

A Service of

ZBU

Leibniz-Informationszentrum Wirtschaft Leibniz Information Centre for Economics

Errouha, Mustapha et al.

## Article

# Optimization and control of water pumping PV systems using fuzzy logic controller

**Energy Reports** 

### **Provided in Cooperation with:** Elsevier

Suggested Citation: Errouha, Mustapha et al. (2019) : Optimization and control of water pumping PV systems using fuzzy logic controller, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 5, pp. 853-865, https://doi.org/10.1016/j.egyr.2019.07.001

This Version is available at: https://hdl.handle.net/10419/243633

#### Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

#### Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet. or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



ND https://creativecommons.org/licenses/by-nc-nd/4.0/





Contents lists available at ScienceDirect

# **Energy Reports**

journal homepage: www.elsevier.com/locate/egyr

# Optimization and control of water pumping PV systems using fuzzy logic controller

Mustapha Errouha \*, Aziz Derouich, Saad Motahhir, Othmane Zamzoum, Najib El Ouanjli, Abdelaziz El Ghzizal

Laboratory of Production Engineering, Energy and Sustainable Development, higher school of technology, km5 Rte Imoouzzer, BP 2427, USMBA Fez, Morocco

#### ARTICLE INFO

Article history: Received 11 April 2019 Received in revised form 28 June 2019 Accepted 1 July 2019 Available online xxxx

Keywords: Photovoltaic water pumping system (PWPS) Direct torque control (DTC) Fuzzy logic control (FLC) Induction machine (IM) Optimization Variable step size Perturb and observe (P&O)

#### 1. Introduction

The diesel engine pumps are used for agriculture in remote area, since they are simple to install, but these types of systems cause environmental problems because they work with fossil fuels (Yahyaoui and Serna Cantero, 2018). The renewable energy based water pumps present alternative solution, because it produces electricity without harming the environment, and they are mostly used due to high distribution costs/non-availability of grid-power (Drissi et al., 2017; Matam et al., 2018). Thus, frequent repairs and maintenance of diesel pumps are generally 2–4 times more than photovoltaic pumps (Chandel et al., 2017).

The induction motor is the principal element of the pumping systems (Chihi et al., 2017). DC motors were used for speed controls because of their simple design in controlling flux and torque (Azab, 2015). However, DC motors need regular maintenance (Reza et al., 2014). To surmount this weakness, Brushless permanent-magnet motors have been proposed (Gopal et al., 2013). But, these engines are limited for low-power PV systems (Chandel et al., 2015). Then, PV pumping systems based on AC motors have been used because they are more efficient, maintenance-free and low costs (Talbi et al., 2018; Vas, 0000).

\* Corresponding author. E-mail address: mustapha.errouha@usmba.ac.ma (M. Errouha). However, the flux, torque and speed controls of these induction motors are complex due to its nonlinear model (Reza et al., 2014).

Field oriented control (FOC) is the most used technique to drive the IM (Hannan et al., 2018), it consists of two control techniques: indirect FOC (IFOC) (Hussein, 2014; Rafa et al., 2014) and direct FOC (DFOC) (Reza et al., 2014; Alsofyani and Idris, 2013). The reason behind using this type of control is to obtain torque and flux decoupling even with their complex mathematical equations for IM (Bouhoune et al., 2017). These methods have been used by numerous researchers in several studies because of the high performance of controller in IM drives (Rafa et al., 2014; Allirani S, 2014). However, the FOC technique is complex and the system performances are influenced by external load disturbances and uncertainties, parameter variations (Amezquitabrooks et al., 2013; Harnefors et al., 2013; Hedjar R and Boucher, 2013; Lekhchine et al., 2014). To surmount these drawbacks, a new control method which is Direct Torque Control (DTC) was proposed (Reza et al., 2014). Several studies showed that DTC presents some advantages compared to FOC (Alsofyani and Idris, 2013). However, DTC has major drawbacks which are high ripples in the flux and electromagnetic torque and variable switching frequency due to the use of hysteresis controllers (Achour et al., 2016). These disadvantages produce undesirable acoustic noise and mechanical vibrations which lead to a deterioration of the machine performances and generate high currents distortion which degrades the quality of the output power.







https://doi.org/10.1016/j.egyr.2019.07.001

#### ABSTRACT

The aim of this work is to search for better control and optimization of a photovoltaic (PV) water pumping system (PWPS) using the induction motor. A proposed method based on Fuzzy Logic Control (FLC) is introduced and investigated to improve the conventional Direct Torque Control (DTC). Variable step size Perturb and observe (P&O) is used to extract the maximum possible power from the PV panel. The validation of the control strategy is ensured by reducing the high torque, stator flux ripples and current harmonics in induction machine and increasing pumped water flow. Simulation results of the DTC based on FLC are compared with those of the conventional DTC using MATLAB/SIMULINK. The comparison results show the effectiveness of the FLC controller in terms of torque and flux ripples reduction, and daily pumped water.

© 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

<sup>2352-4847/© 2019</sup> The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).



Fig. 1. Description of the photovoltaic pumping system.



Fig. 2. Equivalent circuit of a photovoltaic cell.

Researchers proposed several solutions to improve DTC. D. Mohan et al. and D.isalm et al. used multilevel inverters, this method reduces the ripples, but the switching losses and the cost are increased due to the high number of power devices (Mohan et al., 2017; Islam et al., 2015). In Refs. Mahanta and Patnaik (2015) and Lgeb (0000), the authors propose space vector modulation (SMW), however, this technique needs accurate design of torque and flux controllers. DTC is also improved by sliding mode control as given in Benamor et al. (2019), but the chattering phenomenon appeared which present the main problem of this method. In the recent years, the use of artificial intelligent techniques like neural network-based DTC have been used by many researchers to improve the controller performances. This technique provides high performance, but it requires the training process which retards the performance of the controller (Sutikno et al., 2014a).

Fuzzy logic controller is an intelligent control strategy which is characterized by its logical resemblance to a human operator (Castillo et al., 2016). The structure of FLC is adjusted based on the components of its internal configuration like Fuzzy rules, fuzzification and defuzzification blocks. The main advantages of Fuzzy logic controller are adapted to the nonlinear control command and not based on the model of the induction machine (Cervantes and Castillo, 2015). It has very effective techniques for complicated and imprecise processes where there does not exist any mathematical model. These features make the FLC not only easy to use, but also easy to design. Sancheza et al. (2015)

Many authors introduced FLC for doubly fed induction machine (DFIM), doubly fed induction generator (GFIM) and permanent magnet synchronous motor (PMSM) (Benamor et al., 2019; El Ouanjli et al., 2019; El-samahy and Shamseldinb, 2018). In fact, the use of FLC results in reducing torque and flux ripples.

However, to the authors best knowledge, the previous studies about photovoltaic water pumping systems do not use fuzzy logic controllers to control the induction motor (IM). For this, an improved DTC of IM based water pumping system using FLC is proposed. The proposed method consists of substituting the hysteresis controllers and the look-up table by fuzzy logic switching vector selection scheme. To show the performance of the proposed method, a comparative study between the proposed method and the conventional DTC is presented under different operating conditions. Simulation results demonstrate the superiority of the proposed method in terms of daily cumulative water, power and the overall efficiency. Moreover, the quality of current signals is improved with a THD around 3.06%. To ensure the maximum power point whatever the climatically conditions, variable step size P&O are used to track maximum power of photovoltaic pumping system. This work is structured as follows: Section 2 presents the modeling of the system components (Fig. 1). The variable step size P&O is presented in Section 3. The conventional DTC used for controlling the asynchronous machine is developed and FLC-DTC is detailed in depth in Section 4. The results and discussion are illustrated in Section 5. Finally, the conclusions of this work are given in Section 6.

#### Nomenclature

a	: Diode's ideality factor
G	: Solar irradiation [W/m <sup>2</sup> ]
Ι	: Panel output current [A]
Io	: Diode saturation current [A]
I <sub>ph</sub>	: Panel photocurrent [A]
I <sub>r</sub>	: Rotor current [A]
Is	: Stator current [A]
К	: Boltzmann constant [] K <sup>-1</sup> ]
K <sub>v</sub>	: Temperature coefficient of open circuit
	voltage [V/°C]
Ki	: Temperature coefficient of short circuit
-	current [A/°C]
l <sub>r</sub>	: Rotor inductance [H]
ls	: Stator inductance [H]
Μ	: Mutual inductance [H]
Ns	: Number of cells connected in series
Offset	: Step size
q	: Electron charge [C]
R <sub>r</sub>	: Rotor resistance $[\Omega]$
R <sub>s</sub>	: Series resistance [Ω]
R <sub>sh</sub>	: Shunt resistance $[\Omega]$
R <sub>sm</sub>	: Stator resistance $[\Omega]$
Т	: Junction temperature [K]
V	: Panel output voltage [V]
Greek Letters	
α	: Duty cycle
Abbreviation	5
CDTC	: Conventional direct torque control
DTC	: Direct torque control
FDTC	: Fuzzy direct torque control
FFT	: Fast Fourier Transform
MPPT	: Maximum Power Point Tracking
P & O	: Perturb and observe
PV	: Photovoltaic
STC	: Standard Test Conditions



Fig. 3. Variable step size P&O.



Fig. 4. Partition of the complex plan in six angular sectors.



**Fig. 5.** The fuzzy membership functions of  $\varepsilon_{\phi}$ .



**Fig. 6.** The fuzzy membership functions of  $\varepsilon_{\text{Tem}}$ .



**Fig. 7.** The fuzzy membership functions of  $\theta_s$ .



Fig. 8. The fuzzy membership functions of the output.

## 2. Modeling of pumping system

#### 2.1. Modeling of photovoltaic generator

equations (Chaibi et al., 2018; Motahhir et al., 2018a).

$$I = I_{ph} - I_o \left( \exp \frac{q(V + R_s I)}{aKTN_s} - 1 \right) - \frac{(V + IR_s)}{R_{sh}}$$
(1)

Fig. 2 shows the model of Photovoltaic generator used in this work, which composed of a photocurrent source and a diode connected with series and shunt resistances. The characteristic of the Photovoltaic generator can be presented by the following

$$I_{ph} = (I_{sc} + K_i (T - 298.15)) \frac{G}{1000}$$
(2)



Fig. 9. Block diagram of Fuzzy controller.



Fig. 10. Photovoltaic water pumping system based on Conventional DTC.

(4)

$$I_{o} = \frac{I_{sc} + K_{i}(T - 298.15)}{\exp(\frac{q(V_{oc} + K_{v}(T - 298.15))}{\rho k T N_{v}}) - 1}$$
(3)

The dynamic behavior of three phase induction motor can be described in  $(\alpha, \beta)$  reference frame as follows (Sudheer et al.,

The stator voltage component in  $\alpha$ - $\beta$  coordinate system:

$$V_{\beta s} = R_s I_{\beta s} + \frac{d}{dt} \phi_{\beta s} \tag{5}$$

The rotor voltage component in  $\alpha$ - $\beta$  coordinate system:

# $0 = R_r I_{\alpha r} + \frac{d}{dt} \phi_{\alpha r} + w_m \phi_{\beta r}$ (6)

$$0 = R_r I_{\beta r} + \frac{d}{dt} \phi_{\beta r} + w_m \phi_{\alpha r} \tag{7}$$

The stator flux component in  $\alpha$ - $\beta$  coordinate system

$$\phi_{\alpha s} = l_s I_{\alpha s} + M I_{\alpha r} \tag{8}$$

$$\phi_{\beta s} = l_s I_{\beta s} + M I_{\beta r} \tag{9}$$

2.2. Machine model

 $V_{\alpha s} = R_s I_{\alpha s} + \frac{d}{dt} \phi_{\alpha s}$ 

2017):



Fig. 11. Photovoltaic water pumping system based on FLC - DTC.

The rotor flux component in  $\alpha$ - $\beta$  coordinate system

$$\phi_{\alpha r} = l_r I_{\alpha r} + M I_{\alpha s} \tag{10}$$

$$\phi_{\beta r} = l_r I_{\beta r} + M I_{\beta s} \tag{11}$$

and the electromagnetic torque developed:

$$C_{em} = \frac{3}{2} P(\phi_{\alpha s} I_{\beta s} - \phi_{\beta s} I_{\alpha s})$$
(12)

where  $l_s$ ,  $l_r$ ,  $R_s$ ,  $R_r$  and M denote mutual inductance, stator inductance, rotor inductance, stator resistance, rotor resistance of induction motor. Is and Ir represent the stator and rotor current component in  $\alpha - \beta$  coordinate system

#### 2.3. Centrifugal pump

As shown in Eq. (13), the centrifugal pump load torque  $T_r$  is given as

$$T_r = \mathbf{K}\Omega^2 \tag{13}$$

The centrifugal pumps verify the similarity laws (14), from a characteristic curve (P, H, Q) established for a rotation speed N of the impeller pump, the characteristic (P', H', Q') can be obtained for any rotation speed N' (Errouha and Derouich, 2019).

$$Q' = Q \times \left(\frac{N'}{N}\right); \quad H' = H \times \left(\frac{N'}{N}\right)^2; \quad P' = P \times \left(\frac{N'}{N}\right)^3$$
(14)

#### 3. MPPT algorithm

#### 3.1. Variable step size P&O algorithm

For best operating, the PV panel must be functioned at their maximum power point. Several Maximum Power Point Tracking (MPPT) algorithms are available in the literature, each one has its designations and particularizations (Karami et al., 2017).

Acceptable performance is obtained using conventional MPPT methods based on fixed step, but they are slow and present oscillations around the MPP and the results are not satisfactory during sudden change of climatic conditions.

A fast follow-up can be realized by increasing step, but we have oscillations in steady state. Many contributions have been introduced using a variable step, where the algorithm automatically changes the step size as shown in Fig. 3. In this paper we used the variable step size P&O in order to find a compromise between rapidity and precision of the system (Rawat et al., 2016).

#### 4. Control strategy for the studied system

#### 4.1. Direct torque control of induction motor

The direct Torque Control (DTC) strategy was introduced by Takahashi in 1984 and proposed by Depenbrock in 1985 for the control applications of induction motors.



Fig. 12. (a) Irradiation profile in June at Fes. (b) Photovoltaic power. (c) Electric speed. (d) water Flow. (e) Stator flux responses using CDTC. (f) Stator flux responses using FDTC. (g) FFT analysis of stator current using CDTC (h) FFT analysis of stator current using FDTC. (i) Inverter switching state for CDTC. (j) Inverter switching state for FDTC. (k) Electromagnetic torque.

This type of control is characterized by its fast dynamic response, simple implementation and robustness to the rotor parameter variation without the need for a complex field orientation block and inner current regulation loop.

The basic principle in DTC for induction motors is to directly select stator voltage vectors, which makes the flux rotate and produce the desired torque (Fig. 10). The stator flux ( $\phi^*$ ) and torque references ( $C_{\rm em}^*$ ) are compared with the corresponding estimated values. The torque error is the input of a three-level hysteresis comparator, where the error stator flux magnitude is the input of a two-level hysteresis comparator. The stator flux space is composed of six sectors of 60° each (Fig. 4). The outputs of the flux hysteresis band, torque hysteresis band and flux sector are used to select the switching vector of voltage source inverter (VSI). Switching Table allows to determine the VSI switching vector as illustrated in Table 1. The VSI is composed of six actives witching states and two zero switching states.

This technique need to determine several parameters in order to estimate the electromagnetic torque and the stator flux. Equation represent the stator currents  $I_a$  and  $I_b$  which are transformed into  $\alpha$ - $\beta$  coordinates (Sutikno et al., 2014b).

$$I_{\alpha} = I_a \tag{15}$$

$$I_{\beta} = \frac{\sqrt{3}}{3} (I_a + 2I_b)$$
(16)

The stator voltages in the  $\alpha$ - $\beta$  reference frame are computed from the switching status (Sa, Sb and Sc) produced by the

switching table.

$$V_{\alpha} = \frac{V_{dc}}{3} (2S_a - S_b - S_c)$$
(17)

$$V_{\beta} = \frac{\sqrt{3}}{3} V_{dc} (S_b - S_c)$$
(18)

The stator flux can be estimated using calculated current  $I\alpha$ ,  $I\beta$  and voltage vectors  $V\alpha$ ,  $V\beta$  as follows

$$\phi_{\alpha} = \phi_{\alpha old} + (V_{\alpha} - R_s I_{\alpha}) T_s \tag{19}$$

$$\phi_{\beta} = \phi_{\beta old} + \left( V_{\beta} - R_{s} I_{\beta} \right) T_{s}$$
<sup>(20)</sup>

 $\phi_{\alpha old}$  and  $\phi_{\beta old}$  are the initial stator flux values.

Therefore, the flux magnitude can be calculated as given below:

$$\phi_s = \sqrt{\phi_\alpha^2 + \phi_\beta^2} \tag{21}$$

The electromagnetic torque can be estimated through Eq. (22)

$$C_{em} = \frac{3}{2} P(\phi_{\alpha s} I_{\beta s} - \phi_{\beta s} I_{\alpha s})$$
(22)

#### 4.2. DTC base on fuzzy logic controller

In this section, a fuzzy approach is proposed to improve the DTC (Fig. 11), the fuzzy logic controller is used to determine the



Fig. 12. (continued).

1	a	b	le	1	

Switchi	ng table.						
$E_{\phi}$	E <sub>Tem</sub>	S1	S2	S3	S4	S5	S6
1	1	V2	V3	V4	V5	V6	V1
	0	V7	V0	V7	V0	V7	V0
	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

V1, V2, V3, V4, V5, V6 represent the six active vectors produced by a voltage source inverter (VSI). V0 and V7 are the two zero voltage.

desired inverter vector state. Fig. 9 shows the proposed diagram of the fuzzy logic DTC of induction motor.

The FLC is composed of tree inputs which are torque error, the stator error, the stator flux angle and one output.

An FLC generally consists of four principal steps (Sancheza et al., 2015; Ontiveros-Robles et al., 2018):

#### • A fuzzifier

The analog inputs are converted into fuzzy variables which are produced by using membership functions (MF), the fuzzy system performance is described using a fuzzy rule base that stores fuzzy rules. An approximative reasoning will be done by associating input variable with fuzzy rules using a fuzzy inference engine. During the defuzzification step, the FLC 's fuzzy output is converted to a crisp value for the actual system input. The shape of the membership function, the fuzzy reasoning rules and the defuzzification method influence the response of the FLC.

In order to make the stator flux variations medium, the stator flux error is composed into three linguistic variables: negative (N), zero (Z) and positive (P). The (N) and (P) variables are represented by two symmetric trapezoidal membership functions and Z by an equidistant isosceles triangular (Fig. 5).

To make the torque error variations smaller, the torque error is divided into five linguistic variables: negative large (NL) negative small (NS) zero (Z) positive small (PS) and positive large (PL). The torque error membership function is represented by three equidistant isosceles triangular and two symmetric trapezoidal (Fig. 6).

The stator flux angle is divided into six sectors, for more precision, the universe of discourse is divided into 12 fuzzy sets. The stator flux angle membership function is represented by twelve equidistant isosceles triangular of  $60^{\circ}$  wide and an overlap of  $30^{\circ}$  with neighborhood fuzzy sets which each fuzzy set works for an angle of  $30^{\circ}$  (Fig. 7). Fig. 8 shows the output variable of the fuzzy controller which is composed of into seven switching states (one zero8 switching state and six active switching states).

#### • Fuzzy control rules

The optimal switching state is given by fuzzy rules. The fuzzy rules are established using expert knowledge and intuition in order to govern the behavior of the fuzzy controller. Stator flux angle, torque error and flux error: these elements are based on to determine the sector of stator flux. In order to get to the reference



Fig. 13. (a) Irradiation profile in March at Fes. (b) Photovoltaic power. (c) Electric speed (d) water Flow. (e) Stator flux responses using CDTC. (f) Stator flux responses using FDTC. (g) FFT analysis of stator current using CDTC h) FFT analysis of stator current using FDTC. (i) Inverter switching state for CDTC. (j) Inverter switching state for FDTC. (k) Electromagnetic torque.

values of the motor torque and flux, the switching state has to be chosen. Table 2 shows the fuzzy rule base with 180 rules which can be obtained from membership functions for three inputs (3  $\times$ 5  $\times$ 12).

#### • Fuzzy inferences

In this work, the inference method is developed using Mamdani's procedure based on min–max decision (Gdaim et al., 2014).  $\mu Ai (e\varphi)$ ,  $\mu Bi (eT)$  and  $\mu Ci (\theta)$  represent the membership values of torque error, flux error and stator flux angle.  $\alpha_i$  is the weighting factor for ith rule and it can be written as Eq. (23):

 $\alpha_{i} = \min(\mu Ai(e\varphi), \mu Bi(eT), \mu Ci(\theta))$ (23)

$$\mu' Vi(V) = \max(\alpha i, \mu Vi(V))$$
(24)

#### • Defuzzifier

This operation converts the fuzzy values back into a numerical value at the out-put, which are one zero voltage (V0 or V7) and six non-zero voltage vectors (Fig. 8). For this step, the max method is used and expressed by the Eq. (25). By this method, the value of fuzzy output which has the maximum possibility distribution is used as control output.

$$\mu' Vout (V) = max_{i=1}^{180} \max(\mu' Vi(V))$$
(25)

In this proposed system, a 1880 W is extracted from CSUN 235-60P modules (Table 7) in order to feed the centrifugal pump. the extracted power is higher than the motor rating because some losses are existing into the PV system. For this, our pumping system is composed of 8 modules which must be connected in series. The sizing of the photovoltaic system components is summarized in Table 3. The induction machine is characterized by the parameters presented in Table 6.

Table 2					
Voltage	vector	fuzzy	control	table.	

	0.		5										
$\theta_{\rm s}$		$\Theta 1$	Θ2	Θ3	$\Theta 4$	$\Theta 5$	$\Theta 6$	$\Theta$ 7	Θ8	Θ9	$\Theta 10$	$\Theta 11$	Θ12
$\varepsilon \varphi$	$\varepsilon_{\text{Tem}}$												
	PL	V2	V3	V3	V4	V4	V5	V5	V6	V6	V1	V1	V2
	PS	V2	V2	V3	V3	V4	V4	V5	V5	V6	V6	V1	V1
Р	Z	V0	V7	V7	V0	V0	V7	V7	V0	V0	V7	V7	V0
	NS	V1	V1	V2	V2	V3	V3	V4	V4	V5	V5	V6	V6
	NL	V6	V1	V1	V2	V2	V3	V3	V4	V4	V5	V5	V6
	PL	V2	V3	V3	V4	V4	V5	V5	V6	V6	V1	V1	V2
	PS	V2	V3	V3	V4	V4	V5	V5	V6	V6	V1	V1	V2
Ζ	Z	V7	V0	V0	V7	V7	V0	V0	V7	V7	V0	V0	V7
	NS	V7	V0	V0	V7	V7	V0	V0	V7	V7	V0	V0	V7
	NL	V6	V1	V1	V2	V2	V3	V3	V4	V4	V5	V5	V6
	PL	V3	V4	V4	V5	V5	V6	V6	V1	V1	V2	V2	V3
	PS	V4	V4	V5	V5	V6	V6	V1	V1	V2	V2	V3	V3
Ν	Z	V7	V7	V0	V0	V7	V7	V0	V0	V7	V7	V0	V0
	NS	V5	V5	V6	V6	V1	V1	V2	V2	V3	V3	V4	V4
	NL	V5	V6	V6	V1	V1	V2	V2	V2	V3	V4	V4	V5

#### 5. Simulation results and discussion

With the aim of testing and evaluating the effectiveness of the proposed control strategy, a simulation test is carried out in MATLAB/SIMULINK environment using the real data of solar radiation from (Fes, Maroc) for three different months where the climate conditions is different: Warm month (Summer), Mild month (Spring), Cold month (Winter).

Figs. 12.a, 13.a, 14.a, 12.b, 13.b, and 14.b show the evolution of the solar radiance and the PV power corresponding to Warm



Fig. 13. (continued).

 Table 3

 Design of parameters of the system

Component	Expression	Used value
$V_{dc}^*$	$V_{dc} = \frac{2\sqrt{2}}{\sqrt{3}}V_{LL}$	400 V
C <sub>dc</sub>	$C_{dc} = \frac{6aV_{LL}I_t}{[V_{dc}^{*2} - V_{dc1}^2]}$	2000 µF
α	$lpha = rac{V_{dc} - V_{mp}}{V_{dc}}$	0.26
$L_{pv}$	$L_{pv} = rac{lpha V_{mp}}{\Delta l f_s}$	3 mH

month (June 2016), mild month (Mars 2016), Cold month (December 2016). Figs. 11.c, 12.c and 13.c show the characteristics of electric speed using the conventional and the suggested method. The simulation results show that in rapid changing in atmospheric conditions, the proposed method shows better response as compared to the conventional one in terms of tracking speed.

Figs. 12.d, 13.d and 14.d illustrate the pumped water volume obtained using the conventional DTC and FLC-DTC in the three seasons: cold, medium, and hot seasons. Fig. 15 and Table 5 show that, using the FLC-DTC, the pumped volume is clearly higher than using the conventional method.

Figs. 12.e, 13.e, 14.e, 12.f, 13.f, 14.f show the developed flux responses of IM drive with zoom-in view using the conventional and the proposed method. The hysteresis band of flux is limited to  $\pm$  1. The simulation results illustrate that the response of stator flux magnitude of fuzzy DTC represent low oscillations compared with conventional DTC and better tracking reference.

To illustrate the impact of the CDTC and the proposed method on the quality of the signal, a FFT (Fast Fourier Transform) analysis of the stator current waveforms is done. Figs. 12.g, 13.g, 14.g, 12.h, 13.h, 14.h show the frequency spectrum. It can be seen that, the FDTC provides a lower total harmonic distortion (THD) in comparison with the CDTC.

Figs. 12.i, 13.i, 14.i, 12.j, 13.j, 14.j shows the inverter switching state of the first voltage phase (Sa) for both techniques, we can see that the switching frequency is variable, which is a major disadvantage in the conventional DTC. Contrariwise, the switching frequency is constant using FLC-DTC, therefore, the commutation losses are reduced.

Figs. 12.k, 13.k, 14.k, 14k show the corresponding torque responses for the conventional DTC and the proposed DTC using fuzzy logic controller. The hysteresis band of torque is limited to  $\pm$  4. The torque response clearly shows that the torque's ripples with the proposed method is reduced significantly compared with conventional DTC.

The torque and flux ripples of the proposed method compared to conventional DTC are calculated and shown in Table 4. From the presented data, our method has good performances than the Conventional DTC with maintaining a good torque response and respect to reducing the torque and flux ripple.

The improvement is calculated using Eq. (26) and presented in Table 4.

Improvement (%) = 
$$\frac{V_{CDTC} - V_{FDTC}}{V_{CDTC}}$$
 (26)

#### 6. Conclusion

An optimal process of a photovoltaic water pumping system (PWPS) based on an induction machine and driving a centrifugal



Fig. 14. (a) Irradiation profile in December at Fes. (b) Photovoltaic power. (c) Electric speed (d) water Flow. (e) Stator flux responses using CDTC. (f) Stator flux responses using FDTC. (g) FFT analysis of stator current using CDTC. (h) FFT analysis of stator current using FDTC. (i) Inverter switching state for CDTC. (j) Inverter switching state for FDTC. (k) Electromagnetic torque.

#### Table 4

1	l'orque,	flux	ripples	and	THD	ot	the	CDIC	and	FDTC.	

Performance			Season			
			June	Mars	December	
T (N m)	$\Delta T$	DTC-conventional DTC - FLC	$\pm$ 3.85 $\pm$ 2.29	$\pm 2.89$ $\pm 2$	$_{\pm 4.135}$ $_{\pm 3.365}$	
	Improv	/ement (%)	40.5	30.7	18.6	
φ (Wb)	$\Delta \phi$	DTC-conventional DTC - FLC	0.037 0.003	0.028 0.003	0.03 0.004	
	Improvement (%)		91.8	89.2	86.8	
THD (%)	DTC-conventional DTC - FLC		6.77 3.06	6.11 4.94	6.28 3.91	

#### Table 5

Pump flow using the conventional and FLC-DTC methods.

Season	Volume obtained with FDTC $(m^3/day)$	Volume obtained with CDTC (m <sup>3</sup> /day)
Hot season	458.64	438.48
Moderate season	375.84	354.96
Cold season	297.3	277.26

pump is investigated. The PV system was studied using conventional DTC which contains a hysteresis controller, in order to improve the efficiency of PV systems, Fuzzy Logic Control has been proposed. The performances of FLC applied to induction motor has been tested and compared with the conventional DTC. The simulation results show the increase of both the daily pumped quantity and reduction in the torque, stator current and flux

Table	6		
-------	---	--	--

Parameters of induction machine.						
Stator resistance $[\Omega]$	4.85	Mutual inductance [H]	0.258			
Rotor resistance $[\Omega]$	3.805	Inertia moment [kg m <sup>2</sup> ]	0.031			
Stator inductance [H]	0.274	Nominal power [kW]	1.5			
Rotor inductance [H]	0.274	Viscous Friction [N m s/rad]	0.00114			
Pairs poles number 2						

#### Table 7

Electrical characteristics of the csun235-60p photovoltaic model.					
Photovoltaic panel CSUN235-60P					
Maximum Power, Pmax	235 W				
Open Circuit Voltage, Voc	36.8 V				
Short Circuit Current, Isc	8.59 A				
Maximum Power Voltage Pmax, Vmpp	29.5 V				
Maximum Power Current Pmax, Impp	7.97 A				
Standard Test Condition (STC)	1000 W/m <sup>2</sup> , 25 °C, AM 1.5				
Number of cell	60				
Temperature coefficient of open-circuit	−0.37%/°C				
voltage Voc, Kv					
Temperature coefficient of short-circuit 0.07%/°C					
current Isc, Ki					

ripples due to the use of a comparator with hysteresis reached by FLC.

In our future research we intend to concentrate on implementing the proposed control strategy on a dSpace system and developing other intelligent control techniques to improve the efficiency of PV water pumping system





Fig. 15. Water volume comparison.

#### Appendix

See Tables 6 and 7.

#### References

- Achour, A., Rekioua, D., Mohammedi, A., Mokrani, Z., Rekioua, T., Bacha, S., 2016. Application of direct torque control to a photovoltaic pumping system with sliding-mode control optimization. Electr. Power Compon. Syst. 44 (2).
- Allirani S, J.V., 2014. Direct torque control technique in induction motor drives-A review. J. Theor. Appl. Inf. Technol. 60 (3).

- Alsofyani, I.M., Idris, N.R.N., 2013. A review on sensorless techniques for sustainable reliablity and efficient variable frequency drives of induction motors. Renew. Sustain. Energy Rev. 24, 111–121.
- Amezquita-brooks, L., Liceaga-castro, J., Member, E.L., 2013. Speed and Position Controllers Using Indirect Field Oriented Control: A Classical Control Approach, Vol. c. pp. 1–16.
- Azab, M., 2015. Identification of one-diode model parameters of PV devices from nameplate information using particle swarm and least square methods. In: 1st Work. Smart Grid Renew. Energy, SGRE 2015.
- Benamor, A., Benchouia, M.T., Srairi, K., Benbouzid, M.E.H., 2019. Electrical power and energy systems a novel rooted tree optimization apply in the high order sliding mode control using super-twisting algorithm based on DTC scheme for DFIG. Electr. Power Energy Syst. 108 (February 2018), 293–302.
- Bouhoune, K., Yazid, K., Boucherit, M.S., Chériti, A., 2017. Hybrid control of the three phase induction machine using artificial neural networks and fuzzy logic. Appl. Soft Comput. J. 55, 289–301.
- Castillo, O., Leticia, A., Castro, J.R., Garcia-Valdez, M., 2016. A comparative study of type-1 fuzzy logic systems, interval type-2 fuzzy logic systems and generalized type-2 fuzzy logic systems in control problems. Information Sciences 354, 257–274.
- Cervantes, L., Castillo, O., 2015. Type-2 fuzzy logic aggregation of multiple fuzzy controllers for airplane flight control. Inf. Sci. 324, 247–256.
- Chaibi, Y., Salhi, M., Eljouni, A., Essadki, A., 2018. A new method to determine the parameters of a photovoltaic panel equivalent circuit. Sol. Energy 163 (January), 376–386.
- Chandel, S.S., Nagaraju Naik, M., Chandel, R., 2015. Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. Renew. Sustain. Energy Rev. 49, 1084–1099.
- Chandel, S.S., Naik, M.N., Chandel, R., 2017. Review of performance studies of direct coupled photovoltaic water pumping systems and case study. Renew. Sustain. Energy Rev. 76 (March), 163–175.
- Chihi, A., Ben Azza, H., Jemli, M., Sellami, A., 2017. Nonlinear integral sliding mode control design of photovoltaic pumping system: real time implementation. ISA Trans. 70, 475–485.
- Drissi, H., Khediri, J., Zaafrane, W., Ben Braiek, E., 2017. Critical factors affecting the photovoltaic characteristic and comparative study between two

maximum power point tracking algorithms. Int. J. Hydrog. Energy 42 (13), 8689–8702.

- El Ouanjli, N., Motahhir, S., Derouich, A., El Ghzizal, A., Chebabhi, A., Taoussi, M., 2019. Improved DTC strategy of doubly fed induction motor using fuzzy logic controller. Energy Rep. 5 (February), 271–279.
- El-samahy, A.A., Shamseldinb, M.A., 2018. Brushless DC motor tracking control using self-tuning fuzzy PID control and model reference adaptive control. Ain Shams Eng. J. 9, 341–352.
- Errouha, M., Derouich, A., 2019. Study and comparison results of the field oriented control for photovoltaic water pumping system applied on two cities in Morocco. Bull. Electr. Eng. Informatics 8 (4), 1–7.
- Gdaim, S., Mtibaa, A., Mimouni, M.F., Design and Experimental Implementation of DTC of Induction Machine based on Fuzzy Logic Control on FPGA, 6706(c), 2014.
- Gopal, C., Mohanraj, M., Chandramohan, P., Chandrasekar, P., 2013. Renewable energy source water pumping systems - A literature review. Renew. Sustain. Energy Rev. 25, 351–370.
- Hannan, M.A., Ali, J.A., Mohamed, A., Hussain, A., 2018. Optimization techniques to enhance the performance of induction motor drives: A review. Renew. Sustain. Energy Rev. 81 (2016), 1611–1626.
- Harnefors, L., Member, S., Saarakkala, S.E., Hinkkanen, M., 2013. Speed Control of Electrical Drives Using, Vol. 1, pp. 1–10.
- Hedjar R, D.D., Boucher, P., 2013. Robust nonlinear receding-horizon control of induction motors. Int. J. Electr. Power Energy Syst. 353, 46–65.
- Hussein, S., 2014. Efficiency optimization of vector-controlled induction motor drive. Int. J. Adv. Eng. Technol. (7), 666.
- Islam, D., Reza, C.M.F.S., Mekhilef, S., 2015. Modeling and Experimental Validation of 5-level Hybrid H-bridge Multilevel Inverter Fed DTC-IM Drive, Vol. 10.
- Karami, N., Moubayed, N., Outbib, R., 2017. General review and classification of different MPPT techniques. Renew. Sustain. Energy Rev. 68 (September 2016), 1–18.
- Lekhchine, S., Bahi, T., Soufi, Y., 2014. Electrical power and energy systems indirect rotor field oriented control based on fuzzy logic controlled double star induction machine. Int. J. Electr. Power Energy Syst. 57, 206–211.
- Lgeb, B., Doctorat en : Génie Electrique Option : Commande des systèmes énergétiques Thèse préparée au Laboratoire de Génie Electrique de Biskra LGEB Amélioration des Performances de la Commande Directe de Couple ( DTC ) de La Machine Asynchrone par des Techniques.
- Mahanta, U., Patnaik, D., 2015. Dynamic Modeling and Simulation of SVM-DTC of Five Phase Induction Motor. pp. 3–8.

- Matam, M., Barry, V.R., Govind, A.R., 2018. Optimized reconfigurable PV array based photovoltaic water-pumping system. Sol. Energy 170 (November 2017), 1063–1073.
- Mohan, D., Member, S., Zhang, X., Foo, G., Generalized DTC Strategy for Multilevel Inverter fed IPMSMs with Constant Inverter Switching Frequency and Reduced Torque Ripples, 8969(c), 2017, 1–10.
- Motahhir, S., El Ghzizal, A., Sebti, S., Derouich, A., 2018a. Modeling of photovoltaic system with modified incremental conductance algorithm for fast changes of irradiance. Int. J. Photoenergy 2018, 13.
- Motahhir, S., El Hammoumi, A., El Ghzizal, A., 2018b. Photovoltaic system with quantitative comparative between an improved MPPT and existing INC and P & O methods under fast varying of solar irradiation. Energy Rep. 4, 341–351.
- Ontiveros-Robles, E., Melin, P., Castillo, O., 2018. Comparative analysis of noise robustness of type 2 fuzzy logic controllers. Kybernetika 54 (1), 175–201.
- Rafa, S., Larabi, A., Barazane, L., Manceur, M., Essounbouli, N., Hamzaoui, A., 2014. Implementation of a new fuzzy vector control of induction motor. ISA Trans. 53 (3), 744–754.
- Rawat, R., Kaushik, S.C., Lamba, R., 2016. A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system. Renew. Sustain. Energy Rev. 57, 1506–1519.
- Reza, C.M.F.S., Islam, M.D., Mekhilef, S., 2014. A review of reliable and energy efficient direct torque controlled induction motor drives. Renew. Sustain. Energy Rev. 37, 919–932.
- Sancheza, M.A., Castillo, O., Castro, J.R., 2015. Generalized type-2 fuzzy systems for controlling a mobile robot and a performance comparison with interval type-2 and type-1 fuzzy systems. Expert Syst. Appl. 42 (14), 5904–5914.
- Sudheer, H., Kodad, S.F., Sarvesh, B., 2017. Improvements in direct torque control of induction motor for wide range of speed operation using fuzzy logic. J. Electr. Syst. Inf. Technol..
- Sutikno, T., Idris, N.R.N., Jidin, A., 2014a. A review of direct torque control of induction motors for sustainable reliability and energy efficient drives. Renew. Sustain. Energy Rev. 32, 548–558.
- Sutikno, T., Rumzi, N., Idris, N., Jidin, A., 2014b. A review of direct torque control of induction motors for sustainable reliability and energy ef fi cient drives. Renew. Sustain. Energy Rev. 32, 548–558.
- Talbi, B., Krim, F., Rekioua, T., Mekhilef, S., Laib, A., Belaout, A., 2018. A highperformance control scheme for photovoltaic pumping system under sudden irradiance and load changes. Sol. Energy 159 (2017), 353–368.
- Vas, P., 0000. Vector Control of AC Machines / Peter Vas. Oxford: Clarendon Press.
- Yahyaoui, I., Serna Cantero, A., 2018. Scalar and Vector Control of Induction Motor for Online Photovoltaic Pumping, Vol. 1. Elsevier Inc..