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Direct Torque Control - DTC of Induction Motor Used for Piloting a Centrifugal Pump Supplied by a Photovoltaic Generator

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***Abstract*—**In this paper we propose the study of a centrifugal pump control system driven by a three-phase induction motor, which is supplied by a PhotoVoltaic PV generator. The system includes solar panel, a DC / DC converter equipped with its MPPT control, a voltage inverter to three-phase Pulse Width Modulation - PWM and a centrifugal pump driven by a three phase induction motor. In order to control the flow of the centrifugal pump, a Direct Torque Control - DTC of the induction machine is used. To illustrate the performances of the control, simulation results are carried out using Matlab/Simulink.

***Keywords*—**Photovoltaic generators, Maximum power point tracking (MPPT), DC/DC converters, Induction motor, Direct torque control (DTC).

I. Introduction

PHOTOVOLTAIC energy is a renewable energy source, inexhaustible and non-polluting. To be used for different applications and to meet the economic constraints, the design and implementation of PV systems are necessary and currently facing many problems. The PV system must be made robust, reliable and with high efficiency. PV systems require little maintenance, are quiet and do not emit pollutants. These PV systems, electricity generators, can be operated in different places: electrification of remote sites, installation in buildings, direct connection to the network, pumping water...

The use of solar energy for water pumping is particularly well suited to rural areas where water is lacking. The growing demand for water in these areas is a great interest in the use of solar panels as a source of energy groups. The major part of the pumping systems currently implemented operates as electric actuator using the DC motor or brushless motor BLDC. The problems of cost and maintenance of these motors have encouraged the industrials to be equipped of the induction motor which thus constitutes a new alternative.

It is well known that the main problem posed by the use of PV panels is their non-linear nature. The energy extracted from the PV module is dependent of the climatic conditions. In fact, such module has an optimum operating point, called the Maximum Power Point (MPP), which depends greatly on the intensity of illumination. The adaptation of the PV panels to the load is therefore necessary to extract the PV module maximum power. This is done through the DC-DC energy converters controlled by a control command called Maximum Power Point Tracking – MPPT.

Currently, the induction motor is more and more used in photovoltaic pumping systems. This kind of motors has been adopted due to its low cost and the low maintenance requirements. In addition, the increased efficiency of solar pumping systems makes this latter particularly attractive, even more the additional cost of the inverter is less significant. In recent years, the advent of efficient inverter to control the speed of these motors has allowed their use for solar pumping applications.

In this paper, the pump used is the centrifugal type driven by a three phase asynchronous motor which is powered by a three-phase inverter. In fact, in some applications and especially for agricultural irrigation, sometimes we need to control the water flow. It is therefore necessary to establish a system for monitoring the speed of the drive motor. The method of Direct Torque Control (DTC) is used in our work.

II. Photovoltaic Pumping System

Fig. 1 shows the proposed structure of the photovoltaic pumping system.

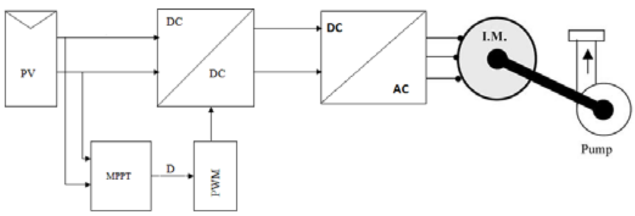

Fig. 1 Structure of the photovoltaic pumping system

A. Model of the Solar Cell

The model consists of a current source (*Isc*), a diode (*D*), and a series resistance (*Rs*), shown in Fig. 2 [1]-[4].

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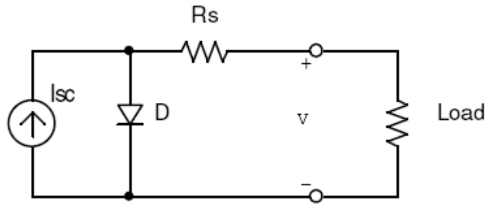

Fig. 2 Equivalent circuit of the solar cell

The equation that describes the current-voltage relationship of the PV cell is:

$$I = I_{sc} - I_0 \left[e^{q\left(\frac{V+I*R_s}{nkT}\right)} - 1 \right] \quad (1)$$

where:

I is the cell current,

V is the cell voltage,

T is the cell temperature in *Kelvin* (K),

Io is the reverse saturation current of diode (A),

q is the electron charge (1.602×10^{-19} C),

k is the Boltzmann's constant (1.381×10^{-23} J/K).

BP Solar BP SX 150S PV module is chosen for a MATLAB simulation model. The following table shows its electrical specification [5].

TABLE I
ELECTRICAL CHARACTERISTICS DATA OF PV MODULE

Electrical Characteristics	
Maximum Power (*Pmax*)	150W
Voltage at *Pmax* (*Vmp*)	34.5V
Current at *Pmax* (*Imp*)	4.35A
Open-circuit voltage (*Voc*)	43.5V
Short-circuit current (*Isc*)	4.75A
Temperature coefficient of *Isc*	0.065 ± 0.015 %/ ^{o}C
Temperature coefficient of *Voc*	-160 ± 20 mV/ ^{o}C
Temperature coefficient of power	-0.5 ± 0.05 %/ ^{o}C
NOCT	47 ± 2^{o}C

B. MPPT Based On DC-DC Boost Converter

To extract, at each moment, the maximum power available at the terminals of the PV and transfer this latter to the load, the technique conventionally used is to achieve an adaptation stage between the PV and the load. This stage plays the role of an interface between the two elements ensuring throughout control process, the transfer of the maximum power supplied by the generator to make it as close as possible to Pmax.

DC-DC converters, as voltages elevators, are also used in photovoltaic applications, especially in photovoltaic pumping system. In our study we use a boost converter which is a power converter with an output voltage greater than its input voltage.

The MPPT control acts on the duty cycle of the converter as so that the power supplied by the PV will be equal to Pmax provided at its terminals. The MPPT algorithm can be more or less complicated to find the Maximum Power Point MPP, but generally it is based on the variation of the duty cycle of the converter to be putted on the MPP: in terms of changes in input parameters converter (IPV and VPV) [6]-[8].

C. Centrifugal Pump Model

The flow-head characteristic of a centrifugal pump can be approximated by quadratic form using Pfleider–Peterman model, and can be expressed approximately by the following form [9]-[12]:

$$H = a_0\omega^2 + a_1\omega Q + a_2Q^2 \quad (2)$$

where:

Q: the water flow (m^3/s)

H: the total head (m)

a_0, a_1, a_2 are the coefficients given by the manufacturers.

The H-Q characteristic of the pipe network can be expressed by:

$$H = H_g + \psi Q^2 \quad (3)$$

where:

Ψ: is a constant which depends on conduit diameter and the frictional losses of the pipe network.

H_g: the geodetic head (m)

The load torque of the centrifugal pump can be described by:

$$T_r = C_r\omega^2 \quad (4)$$

According to [13], knowing the flow rate Q of a centrifugal pump for the speed ω, the laws of similitude allows to determine the flow rate Q' to a speed ω' using the following relationships:

$$Q' = Q\frac{\omega'}{\omega} \quad (5)$$

D. Simulation Results

The following figures show the simulation results of the photovoltaic system studied for 1Kw/m^2 irradiance and a temperature of 25°C.

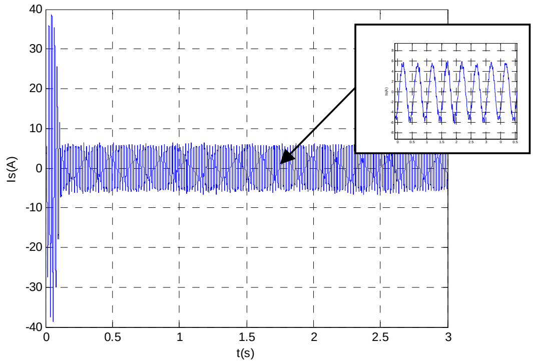

Fig. 3 The stator current

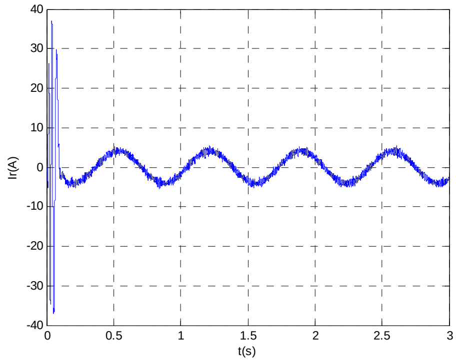

Fig. 4 The rotor current

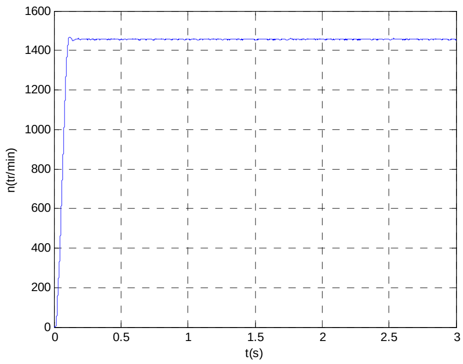

Fig. 5 The motor speed

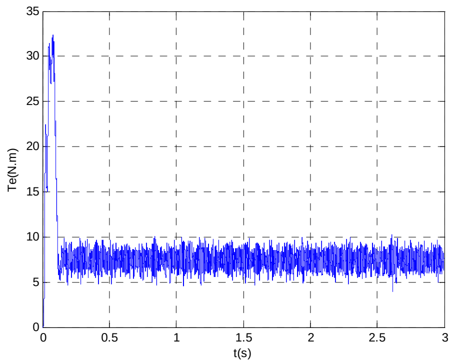

Fig. 6 The electromagnetic torque

III. Direct Torque Control of the Induction Motor

In order to have an adjustable flow rate of the pump, we propose a control system of induction motor based on the method of Direct Torque Control DTC. This method is characterized by its simple implementation and a fast dynamic response.

DTC was introduced in 1985 by I. Takahashi from the directed flow method and the principle of DC motor. He proposed replacing the decoupling vector transformation through a nonlinear control such as switching states of the inverter are imposed through a separate control of the stator flux and the electromagnetic torque of the motor.

The basic functional blocks used to implement the DTC scheme are represented in Fig. 7. The instantaneous values of the stator flux and torque are calculated from stator variable by using a closed loop estimator. Stator flux and torque can be controlled directly and independently by properly selecting the inverter switching configuration [14].

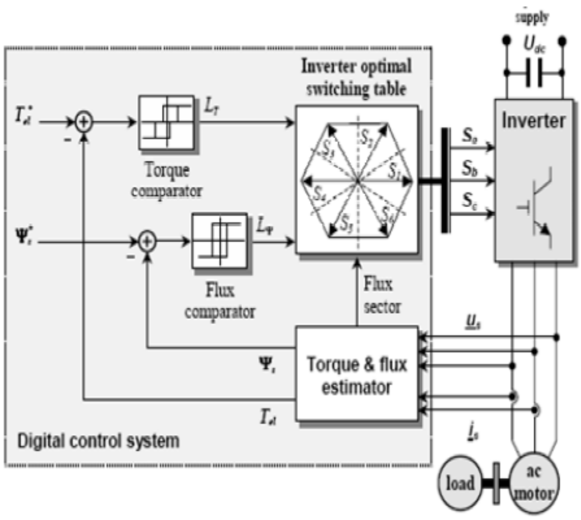

Fig. 7 Basic DTC scheme for ac motor drives

A. Vector Model of Inverter Voltage

In the PWM voltage source inverters, the switching commands of each inverter arm are complementary. So, for each arm, a logic state C_i (i=1,2,3) can be defined:

$C_i = 1$: if the upper switch is closed and the lower switch is open.

$C_i = 0$: if the upper switch is open and the lower switch is closed.

Thus, the voltage vector V_s can be written as in [14], [15]:

$$V_s = \sqrt{\frac{2}{3}} U_0 \left[C_1 + C_2 e^{j\frac{2\pi}{3}} + C_3 e^{j\frac{4\pi}{3}} \right] \tag{6}$$

The combinations of the three variables (C_1, C_2, C_3), can generate eight positions of the vector V_s, whose two correspond to the zero vector:

(C_1, C_2, C_3) = (111) or (000), as shown in Fig. 8.

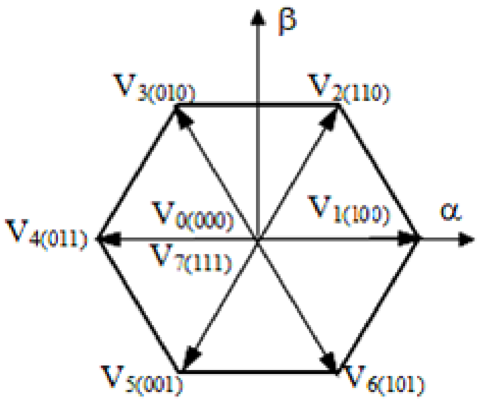

Fig. 8 Voltage vectors and sequences of phase levels of the inverter

B. Stator Flux and Torque Estimation

The components of the current (Isα, Isβ), and stator voltage (Vsα, Vsβ) are obtained by the application of the next transformation [16]:

$$\begin{cases} I_{s\alpha} = \sqrt{\frac{2}{3}} I_{sa} \\ I_{s\beta} = \frac{1}{\sqrt{2}}\left(I_{sb} - I_{sc}\right) \end{cases} \quad (7)$$

$$\begin{cases} V_{s\alpha} = \sqrt{\frac{2}{3}} U_0\left(C_1 - \frac{1}{2}(C_2 + C_3)\right) \\ V_{s\beta} = \frac{1}{\sqrt{2}} U_0 (C_2 - C_3) \end{cases} \quad (8)$$

The components of the stator flux ($\varphi_{s\alpha}$, $\varphi_{s\beta}$) are given by:

$$\begin{cases} \overline{\varphi}_{s\alpha} = \int_0^t \left(\overline{V}_{s\alpha} - R_s \overline{I}_{s\alpha}\right) dt \\ \overline{\varphi}_{s\beta} = \int_0^t \left(\overline{V}_{s\beta} - R_s \overline{I}_{s\beta}\right) dt \end{cases} \quad (9)$$

The value of the stator flux is:

$$\varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \quad (10)$$

From the estimation of the values of ($\varphi_{s\alpha}$, $\varphi_{s\beta}$, $I_{s\alpha}$ and $I_{s\beta}$), we can obtain electromagnetic torque:

$$\Gamma_{em} = p\left(\varphi_{s\alpha} I_{s\beta} - \varphi_{s\beta} I_{s\alpha}\right) \quad (11)$$

The stator flux of the induction machine is obtained from the following equation:

$$\overline{\varphi}_s = \int_0^t \left(\overline{V}_s - R_s \overline{I}_s\right) dt \quad (12)$$

The voltage drop due to the resistance of the stator R_s can be neglected for high speeds, we then find:

$$\overline{\varphi}_s = \overline{\varphi}_{s0} - \int_0^t \overline{V}_s dt \quad (13)$$

During a sampling period T_e, the applied voltage vector remains constant, and then we can write:

$$\overline{\varphi}_s(t) \approx \overline{\varphi}_{s0} + \overline{V}_s T_e \quad (14)$$

C. Simulation Results

To validate the method, proposed in this paper, simulations based on Matlab/Simulink have been implemented. The induction machine, used for these simulations, has the following parameters:

P_n = 4KW, U_n = 400V, f = 50Hz, R_s = 1.405Ω, R_r = 1.395Ω, p=2, L_s = L_r = 0.005839H, L_m = 0.1722H, J = 0.0131kgm^2.

The performances of the centrifugal pump at a speed of 2900rpm are [13]:

Q = 30m^3/h, H = 80m, P = 14Kw.

In this part, we took the starting value of 1200rpm as the reference speed of the induction motor. At time t=2s, a change in the reference speed to a speed of 1400 rpm is caused, then to a speed of 600rpm at t=4s. The values of the irradiance and temperature are kept respectively at 1Kw/m2 and 25°C. Simulation results are given in the following figures.

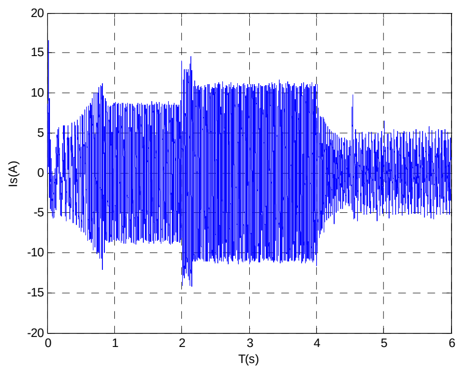

Fig. 9 The stator current

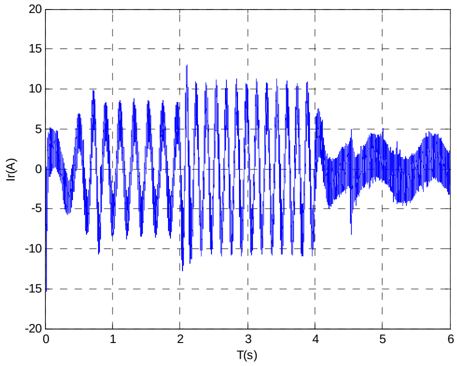

Fig. 10 The rotor current

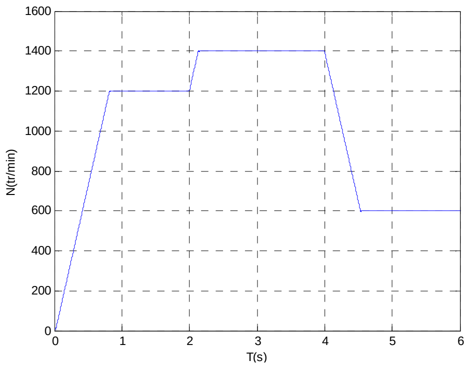

Fig. 11 The motor speed

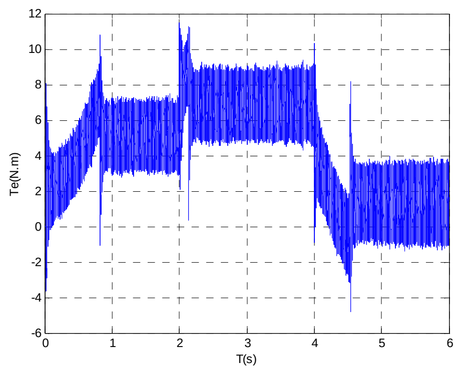

Fig. 12 The electromagnetic torque

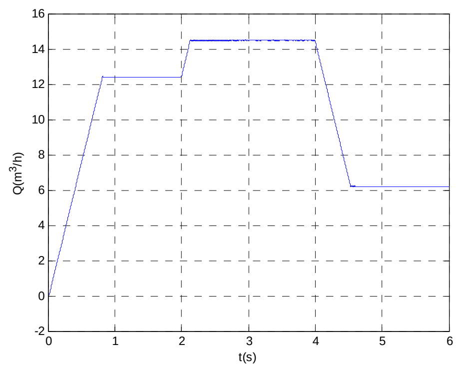

Fig. 13 The water flow

Simulation results are satisfactory, indeed Figs. 11 and 13 show that the speed of the induction motor follows the reference speed and consequently the value of the desired flow.

IV. Conclusion

In this paper, we studied a control structure using both the concept of Direct Torque Control (DTC) method for induction motor and the operation at MPPT for the DC-DC converter. The strategy of Direct Torque Control served here as a way to control the flow of the pumping station. The command with the adapter MPPT optimizes power delivered by the photovoltaic generator according to the irradiance and the temperature. This allowed the station to operate at the optimal operating point. Simulation results are satisfactory. Indeed, the motor speed tracks the value of the reference speed desired and consequently the value of the desired pump flow.

Acknowledgments

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