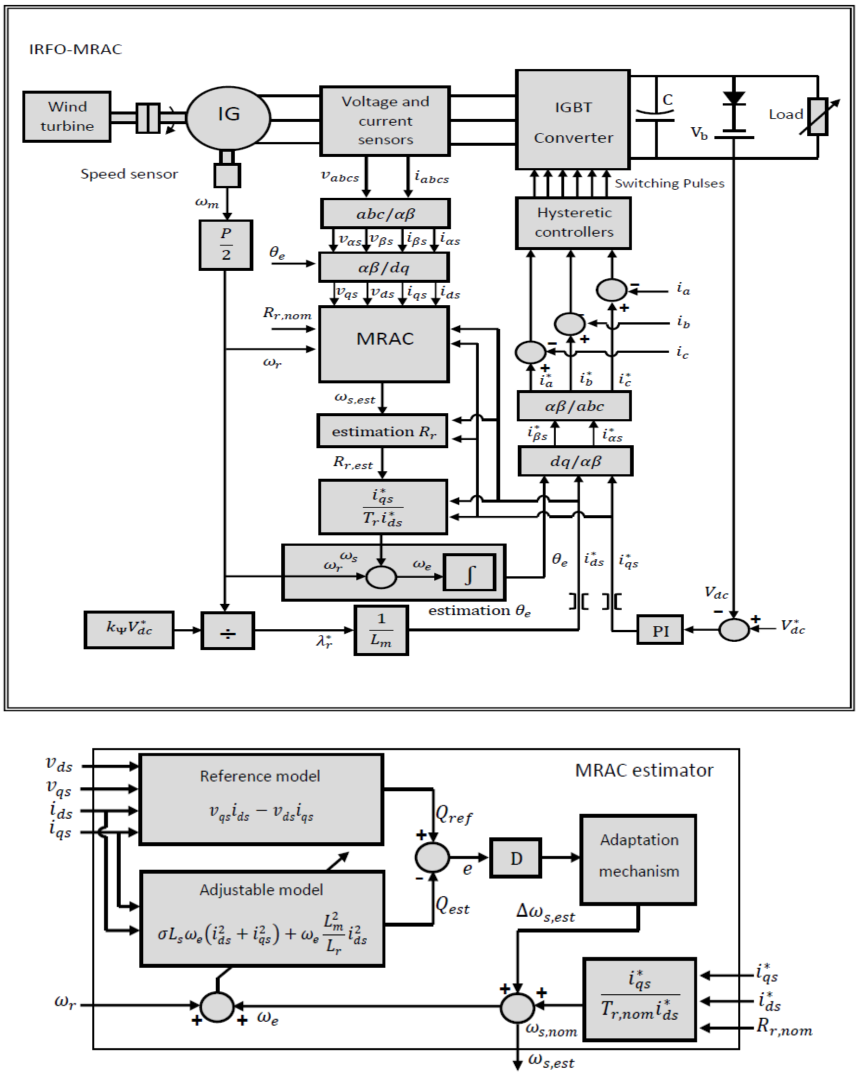

Fig. 7. The proposed control strategy

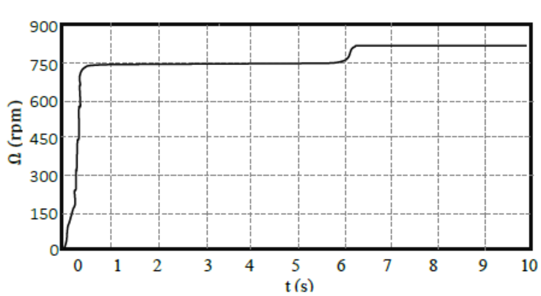

Fig. 8. Rotor speed

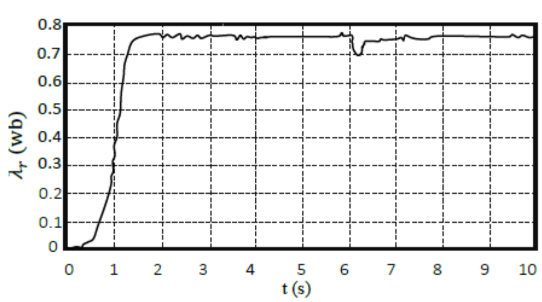

Fig. 9. Changes in rotor flux

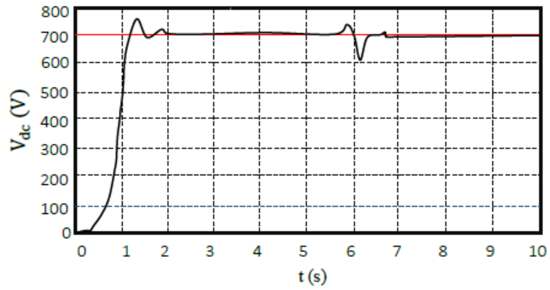

Fig. 10. The generated DC voltage

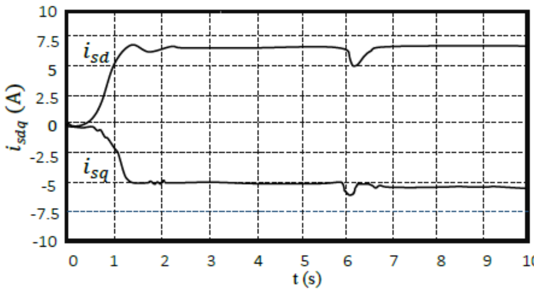

Fig. 11. Changes in the d and q components of the stator current

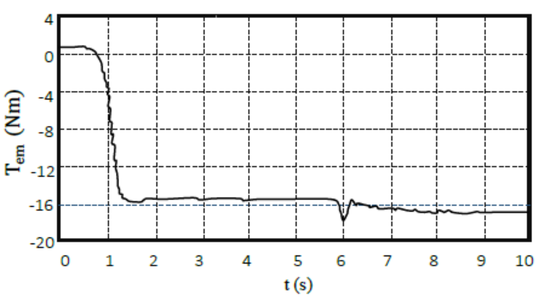

Fig. 12. Changes in the electromagnetic torque

VI. CONCLUSION

In this paper, a new control strategy is proposed for an autonomous self-excited induction generator (SEIG) connected to a variable speed wind turbine which is based on the principles of vector control in order to maintain a constant dc-bus voltage. The proposed control strategy uses indirect rotor flux orientation (IRFO) which doesn't need a decoupling circuit and is less complex and easier to perform than the stator flux oriented strategy. The indirect strategy is chosen because of the shortcomings of the direct technique, namely the need for a flux sensor which results in the high volume and high costs. In order to design the vector control system, the effects of core losses and saturation are both taken into account in the dynamic model of the induction machine in a way that the iron loss resistance is a function of synchronization frequency and flux, and the magnetizing inductance is a function of magnetizing current. This leads to high precision and low calculation complexity while maintaining the simplicity. It also reduces the hardware and software requirements and thus the cost. In order to improve the dynamic performance of the studied vector control system, a model reference adaptive system (MRAS) is used for the online estimation of the rotor time constant. This resolves the main drawbacks of this strategy which are the effects of changes in machine parameters on the estimation of the rotor flux and slip speed, the creation of instability problems and the system leaving vector control mode. The simulation results indicate that the proposed controller has displayed optimal performance in the adjustment of the voltage of the induction generator in autonomous mode.

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