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Sliding mode control of the speed pumping system Supplied by a Photovoltaic generator

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Abstract— **This paper presents a stand alone photovoltaic system for water pumping without battery storage. The system is controlled by fuzzy logic to ensure the maximum power for photovoltaic generator and the sliding mode technique is used to control the speed. The simulation results are presented based on different cases of irrigation pumping application and availability of solar irradiance is studied. This results show that the performance of the controllers both in transient as well as in steady state is quite satisfactory.**

Keywords— **Solar energy, Control, Fuzzy logic, Sliding mode, Maximum power point tracking.**

I. INTRODUCTION

The problems of cuts due to lack of electricity in the continent of Africa countries is one of the main hurdles in the development such as in rural sites Algeria. Their grid system is considerably under developed a major sections its populace still surviving out grid. Particularly in the Algerian territory, the stand-alone solar systems are gaining an increasing interest and they are becoming a very competitive solution, because many sunny days are available throughout the year. Moreover, environmental issues such as population and global warming effects are driving incites researchers towards the development of renewable energy sources including solar systems.

One of the most important applications of Photovoltaic (PV) systems is for water pumping, hence, in rural areas that have a considerable amount of solar radiation and have no access to national grids. An effective solution must ensure that the PV generator (PVG) runs at the maximum power point (MPP) and that the motor runs at a high efficiency level.

Photovoltaic power system requires controlled by maximum power point tracking (MPPT), which this system that operates the Photovoltaic (PV) modules in a manner that allows the modules to produce all the power they are capable of. There are different types of MPPT algorithms such as Perturbation and Observation (P&O) Method, incremental conductance method, which can be known as traditional techniques [1-4]. Other techniques called Artificial Intelligence (AI) are becoming useful as alternate approach for conventional modeling techniques as they do not require the knowledge of internal system parameters, involve less computational effort and offer a compact solution for multivariable problems. They have been used to solve complicated practical problems in various areas and are becoming more popular in PV systems that exhibits non-linear features [5-7]. Artificial neural networks (ANN) and fuzzy logic (FL) are used to design the MPPT controller for PV system [8].

The controller MPPT is important in solar power systems because it reduces the solar array cost by decreasing the number of solar panels needed to obtain the desired output power [9-10]. PV pumping systems usually employ low power pumps. They are widely used in domestic and livestock water supplies and small-scale irrigation systems and they have recently received considerable attention due to major developments in the field of solar cell materials and technology. A number of DC motor driven pumps are already in use in several parts of the world [11], but they suffer from maintenance problems due to the presence of the commutator and brushes. Hence, a pumping system based on an Induction Motor (IM) can be an attractive proposal where reliability and maintenance free operations are important.

In the water pumping system the main input variable is the solar irradiance and the output variable is the water discharge. The reference DC link voltage (V_{ref}) obtained by MPPT algorithm based of fuzzy logic controller. Water discharge is depends on head (H) and speed of the IM, but in this word the head is fixed. Speed motor can be controlled by frequency supplied by the inverter to the motor. So, the control parameters include the DC link voltage and the frequency of the inverter.

These systems of pumping without battery can provide a cost-effective use of solar energy. Nowadays, due to development of alternative IM drive systems it is possible to use a more robust and less expensive motor for photovoltaic pumping application [12-15].

II. STUDY SYSTEM

The study system is shown in Fig. 1. This system consists of PV array, chopper, inverter, and induction motor and pumping system.

The water pumping system is one of the most common applications of distributed energy generation system. The three-phase inverter generates an output variable frequency

wave form to drive. The motor drives a centrifugal pump that delivers the water output.

Several types of pumps and motors are available on the PV pumping market. The most commonly employed pump type is the centrifugal pump. Single-stage centrifugal pumps are frequently used in PV shallow water pumping for low head applications. For PV subterranean water pumping and surface water pumping with higher heads, multistage centrifugal pumps are more suitable [16]. The centrifugal pump is characterized by its head-flow rate performance curve at the nominal speed. The flow rate is directly proportional to the impeller speed, the head is proportional to the square of the speed and the hydraulic power is proportional to the cube of the speed.
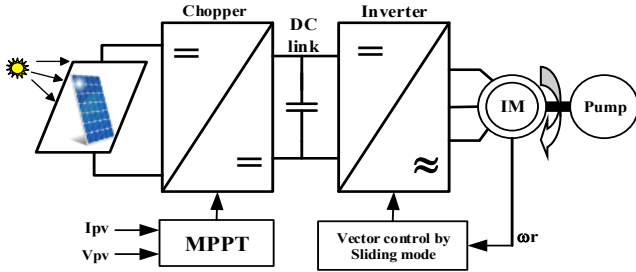

Fig. 1 Bloc diagram of a photovoltaic pumping system

A. Photovoltaic Array

Solar cells as they are often called are semiconductor devices that convert sunlight into direct current (DC) electricity.

The solar be model is presented by a current source in parallel with a diode with shunt and series resistance noted by R_{sh} and R_s respectively. So, the equivalent circuit is shown in Fig. 2.
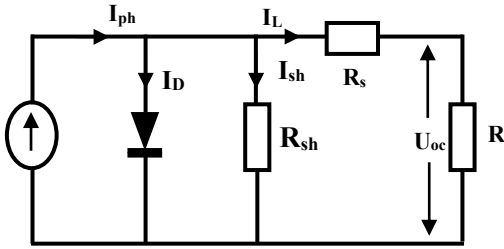

Fig. 2 Equivalent circuit for a solar cell

Photovoltaic panel is composed of N_P parallel modules, each one including N_S photovoltaic cell serial connected. The fundamental equation for PV model is given by [8]:

$$I_L = N_p\, I_{ph} - N_p I_0 \left\{ exp\left[\frac{q(U_{oc}+I_L R_s)}{akTN_S}\right] - 1 \right\} - \frac{U_{oc}+I_L R_S}{R_{sh}} \tag{1}$$

Where ,
  I_L : PV panel output current;
  U_{oc}: PV panel output voltage;
  I_{ph} : generated photocurrent;
  R_{sh}: parallel resistance;
  R_s : series resistance;
  q: electron charge;
  k: Boltzmann's constant;

a: p–n junction ideality factor;
  T: cell temperature;
Otherwise, the cell reverse saturation current (I_0) is related to the temperature T as follows:

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

Where,
  T_r: cell reference temperature;
  I_{0r}: reverse saturation current.

Similarly, the photocurrent I_{ph} is expressed as follows:

$$I_{ph} = \{I_{scr} + k_i(T - 298)\}\frac{G}{1000} \tag{3}$$

When,
  I_{sc}: short-circuit current;
  G: solar radiation;
  k_i: temperature coefficient for short circuit current.

B. Modelling of chopper

The power supplied by the photovoltaic generator is fed to a boost converter, which is controlled using the MPPT controller based by Fuzzy logic controller (FLC).The boost converter is used to boost the DC voltage of the panel. Duty cycle of the switch is decided from the MPPT controller which senses the present climatic condition and produces an optimum value of duty cycle, as shown in Fig. 3.
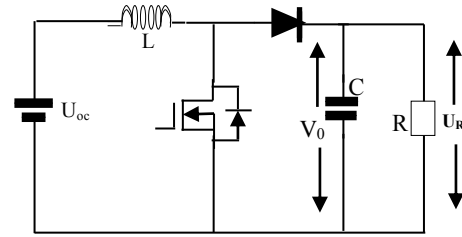

Fig. 3 Boost converter circuit diagram.

In steady state, the output voltage of the chopper amplifier can be expressed by the relations "(4)" and "(5)" [17-19].

$$V_0 = \frac{U_{oc}}{1-D} \tag{4}$$
$$V_0 = U_R \tag{5}$$

C. Modelling of the PWM inverter

The three-phase inverter consists of three independent arms. Each one includes two switches which are complementary and controlled by the Pulse Width Modulation (PWM) [20, 21]. The induction motor stator voltages (v_{sa}, v_{sb}, v_{sc}) are expressed in terms of the upper switches as follows:

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{V_0}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} \tag{6}$$

K_1, K_2 and K_3 are the controller signals applied to the switches.

The photovoltaic current is given by:

$$I_{pv} = K_1 i_{sa} + K_2 i_{sb} + K_3 i_{sc} + I_c \qquad (7)$$

Where (i_{sa}, i_{sb}, i_{sc}) are the induction motor stator currents of the inverter and I_c is given by "(8)".

$$I_c = C \frac{dV_{pv}}{dt} \qquad (8)$$

D. Induction motor model

The electrical model of the induction machine in the d-q referential axis linked to rotating field is given by "(9)"[22-24].

$$\begin{cases} \frac{di_{ds}}{dt} = (\frac{1}{\sigma L_s})\left[-R_{sm}i_{ds} + \sigma L_s\omega_s i_{qs} + (\frac{M}{L_r})\left((\frac{\Phi_{dr}}{T_r}) + \omega_r\Phi_{qr}\right) + v_{ds}\right] \\ \frac{di_{ds}}{dt} = (\frac{1}{\sigma L_s})\left[-R_{sm}i_{qs} - \sigma L_s\omega_s i_{ds} + (\frac{M}{L_r})\left((\frac{\Phi_{qr}}{T_r}) - \omega_r\Phi_{dr}\right) + v_{qs}\right] \\ \frac{d\Phi_{dr}}{dt} = (\frac{M}{T_r})i_{ds} + (\omega_s - \omega_r)\Phi_{qr} - \frac{\Phi_{dr}}{T_r} \\ \frac{d\Phi_{qr}}{dt} = (\frac{M}{T_r})i_{qs} - (\omega_s - \omega_r)\Phi_{dr} - \frac{\Phi_{qr}}{T_r} \end{cases} \qquad (9)$$

With,

$$R_{sm} = R_s + \frac{R_r M^2}{L_r^2} \qquad (10)$$

And the mechanical modeling part of the system is given by:

$$\frac{Jd\Omega}{dt} = (T_e - T - f\Omega) \qquad (11)$$

Where, the electromagnetic torque is given by:

$$T_e = (\frac{3pM}{2L_r})[\Phi_{dr}i_{qs} - \Phi_{qr}i_{ds}] \qquad (12)$$

R_s , R_r: stator and rotor resistances respectively;
L_s , L_r: stator and rotor inductances respectively ;
T_r: rotor time constant ($T_r=L_r/ R_r$);
M: mutual inductance;
ω_s: stator angular frequency;
ω_r: rotor speed;
σ: total leakage coefficient ($\sigma=1-M^2/L_sL_r$);
J : total inertia of the machine;
f : coefficient of friction;
T_m : load torque.

E. Modeling of the centrifugal pump

The hydrodynamic load torque of the centrifugal pump is given by the following expression [25].

$$T_m = A_p\omega_r^2 \qquad (13)$$

Where A_p is the torque constant ($A_p = P_n/\omega_{rn}^3$), P_n is the nominal power of the induction-motor and ω_{rn} is the rotor nominal speed.

The centrifugal pump is described by the lows of similarity that are given by:

$$\begin{cases} Q' = (\frac{N'}{N}).Q \\ H' = (N'/N)^2.H \end{cases} \qquad (14)$$

Where: Q' and Q are respectively the flow and the nominal flow of the pump, H' and Hare respectively his height and total height; N' and N are respectively his speed and nominal speed.

III. MPPT CONTROLLER

These techniques are becoming useful as alternate approach for conventional physical modeling techniques as they do not require the knowledge of internal system parameters, involve less computational effort and offer a compact solution for multivariable problems. They have been used to solve complicated practical problems in various areas and are becoming more popular nowadays in PV systems which exhibits non-linear features [4]. Fuzzy logic of artificial intelligence techniques are used to design the MPPT controller for PV system [8, 26]. AI based MPPT controller DC output from the solar panel is used as the source. This output is boosted up using the DC- DC converter and then used to feed the load after required conversion. Solar panel power is influenced by availability of solar radiation and depends on the temperature. MPPT controller is used to operate the system at MPP at that instant. Proposed work uses solar radiation and temperature to track MPPT. The Fuzzy Logic controller fined the optimum duty cycle (D_{opt}) to be fed to the switch of the converter [8].

A. Fuzzy Logic Controller

The fuzzy Logic has the advantage to be robust and relatively simple to design as they do not require the knowledge of the exact model. They do require in the complete knowledge of the operation of the PV system. Compared to other methods such as ANNs and genetic algorithm, it provides fast results using the expert knowledge and measured database. The algorithm for MPPT controller approach using fuzzy logic is based on three steps: fuzzification, inference and defuzzification.
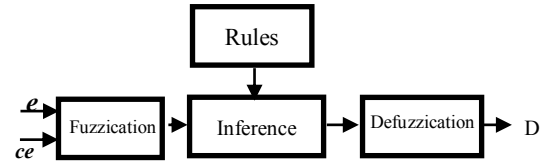

Fig. 4 Generalized fuzzy logic controller

Fig. 4 shows the general block diagram of fuzzy Logic Controller .The two inputs, error (e) and derivative of error (ce) are provided to the controller based on the knowledge base it produces the optimum duty cycle. Where duty cycle the associated fuzzy sets involved in the fuzzy control rules are defined as:

NB: Negative big; NM: Negative medium NS: Negative small; ZE: Zero; PS: Positive small; PM: Positive medium; PB: Positive big.

The input output relationship between the variables are defined using the fuzzy rules described in TABLE I. Optimum duty cycle is fed to the boost converter and hence it operates at to deliver the maximum power [27].

e \ ce	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

IV. SLIDING MODE CONTROL OF INDUCTION MOTOR

The controller is based on power balance between load and PV panel. In water pumping system the motor torque is dependent on head and for constant head load torque is constant. As load torque becomes constant, the load power dependents on only speed of the motor. So the power mismatch between load and generated power will reflects the change in speed. Therefore, in proposed control technique the reference speed is obtained from PV and load powers. The detailed controller of speed is shown in Fig. 5.
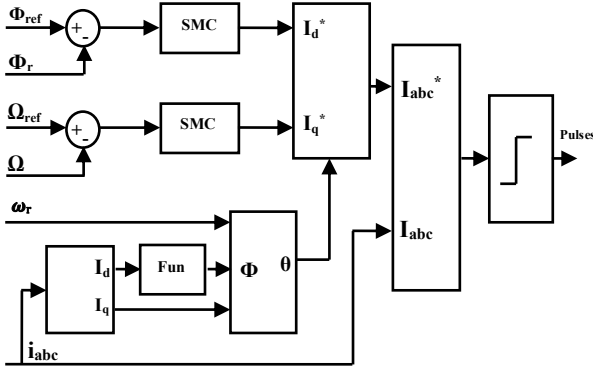

Fig. 5 Sliding mode control of IM

The sliding mode control (SMC) theory is applied to the rotor field oriented induction motor in such away to obtain simple surfaces. The internal loops allow to control the stator current components (i_{ds}, iqs); whereas the external loops provide the speed and the rotor flux (Ω, Φ_r). The control of the inverter-induction motor uses two switching functions in order to control simultaneously speed and rotor flux [28].

The four switching functions defining the sliding surfaces are as follows:

$$\begin{cases} S_1 = \varphi_r - \varphi_r^* \\ S_2 = \omega - \omega^* \end{cases} \quad (15)$$

as:

$$\begin{bmatrix} \dot{S_1} \\ \dot{S_2} \end{bmatrix} = \begin{bmatrix} K_1 \, sgn(s_1) \\ K_2 sgn(s_2) \end{bmatrix} \quad (16)$$

V. SIMULATION AND INTERPRETATION

The results of simulations of the PV water pumping system are presented. Fig.6 presents the simulation diagram of considered system.
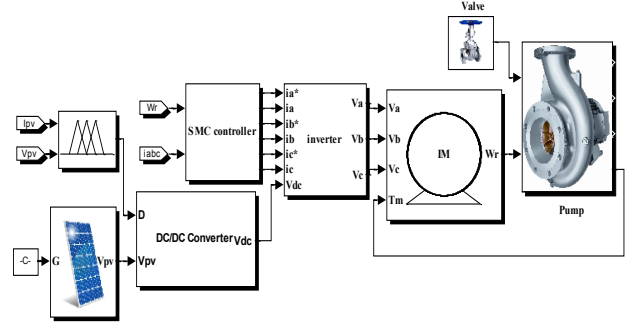

Fig. 6 Simulation Bloc diagram

The simulation results obtained for a light 1000 w/m² and a temperature 25°C are the following:

Fig. 7 shows the evolution of the voltage, current and power output of the generator output. The fuzzy controller provides better performance: a response time of about 0.03s and exceeded acceptable.

Fig. 8 shows that the speed follows the reference because of SMC, it waits the state regime permanent at time 0.17s and remains stable regardless of the valve opening.
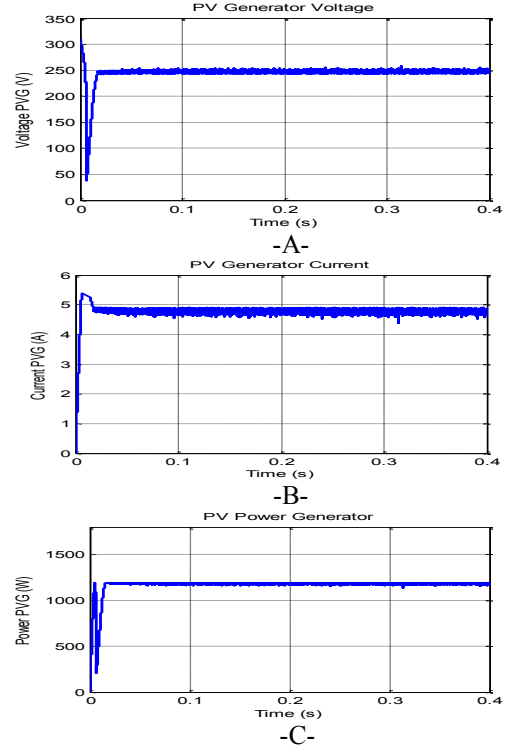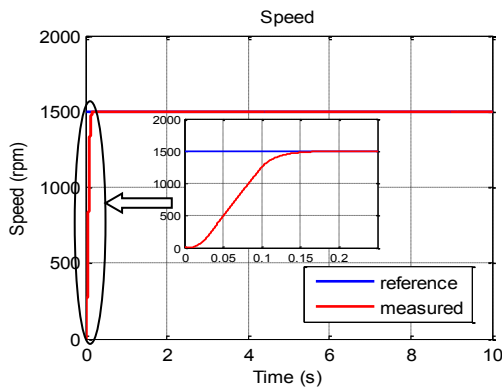

-A-

-B-

-C-

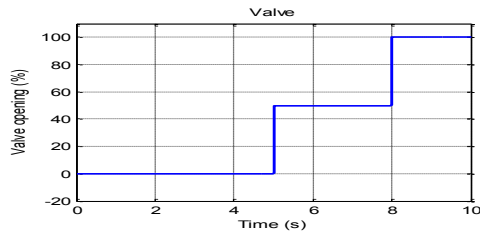Fig. 7 Voltage, current and power of PV generator
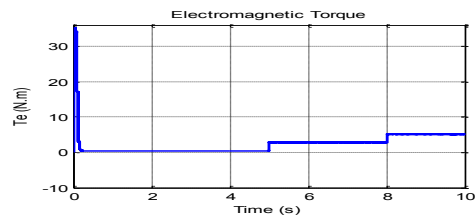
Fig. 8 Speed of induction motor
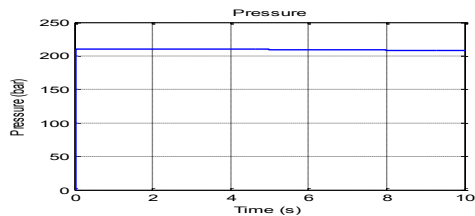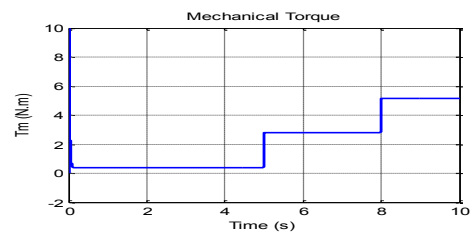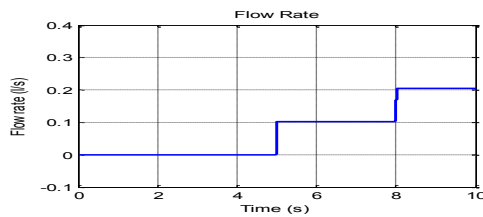

Fig. 9 Valve opening

- a -

- b -

- c -

- d -

Fig. 10 Study of robustness of the system

VI. CONCLUSION

The vector control by sliding mode applied to the filed oriented induction motor pump has succeeded in regulation of the motor speed and then in optimization of performances of the system to control the torque and speed. Such a control scheme provides protection of connected inverter and machine with regards to stator current since these latter are controlled. Besides, the robustness quality of the proposed controllers appears clearly in the test results.

APPENDIX

TABLE II
SYSTEM PARAMETERS

PVG Parameters	
P_{pv} = 84,62 (Wc)	V_{pv} = 17,2 (v)
I_{pv}= 4,85(A)	N_s=10 and N_p=1
Induction motor parameters	
Rs=4.1(Ω),Rr=2.5(Ω)	Ls=Lr=M=0.54(H)
J=0.04 (Kg.m²) and P= 2 pairs	N=1470 (tr/min)
Centrifugal pump parameters	
Q = 2 (l/s)	H=10 (m)

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