2ème conférence Internationale des énergies renouvelables CIER-2014
Proceedings of Engineering and Technology - PET

Direct Torque Control for Switched Reluctance Motor (6/4) powered by PV array

B. Goumeidane[1], D. Rahem[1], A .Haddoun[1] and T. Bahi[2]
[1] LGEA Laboratory, Oum El Bouaghi University 04000, Algeria
[2]Electrical Engineering Department, Annaba University
rahem_djamel@yahoo.fr
tbahi@hotmail.com

***Abstract*— The performance, efficiency and peak torque characteristics of switched reluctance machines, combined with its typical robust, low cost construction make this technology an attractive alternative to other motor types. Because of nonlinearity and variables strongly coupling characteristic in SRM, there are lots of difficulties to model and control. This paper presents dynamic control technique called Direct Torque Control (DTC) for switched reluctance machine drives. The Direct Torque Control (DTC) technique can minimize the torque ripple by regulating torque within specified hysteresis band. In most practical situations involving motion control, vectorial command allows to command independently the flux and the electromagnetic torque. Indeed, there is attractive type of control called DTC, This type of control based on hysteresis regulators presents less performance at low speed and the commutation frequency is not controlled. For these reasons, we propose the implantation of a new approach of DTC confronted to the FOC strategy. Simulation of the switched reluctance machine supplied with a PWM voltage inverter is carried out. The results of simulation show that proposed DTC presents better performances and many advantages than vector control, such superior dynamic torque and speed response, simpler implementation and without speed sensor. The switched reluctance machines coupled with centrifugal pump has the better performance when directly powered by photovoltaic array. The best motor efficiency is obtained when extract the maximum power from PV array.**

***Keywords*— Switched reluctance machine; Direct torque control; PV array; Hysteresis; MPTT.**

I. INTRODUCTION

New types of electric motors like Permanent Magnet(PM) Motors, Switched Reluctance Motors (SRM) and Stepper Motors(SM) have emerged due to the development in engineering material technology and tremendous improvement in solid state devices and circuits. The switched reluctance motor (SRM) has considerable potentials for industrial and electric vehicle applications because of high reliability and fault tolerance. In addition, it's high speed ability, high efficiency, and low cost are very attractive features for industrial applications. They are known to have high-peak torque-to-inertia ratio and the rotor mechanical structure is well suited for high-speed applications [1], [2].

It is now recognized that the two high-performance control strategies for SRM are field-oriented control (FOC) and direct torque control (DTC). These control strategies are different on the operation principle but their objectives are the same. They aim both to control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any extraneous disturbances. Both control strategies have been successfully implemented in industrial products.

Direct Torque Control (DTC) was proposed by M. Depenbrock and Takahashi [3], [4]. Direct torque control (DTC) is known to produce quick and robust response in AC drives. However, during steady state notable torque, flux and current pulsations occur. They are reflected in speed estimation, speed response and also in increased acoustic noise.

This method presents the advantage of a very simple control scheme of stator flux and torque by two hysteresis controllers, which give the input voltage of the motor by selecting the appropriate voltage vectors of the inverter through a look-up-table in order to keep stator flux and torque within the limits of two hysteresis bands.

The use of photovoltaic as the power source for pumping water is one of the most promising areas in photovoltaic applications.

The high performances and advantages of this motor have given a scope to application in photovoltaic pumping system.

The purpose of this paper is to present a study direct torque control for switched reluctance motor coupled with water pump and powered by photovoltaic array.

II. MODEL OF SRM

Fig. 1 shows one conventional 6/4 three phase SRM structure.

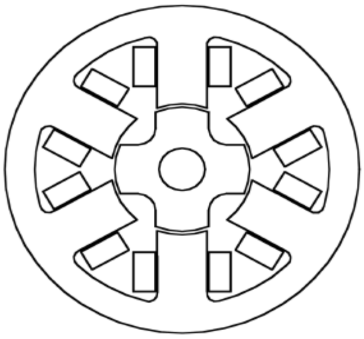


Fig.1: Conventional 6/4 SRM

A SR motor is a variable reluctance motor that is designed to convert energy efficiently. The motor is double salient, and it is essential for the machine operation that the number of rotor and stator poles be different. Torque is produced by the tendency of the rotor poles to align with the poles of the excited stator phase. A SRM is of very simple structure: its rotor is brushless and has no winding of any kind. The motor is singly excited from stator windings, which are concentric coils wound in series on diagonally opposite stator poles. Both rotor and stator are made of laminated iron.
The electrical and mechanical equations of the SRM in the rotor reference (d-q) frame as follows:

$$V_d = r_s\, i_{ds} + L_d \frac{di_{ds}}{dt} + p\Omega L_d\, i_{ds}$$
$$V_q = r_s\, i_{qs} + L_q \frac{di_{qs}}{dt} - p\Omega L_q\, i_{qs} \quad (1)$$

$$\phi_{dq} = A i_{dqs} \quad (2)$$

Where : $A = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}$

And the electromagnetic torque C_e is given by:

$$C_e = \frac{3}{2} p\left[\left(L_d - L_q\right) i_{ds}\, i_{qs}\right] \quad (3)$$

The equation for the motor dynamics is:

$$J\dot{\Omega} = C_e - C_r - f\Omega \quad (4)$$

Where:
V_{dq} : supply voltage, i_{dqs} : phase current, r_s : phase resistance, Φ_{dq} : flux, J : moment of inertia, f: the friction coefficient, L : inductance, C_e : electromagnetic torque, C_r : load torque, Ω : angular velocity of rotor, θ : angle of electrical position.

III. DIRECT TORQUE CONTROL OF SRM

Since M. Depenbrock and I. Takahashi proposed Direct Torque Control (DTC) for induction machines in the middle of 1980's. The basic idea of DTC is to control the torque and flux linkage by selecting the voltage space vectors properly, which is based on the relationship between the slip frequency and torque.
The basic principle of the DTC is to select proper voltage vectors using a pre-defined switching table [5], [6], [7].
The selection is based on the hysteresis control of the stator flux linkage and the torque. In the basic form the stator flux linkage is estimated with:

$$\begin{cases} \phi_{s\alpha} = \int_0^t \left(V_{s\alpha} - r_s i_{s\alpha}\right) dt \\ \phi_{s\beta} = \int_0^t \left(V_{s\beta} - r_s i_{s\beta}\right) dt \end{cases} \quad (5)$$

Where : r_s is stator resistance and $V_{s\alpha}$, $V_{d\beta}$, $i_{s\alpha}$, $i_{s\beta}$ are voltage and current $(\alpha\beta)$ components.
Thus, flux magnitude depends on the stator voltage. The torque is thus controlled by varying the relative angle between the stator flux and the rotor flux. So, the torque can be almost instantaneous controlled by accelerating, decelerating or stopping the rotation of the stator flux vector relative to the rotor flux vector, which can be assumed to remain unchanged during the control action.
The developed torque is obtained by the product of stator current and flux as:

$$C_e = \frac{3p}{2}(\phi_{s\alpha}\, i_{s\beta} - \phi_{s\beta}\, i_{s\alpha}) \quad (6)$$

The stator Flux vector magnitude and phase are given by:

$$\begin{cases} \hat{\phi}_s = \sqrt{\hat{\phi}_{s\alpha}{}^2 + \hat{\phi}_{s\beta}{}^2} \\ \angle\hat{\phi}_s = arctg \dfrac{\hat{\phi}_{s\beta}}{\hat{\phi}_{s\alpha}} \end{cases} \quad (7)$$

To control the variation of the motor flux, the controller selects one of six voltage vectors from a voltage source inverter.
The six voltage vectors which are available to control the torque and flux in a conventional ac motor are derived by considering the three phase voltage source inverter.
Thus, by writing the phase voltages in terms of the switch states the space vector for voltage can be derived:

$$\vec{v}_s = \frac{2}{3} E \left(S_a + S_b\, e^{j2\pi/3} + S_c\, e^{-j2\pi/3} \right) \quad (8)$$

Where v_s the space voltage vector; E inverter dc link voltage and S_a, S_b and S_c are the states of the upper switches.
Using the derived space vector, the conventional DTC motor phase switching strategy for AC machines is to choose a voltage space vector in each sampling period which maintains the torque and stator flux amplitudes within the limits of two hysteresis bands.
The basic concept behind the DTC of AC drive, as its name implies, is to control the electromagnetic torque and flux linkage directly and independently by the use of six or eight voltage space vectors found in lookup tables. The possible eight voltage space vectors used in DTC are shown in Fig.2.

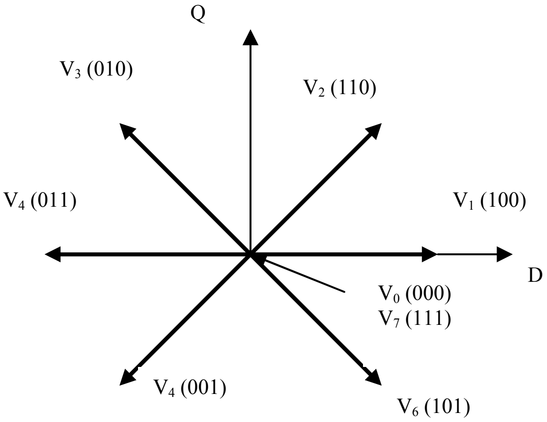


Fig. 2 Eight possible voltage space vectors obtained

Combining the flux error output, the torque error output and the sector number of the flux vector, a switching table can be realized to obtain the switching states of the inverter.
Finally, the classical DTC lookup table is shown in Table 1.

TABLE I
SWITCHING STATES FOR DTC

ΔΦ$_s$	**ΔC$_e$**	**S$_1$**	**S$_2$**	**S$_3$**	**S$_4$**	**S$_5$**	**S$_6$**
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	**V_1**	V_2
	0	V_7	V_0	V_7	V_0	**V_7**	V_0
	-1	V_5	V_6	V_1	V_2	**V_3**	V_4

$S_{i=1,\dots,6}$ The sectors of the stator flux vector;

Fig. 1 Example of an unacceptable low-resolution image

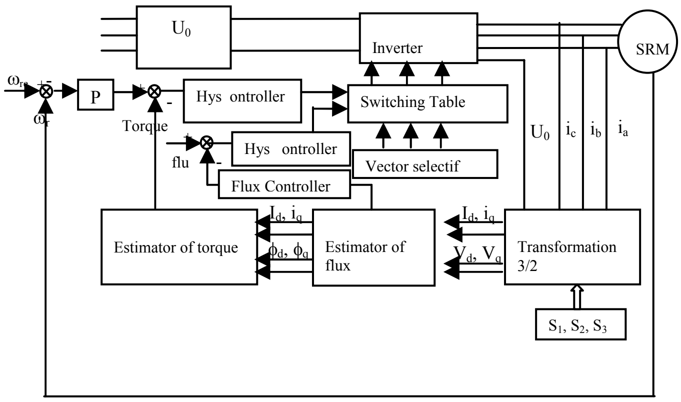


Fig. 3 The bloc diagram of an SRM drives with DTC

IV. DIRECT COUPLED PV PUMP SYSTEM

Directly coupled, PV pump system has an electrical side with voltage, V and current I to drive a motor load and hydraulic side in which a pump creates a pressure, H (head of water flow) that drive water at some discharge rate Q through pipes.
The photovoltaic array directly converts solar insulation into DC electrical power and the magnitude of photovoltaic array current depends upon the intensity of sunlight. This current is fed to the inverter which supplies the necessary power to the motor in order to drive the water pump.
In the photovoltaic pumping system, the size of a motor is determined by knowing the amount of water supply to be pumped. So, if the losses due to the coupling motor-pump are neglected, we can define the output power of motor by the relation:

$$\eta_p \cdot P_m = Q\rho g h \quad (9)$$

Where: Q is the flow rate (m^3/s), ρ is the water density (kg/m^3), g is the gravitation acceleration (m/s), h is the water head (m), η_p is the pump efficiency.
For the determination of the pump operating point it is required to know both the pump and pipeline characteristics which may be approximated by the second order polynomials [10], [11], [12], [13]. These functional representations may be written as:

$$H = \alpha_0 + \alpha_1 Q + \alpha_2 Q^2 \quad (10)$$

$$H = \beta_0 + \beta_1 Q^2 \quad (11)$$

Where, α_1, α_2, α_3, β_0 and β_1 were obtained by pump dimensions.
The equation (10) represented the pump head versus flow rate at reference speed and the equation (11) show the head required by pipeline versus flow rate.

The performance of the photovoltaic system is highly influenced by the weather, especially the insulation and the temperature. So, to track the optimum power output of the solar generator, a maximum power point tracker (MPPT) is installed.

V. RESULT OF SIMULATION

To study the performance of the DTC control powered by PV array, the simulation of the system was conducted using Matlab programming environment.

Motor parameters are: Rs=4.2Ω, J=0.00076[Kg.m^2], p=2, L_d =318Mh, L_q=128Mh.

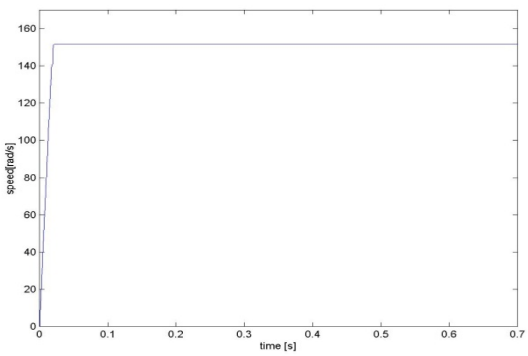
Figure 4 shows the unload dynamic performance of SRM with Direct torque controlled (DTC).

Figure 5 shows dynamic performance of SRM with direct torque controlled (DTC). The trajectory of the stator flux is a circular. We observe also the evolution of the trajectory of stator current in the stator referential (dq) frame.

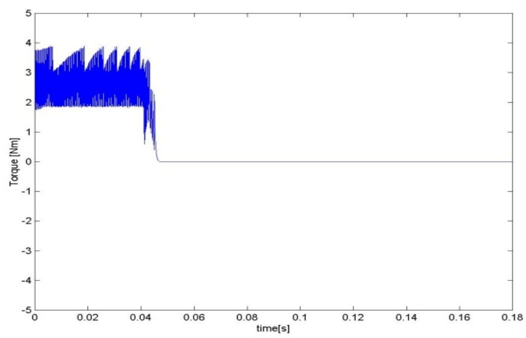
The photovoltaic pumping system characteristics are shown in figure 6 for different values of insulation, where we observed the influence by solar irradiation to the photovoltaic system. Since, the function of MPPT is to control and adjust the voltage output.

We observed in Figure 7 that the system efficiency as reduction to the generator efficiency. So, it's recommend to optimized the system to operate in optimal point why obtained a maximum power.

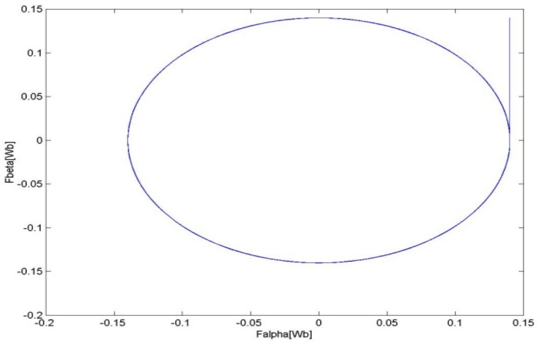
Figure 8 show the flow rate for different values of insulation, where the pump starts pumping water after value of insulation about 200 W/m^2.



-a-

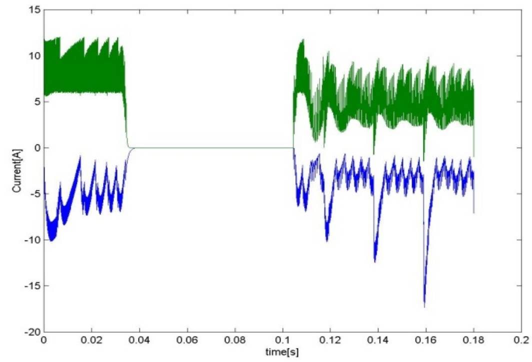


-b-

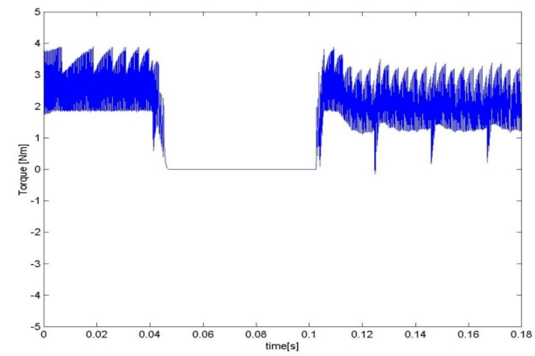


-c-

Fig.4. Unload dynamic responses of SRM with DTC
a- Speed, b- Torque and c- Flux



-a-



-b-

Fig.5 Dynamic responses of SRM with DTC
a- Current and b- Torque

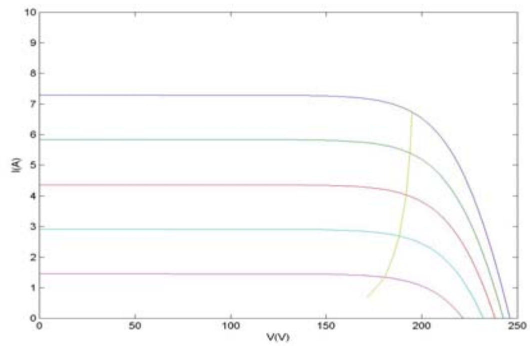


Fig. 6 Photovoltaic pumping system characteristics (36 modules at T = 40°C), -: Curve with MPPT.

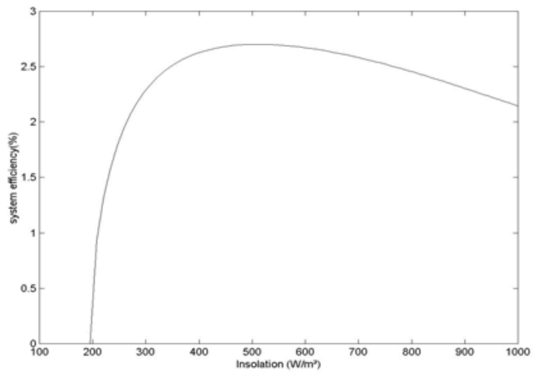


Fig. 7 Efficiency system versus insulation

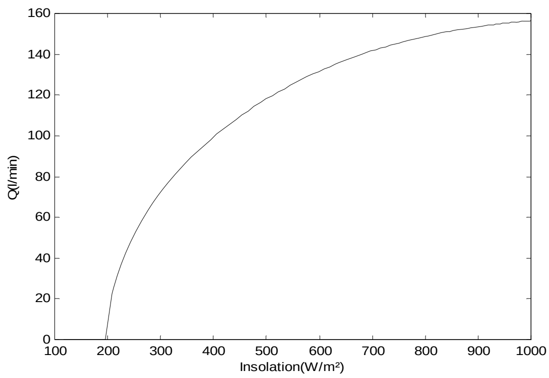


Fig. 8 Flow rate of the pump versus insulation

VI. CONCLUSION

In this papers performance of the switched reluctance machine coupled with PV array is presented and the main concepts of DTC method of 3-phase 6/4 SRM were proposed. Compared with vector control, direct torque control has many advantages such superior dynamic torque and speed response, simpler implementation and without speed sensor.

The disadvantage of DTC is the variation of the switching frequency and the dependence by the stator resistance and the hysteresis band comparator.

A simulation model of PV based water pumping system with a 6/4 SRM is developed. The using of PV in pumping and machines control seems to be reliable especially in stand alone PV plants.

The performance analysis of the directly PV-powered SR motor pump will be useful to select the suitable motor and load for water-pumping applications in remote areas.

REFERENCES

[1] J. Choi, J. Ko, D. Chung "Efficiency Optimization Control of SynRM Drive", SICE-ICASE International Joint Conference Oct. 18-2 1, 2006 in Korea.

[2] F. Soares, P.J. Costa Branco, "Simulation of a 6/4 Switched Reluctance Motor Based on Matlab/Simulink Environment", Aerospace and electronic system. IEEE transactions, Vol. 37 pp. 989–1009, July 2001.

[3] I. Takahashi and Y. Ohmori, 'High-Performance Direct Torque Control of an Induction Motor', IEEE Transactions on Industry Applications, Vol. 25, pp. 257 - 264, March/April 1989.

[4] Takahashi and. S. Asakawa, "Ultra-wide speed control of induction motor covered 10A6 range", IEEE Trans. Ind. Applicat. IA-25: 227-232, 1987.

[5] R. Krishnan, "Switched Reluctance Motor Drives: "Modeling, Simulation, Analysis, Design, and Applications", CRC Press LLC, 2001.

[6] T. LUBIN, « Modélisation et commande de la machine synchrone à réluctance variable. Prise en compte de la saturation magnétique». 18 avril 2003 Docteur de l'Universit é Henri Poincaré, Nancy-I.

[7] Fatma Ben Salem and Ahmed Masmoudi : "A comprehensive analysis of the inverter switching frequency in Takahashi DTC strategy" search Unit on Renewable Energies and Electric Vehicles, Sfax Engineering School, University of Sfax, Tunisia Vol. 26 No. 1, 2007 pp. 148-166

[8] R. Jeyabharath, P.Veena, and M.Rajaram "A Novel DTC Strategy of Torque and Flux Control for Switched Reluctance Motor Drive" IEEE 2006

[9] B. Goumiedane, S. Merzougui, D. Rahem and A. Haddoun " Comparaison of Fiel-Oriented Control and Direct Torque Control for Switched Reluctance Motor (6/4)" ICEES2013 Annaba.

[10] Harsono Hadi, Shinobu Tokuda and Slamet Rahardjo " Evaluation of performance of photovoltaic system with maximum power point (MPP)" Solar Energy Material & Solar Cells 75. ELSEVIER 2003. pp. 673- 678 .

[11] D. P. Kothari, M. Kolhe, J.C. Joshi and K. Agbossou « Performance of Directly Coupled Photovoltaic Water Pumping System » CCECE, Montréal Mai 2003 IEEE.

[12] H. B. Metwally and W. R. Anis " Performance Analysis of PV Pumping System using Switched Reluctance Motor Drives " Solar Energy Vol 56 N°2 161-168, 1996.

[13] H. Vasquez and J. K. Parker "A new simplified mathematical model for a switched reluctance motor in a variable speed pumping application" Mechatronics 14 (2004) .