Nonlinear control of permanent magnet synchronous generators (PMSG) using feedback linearization

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Abstract - *This paper presents nonlinear control of permanent magnet synchronous generators using feedback linearization. Permanent-magnet synchronous generators (PMSGs) are commonly used for small variable-speed wind turbines to produce high-efficiency, high-reliability, and low-cost wind power generation. To eliminate the effects of nonlinearity caused by magnetic saturation, an input–output feedback linearization technique is applied to design the high-performance nonlinear current controllers. With this nonlinear control scheme, output voltage responses become faster than those in cascade control structures. Thus, the size of the output filter capacitor can be much reduced since fast voltage control is feasible. As with usual PWM power converters, in addition, the input current is regulated in a sinusoidal waveform. The proposed control scheme provides the wind generation system with the maximum efficiency and high dynamic performance.*

Résumé - *Ce papier présente de contrôle non linéaire des générateurs synchrones à aimants permanents à l'aide de la commande non linéaire. Générateurs synchrones à aimants permanents (PMSGs) sont couramment utilisés pour les petites éoliennes à vitesse variable pour produire à haut rendement et haute fiabilité, et la production à faible coût de l'énergie éolienne. Pour éliminer les effets du non linéarité causée par la saturation magnétique, une technique d'entrées-sorties linéarisation est appliquée à la conception de la haute performance non linéaire régulatrice de courant. Avec ce système de contrôle non linéaire, la tension de sortie des réponses plus rapides que ceux des structures de régulation en cascade. Ainsi, la taille de la sortie du condensateur de filtrage peut être très réduite lorsque la tension de contrôle de la tension est ssible. Comme d'habitude avec les convertisseurs de puissance PWM, en outre, le courant d'entrée a une forme d'onde sinusoïdale. Le schéma de contrôle proposé prévoit le système de production d'énergie éolienne avec le maximum d'efficacité et des performances dynamiques élevées.*

Keywords: Feedback - PMSG - Nonlinear - PWM - IGBT.

1. INTRODUCTION

The PMSG is a regular Synchronous Machine, where the DC excitation circuit is replaced by permanent magnets, by this eliminating the brushes. Without the brushes and the slip rings, and because of the permanent magnets, the PMSG has a smaller physical size, a low moment of inertia which means a higher reliability and power density per volume ratio.

Also by having permanent magnets in the rotor circuit, the electrical losses in the rotor are eliminated. Due to the mentioned advantages, the PMSG are becoming an interesting solution for wind turbine applications. [1]

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The use of permanent-magnet synchronous machines 'PMSMs' for wind power generation has received increasing attention in recent years. The PMSMs can provide high-efficiency and high-reliability power generation, since there is no need for external excitation and no copper losses in the rotor circuits. In addition, the high-power-density PMSMs are small in size, which reduces the cost and weight of wind turbines.

Furthermore, in the wind generation system equipped with a PMSM and power-electronic converters, the wind turbine can be operated to extract the maximum power from the wind at various wind speeds by adjusting the shaft speed optimally.

Therefore, the PMSMs are commonly used for small variable-speed wind turbines to produce high-efficiency, high-reliability, and low-cost wind power generation.

Among various PMSMs, the interior PMSM 'IPMSM' can offer high-efficiency and high-controllability generation by utilizing the reluctance torque, in addition to the magnet torque and achieve a constant power in a wide speed range by utilizing flux weakening along the $d-axis$.

However, due to the effect of magnetic saturation, the $q-axis$ inductance of the IPMSM varies depending on the $q-axis$ stator current. Consequently, the generated electrical torque and EMF of the IPMSM are nonlinear functions of the stator currents.

In addition, in an IPMSM, both $d-axis$ and $q-axis$ components of the stator currents contribute to the developed torque. As a result, the system nonlinearity becomes severe if the IPMSM operates in the flux weakening region where the $d-axis$ stator-current component $i_d = 0$.

This nonlinearity complicates direct application of well-developed linear-system theory. To solve this problem, nonlinear control schemes have been developed to improve the performance of the IPMSMs, [2].

Many research results focusing on the control point view have been reported. Reference analyzed design methods and the performance of the voltage and current proportional plus integral (PI) controllers, which are usually made up of inner current control loops and an outer voltage control loop in a cascade structure. The cascade control structure is not so effective for the system control of which both dynamics are close to each other.

The PWM converter have been modelled in a single nonlinear system using a power balance concept between the input and output sides. There however, the nonlinear system was analyzed and the controllers were designed using small-signal analysis, which is valid only around specified operating points, not in the whole operating rang.

On the other hand, a linearization technique using input-output feedback was applied to the electric motor drives, were the electrical and mechanical dynamics of the motor were modelled in nonlinear system. [3]

2. MATHEMATICAL MODEL OF THE PMSG

The dynamic model of PMSG has been built in the $d-q$ rotating reference frame, where the $q-axis$ goes ahead 90 from the $d-axis$ with respect to the direction of rotation. The electrical model of the PMSG in the $d-q$ synchronous reference frame, with the voltage and torque equations are given by [4, 5]:

$$V_d = -R_s \times I_d - \frac{d}{dt}\varphi_d + \omega_r \times \varphi_q \tag{1}$$

$$V_q = -R_s \times I_q - \frac{d}{dt}\varphi_q - \omega_r \times \varphi_d \tag{2}$$

$$\varphi_d = L_d \times I_d + \varphi \tag{3}$$

$$\varphi_q = L_q \times I_q \tag{4}$$

And the electromagnetic torque T_e is given by, [6]:

$$T_e = \frac{3}{2} P \times \left[(L_d - L_q) \times I_d \times I_q + I_q \times \varphi \right] \tag{5}$$

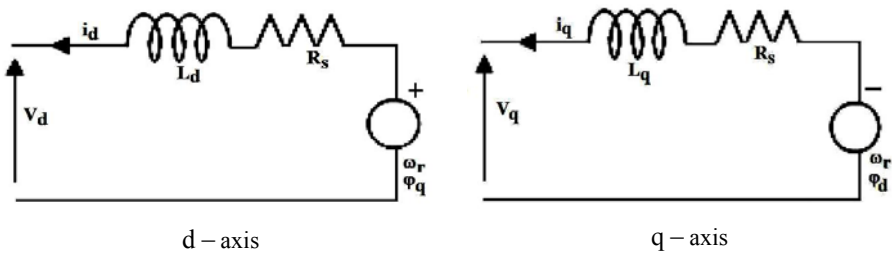d − axis   q − axis

Fig. 1: Equivalent circuit of a PMSG in the synchronous reference frame

For fast voltage control, the input power should supply instantaneously the sum of load power and charging rate of the capacitor energy. By the power balance between the ac input and the dc output.

$$p = \frac{3}{2} \times (e_d . I_d + e_q . I_q) = V_{dc} \times I_{dc} \tag{6}$$

Where V_{dc} and i_{dc} are the dc output voltage and current, respectively, and the resistance loss and the switching device loss are neglected.

On the dc output side

$$i_{dc} = C \times \frac{d V_{dc}}{dt} + I_L \tag{7}$$

Where i_{dc} is the load current. From (6) and (7)

$$\frac{3}{2} \times (e_d . I_d + e_q . I_q) = C \times V_{dc} \times \frac{d V_{dc}}{dt} + V_{dc} \times I_L \tag{8}$$

Equation (8) represents that the system is nonlinear with regard to V_{dc}. From (1), (2), and (6), a statespace modelling of the system is given by.

$$
\begin{bmatrix} \dot{I}_d \\ \dot{I}_q \\ \dot{V}_{dc} \end{bmatrix} = \begin{bmatrix} -\dfrac{R_s}{L_d} \times I_d + \dfrac{L_q}{L_d} P I_q \,\omega \\ -\dfrac{R_s}{L_q} \times I_q - \dfrac{L_d}{L_q} P I_q \,\omega \\ \dfrac{3}{2C \times V_{dc}} (e_d \times I_d + e_q \times I_q) \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L_d} & 0 \\ 0 & \dfrac{1}{L_q} \\ 0 & 0 \end{bmatrix} \times \begin{bmatrix} e_d - V_d \\ e_q - V_q \end{bmatrix} \qquad (9)
$$

3. FEEDBACK LINEARIZATION

Before applying the nonlinear control to the PWM converter, a feedback linearization theory for multivariable systems is described, [3, 7].

Consider a multi-input multi-output (MIMO) system as follows:

$$
\dot{x} = f(x) + g \times u \qquad (10)
$$

$$
y = h(x) \qquad (11)
$$

where, x, State vector; u, Control inputs; y, Outputs; f, g, Smooth vector fields; h, Smooth scalar function:

An approach to obtain the input-output linearization of the MIMO system is to differentiate the output y of the system until the inputs appear. By differentiating (11),

$$
\dot{y}_i = L_f \times h_i + \sum_{i=1}^{m} (L_{gi} h_i) u_i \qquad (12)
$$

where $L_f \times h$ and $L_g \times h$ represent lie derivatives $h(x)$ with respect to $f(x)$ and $g(x)$, respectively. If $L_{gj} \times h_i(x) = 0$ for all i, then the inputs do not appear and we have to differentiate repetitively as

$$
y_i^{ri} = L_i^{ri} \times h_i + \sum_{i=1}^{m} (L_{gi} L_f^{ri-1} h_i) \times u_i \qquad (13)
$$

with $L_{gi} \times L_f^{ri-1} \times h_i(x) \neq 0$ for at least one i. If we perform the above procedure for each output y_i, we can obtain a total of m equation in the above form, which can be written compactly as:

$$
\begin{bmatrix} y_1^{(r_1)} \\ \dots \\ \dots \\ y_m^{(r_m)} \end{bmatrix} = \begin{bmatrix} L_f^{r_1} h_1(x) \\ \dots \\ \dots \\ L_f^{r_m} h_m(x) \end{bmatrix} + E'(x) \times \begin{bmatrix} u_1 \\ \dots \\ \dots \\ u_m \end{bmatrix} \qquad (14)
$$

Where the $m \times x$ matrix $E(x)$ is defined as:

$$E(x) = \begin{bmatrix} L_{g1} \times L_f^{r_1-h_1} & \cdots & L_{gm} \times L_f^{r_1-h_1} \\ L_{g1} \times L_f^{r_m-h_m} & \cdots & L_{gm} \times L_f^{r_{1m}-h_m} \end{bmatrix} \tag{15}$$

The matrix $E(x)$ is called the decoupling matrix for the MIMO system. If the $E(x)$ is non-regular, then the input transformation can be obtained as:

$$u = -E^{-1}(x) \times \begin{bmatrix} L_f^{r_1 \times h_1(x)} \\ L_f^{r_m \times h_m(x)} \end{bmatrix} + E^{-1}(x) \times \begin{bmatrix} u_1 \\ u_m \end{bmatrix} \tag{16}$$

Substituting (14) into (16) results in a linear differential relation between the output y and u.

$$\begin{bmatrix} y_1^{(r_1)} \\ y_m^{(r_m)} \end{bmatrix} = \begin{bmatrix} u_1 \\ u_m \end{bmatrix} \tag{17}$$

Note that the above input – output relation is decoupled, in addition to being linear.

4. THE FEEDBAK LINEARIZATION APPLICATION

Figure 2, shows the proposed nonlinear control using feedback linearization.
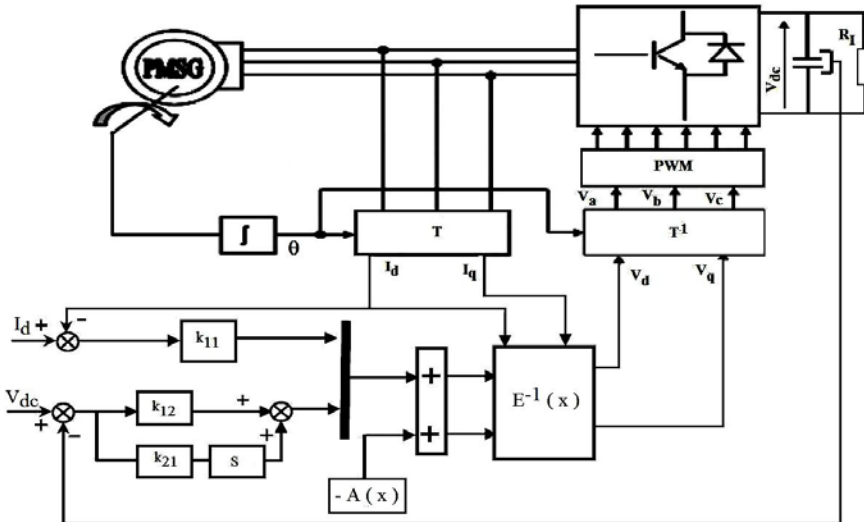

Fig. 2: Block diagram of DC voltage regulation of PMSG using nonlinear control

When the PMW converter dynamic model of (9) is expressed in the form of (10) and (11), we obtain: [3]

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{bmatrix} = \begin{bmatrix} -\dfrac{R_s}{L_d} \times I_d + \dfrac{L_q}{L_d} P I_q \omega \\ -\dfrac{R_s}{L_q} \times I_q - \dfrac{L_d}{L_q} P I_q \omega \\ \dfrac{3}{2C \times x_3} E x_2 - \dfrac{I_L}{C} \end{bmatrix} \tag{18}$$

$$g = \begin{bmatrix} g_1 & 0 \\ 0 & g_2 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} \dfrac{1}{L_d} & 0 \\ 0 & \dfrac{1}{L_q} \\ 0 & 0 \end{bmatrix} \tag{19}$$

$$X = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} = \begin{bmatrix} I_d \\ I_q \\ u_{dc} \end{bmatrix} \tag{20}$$

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} e_d - u_d \\ e_q - u_q \end{bmatrix} \tag{21}$$

Where $E = e_q$ and $e_d = 0$

Since there are two control inputs for the given system, we should have two outputs for input-output decoupling. One control input is used to regulate the input line current and the other is for the capacitor voltage. If the system is required to operate at unity power factor, the reactive component i_{de} of the line current should be zero. Then, we choose the two outputs as:

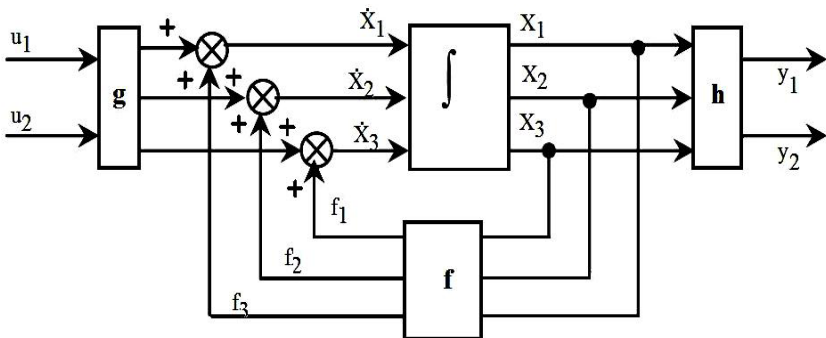$$y_1 = x_1 = I_d \tag{22}$$

$$y_2 = x_3 = V_{dc} \tag{23}$$

Fig. 3: Nonlinear model block diagram

From (10), (11) and (18)-(23), the nonlinear model block diagram of the PWM converter is given in figure 2.

Differentiating y_1 and y_2 until a control input appears and arranging them in the form of (14), [8, 9].

$$\begin{bmatrix} \dot{y}_1 \\ \ddot{y}_2 \end{bmatrix} = A(x) + E(x) \times \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{24}$$

where

$$A(x) = \begin{bmatrix} f_1 \\ \dfrac{3}{2CV_{dc}} E f_2 - \dfrac{3f_3}{2Cx_3} E x_2 + \dfrac{\dot{I}_L}{C} \end{bmatrix} \quad ; \quad E(x) = \begin{bmatrix} g_1 & 0 \\ 0 & \dfrac{3Eg_2}{2Cx_3} \end{bmatrix}$$

Since $E(x)$ is non-singular in the operating rate of V_{dc}, the control law is given from (24) as

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = E^{-1}(x) \times \left[-A(x) + \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \right] \tag{25}$$

where

$$E^{-1}(x) = \begin{bmatrix} \dfrac{1}{g_1} & 0 \\ 0 & \dfrac{2Cx_3}{3Eg_2} \end{bmatrix}$$

For tracking control, the new control inputs are given by:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} \dot{y}_{1ref} - k_{11} e_1 \\ \dot{y}_{2ref} - k_{21} \dot{e}_2 - k_{22} e_2 \end{bmatrix} \tag{26}$$

Where $e = y - y_{ref}$ and $\dot{e} = \dot{y} - \dot{y}_{ref}$. Then, the output errors are governed by:

$$\dot{e}_1 + \dot{k}_{11} \times e_1 = 0 \tag{27}$$

$$\ddot{e}_2 + k_{21} \times \dot{e}_2 + k_{22} \times e_2 = 0 \tag{28}$$

By locating the desired poles on the left-half plane, the gains k_{ij} are calculated and asymptotic tracking control to the reference is achieved.

Even through the nonlinear system can be linearized by exact feedback linearization, there may exist a tracking error in the presence of parameter variations.

5. CONVERTER

The equivalent circuit of a voltage source converter is presented in Fig. 4. A sit can be seen in the figure, a three phase converter has 6 semiconductors (IGBTs) displayed in three legs: a , b and c .

The 6 semiconductors are considered as ideal switches. Only one switch on the same leg can be conducting at the same time. [1]
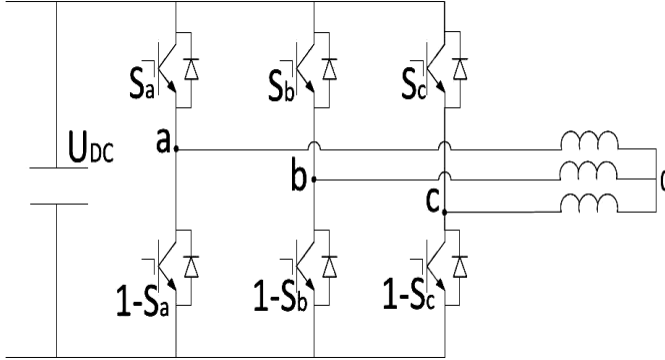

Fig. 4: Voltage source converter

In the figure, S_a, S_b, S_c are variables which represent the switching status for each leg. S can only have two values: 1 for the conduction state and 0 for the block state. The desired output voltages are obtained by programming the duty cycles of the 6 IGBTs.

According to for the connection presented in Fig.2 the applied voltages at the machine terminals, U_{an}, U_{bn} and U_{cn} and the DC-link current I_{dc} may be found as:

$$
\begin{bmatrix} U_{an} \\ U_{bn} \\ U_{ccn} \end{bmatrix} = \frac{U_{DC}}{3} \times \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \times \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{29}
$$

$$
I_{DC} = \begin{bmatrix} S_a & S_b & S_c \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{30}
$$

And the model of the PWM converter is:

$$
\begin{cases} V_{sd} = \dfrac{1}{2} S_d \times V_{dc} \\ V_{sq} = \dfrac{1}{2} S_q \times V_{dc} \end{cases} \tag{31}
$$

$$
C \frac{d V_{dc}}{d t} = \frac{1}{2} \left(S_d \times V_{dc} + S_q \times V_{dc} \right) - \frac{V_{dc}}{R_L} \tag{32}
$$

V_{dc} is he DC voltage.

6. SIMULATION RESULTS

Extensive simulations have been performed using Matlab/Simulink software to examine control algorithm of the nonlinear Control of permanent magnet synchronous generator.

In order to vali1date the control strategies as discussed, digital simulation studies were made the system described in figure 2.

Three phases PMSG parameters:

$R_s = 1.4\ \Omega$; $\varphi = 0.15$ Wb ; $L_d = 6.6$ mH ; $L_q = 5.8$ mH ; $f = 0.00038$ N.m.s/rad ; $J = 0.00176$ kg.m^2.

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)

The validity of the control is demonstrated through the results shown in Fig. 5, 6, 7, the response for step in DC voltage command is chow in Fig. 5, the DC voltage response is completely robust with perfect rejection of load disturbances,

Fig. 6, show the response of the components i_d and I_q. The stator currents which are controlled by PWM generated by nonlinear control.

High accuracy and strong robustness of the sliding mode control are providing by Fig. 7, when resistance load (100 Ω, 1000 Ω) are applied. A rapid response is obtained and the introduced perturbation is immediately rejected by the control system.
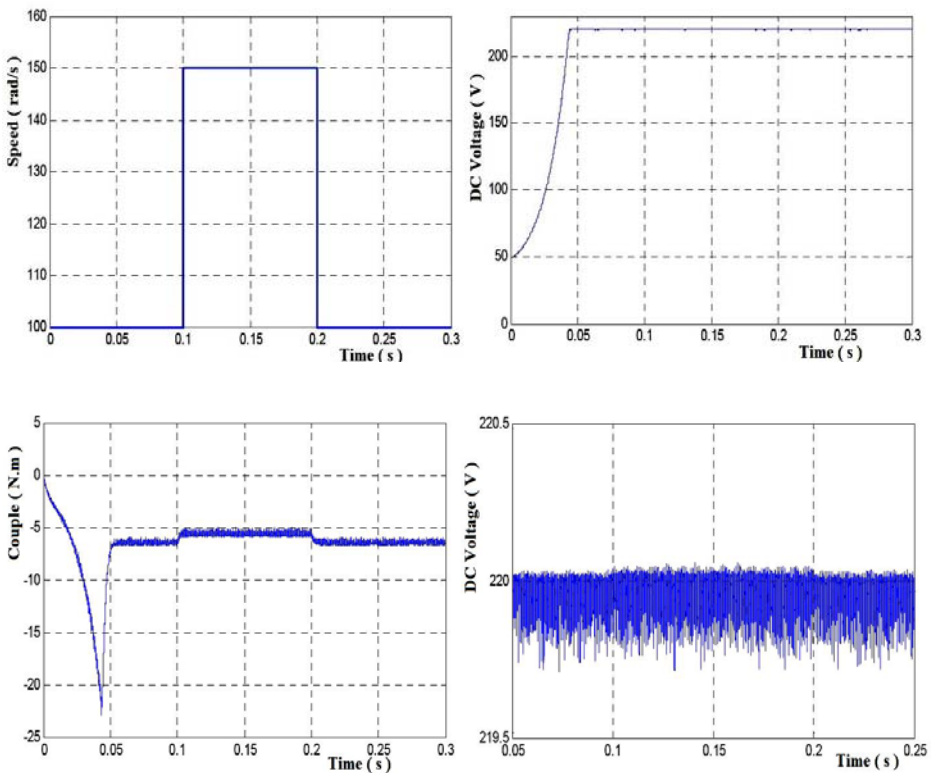

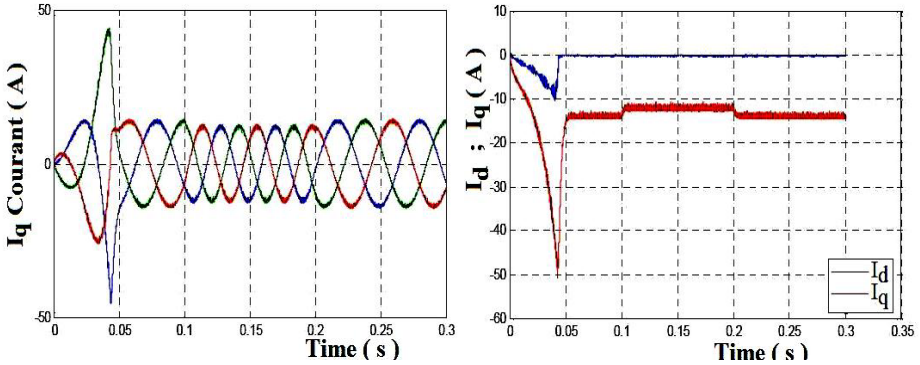Fig. 5: Response under load disturbance (variation of speed)
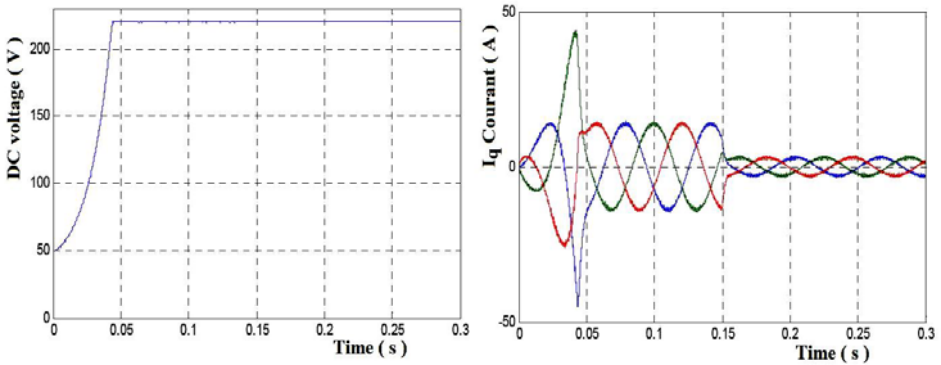
Fig. 6: Stator current under load disturbance

Fig. 7: Response under load disturbance (Variation of resistive load)

7. CONCLUSION

This paper proposes a robust nonlinear feedback linearization control scheme for a PMSG which guarantees the robustness in the presence of parameter variations and speed. For high-performance control of AC/DC PWM converts. Simulation Results show good performances obtained with proposed control, with a good choice of parameters of control. The DC voltage control operates with enough stability.

In this approach the components i_d and i_q is regulated using nonlinear control, so that i_d is zero, the controller is designed in the total system including switching devices. The simulation results show, Fast response without overshoot and robust performance to parametric variation and disturbances in all the system.

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