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Fuzzy Logic Space Vector Direct Torque Control of PMSM for Photovoltaic Water Pumping System

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Abstract

This paper presents an intelligent artificial speed control approach of permanent magnet synchronous motor which leads photovoltaic water pumping system. The photovoltaic solar energy source is connected to boost converter, then it will be controlled using fuzzy logic technical, in order to ensure the maximum power point whatever the climatically conditions and load variation, when their characterises is non-linear. However, an effective solution must ensure that the photovoltaic generator operated at the maximum power and that the motor runs at a high efficiency level. The three-phase inverter and two levels that supplies permanent magnet synchronous motor when was controlled by a space vector pulse weigh modulation. The space vector direct torque control is also studied. So, to analyze the performance of speed control between the fuzzy logic controller and proportional integrator controlled. The performance index based on speed error is assigned to provide a numerical comparison among different controllers. When compared with other methods, the torque ripples are reduced remarkably with the proposed method. The topology of these speed controllers is developed and the simulations with Matlab/Simulink according to the speed and load variation tests are shown and discussed.

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Keywords: Photovoltaic; Water pumping; MPPT; Fuzzy logic; Direct torque Control; Simulation.

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1. Introduction

Nowadays, there are many forms of renewable energy, the most commonly used are: solar, wind and hydraulic. The sun is in the form of heat that is transmitted by infrared radiation, these exhibits under effect of photovoltaic (PV).

The speed control of AC drive supplied by PV is one of the most important applications in PV systems, it has become a favorable solution for many applications, because of gaining more acceptance and market share, particularly in rural: areas that have a substantial amount of insolation and have no access to an electric grid. So, photovoltaic systems are used to pump water for livestock, plants or humans. Since the need for water is greatest on hot sunny days, the technology is an obvious choice for this application. Agricultural watering needs are usually greatest during sunnier periods when more water can be pumped with a solar system [1, 2].

In the North Mediterranean countries like Algeria has one of the fastest growing surfaces in this continent. However, it is remotely isolated rural areas posed problems to rural energy management and development of renewable energy sources. The average annual daily solar radiation is within the range of 5:7 kWh/m²/day [3]. The major problem of Photovoltaic Generator (PVG) is their nonlinear elements[4], where its optimum operating point depends on climatic conditions such as the temperature, the solar radiation and also the load variations. Indeed, an effective solution must ensure that the PVG runs at the maximum power point (MPP) and that the motor runs at a high efficiency level. The latter's role is to pursue maximum power, it is mounted up stream of a converter. The objective is to control the DC-DC converter type boost, on the one hand by acting on the duty cycle (d) by using the maximum power point tracking (MPPT) based on fuzzy logic controller (FLC)[5]. The inverter on the other control by using the vector mode by FLC direction of rotor flux in order to control the torque and speed. Generally, the DTC is insensitive to the motor parameters variations [6, 7], however, in renewable energy application, it is interesting to verify that quality is checked under the constraint of the variation of the load torque and the DC bus voltage of the inverter which varied inevitably.

In this work, the speed control of permanent magnet synchronous motor (PMSM) is considered in the aim to achieve high accuracy and a fast dynamic response. In this way, the direct torque control-space vector modulation (DTC-SVM) technic is used for to optimize the switching selection table and offer more voltage space vector than traditional DTC [8, 9].The paper is organized as follows: in section II the proposed and study system is presented. Section III we illustrate the design of fuzzy logic methodology. In section IV the speed control and the direct torque control-space vector modulation are developed. Finally, section V presents the simulation and results obtained with the proposed techniques.

Nomenclature

a	p-n junction ideality factor
d	Duty cycle
de(k)	derivate variable of error
e(k)	Error input variable of fuzzy logic
Eg	Band Gap
G, G_r	Real and reference solar radiation
h',h	Height and total height
I_0	Cell reverses saturation current
I_{0r}	Reverse saturation current
I_D	Diode Current
i_d, i_q	Current components in d-q system
I_{ph}	Generated photocurrent
I_{sc}	Short-circuit current
I_{scr}	Reference short-circuit current
K	Boltzmann's constant
k_i	Temperature coefficient
NB	Negative big
NM	Negative medium

NS	Negative small
n_s	Number cell series
P	Number of pole pairs
P',P	Power and nominal power
Ppv(k)	PV array output power
PB	Positive Big
PS	Positive small
q	Electron charge
Q', Q	Flow and the nominal flow pump
R_p, R_{se}	Parallel and serie resistances
R_S, L_S	Resistance and the inductance stator
T_e,T_{ref}	Real and reference electromagnetic torque
Tl	Load torque
T,T_r	Real and reference temperator
$T_{1:3}$	Sector number
$T_{a:c}$	Action time of three phase
u_d,u_q	Stator voltage in the d-q axis
V_{pv}	PV panel output voltage
V_{dc}	Output voltage of boost converter
ZE	Zero
ω_{ref} ,θ	Reference speed and position of rotor
ω_r	Real speed
Φ_f	Flux of permanent magnet
$\Psi_{d,q}$	flux of permanent magnet in d, q coordinate system

2. Structure of system

The photovoltaic water pumping system consists at the PVG, power converters (Boost converter and DC-AC converter), permanent magnet synchronous motor and centrifugal pump, see Fig. 1.

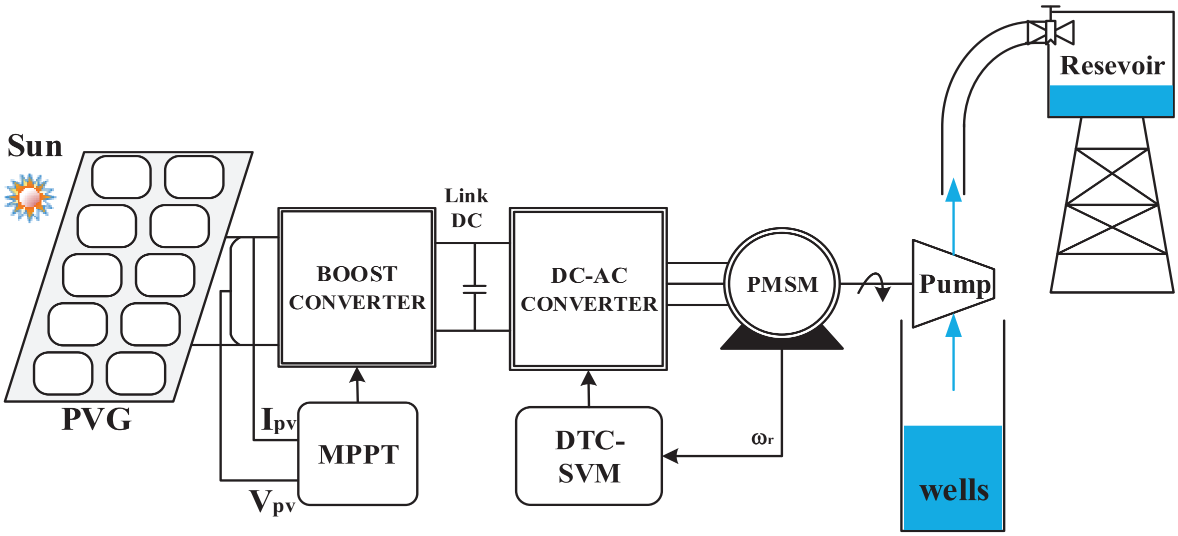

Fig. 1. Synoptic bloc of photovoltaic water pumping.

2.1. Modeling of photovoltaic generator

The PV panel is composed of many cells, placed in series N_s or in shunt N_{sh}. Where it can be modelled by current source connected in parallel with diode according with shunt and series resistor noted by R_{sh} and R_{se} as illustrated in Fig. 2.

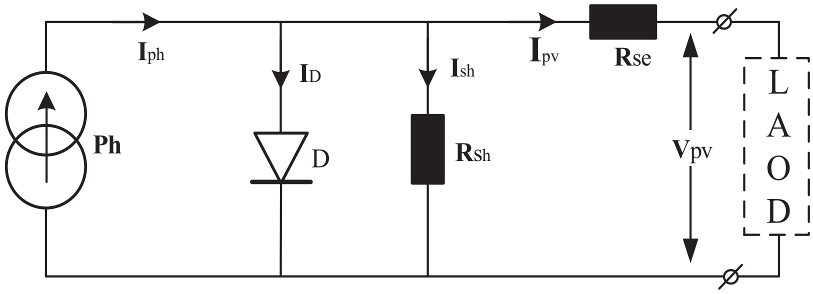

Fig. 2. Photovoltaic array circuit.

The output current is given by the following equation [10]:

$$I_{pv} = N_{sh}\, I_{ph} - N_{sh} I_0 \left\{ \exp\left[\frac{q\left(V_{pv} + \frac{N_s}{N_{sh}} I_{pv} R_{se}\right)}{akTn_s} \right] - 1 \right\} - \frac{V_{pv} + \frac{N_s}{N_{sh}} I_{pv} R_{se}}{\frac{N_s}{N_{sh}} R_{sh}} \tag{1}$$

Where, the cell reverse saturation current is related to the temperature (T) as follows [11]:

$$I_0 = I_{or} \left(\frac{T}{T_r}\right)^3 \exp\left\{ \frac{qE_G}{Ka} \left[\frac{1}{298} - \frac{1}{T} \right] \right\} \tag{2}$$

Similarly, the photocurrent I_{ph} depends on the solar radiation (G) and the cell temperature (T) [12]:

$$I_{ph} = \{I_{scr} + k_i (T - 298)\} \frac{G}{G_r} \tag{3}$$

2.2. Modeling of power converters

The PVG is fed the DC voltage converter, see Fig. 3, where the optimum value of duty cycle d is decided from the MPPT controller who depends of climatic conditions but the inverter (DC/AC converter) is controlled by space vector pulse width modulation (SVPWM).

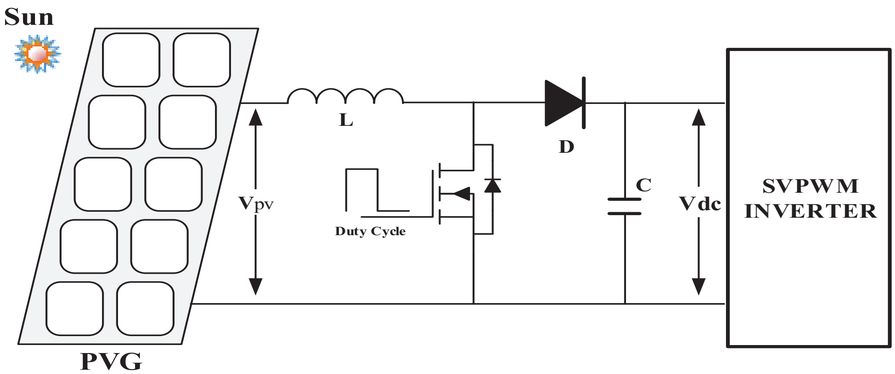

Fig. 3. Boost converter circuit.

The output voltage (V_{dc}) is expressed by following relation [13]:

$$V_{dc} = \frac{V_{pv}}{1-d} \tag{4}$$

The SVPWM has object to provide motor with circular magnetic field [14]. So, according to ideal flux circle generated by three-phase symmetric sinusoidal voltage, we defined the following expressions of the voltage and the conducting time of each inverter switch is shown in Table 1:

$$\begin{cases} U_{ref\,a} = U_\beta \\ U_{ref\,b} = U_\alpha(1.73) - U_\beta \\ U_{ref\,c} = -U_\alpha(1.73) - U_\beta \end{cases} \tag{5}$$

Table 1. T_1 and T_2 in Different Sectors.

N	1	2	3	4	5	6
T_1	-Z	Y	X	Z	-Y	-X
T_2	X	Z	-Y	-X	-Z	Y

With,

$$\begin{cases} X = U_\beta . T(1.73)/V_{dc} \\ Y = \left(3U_\alpha + U_\beta(1.73)\right)T/2V_{dc} \\ Z = \left(-3U_\alpha + U_\beta(1.73)\right)T/2V_{dc} \end{cases} \tag{6}$$

So, the action time are defined as following:

$$\begin{cases} T_a = (T - T_1 - T_2)/4 \\ T_b = 0{,}5T_1 + T_a \\ T_c = 0{,}5T_2 + T_b \end{cases} \tag{7}$$

Assign T_1, T_2 and T_3 according to Table 2, where are defined as the conducting time of phase a, b and c, respectively.

Table 2. Calculation of Switch Point.

N	1	2	3	4	5	6
T_1	T_c	T_a	T_b	T_c	T_a	T_b
T_2	T_a	T_c	T_b	T_a	T_a	T_c
T_3	T_b	T_b	T_a	T_b	T_c	T_a

2.3. Modeling of Permanent Magnet Synchronous Motor

Suppose to ignore the core saturation, eddy current, and hysteresis loss of the motor and there is no damper winding in rotor, the following equations describe the mathematical model of PMSM in the d-q coordinate system [15]:

$$\begin{cases} u_d = R_s i_d + \frac{L_s di_d}{dt} - \omega_r \Phi_f \sin\theta \\ u_q = R_s i_q + \frac{L_s di_q}{dt} + \omega_r \Phi_f \cos\theta \end{cases} \tag{8}$$

$$\begin{cases} \Psi_d = \int (u_d - R_s i_d)\, dt \\ \Psi_q = \int \left(u_q - R_s i_q\right) dt \end{cases} \tag{9}$$

$$T_e = \frac{3}{2} p(\Phi_d i_q - \Phi_q i_d) \tag{10}$$

2.4. Modeling of Centrifugal Pump

The centrifugal pump applies a load torque proportional to the square of the rotational speed of the motor. Centrifugal pump is the most commonly employed type of pumps [16], it has a relatively high efficiency and capable of pumping a high volume of water. The performances Q, h and P are given in terms of the speed using the following relationships:

$$\begin{cases} Q' = Q.Z \\ h' = h.Z^2 \\ P' = P.Z^3 \end{cases} \tag{11}$$

Where, $Z = \omega_r'/\omega_r$.

3. Direct torque space vector control

The basic principle in conventional DTC for induction motors is to directly select stator voltage vectors by means of a hysteresis stator flux and torque control. As it is seen in Fig. 4 [17].

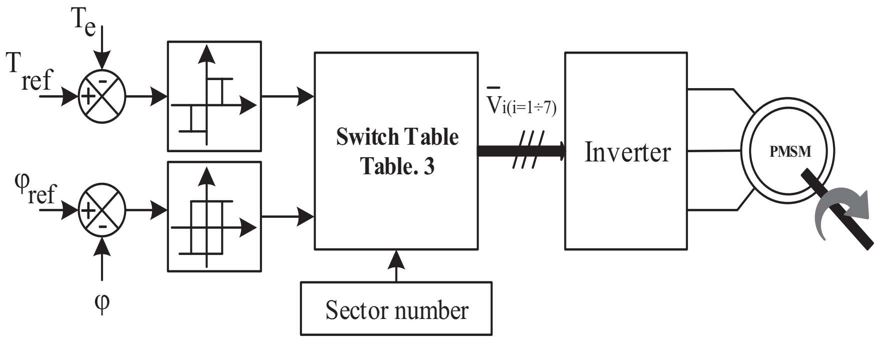

Fig. 4. The diagram block of traditional DTC.

According to Fig. 4 stator flux (φ_{ref}) and torque references (T_{ref}) can be obtained and then compared with the corresponding real values. Both stator flux and torque errors ($\Delta\varphi$), and (ΔT_e), are processed by means of a hysteresis band comparators. In particular, stator flux is controlled by the two-level hysteresis comparator. On the basis of the hysteresis comparators and stator flux sector a proper VSI voltage vector is selected by means of the switching table given in Table 3.

Table 3. Basic DTC Switching table.

Sector number		1	2	3	4	5	6
$\varphi = 1$	Te = 1	V5	V6	V1	V2	V3	V4
	Te = 0	V0	V7	V0	V7	V0	V7
	Te = -1	V3	V4	V5	V6	V1	V2
$\varphi = 0$	Te = 1	V6	V1	V2	V3	V4	V5
	Te = 0	V7	V0	V7	V0	V7	V0
	Te = -1	V2	V3	V4	V5	V6	V1

In direct torque control with space vector pulse width modulation (DTC-SVM) with close loop flux control, with close loop torque control and with close loop flux and torque control, the calculation of reference voltage vector is based on demanded.

This differentiation algorithm is very sensitive to disturbances. In case of errors in the feedback signals, the differentiation algorithm may not be stable .and this is very serious drawback of these methods that causes torque and flux ripple with deteriorate the performance of system. The proposed method DTC-SVM based on amplitude stator voltage and stator flux angle is used to modify the control system. The stator flux angle is controlled by rotor angular frequency and slip angular frequency. Figure. 5 shows the block diagram of sensor DTC –SVM based on amplitude voltage and stator flux angle. This control system is consist of PI controller for slip angular frequency, PI torque controller, PI flux controller and Cartesian to polar transformation block to calculate amplitude of stator voltage, while polar to Cartesian block is used to calculate stator voltages in direct and quadrature reference frame at next sampling time. Ziglar nicals method is used to tune K_p and K_i gains of PI where in this method the damping ratio is fixed at 1 and the rise time $t_r = 0.5s$. In this method, the PI speed controller is used to optimize the reference torque (T_{ref}) of the motor from the error between reference speed and the rotor speed (ω_{ref}, ω_r) respectively.

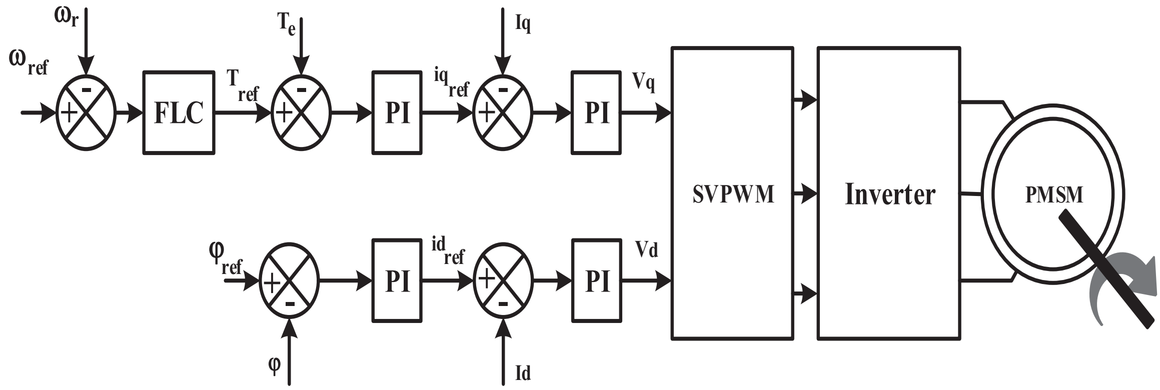

Fig. 5. Scheme of DTC-SVM.

4. Maximum power point tracking

The maximum power that can be delivered by a PV panel depends greatly on the insulation level and the operating temperature. Therefore, it is necessary to track the MPP all the time. They have the advantage to be robust and relatively simple to design as they do not require the knowledge of the exact model. They do require on the other hand the complete knowledge of the operation of the PV system. The FLC input variables are the error (e) and derivate of error (de) at sampled times k defined by [18]:

$$\begin{cases} e(\mathrm{k}) = \frac{\mathrm{P_{pv}(k)-P_{pv}(k-1)}}{\mathrm{V_{pv}(k)-V_{pv}(k-1)}} \\ de(\mathrm{k}) = e(\mathrm{k}) - e(\mathrm{k}-1) \end{cases} \tag{12}$$

The FLC tracks the MPP based on master rule of "*If X and Y, Then Z*" [19, 20]. To determine the output of the positive, negative and zero sequence voltages, currents, and impedances fuzzy logic, the inference is used. There are many methods for inference but the popular one is Memdani. Other methods include compositional rule of inference, generalized modus ponens and Sugeno inference method. The fuzzy inference is carried out by using Memdani's method and the defuzzification uses the centre of gravity to compute the output of this FLC which is the optimum duty cycle. The control rules are indicated in Table 4 with (*e*) and (*de*) as inputs and d as the output, where d is associated fuzzy sets involved in the fuzzy control rules .

Table 4. Fuzzy rules.

de|e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

4. Simulation results

The diagram bloc of the PV water pumping system with Matlab is seen in Fig.6

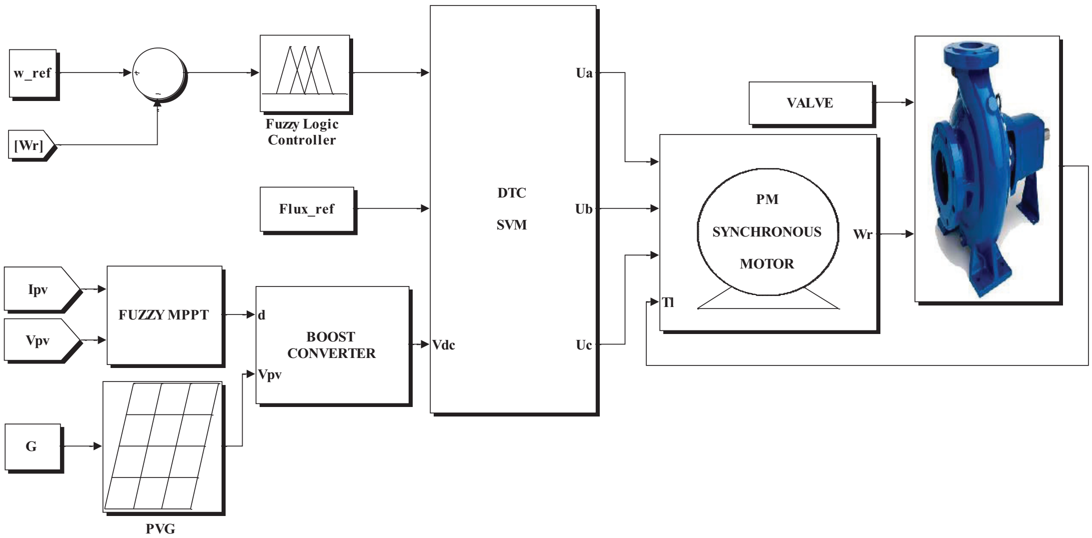

Fig. 6. The simulation bloc of system.

In order to establish a good test of the proposed system (fuzzy logic space vector direct torque control of PMSM for photovoltaic water pumping system), two simulation conditions operation are applied:

- Two speed references (- 120 rad/s and +120 rad/ s) are considered are explained by Fig. 9.
- Twice negative, twice positive and fours nulls reference torque are illustrated in Fig. 10.

According to figure 9 it shown that the speed with PI and FLC shows their reference, it note that with using PI controller there are a short speed response time accompanying with a heaver oscillations. Comparing to PI controller, the FLC design improve the more soupless response, not speed oscillations but more speed response time.

Figure.10 demonstrates the variation reference of the torque with the two controllers design, the torque present a good pursuit, it's observed with using FLC mains overshoots and oscillations, a grave pics with conventional controller at instants during to start and speed inversion.

Concerning the electrical characteristics Fig. 7 and Fig. 8 presents respectively the response currents with FLC and PI. It's observed that the currents are sinusoidal forms while the PI controller design present a grave pics under realistic speed conditions compared to FLC design.

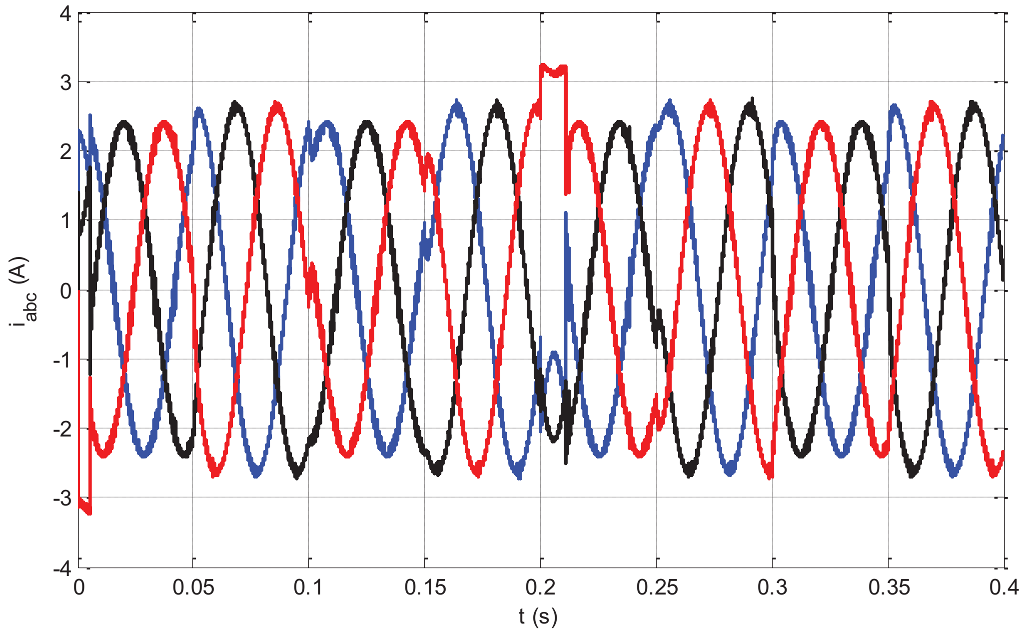

Fig. 7. Response stator current of motor with FLC.

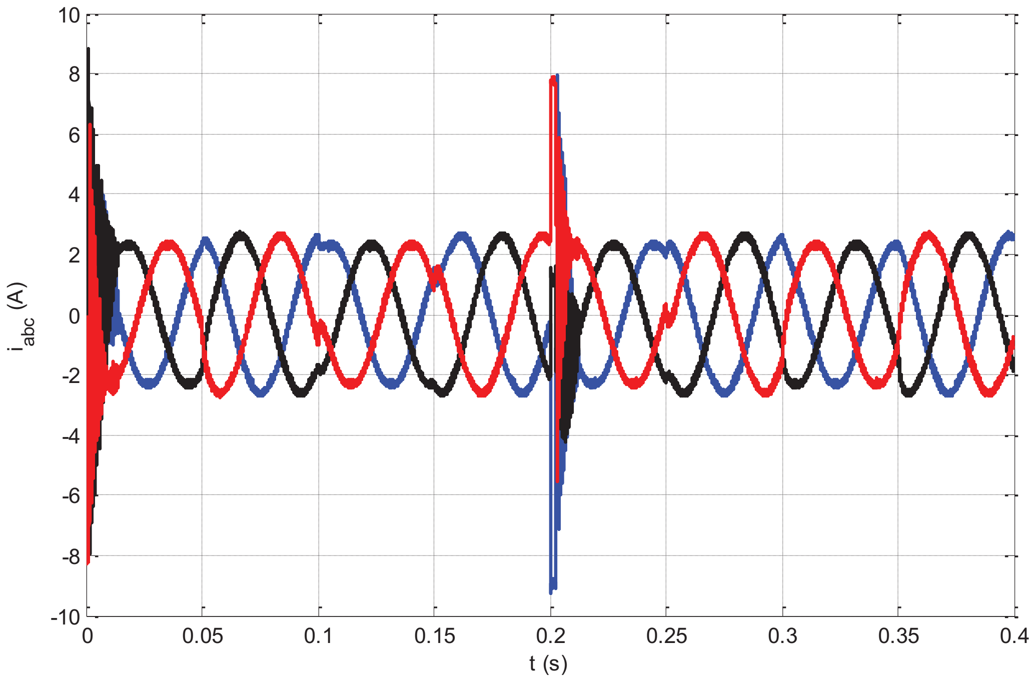

Fig. 8. Response stator current of motor with PI controller.

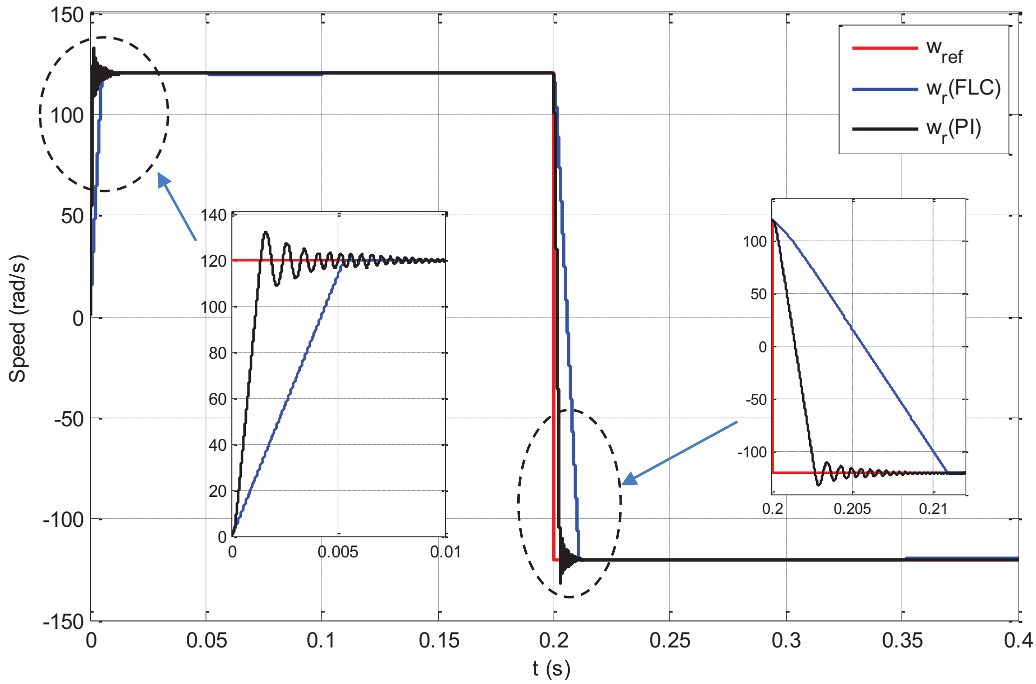

Fig. 9. Speed response PMSM.

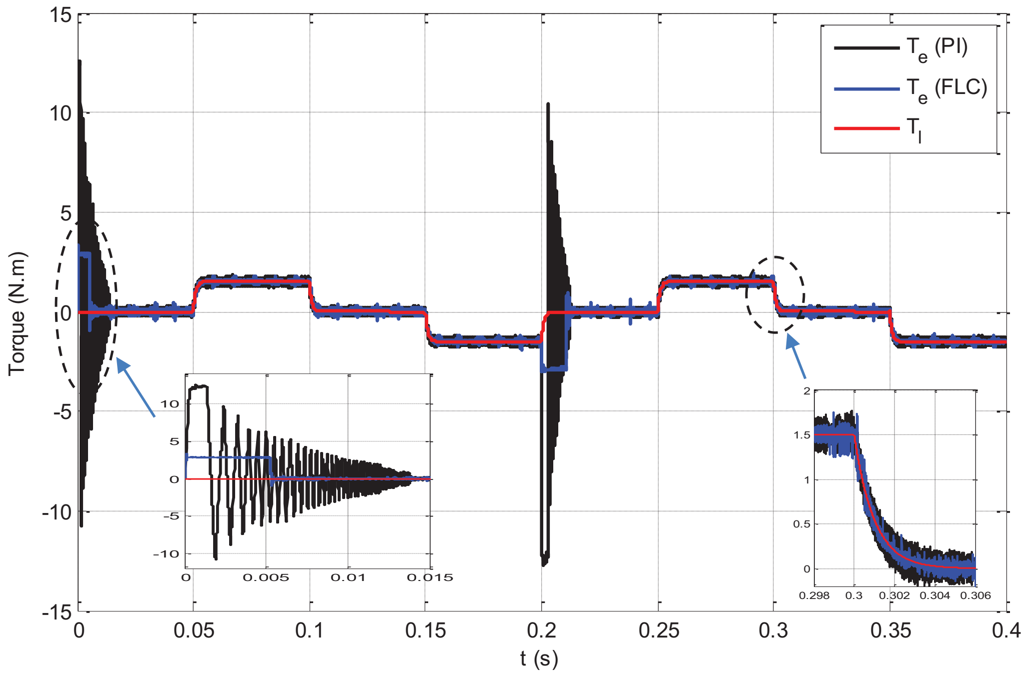

Fig. 10. Torque response of PMSM.

According to Fig.11, the trajectory of flax in a b farm is a cercal form. It's prove that the sinusoidal flux form. It's shown in Fig.12 a good flux reference follows with not any overshoot or oscillates, these improved the DTC-SVM potential. It shows the behavior of the greatness flows.

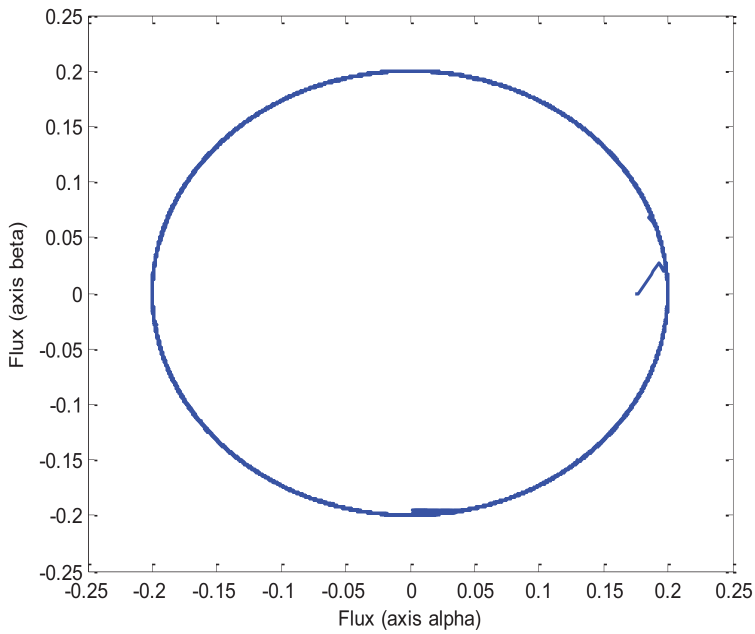

Fig. 11. Flux trajectory in alpha-beta farm.

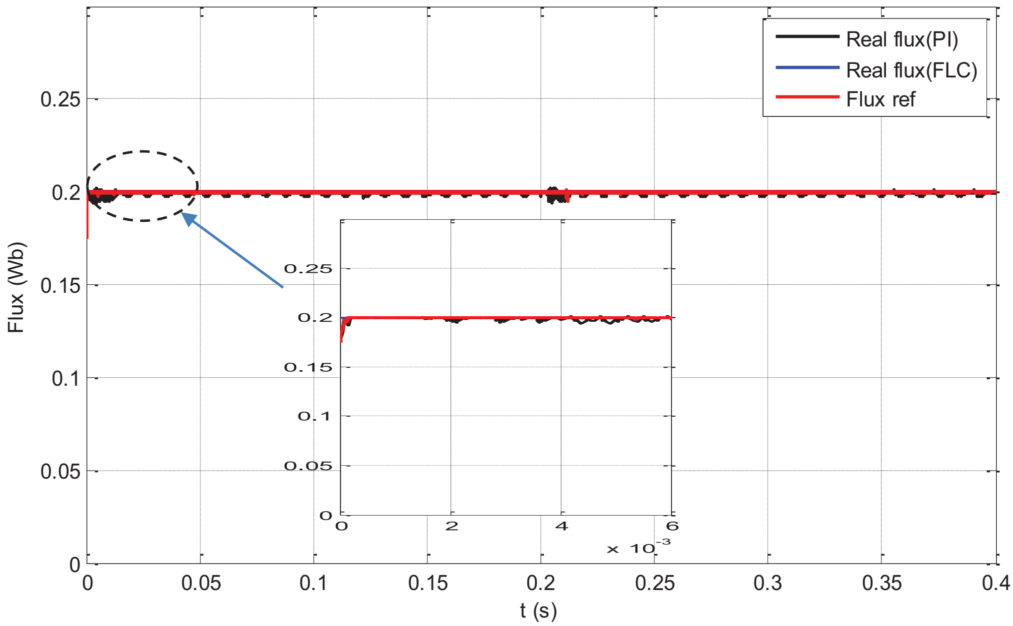

Fig. 12. Flux Response with FLC and PI.

5. Conclusions

The study of performances speed control photovoltaic system with fuzzy logic has been tested. The performances are analyzed in the response time and overflow are analysed and comprised between traditional DTC and DTC-SVM. It is concluded that the propeller torque is proportional to its square of the speed approximately by analyzing the propeller's characteristic.

The simulation results show clearly that the proposed DTC-SVM proposed for torque ripple reduction is very appropriate for electric propulsion ship. The DTC system based on SVPWM manifests for continuous output of voltage vector from the converter, making the periodical pulsation of the flux and torque decrease greatly. So, it can meet the requirement of the constant output of torque in real time for propulsion motor.

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