SRM controlled by DTC to optimize the efficiency of solar panel

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Abstract- **We propose in this paper, a so-called optimal design of a system capable of continuing to lead the solar panel to the optimal position to ensure maximum sunlight and thus improve the overall efficiency of the photovoltaic generation system. A direct flux and torque control (*DTC*) is then applied to an Reluctance Synchronous Motors (*RSM*) which can develop the torque required to optimize the location of the solar panel when the sun moves on its trajectory. This is justified by the simplicity of this technique especially for its sensorless implementation and its robustness via the development of a desired useful torque, still RSM is simple and robust and high torque overloads capacity. So it's an economic system with a simple implementation, composed of three main parts: the capture of the sun, the rotation of the solar panel and the transmission of this rotation.**

Keywords- RSM, DTC, Solar panel, solar radiation, optimal position captor.

1. Introduction

The Solar radiation is a major factor to convert energy into electricity, but when the solar rays are not be projected perpendicularly on the photovoltaic cells, this seriously affects the overall performance of this conversion. Several studies have been proposed to resolve this problem while ensuring a minimum investment cost of the entire system, and providing improved efficiency for production.

The performance of solar panels has always been considered to be insufficient and we have to make them more efficient to supply a more significant energy for low and medium power systems.

Among several parameters that influence performance we may cite the irradiation of sunlight projected onto the solar panel and captured by photovoltaic cells. Several studies have been made to improve the overall efficiency and thus benefit the most from the obtained transformed energy [1-5].

This regard, strongly linked to industry and especially for electricity production, is a significant interest in exploiting this clean energy produced. The industry offers all the time solutions to improve the production [7], these solutions are often based technologies using the jacks, usually pneumatic or hydraulic against few studies or projects are responsible for applying techniques recognized command to optimize the photovoltaic [1-5], [7-8].

This work has improved a study already proposed [8], and this was mainly in the system for catching the sunlight. Most studies using the four photodiodes to orient the solar panel in the right direction, however, in this present work we present a design which will use only three, which is beneficial. The autonomous power supply (provided by the panel itself) makes the implementation easy and even encouraging for investment. A good choice for the design of the actuator and the transmission system of rotation, can lead us to an optimal tracking system (cheaper, compact and robust).

However, Direct Torque Control (*DTC*) appears one of the most suitable controls to compensate for the solar system , as it is a technical command which is recognized by its robust and did not need sensors, what its implementation is compact, this makes not only the implementation easy to achieve but with the least possible cost [9-15].

Once applied to an Reluctance Synchronous Motors (RSM), it develops the necessary torque to rotate the solar panel in the case of a movement of the sun on its trajectory.

About choice of motor, the *RSM* has attracted significant interest of industry due to their main advantages are [11][13]:

- Simplicity and robustness
- High torque overloads capacity
- High efficiency over wide speed-range
- Low machine inertia
- decreased maintenance requirements

The absence of windings and magnets on the rotor enables *SR* motors to run high speed and temperature. An SR motor can produce large torque in a wide speed range.

All this reinforces the idea of the optimal design of a system of tracking in the aim to push system solar efficiency to an interval more incentive for investment.

In this paper, we propose the design of an optimal system for a solar panel capable of rotating the solar panel to track the path of the sun to increase the overall performance and exploit the maximum sunlight.

We will discuss in this study a general description of blocks solar system. Then, we will focus on the study of the *DTC* control of the solar panel.

After that we will give the simulation results of the developed control law along with comments and explanations. Finally, we will conclude our work with a general conclusion with some perspectives.

2. Block diagram of the proposed system

In this study we designed a system that contains three main parts, the panel system that captures the maximum sunlight which consists on an electronic analogical block, the tracking system controller of the solar panel which consists of an *RSM* controlled by a *DTC* and powered by a conventional three-phase inverter and the last part consists of a transmission system for rotating mechanical gear to transmit rotary motion of the shaft of *RSM* to the solar panel with a desired precision [6].

A. Optimal position captor

This block is designed by three photodiodes located on the front of the solar panel, whose operating principle is to expose the photodiode on the West in the open sky while on the East will be wrapped in such a way not to receive sunlight as the later 'East' and include the third in the middle into a tube of definite size (depending on the desired precision of the threshold lowering performance) to detect the shade when the sun moves on its trajectory. Fig. 1 illustrates the principle of this system. The system of the motor locks when we reach the two logical states:'100' and '001' where '1' represents an excitation of the photodiode and '0' represents the absence of excitation.

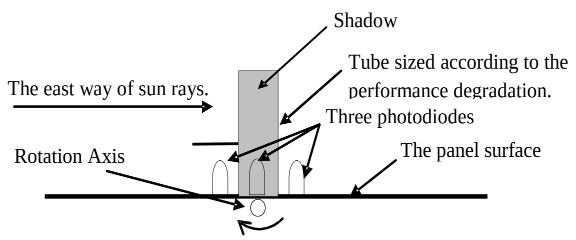

Fig. 1. Implementing the orientation sensing system on the solar panel.

The following table lists all possible states that can occur during the whole day of operation.

TABLE I
SUMMARY OF THE SYSTEM PROPOSED DURING THE DAY

Event	State (logical)	Action (commande)
Sunrise	**100**	Rotate to the East
Ray ⊥ Panel	**011**	Lock (no rotation)
The Sun Moves	**001**	Rotate to the West
Ray ⊥ Panel	**011**	Lock (no rotation)
Clouds / Sunset	**000**	Lock (no rotation)
-Clouds missing	**001**	Rotate to the West
-Sunrise	**100**	Rotate to the East

If we symbolize the state of the first photodiode with 'A', and that of the second with 'B' and then we use 'C' for the third, we can see from the table that the movement will begin in two ways:'100 ' and '001'.

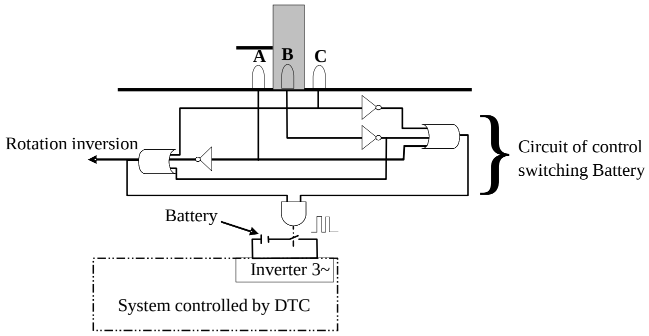

Fig. 2. Functioning diagram for delivering power to the inverter through the sensor sunshine.

The diagram of Fig. 2 illustrates a circuit controlling a switch for opening and closing the supply circuit of the inverter (analogue/digital converters will be needed for implementation).

The output of this circuit generates pulses to the switch of power from the inverter to two feeding levels and that consists of a suitable battery charged from the solar panel itself by providing a power supply.

To reverse the direction of rotation of the panel (when it reaches the end of the path (sunset)), we must use the output specified earlier that takes the value '1' when a '100' (sunrise). Once this output differs from '1' rotation in this direction stops and the tracking the natural path of the sun will be resumed again.

B. Control block of the solar panel orientation

The Direct Torque Control *DTC* method was introduced in 1985-86 by *Takahashi* and *Depenbrock* especially for asynchronous machines. Then, several studies have been developed more precise knowledge of this command. This technique of control was also applied to synchronous machines [9-15].

It is a control strategy that outperforms other methods, based on a feeding a pulse width modulation (PWM) and a decoupling of flux and torque-oriented control of the stator magnetic field.

In steady state, the flux can be easily estimated using the stator current and stator voltage (*Is, Vs*). The fact that the DTC control switches directly without going through regulators, significantly enhances its dynamic performance compared to other commands [9-15].

In our case we are seeking to reduce the maximum cost of implementing the system to increase the overall efficiency of the implementation, such a control strategy that requires no sensor seems the right choice, it is more one of the best strategies, whenever a strong torque is applied (which is necessary in the case of this considered application).

The model adopted for the SRM suitable for DTC control is as follows [6][11][13]:

Where:

$$\begin{cases} \dfrac{dI_d}{dt} = -\dfrac{R_s}{L_d} + \dfrac{L_q}{L_d} P\mu_r I_q + \dfrac{1}{L_d} U_d \\ \dfrac{dI_q}{dt} = -\dfrac{R_s}{L_q} - \dfrac{L_d}{L_q} P\mu_r I_d + \dfrac{1}{L_q} U_q \end{cases} \quad (1)$$

The electromagnetic torque is expressed in the same frame by:

$$T_e = \frac{3P}{2J}(L_d - L_q) I_d I_q \quad (2)$$

The motor mechanical equation is written as follows:

$$J\dot{\Omega} = T_e - T_r - f_r \Omega \quad (3)$$

The *DTC* control is based on the direct determination of the command sequence used to switch a voltage inverter.

This choice is usually based on the use of hysteresis comparators whose function is to control the system state, namely the amplitude of stator flux and electromagnetic torque.

A two levels classical voltage inverter can achieve seven separate positions in the phase corresponding to the eight sequences of the voltage inverter [9-15].

These positions are illustrated in Fig. 3. In addition, Table II shows the sequences for each position, such as: $S_{i\ =\ 1,\ ...,\ 6}$: are the areas of localization of stator flux vector, on the other hand, the error $\Delta\varphi_s$, between the reference flux and the flux estimated, is introduced into a hysteresis comparator for two levels, which delivers '1' if the error is positive and '0' if it is negative as well, the error ΔT_e, between the reference torque and estimated torque is introduced into a hysteresis comparator for three levels that delivers '1' if positive, '0' if zero and '-1' if negative.

The use of three levels to adjust the torque has been proposed to minimize the average switching frequency, because its dynamics is generally faster than the flux [6][11][13].

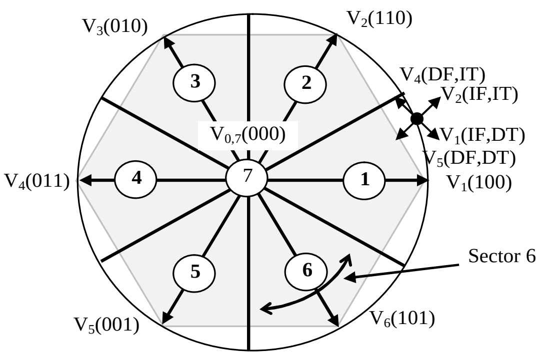

Fig. 3. Different vectors of stator voltages provided by a two levels inverter.

Where:

I(D)F : Increasing (Decreasing) of Flux amplitude.

I(D)T : Increasing (Decreasing) of Torque.

The synthetic sequence can be illustrated through the following example: Assuming that the flux vector is located in sector 1 (Fig. 3), then if the error between the reference flux and the stator flux is positive, we must increase the flux this is only possible by applying a voltage vector in the same direction, according to (4) or V_1 (100), V_2 (110) or V_6 (101). However, applying voltages of opposite direction V_3 (010), V_4 (011) or V_5 (001) decreases the variation of the flux.

On the other hand, if the error between the reference torque and the electromagnetic torque is positive we must increase the electromagnetic torque by applying the voltage vectors in the half plane of positive angles, according to (5), i.e. V_2 (110), V_3 (010) or V_4 (011).

Trying vectors V_1 (100), V_5 (001) or V_6 (101), decreases the torque [6][11][13].

$$\bar{\varphi}_s(k+1) \approx \bar{\varphi}_s(k) + \bar{V}_s T_E \quad \rightarrow \quad \Delta\bar{\varphi}_s \approx \bar{V}_s T_E \quad (4)$$

$$T_e = p(\varphi_{s\sim} i_s \ - \varphi_s \ i_{s\sim}) \quad (5)$$

Combining these states we can decide which sequence should be applied.

TABLE II

STATE LOCALIZATION TABLE

$\Delta\varphi_s$	ΔT_e	S_1	S_2	S_3	S_4	S_5	S_6
1	1	110	010	011	001	101	100
	0	000	000	000	000	000	000
	-1	101	100	110	010	011	001
0	1	010	011	001	101	100	110
	0	000	000	000	000	000	000
	-1	001	101	100	110	010	011

The following diagram describes the process of DTC controlling an SRM associated with a two-level inverter supplied by controlled battery.

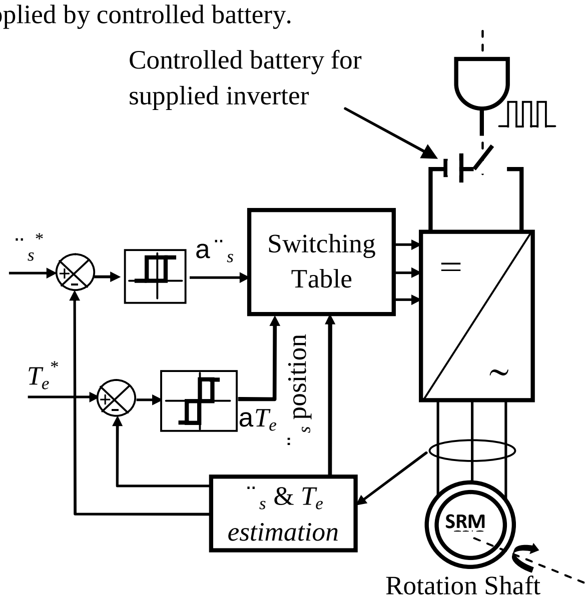

Fig. 4. Block of diagram of the DTC drive system

C. Rotation Transmission Block

The IM moves when its inverter receives the necessary energy from the accumulator, which operates according to the states'100 'and'001' of the sensor system, however, and to allow rotation of the panel according to the path of the sun and therefore ensure the continued optimal rotation should be in two movements, one along the horizontal axis and the other according to the vertical.

We propose a system of gears according to the mechanical design of the panel considered (size, which may be the subject of another study). The following diagram illustrates the idea of the proposed design:

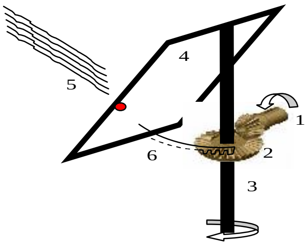

Fig. 5. Gearing for rotation's panel.

Such as:

1: the IM shaft fitted with a bevel gear,
2: fixed gear on the vertical axis of the panel
3: the axis of rotation of the panel,
4: the solar panel,
5: direction of projection sunlight,
6: a toothed bar for vertical rotation.

This system ensures the rotation of the solar panel in both directions, horizontal and vertical directions. For further axially vertically using a toothed bar fixed on a link on the rear panel to allow a torque of strong rotation up and down the other end of the bar to hang on the vertical axis with the possibility of free movement on the surface of the gear'2 '.

3. Simulation and results

We are interested in what follows to illustrate the behavior of *SRM* controlled by the *DTC*, following a short-term scenario where it is assumed that the sun is insured for a time interval and his absence will be (for the photodiode B) due to movement of the sun, then it is assumed then a sunset and a sunrise and finally a shift in the sun.

Note that periods are given for illustrative purposes and do not necessarily reflect reality (e.g. times to bed at sunrise maybe have several hours), however the system maybe validated for extended operation times if it is validated for relatively short time.

Fig. 6 shows the electromagnetic torque developed by the *SRM* is responsible for 10 (Nm), there is a peak to start very short duration after which the torque hangs in its value which is about 9.9 Nm (torque resistance (load) + friction torque).

At t = 0.1 (s) the solar panel reaches its optimal position (perpendicular solar radius) the capture system cut power to the inverter and the mechanism stops rotating.

At t = 0.16 (s), it implies a movement of the sun where the need for the panel rotates up to the optimum position.

At t = 26 (s), it implies a lack of sun radiation, this event causes the panel until one of the photodiodes is excited (in the case of clouds or sunset), in this case we have two possibilities: if the photodiode 'A' is excited panel turns to the east and the photodiode 'C' is that excited the panel looks to the West and in both cases the panel will stop when photodiode 'B' will be excited.

(In the example we will take the case of sunset).

At t = 0.32 (s), the sun rises resulting in a rotation to the East, until the optimal position is reached at t = 0.42 (s) and stop the panel will continue until at t = 0.5 (s) after which the panel resumed its movement of rotation to reach the optimum position.

These events are summarized in the following table.

TABLE III

SCENARIO SIMULATION FOR TRACKING OF SOLAR PANEL.

Period (s)	Event	State (logic)	Action (movement)
0 : 0.10	The Sun moves	**001**	Rotate to the West
0.1 : 0.16	Optimal position	**011**	Lock (no movement)
0.16 : 0.26	The Sun moves	**001**	Rotate to the West
0.26 : 0.32	Sunset	**000**	Lock (no movement)
0.32 : 0.42	Sunrise	**100**	Rotate to the East
0.42 : 0.50	Optimal position	**011**	Lock (no movement)
0.5 : 0.60	The Sun moves	**001**	Rotate to the West

We note that a direct rotation means from east to west and its opposite is the reverse rotation.

Where there are clouds, is similar to the sunset, however, the state that follows takes '001' indicating that the panel should turn clockwise.

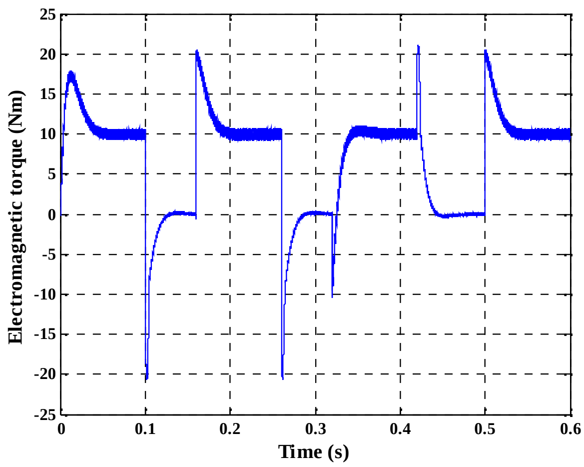

Fig. 6. Electromagnetic torque response.

In our simulation it was assumed that 'A' is excited which is translated as a sunset is the sign changes direction of rotation is turning to the east.

Fig. 7 shows these scenarios and reverses rotation. Note in this occasion that the finesse of style is not so important for the system's goal is to locate the place where the sun's rays will be projected in a manner perpendicular to the surface of the solar panel, thus neither the ripple torque [15-17], or exceeding the speed reference, (Fig. 8), are harmful for the present system design (this problem can be resolved by using adaptive PI regulator).

We notice from Fig. 7 that the speed exceeded will disappear leaving more time for the movement, i.e. a matter of time for the system.

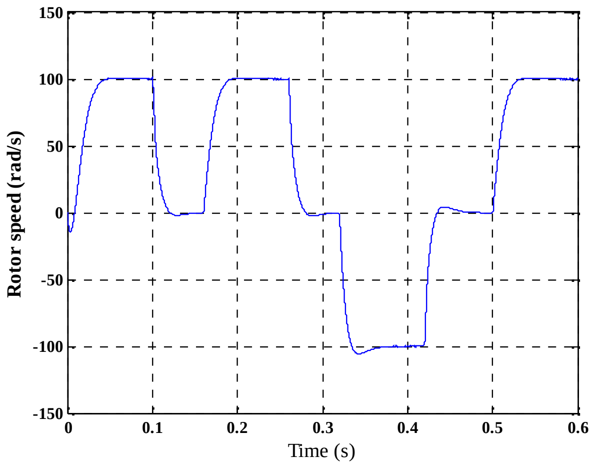

Fig. 7. Evolution of motor's speed at different sequences.

Fig. 8 shows the evolution of the flow in different sequences, there is the well supposed to variations, reflecting a robust flow control.

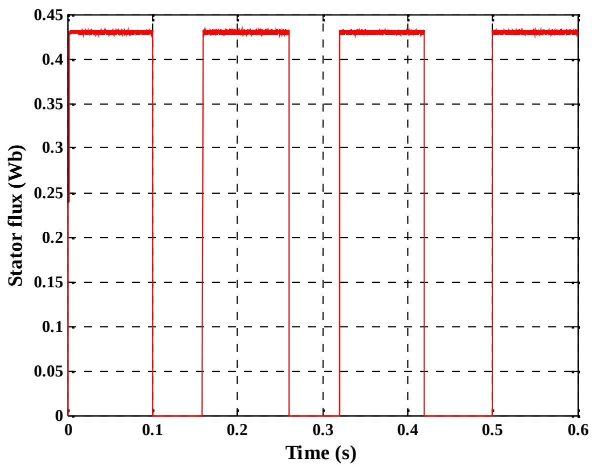

Fig. 8. Evolution of stator flux in different sequences.

In the sunny weather not mean that the sun had moved so that its rays are projected on the panel in a perpendicular, so the performance degrades and the controller must compensate for the panel to continue path of the sun.

4. Conclusion

In this present work we have proposed a design of a system for a solar panel of three blocks, in order to improve the overall efficiency of energy conversion and enhance the robustness of the solar system.

We approached the study of each block and we have clarified the idea of design of each. The electromagnetic part has been more or less detailed. The simplicity of the idea makes this project feasible, although constraints may persist especially in terms of size (study to consider).

In addition, our simulation results from the DSS and therefore the PV system show that this strategy is well suited to the operation without mechanical sensor, thus reducing significantly the cost of implementing the proposed system.

The torque ripple as well as exceeding the speed did no problem for the proper functioning of the system, in addition to solutions such as the use of a multilevel inverter to reduce ripples and the use of an adaptive PI for adjust the speed, can correct these problems, however, implementation costs will be added unnecessarily while seeking to reduce and optimize the system for better overall performance.

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Appendix

- The rated values and parameters used in the simulation program are as follows:

Parameters	Symbols	Values (S.I)
Frequency	f	50
Power	P_n	1500
Supply voltage	V_n	220/380
Rated speed	Ω_n	100
Poles	$2p$	3
Stator resistance	r_s	1.3
d-axisStator inductance	L_d	0,060
q-axisStator inductance	L_q	0,008
Inertia	J	0,0013
Friction coefficient	f_r	0.00004

- The sample time: 100 (µs).
- Gains of PI (speed regulator): $k_p = 0.27$ & $k_i = 17$.