Direct Torque Control-Induction Generator drive scheme for an isolated photovoltaic water pumping system

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***Abstract*—This paper describes a Direct Torque Control (D.T.C) of an induction motor (I.M) associated to a photovoltaic water pumping system. D.T.C method is based on instantaneous space vector theory. By optimal selection of the space voltage vectors in each sampling period, D.T.C archives effective control of the stator flux and torque. The most important advantage of this method is its rotor position free control system. In order to improve the efficiency of the photovoltaic energy generation, maximum power point tracking (MPPT) techniques is investigated. We applied conventional MPPT method (P&O) to the studied system under variable temperature and irradiance conditions. The proposed dive system with DTC-IM drive with the integration of MPPT allows us to obtain a system operating at maximum power and with very good performances and fast response with no overshoot. Results obtained by simulation are presented and prove the feasibility of the proposed system.**

***Keywords*— Photovoltaic, Maximum Power Point Tracking (MPPT), Water Pumping, Direct Torque Control.**

I. INTRODUCTION

The output power induced in the photovoltaic modules depends on solar radiation and temperature of the solar cells. To maximize the efficiency of the system, it is necessary to track the maximum power point of the photovoltaic (PV) array. Several Maximum Power Point Tracking (MPPT) algorithms have been developed and widely adapted to determine the maximum power point [1-10]. The control technique the most used consist to act on the duty cycle automatically to place the generator at its optimal value whatever the variations of the metrological conditions or sudden changes in loads which can occur at any time. The most conventional MPPT method used is Perturb. and Observe (P&O) method [11]. Control of the induction motors has attracted much attention in research. One of the most significant developments in this area has been the field-oriented control, where partial feedback linearization, together with a proportional integral This technique is very useful, except that it is very sensitive to parameter variations such as rotor time constant and incorrect flux measurement or estimation at low speeds. Direct torque control (D.T.C) of induction machines (I.M) is a powerful control method for motors drives. Featuring direct control of the stator flux and torque instead of the conventional current control technique, it provides a systematic solution to improve operating characteristics of the motor and the voltage inverter source [12]. In principle, D.T.C method is based on instantaneous space vector theory. By optimal selection of the space voltage vectors in each sampling period, D.T.C archives effective control of the stator flux and torque [13]. Thus, the number of space voltage vectors and switching frequency directly influence the performance of D.T.C control system. For a prefixed switching strategy, the drive behavior, in terms of torque, switching frequency and torque response, is quite different at low and high speed.

In this paper we present a proposed DTC-IG structure of an isolated photovoltaic water pumping system. In order to optimize the photovoltaic energy generation, the maximum power point tracking (MPPT) is integrated. The P&O is applied to the studied system. The studied system is modelled and simulated in the MATLAB Simulink environment and obtained results and some experimental ones are presented.

II. PROPOSED SYSTEM DESCRIPTION

In the case of variable speed drive system of an induction motor supplied by PV generator, two types of stand-alone PV systems with or without battery energy storage can be considered:

• A structure with two static converters [13]. The DC-DC converter which is included in this configuration is intended to implement the MPPT control algorithm and to keep the DC bus voltage to the value of the optimal voltage of PV module. The voltage inverter is used to perform DC-AC conversion and to control the mechanical motor speed.

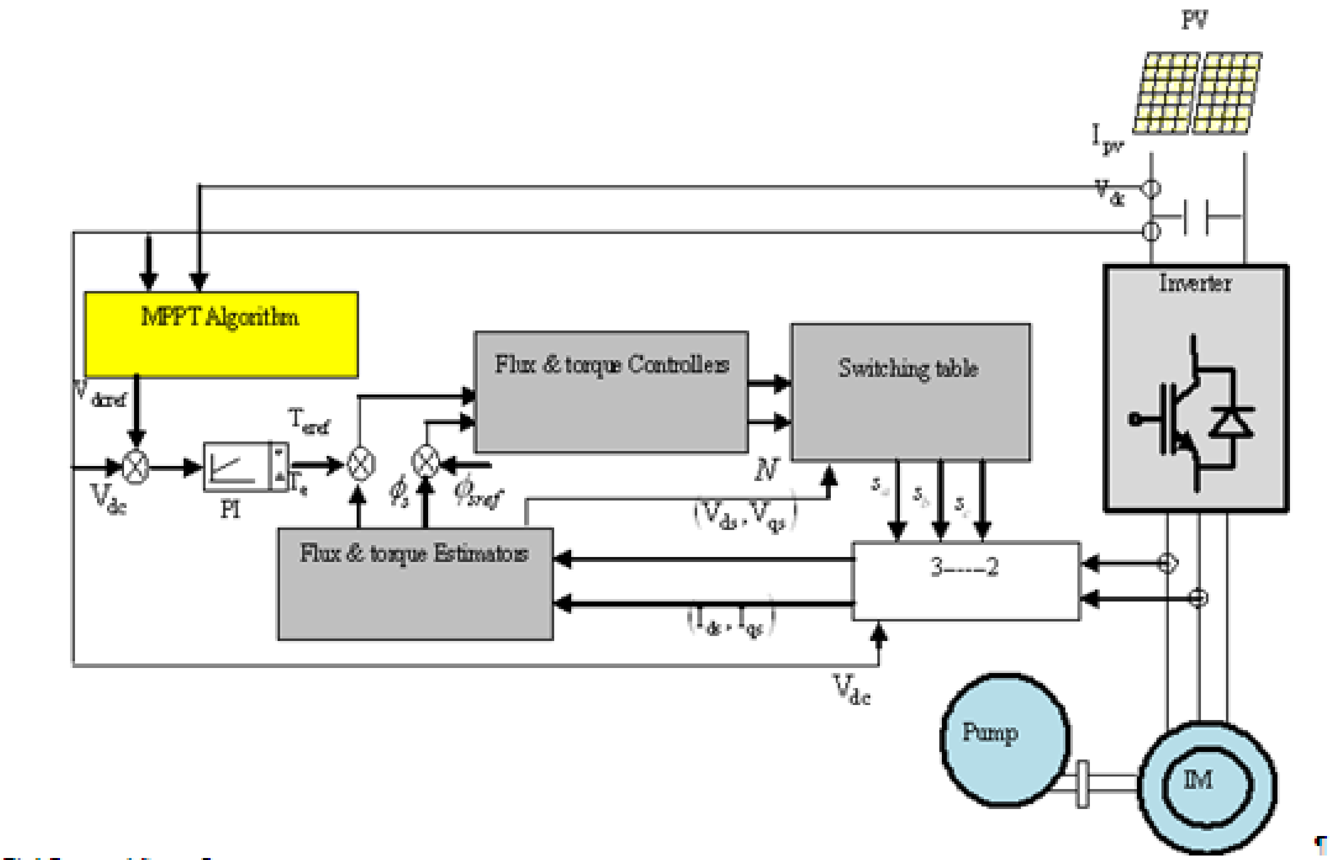


Fig1 Proposed System

Saut de section (continu)

• A single static converter structure. In this case, the inverter has not only to implement the MPPT algorithm to extract the maximum power output of the PV generator and to regulate the DC bus voltage, but it has to supply with sinusoidal waveforms and to regulate stator flux and electromagnetic torque of induction motor.

In this paper, we use the second structure which needs only one converter. In this case, the proposed system is represented in Fig.3. It consists of an induction motor fed by a photovoltaic generator through a three-phase voltage inverter controlled by the DTC technique.

A. Photovoltaic Array Modelling

In literature, there are several mathematical models that describe the operation and behavior of the photovoltaic generator. In our paper we applied the one diode model (Fig.2).

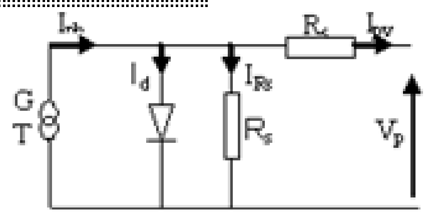


Fig 2 Simplified equivalent circuit of solar cell

$I_{pv}(V_{pv})$ characteristic of this model is given by the following equation [1]:

$$I_{pv} = I_{ph} - I_d - I_{Rsh} \quad \text{.........(1)}$$

or, developing the terms I_d and I_{Rsh} :

$$I_{pv} = I_{ph} - I_0\left[\exp\left(\frac{q(V_{pv}+R_s I_{pv})}{AN_s KT_j}\right)-1\right]-\frac{V_{pv}+R_s I_{pv}}{R_{sh}} \quad \text{.........(2)}$$

The resolution of this equation is made under matlab/simulink. We make validation through an experimental bench and we present comparison between experimental results and simulation ones using PV panel Siemens SM110-24 (table1)

TABLE 1

PARAMETERS OF THE PV PANEL SIEMENS SM110-24 [11]

Parameter	Value
P_{max}	110W
I_{mpp}	3.15A
V_{mpp}	35V
I_{sc}	3.45A
V_{oc}	43.5V
α_{sc}	1.4mA/°C
β_{oc}	-152mV/°C

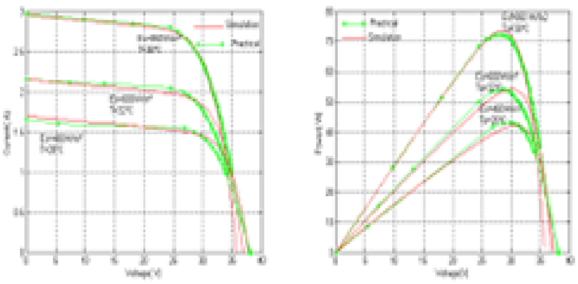


Fig.3. Comparison of experimental results with simulation ones

A. MPPT Algorithm

This is the most widely used method. A feedback loop and few measures are needed. The panel voltage is deliberately perturbed (increased or decreased) then the power is compared to the power obtained before to disturbance. Specifically, if the power panel is increased due to the disturbance, the following disturbance will be made in the same direction. And if the power decreases, the new perturbation is made in the opposite direction. The advantages of this method can be summarized as follows: knowledge of the characteristics of the photovoltaic generator is not required, it is relatively simple. Nevertheless, in steady state, the operating point oscillates around the MPP, which causes energy losses

B. Machine modelling:

An induction motor is modeled using voltage and flux equations which are referred to a general frame and are shown as follows:

-Stator voltage equations:

$$\begin{cases} V_{s\alpha} = R_s I_{s\alpha} + \dfrac{d\Phi_{s\alpha}}{dt} \\ V_{s\beta} = R_s I_{s\beta} + \dfrac{d\Phi_{s\beta}}{dt} \end{cases} \quad \text{.........(3)}$$

Where: α and β indices parameters are the Concordia transformation components of the current and the flux. $I_{s\alpha}$, $I_{s\beta}$ are α,β stator current respectively. $\Phi_{s\alpha}$, $\Phi_{s\beta}$ are α,β stator flux respectively. Rs is the stator resistance.

$$\begin{cases} 0 = V_{R\alpha} = R_R I_{R\alpha} + \dfrac{d\Phi_{R\alpha}}{dt} + \dfrac{d\theta}{dt}\Phi_{R\beta} \\ 0 = V_{R\beta} = R_R I_{R\beta} + \dfrac{d\Phi_{R\beta}}{dt} - \dfrac{d\theta}{dt}\Phi_{R\alpha} \end{cases} \quad \text{.........(4)}$$

Where: $I_{R\alpha}$, $I_{R\beta}$ are α,β stator current respectively, $\Phi_{R\alpha}$, $\Phi_{R\beta}$ are α,β rotor flux respectively, R_r is the rotor resistance.

$$\begin{cases} \Phi_{s\alpha} = L_s I_{s\alpha} + L_m I_{R\alpha} \\ \Phi_{s\beta} = L_s I_{s\beta} + L_m I_{R\beta} \\ \Phi_{R\alpha} = L_R I_{R\alpha} + L_m I_{s\alpha} \\ \Phi_{R\beta} = L_R I_{R\beta} + L_m I_{s\beta} \end{cases} \quad \text{.........(5)}$$

With: L_R, L_S, L_m are stator, rotor and magnetizing inductance respectively.

- Mechanical equation:

$$T_e - T_L = J_m \cdot \frac{d\omega_r}{dt} \quad \text{.........(6)}$$

With: ω_r is the rotor angular speed, J_m is the mechanical inertia.

$$T_e = P \times (\phi_{s\alpha} \times i_{s\beta} - \phi_{s\beta} \times i_{s\alpha}) \quad \text{.........(7)}$$

Where: P is the pole number

C. Inverter modelling

For each possible switching configuration, the output voltages can be represented in terms of space vector, according to the following equation:

$$\vec{V_s} = \vec{V_{s\alpha}} + j\vec{V_{s\beta}} = \sqrt{\frac{2}{3}}\left[V_a + V_b \exp\left(j\frac{2\pi}{3}\right) + V_c \exp\left(j\frac{4\pi}{3}\right)\right] \quad \text{.........(8)}$$

Where V_a, V_b and V_c are phase voltages.

The definition of flux sector and the inverter voltage vectors are shown in Fig. 4, where the stator flux vector is rotating with a speed of ω.

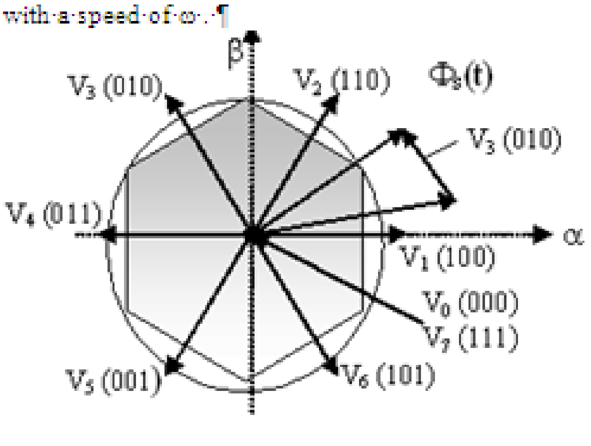


Fig.4. Movement of the inverter voltage in the space-vector plane

D. Pumping system Modelling

A polynomial fit of the third order expresses the relationship between the flow rate and power input, as described by the following equation [14]:

$$P(h,Q) = a(h)Q^3 + b(h)Q^2 + c(h)Q + d(h) \quad \text{.......(9)}$$

where P is the electrical power input of the motor-pump, h is the total head and a(h), b(h), c(h), d(h) are the coefficients corresponding to the working total head.

$$a(h) = a_0 + a_1 h^1 + a_2 h^2 + a_3 h^3 \quad \text{.......(10)}$$

$$b(h) = b_0 + b_1 h^1 + b_2 h^2 + b_3 h^3 \quad \text{.......(11)}$$

$$c(h) = c_0 + c_1 h^1 + c_2 h^2 + c_3 h^3 \quad \text{.......(12)}$$

$$d(h) = d_0 + d_1 h^1 + d_2 h^2 + d_3 h^3 \quad \text{.......(13)}$$

with a_i, b_i, c_i and d_i constants which depend on the type of photovoltaic pumping system.

The calculation of the instantaneous flow in terms of power is calculated using Newton-Raphson method. Thus at the k[th] iteration, the flow Q is given by the following equation: For P > 0, we have:

$$Q_k = Q_{k-1} - \frac{F(Q_{k-1})}{F'(Q_{k-1})} \quad \text{......(14)}$$

With $F(Q_{k-1}) = aQ^3_{k-1} + bQ^2_{k-1} + cQ_{k-1} + d - P_a$ ......(15)

Where $F'(Q_{k-1})$ is the derivative of the function $F(Q_{k-1})$

I. SYSTEM CONTROL OF VARIABLE SPEED DRIVE PV

In a D.T.C scheme system the instantaneous values of flux and torque can be calculated from stator variables and mechanical speed or using only stator variables. Stator flux and torque can be controlled directly and independently by properly selecting the inverter switching configurations. With a three phase voltage source inverter, six non-zero voltage vectors and two zero-voltage vectors can be applied to the machine terminals. The stator flux can be estimated using measured current and voltage vectors [15]:

$$\phi_s(t) = \int_0^t (V_s - R_s i_s)\,dt \quad \text{......(16)}$$

Since stator resistance R_s i, relatively small, the voltage drop $R_s i_s$ might be neglected ($V_s \gg R_s i_s$), we obtain:

$$\phi_s(t) = V_s.T + \phi_s(0) \quad \text{.......(17)}$$

$\phi_s(0)$ is the stator flux initial value at the switching time, T the sampling period in which the voltage vector is applied to stator windings. It is clear that stator flux directly depend on the space voltage vector V_s and the system sampling period T. The stator voltage vector V_s is selected using Table 2., where signs of torque and flux errors E_T and E_ϕ are determined with a zero hysteresis band.

$$E_T = T_{e\,ref} - T_e \quad \text{......(18)}$$

$$E_\phi = \phi_{s\,ref} - \phi_s \quad \text{......(19)}$$

where

$$\phi_s = \sqrt{(\phi_{s\alpha})^2 + (\phi_{s\beta})^2} \quad \text{......(20)}$$

Table.2. shows the associated inverter switching states of the conventional direct torque control strategy.

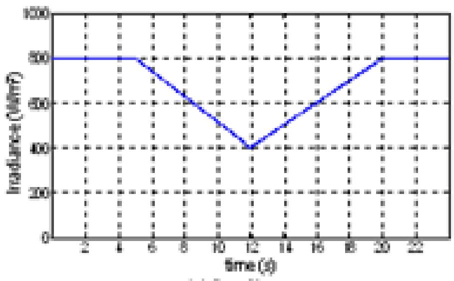
TABLE 2.

SWITCHING TABLE FOR THE CONVENTIONAL D.T.C

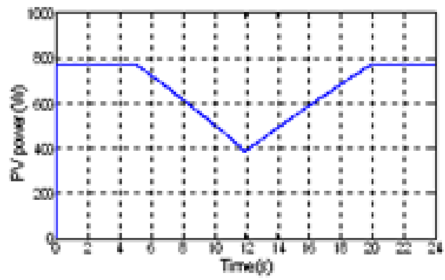
E_T	E_ϕ	N					
		1	2	3	4	5	6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	$E_\phi=0$	V_5	V_6	V_1	V_2	V_3	V_4

We make simulation of the proposed system (Fig.1.) under Matlab/Simulink. Obtained simulation results under irradiance variations are represented in the following figures.

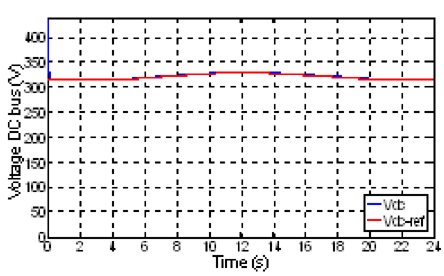
In Fig.7, we present results obtained under sudden irradiations variations. The sampling period of the system is about T=100µs. We note that the voltage DC bus V_{dc} remains constant and follows its reference V_{dcref}. The electromagnetic torque follows the irradiance profile while the stator flux keeps its reference (Φ_{sref}=0.8 Wb) during sudden irradiation variations. Also, with the introduction of the MPPT, the mechanical speed increases resulting in an increase of the water flow. We represent the mechanical power as a function of the water flow output (Fig.8) for different total heads (h=4, 8 and 10 m).



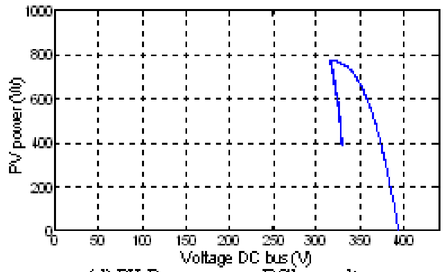
(a) Irradiance



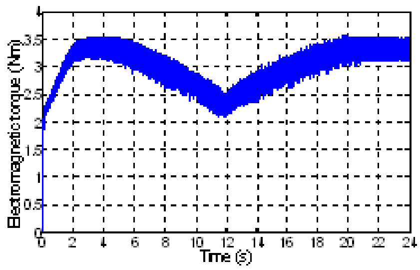
(b) Photovoltaic power



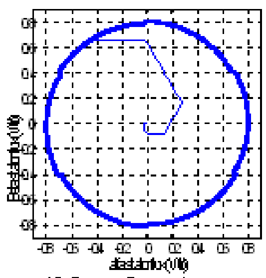
(c) DC bus voltage

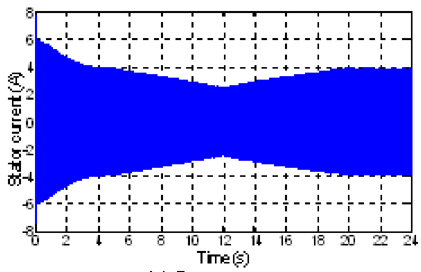


(d) PV Power versus DC bus voltage

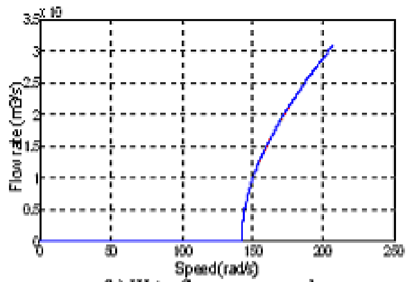


(e) Electromagnetic torque

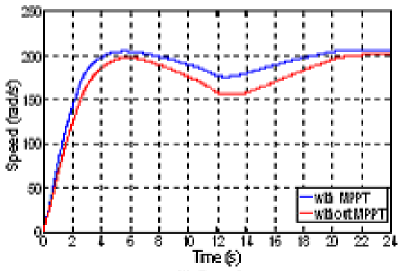

(f) Stator flux trajectory



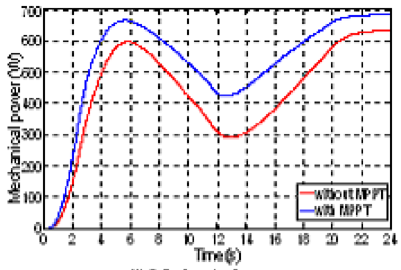
(g) Stator current



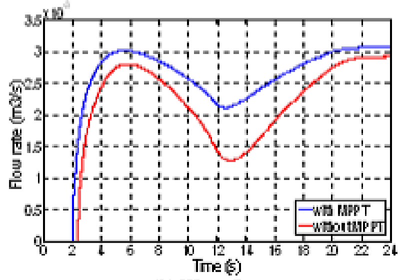
(h) Water flow versus speed



(i) Speed



(j) Mechanical power



(k) Water flow

ig.5. Simulation responses under sudden irradiation

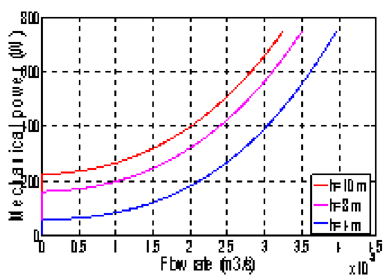


Fig 6.Mechanical power versus flow rate for different heads

I. CONCLUSIONS

A Direct Torque Control of an Induction Generator fed by a photovoltaic system was proposed in this paper. This allows the extendibility of the applicability of the studied system, particularly in the pumping of water. To show the effectiveness and the performances of the developed control scheme, a simulation study was carried out. Good results were obtained. The robustness and the tracking qualities of the proposed control system using direct torque control appear clearly and It will be interesting to implement the proposed system using a D.S.P-based hardware.

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