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Vector Control of PMSM Implemented by Photovoltaic Source

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Abstract: **- In this article we will establish the modeling and the field oriented control of permanent magnet synchronous machines, with a focus on their applications in variable speed domain in photovoltaic source.**

Keywords: **field oriented control, permanent magnet synchronous machines, the inverter, photovoltaic.**

I. INTRODUCTION

The permanent magnet synchronous motor (PMSM) has three phases winding on stator represented by the three axes (a, b, c) phase-shifted of 120 ° with respect to each other (Figure 1) and has permanent magnets in the rotor ensuring its excitation. Depending on how the magnets are placed, we can distinguish two types of rotors; in the first type, the magnets are mounted on the surface of the rotor with a homogeneous air gap, the motor is called "smooth air gap PMSM" and inductors are independent on the rotor position. In the second type, the magnets are mounted inside the rotor mass and the air gap will vary because of the salience effect. In this case, inductors are highly dependent on the rotor position. Synchronous motors have a remarkable feature; the speed is constant regardless of the load. The field oriented control (FOC) is used for many years. It implements Park transformation which shows, like a separately excited dc machine, the expression of the instantaneous torque as a product of magnetic flux and current. In addition, there is the possibility to reduce the oscillations for a desired torque, to save energy delivered, to reduce the current harmonics and to improve power factor. When the motor model used is correct, the FOC works well. [1] [2]

II. THE DYNAMIC MODEL OF A SYNCHRONOUS MOTOR

A. The Mathematical Model of the Permanent Magnet Synchronous Motor (PMSM)

The dynamic model of a permanent magnet synchronous motor with rotor reference frame can be described by the equations below, considering the conditions of non-saturation of the magnetic circuit and the magneto motive force MMF is a sinusoidal distribution created by the stator windings.

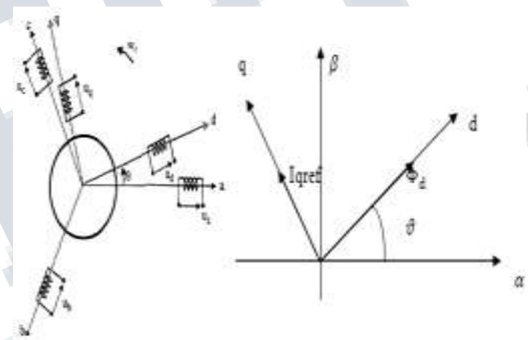

Fig. 1. Diagram representing stator winding in abc and dq frames

$$[V_{abc}] = [RI_{abc}] + \frac{d(\varphi_{abc})}{dt} \qquad (1)$$

$$[V_{abc}] = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}; [i_{abc}] = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}; [\varphi_{abc}] = \begin{bmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{bmatrix}$$

$$[R] = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \qquad (2)$$

With $V_{abc,} i_{abc,} \phi_{abc}$ representing the stator phases' voltages, the stator phases' currents and the total flux produced by the stator currents. *R* indicates the resistance of a stator phase.

Total fluxes are expressed by:

$$(\varphi_{abc}) = (L)(i_{abc}) + (\varphi'_{abc})$$

$$L=\begin{bmatrix} L_{ss} & M_s & M_s \\ M_s & L_{ss} & M_s \\ M_s & M_s & L_{ss} \end{bmatrix} \qquad (3)$$

L_{ss} and M_s representing the self-inductance and the mutual inductance between stator windings. ϕ'_{abc} is the rotor flux seen by the stator windings. It represents the amplitudes of the voltages induced in the stator phases without load. Substituting (3) in (1)

$$[V_{abc}]=(R)(i_{abc})+L\frac{d(i_{abc})}{dt}+\varphi'_{abc} \qquad (4)$$

The electromagnetic torque is expressed by:

$$T_e=\frac{1}{\omega_r}(e_{abc})^t(i_{abc}) \qquad (5)$$

Where $e_{abc}=\frac{d(\phi_{abc})}{dt}$ represents the electromotive forces generated by the stator phases.

ω_r Is rotation speed of the rotor in [rad/s]. Note that the system (4) leads to joined and highly non-linear equations. To simplify this problem, the majority of research in literature prefer to use the Park transformation which, by a transformation applied to real variables (voltages, currents and flux), provides fictive variables called dq components o Park's equations. Physically, this transformation is interpreted as a substitution for stationary windings (a,b,c) by rotating windings (d,q) which rotate with the rotor. This transformation makes the dynamic equations of AC motors simpler. The Park transformation is defined as follows:

$$(x_{dq0})=(K_\theta)(x_{abc}) \quad \text{------------} \ (6)$$

Where X may be a current, a voltage or a flux and θ is the rotor position. X_{dq} represent longitudinal and transversal components of the stator variables (voltages, currents, fluxes and inductances). The transformation matrix K_θ is by:

$$[K_\theta]=\sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & Cos\theta & -Sin\theta \\ \frac{1}{\sqrt{2}} & Cos\left(\theta-\frac{2\pi}{3}\right) & -Sin\left(\theta-\frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & Cos\left(\theta-\frac{4\pi}{3}\right) & -Sin\left(\theta-\frac{4\pi}{3}\right) \end{bmatrix} \qquad (7)$$

The inverse matrix

$$[K_\theta]^{-1}=[K_\theta]^t=\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ Cos\theta & Cos\left(\theta-\frac{2\pi}{3}\right) & Cos\left(\theta-\frac{4\pi}{3}\right) \\ -Sin\theta & -Sin\left(\theta-\frac{2\pi}{3}\right) & -Sin\left(\theta-\frac{4\pi}{3}\right) \end{bmatrix} \qquad (8)$$

Applying the transformation (6) to the system (1) we have the electrical equations in the d_q reference:

$$[V_d]=[R_sI_{sd}]+\frac{d(\varphi_{sd})}{dt}-\omega_r\varphi_{sq} \qquad (9)$$

$$[V_q]=[R_sI_{sq}]+\frac{d(\varphi_{sq})}{dt}-\omega_r\varphi_{sd} \qquad (10)$$

The flux equation:

$$\varphi_{sd}=L_{sd}i_{sd}+\varphi_f \qquad (11)$$

$$\varphi_{sq}=L_{sq}i_{sq} \qquad (12)$$

ϕ_f is the flux created by the magnets in the rotor. By replacing (11) and (12) and in $v_{q,}v_d$ we obtain the following equations:

$$V_d=R_si_{sd}+L_{sd}\frac{di_{sd}}{dt}-\omega_rL_{sq}i_{sq} \qquad (13)$$

$$V_q=R_si_{sq}+L_{sq}\frac{di_{sq}}{dt}+\omega_r\left(L_{sd}i_{sd}+\varphi_f\right) \qquad (14)$$

Equations (13) and (14) form a second order differential equation system that models the electrical behaviour of the synchronous permanent magnet [1] [2].

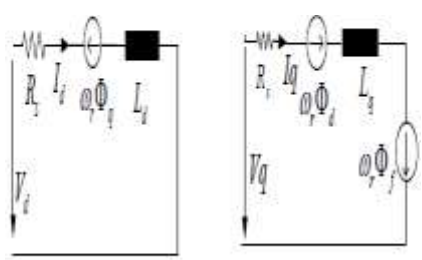

Fig. 2. Equivalent circuit of a permanent magnet synchronous motor in the dq frame

The electromagnetic torque (Te) is produced by the interaction between the poles formed by the rotor magnets and the poles generated by the MMF (stator currents) in the gap.

$$T_e = P\left(\varphi_{sd} i_{sq} - \varphi_{sq} i_{sd}\right) \qquad (15)$$

$$T_e = P\left(\varphi_g L_q + \left(L_d - L_q\right) i_d i_q\right) \qquad (16)$$

The equation of the mechanical torque is

$$T_e = J\frac{d\omega_m}{dt} + T_l + B_{\omega_m} \qquad (17)$$

$$J\frac{d\omega_m}{dt} = T_e - T_l - B_{\omega_m} \text{ and } \omega_m = \frac{\omega_r}{P} \qquad (18)$$

ω_m and ω_r represent the mechanical speed and the electrical speed respectively; with: *B, J, P,* and T_L respectively define the damping coefficient, moment of inertia of the rotor and the number of pairs of poles and the load torque.

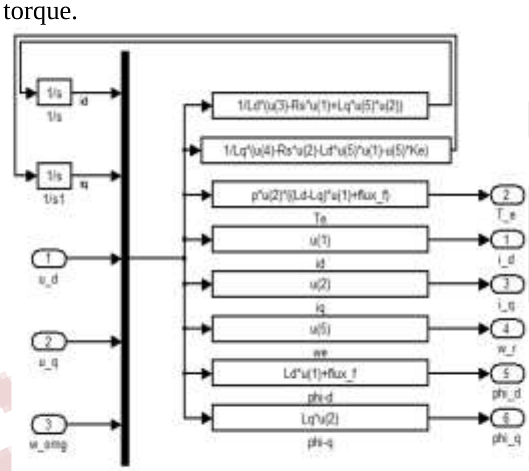

Fig. 3. Implementation of PMSM in Simulink in dq frame

We can deduce the final form of the equations of PMSM in the DQ frame

$$\begin{aligned}
\frac{di_{ds}}{dt} &= -\frac{R_s}{L_d} i_{ds} + \frac{L_q}{L_d}\omega_r P i_{qs} + \frac{V_d}{L_d} \\
\frac{di_{qs}}{dt} &= -\frac{R_s}{L_q} i_{qs} - \frac{L_d}{L_q}\omega_r P i_{ds} - \frac{\varphi_f}{L_q}\omega_{rp} + \frac{V_q}{L_q} \qquad (19) \\
\frac{d\omega_r}{dt} &= \frac{P}{J}\left[\varphi_f i_{qs} + \left(L_d - L_q\right) i_{ds} i_{qs}\right] - \frac{1}{J} T_L - \frac{B}{J}\omega_r
\end{aligned}$$

III. FIELD ORIENTED CONTROL PRINCIPAL

We can determine the reference torque to impose on the motor and the speed reference from the electromagnetic torque equation expressed in terms of Park's components shown in (16), if we impose the current $i_{sdref} = 0$

The torque's formula will be:

$$i_{sqref} = \frac{T_{e(ref)}}{P\varphi_f} \qquad (20)$$

To preserve the torque T_e proportional to the current i_{sq}, we must control the angle α = π / 2, and the angle α is determined by the following formula:

$$\alpha = arctg\left(\frac{i_{sq}}{i_{sd}}\right) \qquad (21)$$

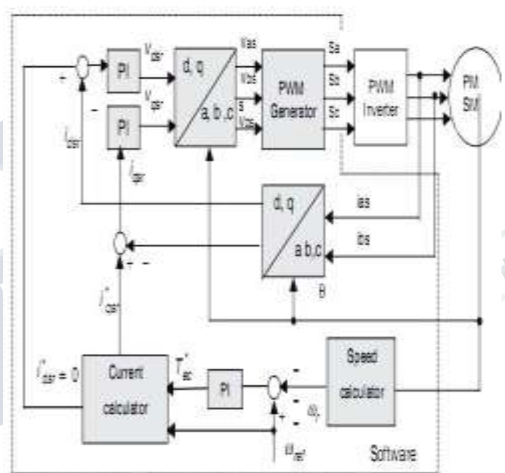

Fig. 4. Speed control principal of a PMSM

A. Inverter Modeling

The inverter transforms a DC voltage into an alternating voltage with a varying amplitude and frequency. Its bridge structure is composed mostly of electronic switches such as IGBTs, power transistors or thyristors. Its operating principle is based on controlled switching in a suitable manner (usually a pulse width modulation), the source is modulated to obtain a wanted AC signal frequency. Two types of inverters are used; the voltage inverter and the current inverter. The voltage inverter with six switches, supplied by the photovoltaic generator and operating in pulse-width modulation (PWM) is commonly used for this application[3].

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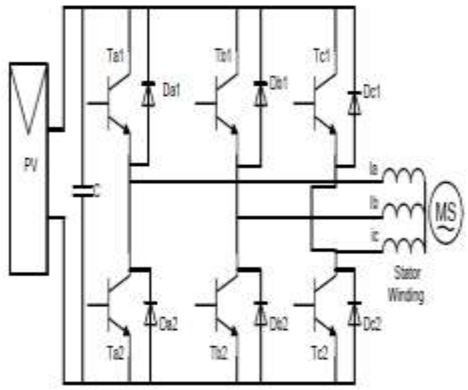


Fig. 5. PMSM supply using voltage inverter

B. The hysteresis current control technique

It is a simple technique directly interested in current control; it limits the maximum current and is less sensitive to load variations. this method is used to control the current of a to follow a sinusoidal reference current calculated from the currents i_{sdref}, i_{sqref} and from the rotor position ϕ. if the error, which is the difference between the reference current of a phase and the same phase current, reached the upper limit $\left(i_{ref} + \Delta I\right)$ the switch arm of the inverter corresponding to the same phase is started and connected to the (-) pole of the power source to reduce the current while, if the error reached the lower limit $\left(i_{ref} - \Delta I\right)$ the switch connected to the positive terminal of the power source should be started to increase the flow of the corresponding phase. The lower and upper limits of the hysteresis band ΔI are set by the motor absorbed current and the maximum switching frequency of switches respectively. A narrow band of hysteresis implies a current more similar to the sine wave with a low harmonic content, and a switching frequency higher and higher, and vice versa.

The current references are given by voltage inverter in such to force the phase currents of the motor These currents are sinusoidal functions of rotor position. They create in the gap a field with magnetic axis in quadrature with the axis of the magnets' field. They are in phase with the electromotive forces induced in these windings by the magnets. When the reference current in a phase deviates from its reference, each controller requires switching the switches of each inverter arm and keeps it within the hysteresis band ΔI [2].

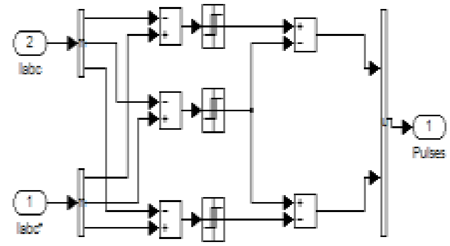
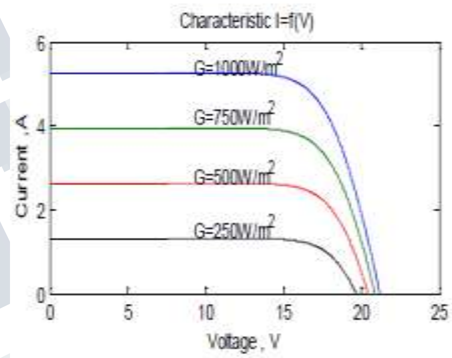


Fig. 6. Representation of hysteresis current control

C. Modeling of the photovoltaic cell

The photovoltaic generator which produces a continuous electrical current is represented by a standard model with a single diode, established by Shockley for a single PV cell and generalized to a PV module by considering it as a set of identical cells connected in series-parallel [4]



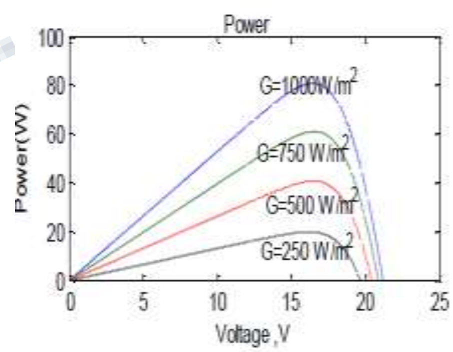


Fig. 8. Characteristics of the power function of the current and the voltage

IV. SPEED CONTROLLER DESIGN

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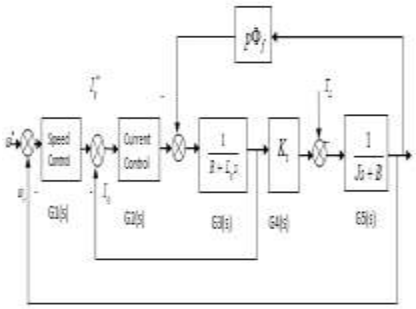

Fig. 9. Bloc diagram of a speed controlled PMSM drive

The design of the speed controller is important from the point of view of imparting desired transient and steady state characteristics to speed controlled PMSM drive system. A proportional pulse integral controller is sufficient for many industrial applications. Selection of the gain and time constant of such a controller by using the symmetric optimum principle is straightforward if the d axis stator current is assumed to be zero. In the presence of a d axis stator current, the d and q current channels are cross couples, and the model is nonlinear, as a result of the torque term.[5][6] A proportional plus integral (PI) controller is used to process the speed error between the speed reference and filtered speed feedback signals, the transfer function of the speed controller is given as:

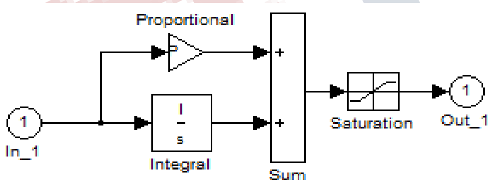

Fig. 10. Implantation the speed controller with saturation in Simulink

A. Current loop:

This induced EMF loop crosses the q axis current loop, and it could be simplified by moving the pick-off point for the induced EMF loop from speed to current output point. This gives the current loop transfer function [5].

V. LOAD TESTING WITH CONSTANT RESISTANCE TORQUE

The system established in Simulink for a drive system of PMSM with reference current hysteresis control method.

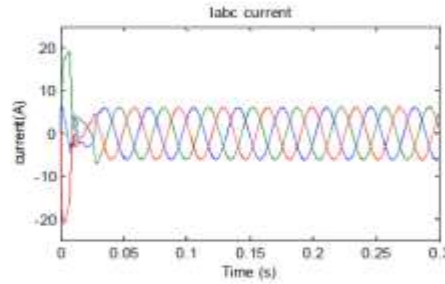

Fig. 11. Diagram of vers I_{abc} us time

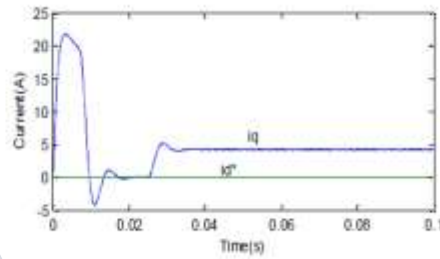

Fig. 12. Diagram of id and iq versus time

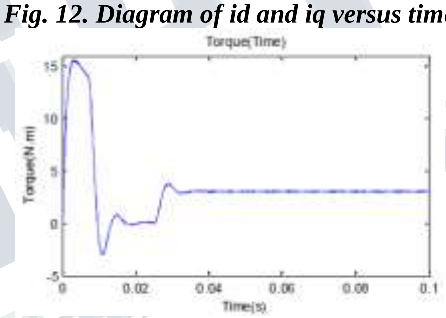

Fig. 13. Diagram of the torque versus time

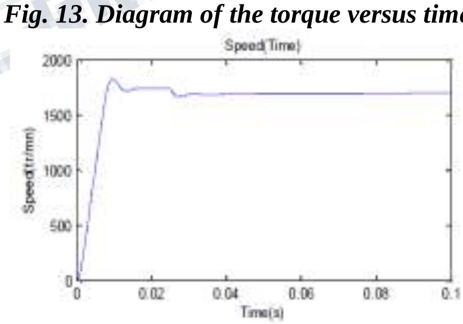

Fig. 14. Diagram of speed versus time

Figure 11 shows phase currents of the synchronous motor with permanent magnet. It is clear that the currents are not sinusoidal at startup and becomes sinusoidal when the motor reaches the steady state. The motor absorbs a high current at start-up. i_{dq} currents increase when the motor is controlled by oriented flux, the current i_d is zero ($i_d = 0$), while i_q current increases at start up then stabilizes in steady state. The torque *Te* developed by the motor follows the instructions properly;

its value at startup is five times the value of the rated torque.

Figure 14 shows speed variation versus time. Steady speed is the same as that of the commanded speed reference (1790tr/mn). Simulink program of Matlab is used for simulation tests The PMSM parameters used in the tests are as follows: stator Resistance Rs = 1.4 Ω, stator inductance $L_d = L_q = 0.0006$ Henry Magnet flux linkage φ_f 0.1679*Tesla* /*m*2 System inertia J = 0.01176 kg m2 , viscous friction coefficient B= 0.00338818 N.s/rad, DC link voltage using the Lookup Table block in Simulink. we insert the values of the voltage at the PV generator. rated electrical speed ω_n = 1850 tr/mn, pole pairs np = 3 The phase voltages are reconstructed from DC-bus voltage and duty cycle; motor currents are filtered by a three-order low pass filter with pass band edge frequency equal to 12666 rad/s

VI. CONCLUSION

The vector control is introduced in order to control the permanent magnet synchronous machine with maximum power. It is based on a transient model. It allows precise adjustment of the torque of the machine and can ensure torque at zero speed. In this paper, we have presented the principle of the permanent magnet synchronous motor field oriented control, fed by a voltage inverter in the presence of a speed loop with a PI corrector. We can conclude that the field oriented control has a good dynamic and static torque and flux results. View that the radiation and temperature are variable in the day it would be interesting in future work to introduce a buck or boost chopper between the PV generator and the inverter to extract maximum energy delivered by the photovoltaic generator.

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