Cascade sliding mode controller
for self-excited induction generator

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Abstract - *This paper presents a simple control structure based on the sliding mode algorithm for an isolated-loaded induction generator (IG). The machine delivers an active power to a dc-load via a converter connected to a single capacitor on the dc side. Since the converter/capacitor model is nonlinear, the sliding mode technique constitutes a powerful tool to ensure the dc-bus voltage regulation. The computer simulations are provided to verify the validity of the proposed control algorithm.*

Résumé - *Ce papier présente une commande de structure simple basée sur l'algorithme du mode de glissement pour une génératrice asynchrone auto excitée. La génératrice délivre une puissance active à une charge continue par la voie d'un convertisseur connecté à un condensateur du côté continu. Puisque le modèle convertisseur / condensateur est non linéaire, la technique du mode de glissement constitue un outil puissant pour assurer la régulation de la tension du bus continu. Les simulations par ordinateur sont fournies pour vérifier la validité de l'algorithme du contrôle proposé.*

Key words: Induction generator - Sliding mode control - DC voltage control.

1. INTRODUCTION

The use of induction generators is becoming more and more popular for renewable energy sources, especially for wind electric systems, both in grid connected and stand alone mode. It is well known that the induction generator can operate in self-excited mode using only the input mechanical power from the rotating prime mover and a source of reactive power. The reactive power can be supplied by a variety of methods, from simple capacitors to complex power conversion systems.

Owing to its many advantages, the self excited induction generator has emerged from among the well known generators as a suitable candidate to be driven by wind turbine. Some of its advantages are small size and weight, robust construction, absence of separate source for excitation and reduced maintenance cost.

When the induction generator is connected to an infinite power net, the analysis becomes simple, since the voltage and frequency are determined by the driving network. However, an autonomous induction machine is able to generate electric power only if self excitation occurs [1-3], and it can be sustained. The main drawback of such generators however is its inherently poor voltage regulation, and it becomes necessary to have an appropriate voltage regulating scheme.

To overcome poor voltage regulation of the SEIG, a number of schemes have been proposed. The scheme based on switched capacitors, this scheme finds limited application because it regulates the terminal voltage in discrete steps [4, 5].

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A saturable reactor scheme of voltage regulation involves potentially large size and weight due to the necessity of a large saturating inductor [6, 7].

In the short shunt and long shunt configuration, the series capacitor used causes the problem of resonance while supplying power to an inductive load [8, 9].

The problems associated with schemes discussed above can be solved by applying nonlinear control to an inverter/rectifier system with a single DC capacitor on the DC link.

In this paper, a review of sliding mode control associated to the flux oriented control technique is applied to a self-excited induction generator. The vector control strategy is employed in order to reduce SEIG mathematical model complexity. The induction generator rotor flux is controlled by the d-axis stator current and the q-axis stator current controls the delivering active stator power.

2. INDUCTION GENERATOR MODEL

The state space model of induction generator in the synchronously rotating reference frame d and q axes are [10, 11]:

$$
\begin{cases}
\dfrac{d\,i_{sd}}{dt} = -\alpha_1\,i_{sd} + \omega_s\,i_{sq} + \alpha_2\,\varphi_{rd} + \omega_m\,\alpha_3\,\varphi_{rq} - \alpha_4\,V_{sd} \\[2mm]
\dfrac{d\,i_{sq}}{dt} = -\alpha_1\,i_{sq} - \omega_s\,i_{sd} + \alpha_2\,\varphi_{rq} - \omega_m\,\alpha_3\,\varphi_{rd} - \alpha_4\,V_{sq} \\[2mm]
\dfrac{d\,\varphi_{rd}}{dt} = \dfrac{M}{\tau_r}\,i_{sd} - \dfrac{1}{\tau_r}\,\varphi_{rd} + \left(\omega_s - \omega_m\right)\varphi_{rq} \\[2mm]
\dfrac{d\,\varphi_{rq}}{dt} = \dfrac{M}{\tau_r}\,i_{sq} - \dfrac{1}{\tau_r}\,\varphi_{rq} - \left(\omega_s - \omega_m\right)\varphi_{rd}
\end{cases}
\tag{1}
$$

where,

$$
\alpha_1 = \frac{1}{\sigma\,\tau_s} + \frac{1-\sigma}{\sigma\,\tau_r}, \quad \alpha_2 = \frac{1-\sigma}{M\,\sigma\,\tau_r}, \quad \alpha_3 = \frac{1-\sigma}{M\,\sigma} \text{ and } \alpha_4 = \frac{1}{\sigma\,L_s}
$$

with, $\quad \tau_s = \dfrac{L_s}{R_s}$ and $\tau_r = \dfrac{L_r}{R_r}$

And the model of the PWM converter is:

$$
\begin{cases}
V_{sd} = \dfrac{1}{2}S_d\,V_{dc} \\[2mm]
V_{sq} = \dfrac{1}{2}S_q\,V_{dc}
\end{cases}
\tag{2}
$$

$$
C\frac{d\,V_{dc}}{d\,t} = \frac{1}{2}\left(S_d\,i_{sd} + S_q\,i_{sq}\right) - \frac{V_{dc}}{R}
\tag{3}
$$

Where,

s and r denote stator and rotor quantities and subscripts d and q are used to indicate direct and quadrature axis, respectively.

V, i and φ represent instantaneous voltages, currents and fluxes respectively, V_{dc} is the DC voltage.

R_s, R_r and R are the stator, rotor and load resistances respectively, C is the capacitor in the DC side.

L_s, L_r and M are stator, rotor and magnetizing inductances respectively.

S_d and S_q are the Park's transformation of the switching functions S_a, S_b and S_c for the PWM technique and their state is defined by the following function:

$$S_k = \begin{cases} +1, & \overline{S_k} = -1 \\ -1, & S_k = +1 \end{cases} \quad \text{for } k = a, b, c$$

When the induction generator is operated under the vector control conditions, the rotor flux estimator can be expressed as ($\varphi_{rd} = \varphi_r$ and $\varphi_{rq} = 0$):

$$\frac{d\varphi_r}{dt} = \frac{M}{\tau_r} i_{sd} - \frac{1}{\tau_r} \varphi_r \tag{4}$$

and the synchronous frame velocity is given by:

$$\omega_s = \omega + \frac{M}{\tau_r} \frac{i_{sd}}{\varphi_r} \tag{5}$$

The variables to be controlled are the rotor flux φ_r and the DC voltage V_{dc} in the DC side.

3. CASCADE SLIDING MODE CONTROL

3.1 General concept

The variable structure system and their associated sliding regimes are characterized by a discontinuous nature of the control action with which a desired dynamic of the system is obtained by choosing appropriate sliding surfaces.

The control actions provide the switching between subsystems which give a desired behavior of the closed loop system [10], [12-16].

The general form of sliding surface which guarantees the convergence of the state x to its reference $x*$ is given as follows:

$$S(x) = \left(\frac{d}{dt} + \lambda \right)^{r-1} (x* - x) \tag{6}$$

where r is the degree of the sliding surface and λ is a strictly positive constant.

It is the first convergence condition which permits dynamic system to converge to wards the sliding surfaces.

It is a question of formulating a positive scalar function $V(x) > 0$ for the system states variables which are defined by the following Lyapunov function:

$$V(x) = \frac{1}{2} S^2(x) \tag{7}$$

To cause the Lyapunov function decreases, it is necessary to ensure that its derivative is negative. This is checked if:

$$\dot{S}(x) \cdot S(x) < 0 \tag{8}$$

Now, to define the control algorithm for the induction generator, it contains two terms, first for the exact linearization, the second discontinuous one for the system stability.

$$U_c = U_{eq} + U_n \tag{9}$$

- U_{eq} is calculated starting from the expression $\dot{S}(x) = 0$.

- U_n is given to guarantee the attractivity of the variable to be controlled towards the commutation surface.

To find the control expression U_c, let us consider a class of nonlinear system described by the following equation:

$$\dot{x} = f(x) + g\,U_c \tag{10}$$

where: x : state vector, U_c : Controls inputs and f , g are smooth vector fields,

Therefore:

$$\dot{S}(x) = \frac{\partial S}{\partial t} = \frac{\partial S}{\partial x}\frac{\partial x}{\partial t} \tag{11}$$

We substitute Eqs. (9) and (10) into (11), we get:

$$\dot{S}(x) = \frac{\partial S}{\partial x}\left(f(x) + g\,U_{eq}\right) + \frac{\partial S}{\partial x}\,g\,U_n \tag{12}$$

when the sliding mode is reached the surface is cancelled and consequently its derivative also $\dot{S} = 0$

Therefore the equivalent control U_{eq} can be written as:

$$U_{eq} = -\left(\frac{\partial S}{\partial x}g\right)^{-1}\frac{\partial S}{\partial x}\,f(x) \tag{13}$$

By replacing U_{eq} in Eq. (12), we obtain:

$$\dot{S}(x) = \frac{\partial S}{\partial x}g\,U_n \tag{14}$$

and the attractivity condition expressed by Eq. (8) becomes:

$$S(x)\frac{\partial S}{\partial x}g\,U_n \tag{15}$$

In order to satisfy this condition, the sign of U_n must be opposed to the one of $S(x)\frac{\partial S}{\partial x}g$.

The simplest equation is the form of relay:

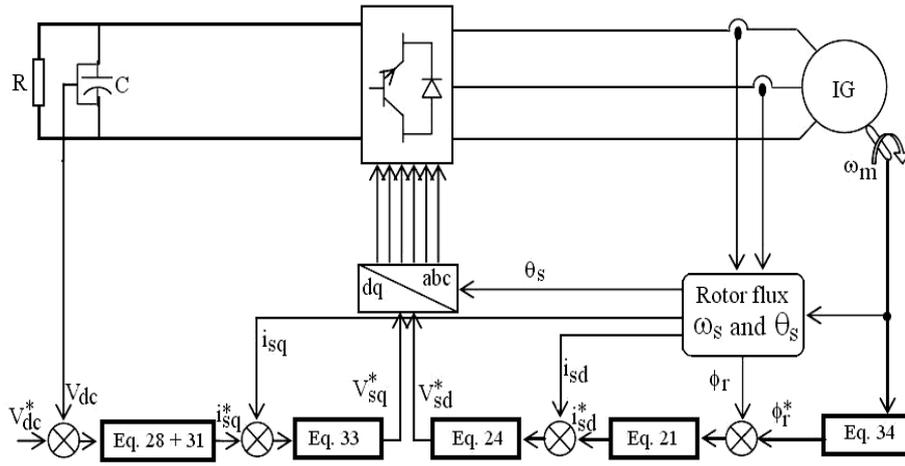$$U_n = k.\mathrm{sign}(S) \tag{16}$$

Fig. 1: Control structure proposed

3.2 Application to the SEIG control

In this study, the sliding mode theory is applied to the rotor field oriented induction generator model, in such a way as to obtain simple surfaces. The proposed Self-Excited Induction Generator, 'SEIG' control scheme is shown in Fig. 4.

It consists of an SEIG, a three phase converter connected to the IG terminals, a DC link voltage and finally a DC load in the DC side converter.

For the IG sliding mode controllers design, four switching surfaces are chosen as:

$$
\begin{cases}
S_1\left(\varphi_r\right) = \varphi_r - \varphi_r^* \\
S_2\left(i_{sd}\right) = i_{sd} - i_{sd}^* \\
S_3\left(V_{dc}\right) = V_{dc} - V_{dc}^* \\
S_4\left(i_{sq}\right) = i_{sq} - i_{sq}^*
\end{cases}
\tag{17}
$$

In order that $S \rightarrow 0$ in finite time, the control law is designed such that:

$$
\begin{bmatrix}
\dot{S}_1 \\
\dot{S}_2 \\
\dot{S}_3 \\
\dot{S}_4
\end{bmatrix}
= -
\begin{bmatrix}
k_1 . \mathrm{sign}\left(S_1\right) \\
k_2 . \mathrm{sign}\left(S_2\right) \\
k_3 . \mathrm{sign}\left(S_3\right) \\
k_4 . \mathrm{sign}\left(S_4\right)
\end{bmatrix}
\tag{18}
$$

We have:

$$
\dot{S}_1 = \dot{\varphi}_r - \dot{\varphi}_r^*
\tag{19}
$$

Eqs. (4) and (19) yield:

$$
\frac{M}{\tau_r}i_{sd} - \frac{1}{\tau_r}\varphi_r = -k_1 . \mathrm{sign}\left(S_1\right)
\tag{20}
$$

The direct stator current set value is deduced as:

$$i_{sd}^{*} = \frac{\tau_r}{M}\left(-k_1 . sign(S_1) + \frac{1}{\tau_r}\varphi_r\right) \tag{21}$$

With the same manner, the direct stator current surface derivative is:

$$\dot{S}_2 = \dot{i}_{sd} - \dot{i}_{sd}^{*} \tag{22}$$

So:

$$-\alpha_1 i_{sd} + \omega_s i_{sq} + \alpha_2 \varphi_{rd} - \alpha_4 V_{sd} - \dot{i}_{sd}^{*} = -k_2 . sign(S_2) \tag{23}$$

Taking into account the Eqs. (1) and (20), we obtain:

$$V_{sd}^{*} = \frac{1}{\alpha_4}\left(k_2 . sign(S_2) - \alpha_1 i_{sd} + \omega_s i_{sq} + \alpha_2 \varphi_r - \dot{i}_{sd}^{*}\right) \tag{24}$$

The best way to calculate the V_{dc} area is to put it into the following form:

$$P^{*} = V_{dc} I_{dc} = V_{dc}\left(C\frac{d V_{dc}}{dt} + \frac{V_{dc}}{R}\right) \tag{25}$$

Therefore:

$$\frac{d V_{dc}}{dt} = \frac{1}{C V_{dc}}\left(P^{*} - \frac{V_{dc}^2}{R}\right) \tag{26}$$

The surface of DC voltage is given by:

$$\dot{S}_3 = \dot{V}_{dc} - \dot{V}_{dc}^{*} \tag{27}$$

Eqs. (18) and (26) give:

$$P^{*} = \frac{V_{dc}^2}{R} - C V_{dc} k_3 . sign(S_3) \tag{28}$$

When losses are not taken into account, the electromagnetic torque will be given by:

$$T_{em} = \frac{P^{*}}{\Omega} \tag{29}$$

Since:

$$T_{em} = p\frac{M}{L_r}\varphi_r i_{sq} \tag{30}$$

Then:

$$i_{sq}^{*} = \frac{L_r}{\omega M}\frac{P^{*}}{\varphi_r} \tag{31}$$

Finally, the surface of i_{sq} is given by:

$$\dot{S}_4 = \dot{i}_{sq} - \dot{i}_{sq}^*$$ (32)

Taking into account the Eqs. (1), (18) and (32), the quadrature stator voltage component reference value is computed as:

$$V_{sq}^* = \frac{1}{\alpha_4}\left(k_4.sign(S_4) - \omega_s\, i_{sd} - \alpha_1\, i_{sq} - \omega_m\, \alpha_3\, \varphi_r - \dot{i}_{sq}^*\right)$$ (33)

The reference rotor flux linkage required at any speed is calculated based on this maximum flux linkage, which corresponds to the minimum rotor speed.

Hence at any rotor speed the reference rotor flux linkage is given by equation (34) and graphically its variation with rotor speed is shown in Fig. 2, [17]:

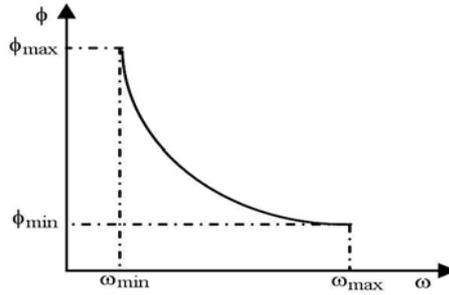$$\varphi_r^* = \frac{\omega_{min}\ \varphi_{r\,max}}{\omega}$$ (34)

Fig. 2: Relationship between rotor speed and rotor flux linkage.

4. SIMULATION RESULTS

The proposed control has been simulated for an induction machine with the following parameters (1.5 kW, $\cos\varphi = 0.8$, 4 poles, 220 V (rms)), whose per-phase equivalent circuit constants are:

$$L_s = L_r = 0.274\ H\ ,\ M = 0.258\ H\ ,\ R_s = 4.85\Omega\ \text{and}\ R_r = 3.805\Omega$$

The DC voltage regulation is obtained using the proposed algorithm controller in spite of the presence of disturbances such as step changing of the resistive load and the mechanical speed (when the SEIG is driven by a wind turbine for example).

Figure 3, shows a no-load operation flowed-up by a step changing of the resistive load (250 Ω) introduced at $t = 0.6$ s when the DC-bus voltage is set to 600 V. A rapid response is obtained and the introduced perturbation is immediately rejected by the control system.

We also showed in the figure 4, the variation in d-axis, q-axis stator currents and electromagnetic torque in the rotating reference frame.

The figure 5 shows the stator current and the build up of generated voltage at the terminals of the induction generator.
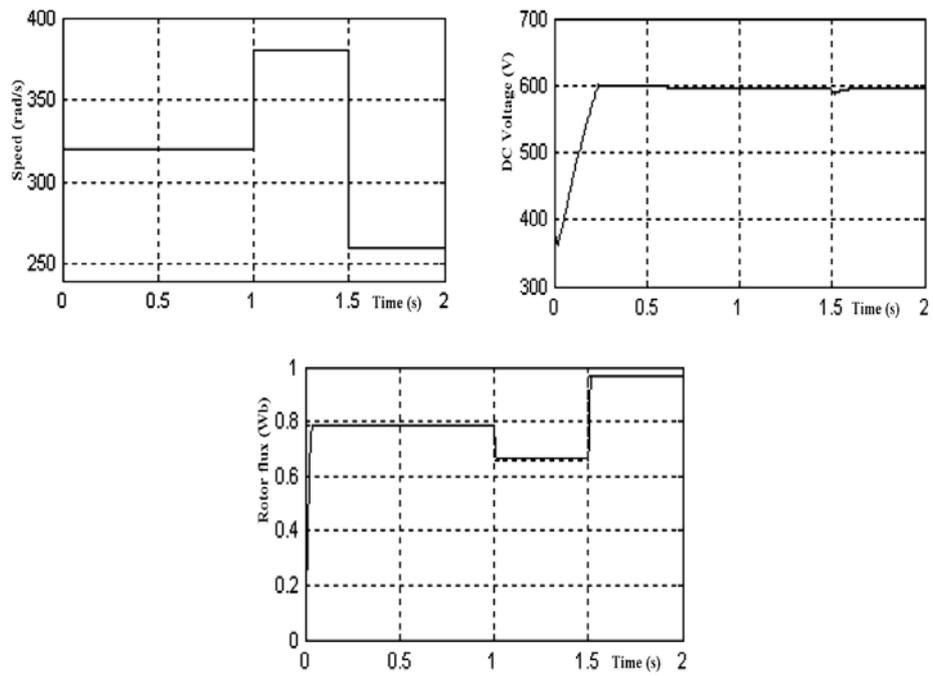
Fig. 3: DC voltage and rotor flux variation with speed and load variation
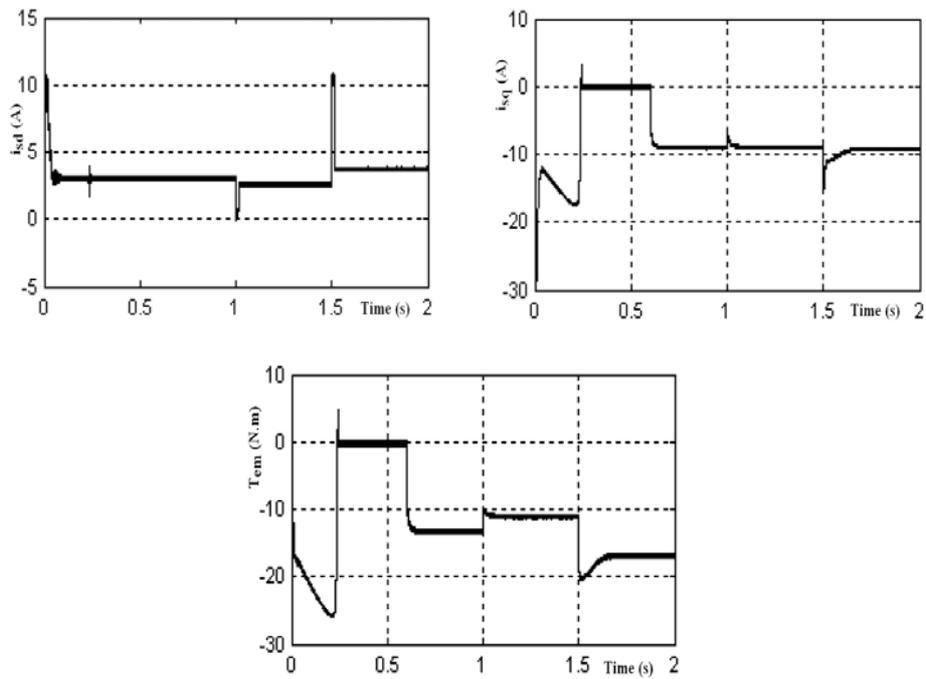

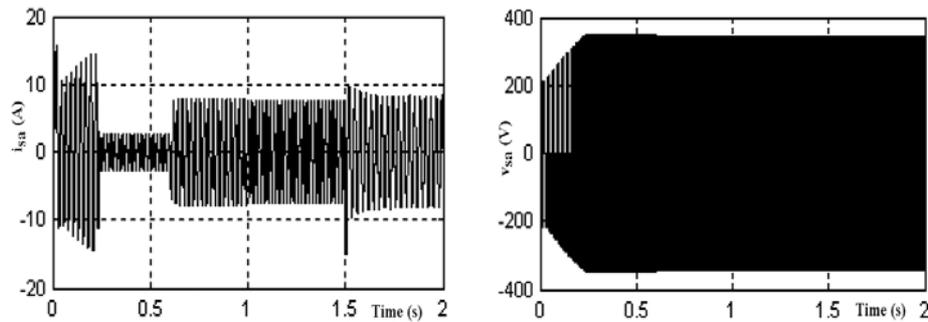Fig. 4: Dynamics of the SEIG during startup and load variation at 0.6 s

Fig. 5: Generated current and voltage at the terminals
of induction generator with load variation at 0.6 s

5. CONCLUSION

A variable speed system conversion using a SEIG with a PWM inverter is proposed.

Stable and independent control of the SEIG rotor flux estimated and the DC-bus voltage by applying the nonlinear sliding mode control is demonstrated.

In spite of taking in the account all the system parameters effects, the sliding mode control provides good dynamic performances of the global SEIG conversion system.

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