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IMPROVED HYBRID PUMPING SYSTEM WITH STORAGE BATTERY BASED ON PARTICLE SWARM ALGORITHM

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Key words: Hybrid photovoltaic-wind energy; Particle swarm algorithm; Direct torque control; Ac load; Dc load

The combination of several renewable energy sources makes it possible to optimize the production of electricity with the aim of improving the human, social, economic, and environmental conditions of daily life. This study focuses on the use of a very promising meta-heuristic optimization technique, particle swarm optimization (PSO), applied to systems powered by hybrid renewable energy sources. This work is divided into two parts, the first part aims to present the maximum power point (MPPT) PSO MPPT-PSO technique. The latter is applied to a photovoltaic (PV) system connected to a resistive load (dc load). The MPPT-PSO technique has been compared to another meta-heuristic technique called MPPT-GWO (grey wolf optimization).

The second part aims to optimize the functioning of a system composed of a wind turbine/PV-battery connected to an induction motor considered as ac load. Thus, we take a closer look at the regulation as well as its optimization using the PSO. We are particularly interested in the setting coefficients of two PI regulators, the first PI regulator is used to keep the dc voltage constant, and the second is to regulate the speed of the induction motor. To confirm the effectiveness of the proposed approach, we will compare it to the techniques of the genetic algorithm (GA) and the bat (BAT) algorithm.

1. INTRODUCTION

World energy consumption is constantly increasing, and this energy demand is mainly covered using fossil fuels. However, the intensive use of fossils pushes it to have a harmful consequence on the environment. It contributes to global pollution and climate change. Today, we can distinguish several sources of clean energy such as wind and solar energy [1].

Hybrid systems are emerging technologies for generating electricity that integrate two or more sources of production from renewable sources as well as conventional sources (usually diesel generators) or a combination of both sources. The methods for evaluating stand-alone hybrid wind / photovoltaic systems and their benefits have grown significantly in recent years. However, this type of hybrid system is very rare, because it does not provide security of supply, it lacks either a conventional source or a storage device. There are several combinations of hybrid systems, namely: wind-diesel [2], photovoltaic-diesel [3], and wind-photovoltaic-diesel [4]. The hybrid system may include a storage device [5,6]. These same sources of energy can be combined with other sources such as hydraulic energy [7]. Nowadays, hybrid systems are becoming more promising and cheaper than autonomous wind or PV systems. Hybrid systems can thus provide a reliable source of energy for an entire community in many developing countries.

For pumping applications, the electric motors used can be direct current (dc) or alternative current (ac). By using a doubly fed induction machine (DFIM) in pumping applications, many benefits can be obtained since it can be powered and controlled from the stator or the rotor by various possible configurations. In recent years, several control methods of the DFIM as motor, as well as a generator, have been proposed, developed, and implemented [8].

The work presented in this paper concerns the control of a pumping chain. This system is powered by a hybrid renewable energy source. In this sense, and for this system to operate at its maximum power, it must include an adaptation stage associated with an MPPT algorithm.

In engineering, several problems require the use of optimization methods to approach or get the optimal solution. Deterministic methods seem to have fulfilled this need, but the problem of local optima constitutes a real trap for accessing the global optimum. Hence the use of so-called meta-heuristic stochastic methods which, in general, have a great capacity to find the global optimum. Among these techniques, those based on collective intelligence, inspired by nature, the most widespread are namely: ant colony algorithms (ACO), genetic algorithms (AGs), and especially particle swarm optimization (PSO).

In our study, we start by presenting a PV system connected to a resistance load. The proposed MPPT algorithm is based on a PSO algorithm. In second, an irrigation system is proposed. It consists of water pump driven by DFIM and powered by hybrid renewable energy system.

A PSO algorithm is used for tuning PI controllers for the renewable hybrid energy conversion system. To have the ability to adjust the water flow, the direct torque method is used. The direct torque control (DTC) has many advantages; it can give us fast torque response. Figure 1 shows the proposed system for both dc and ac loads.

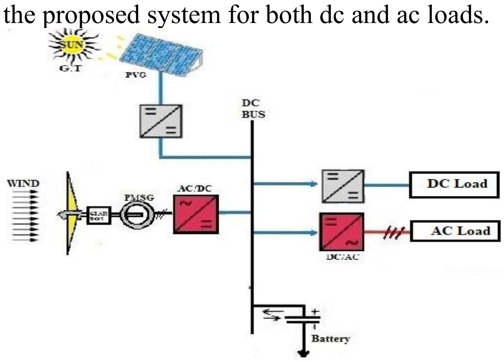

Fig.1 – Scheme of PV-wind source with storage battery connected to ac load and dc load.

2. PV-DC LOAD BASED ON MPPT-PSO

The topology of boost converter is shown in Fig. 2. The boost converter (parallel chopper) is used when it is desired to increase the available voltage of a dc source by controlling the duty cycle of the switching transistor.

Both P&O and INC MPPT algorithms may have difficulty finding the optimum when used in large PV arrays where multiple local maxima can occur [9]. In this

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section, we propose an MPPT based on the PSO algorithm applied to a PV system connected to a boost converter and a resistance as load.

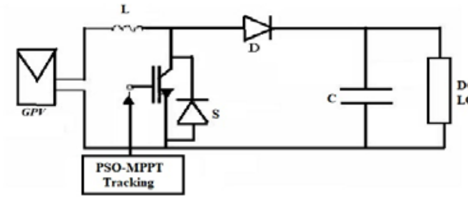

Fig. 2 – Boost Converter controlled by MPP-PSO tracker.

Metaheuristic optimization algorithms have been successfully used in a wide variety of areas. These methods are, for the most part, inspired by physics as simulated annealing (NA), biology as the Genetic Algorithm (GA), or ethology as the Particle swarm Optimization (PSO).

PSO is an algorithm proposed by Kennedy and Eberhart in 1995. It is inspired by the social behavior of animals evolving in swarms (for example: grouped flights of birds). The particles of the same swarm communicate with each other throughout the research to find a solution to the problem posed, and this is based on their collective experience. PSO has the advantage of being effective on a wide variety of problems, without need to modify the basic structure of the algorithm. The particle swarm corresponds to a population of simple agents, called particles. Each particle is considered as a solution of the problem, where it has a position x_{ij} and a speed v_{ij} (displacement) – Fig. 3.

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1), \tag{1}$$

$$v_{ij}(t+1) = wv_{ij}(t) + c_1 r_1 \left(pb_{ij} - x_{ij}(t)\right) + c_2 r_2 \left(gb_{ij} - x_{ij}(t)\right), \tag{2}$$

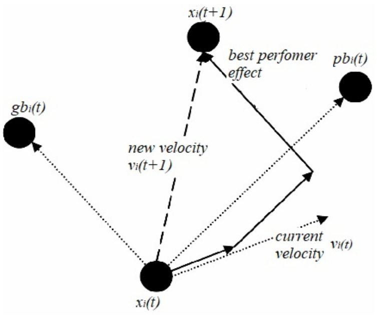

Fig. 3 – Particle displacement strategy

where i – the number of particles, w – the inertia factor, $v_i(t)$ – the velocity of particle i at iteration t, c_{ij} – time varying social and cognitive factor with r_1 and r_2, which follow a uniform law on [0...1].

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Algorithm 1: Basic PSO algorithm with
computed velocity limit at each iteration.
Compute initial velocity limits;
Initialize position;
Initialize velocity;
while termination condition is not fulfilled do
    foreach particle do
        compute velocity (using equation 2 );
        limit velocity;
        compute position (using equation 1 );
        if position in feasible space then
            evaluate position;
        end
    end
    Compute new velocity limit;
end
```

Fig. 4 – The process and pseudo code of the PSO [11].

The algorithm runs until a convergence criterion has been reached. This may be:

– A fixed number of iterations;

– Depending on the fitness;

– When the speed variation is close to 0.

The pseudo code of PSO is depicted in Fig. 4. As mentioned in the introduction, the PSO technique will be compared, in this section, with the GWO algorithm. More details of the GWO algorithm can be find in [10]We calculate the value of the duty cycle D by using the equation (1) and ΔD by using equation (2). The cost function, in this case, is defined to get maximum of power. As shown in Fig. 5, the input of the MPPT-PSO block represents the power ($V_{pv} \times I_{pv}$) and the output is the duty cycle D, with 5 particles; 300 iteration, inertia factor is 0.1, c_1 and c_2 equal to 1.2.

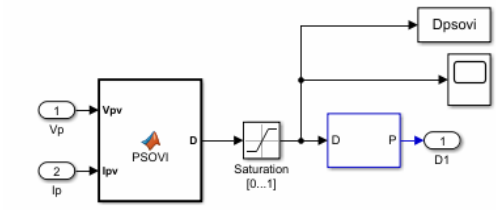

Fig. 5 – Block of MPPT based on PSO.

3. HYBRID-BATTREY CONNECTED TO AC LOAD AND BASED ON PSO METHOD

In this section, we propose a hybrid renewable energy system connected to a water pump as load. The pumping system contains an inverter, DTC, DFIM, and Pump as shown in Fig. 6.

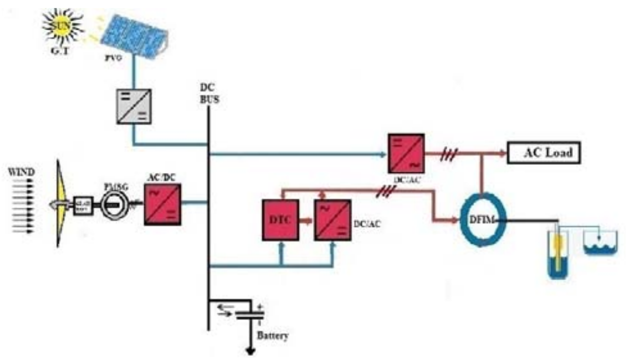

Fig. 6 – Schema of PV-wind source and storage battery connected to ac load.

3.1. DIRECT TORQUE CONTROL

The direct torque control is considered as one of the best alternative solutions compared to the classical one as direct field control. In this work, this technique is proposed to control the doubly fed induction motor of a pumping system connected to a hybrid renewable energy system. In the DTC, the stator flux vector is estimated by taking the integral of the difference between the input voltage and the voltage drop across the stator resistance given by:

$$\phi_s = \int_0^t \left(V_s - Ri_s\right) \mathrm{d}t \quad . \tag{3}$$

Let us replace the estimate of the stator voltage V_s with the true value and write it as:

$$V_s(S_a,S_b,S_c) = \frac{2}{3} U_{dc} (S_a + S_b e^{\frac{j2\pi}{3}} + S_c e^{\frac{j4\pi}{3}}) \; . \tag{4}$$

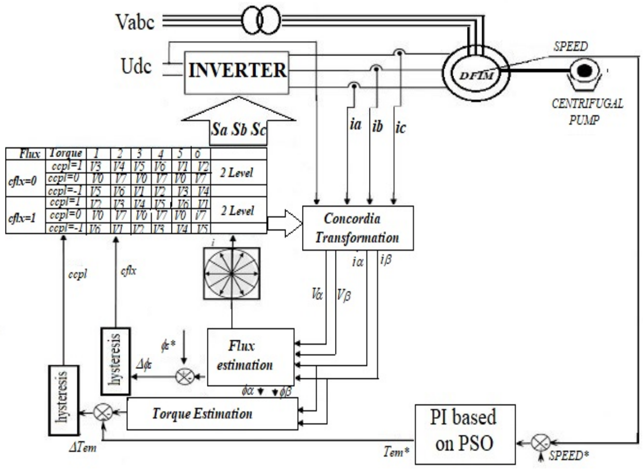

Fig.7 – Schemc of DTC control with PI speed regulator based on PSO.

S_a, S_b, S_c express the state of the three-phase branches. 0 means that the phase is connected to the negative branch and 1 means that the phase is connected to the positive branch [8]. The spatial vector of the stator current is calculated from the measured currents i_a, i_b, i_c:

$$i_s = \frac{2}{3}(i_a + i_b e^{\frac{j2\pi}{3}} + i_c e^{\frac{j4\pi}{3}}) \cdot \tag{5}$$

Torque relationship cited below:

$$T_{em} = \frac{3}{2} p\left(\phi_{s\alpha} i_{s\beta} - \phi_{s\beta} i_{s\alpha}\right) \cdot \tag{6}$$

The voltage plane is divided into six sectors.

3.2. BATTERY CONTROLLER

Battery control is an essential element for the success of autonomous systems. The batteries used in these systems are generally of lead-acid (Pb) type. Cadmium-nickel (NiCd) batteries are rarely used anymore because their price is much higher, and they contain cadmium (toxic). In this paper, nickel-metal hydride batteries (NiMH) are used.

Treating the controller output as the reference current for the battery as shown in Fig. 8. A hysteresis band approach is adapted to switch either Q_1 or Q_2 of the dc-dc converter as shown Fig. 8. In this work, the battery act as a source or sink, Nominal voltage is 300V, initial state of discharge is 60 %. The proposed hybrid PV/Wind-battery system is shown in Fig. 20.

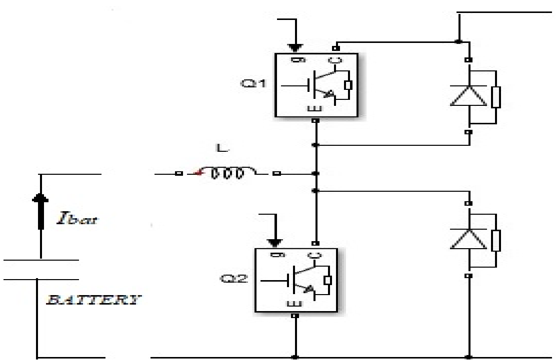

Fig. 8 – Controller battery.

The battery is also connected to dc link through a dc-dc converter. This dc-dc converter is used to maintain the dc voltage (U_{dc}) constant in order to feed our pumping system.

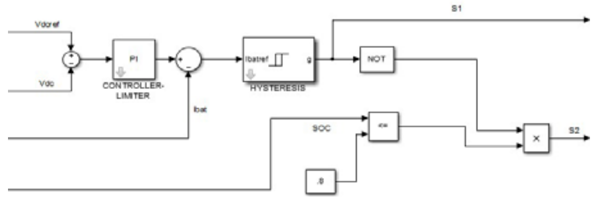

Fig. 9 – Dc-dc converter controller.

3.3. PI CONTROLLER BASED ON PSO

The error values represent the input of the two PI controllers. These errors are calculated by the difference between the reference and instantaneous value. The first PI speed controller input is represented by $e_1 = w^* – w$ (Fig. 7). The second PI-dc voltage controller input is depicted by $e_2 = U_{dc}^* – U_{dc}$ (Fig. 9).

In our case, we need to get the minimum of errors, so as input, we have error and as output, we have two variables K_p and K_i. The PI controller for the above system can be presented as the following expression

$$u = K_p e(t) + K_i \int e(t) \mathrm{d}t . \tag{7}$$

The cost function of the two PI-PSO controllers is presented by the calculation of the error as cited above.

The numbers of iterations and population used in this work are the same; iteration = 50, particles = 15; $w = 1$; $c_1 = 2$, and $c_2 = 2$.

Table 1 presents a comparative study between different meta-heuristic techniques applied to control dc voltage. It can be noticed that PSO gives better results than the others (GA or BAT). For this reason, we will apply it directly and compare it to the classical technique (Poles placement method) in the case of speed PI controller

Table 1

The tuning gain of (PI-dc voltage) by meta-heuristic algorithm

TUNING GAIN ALGORITHMS “META-H”		OPTIMUM OBTAINED
Single solution	NA	0.053
	ST	0.051
Multiple solution (Population num = 15 Iteration num = 50)	**PSO**	**0.037**
	ABC	0.054
	ACO	0.062
	GA	**0.392**
	FFA	0.047
	BAT	**0.391**

Annealing simulated (NA), search tabu (ST), particle swarm optimization (PSO), ant colony optimization (ACO), fire fly optimization (FFA), artificial bee colony (ABC), genetic algorithm (GA), bat algorithm (BAT).

You can find more details about the principal of each algorithms using, in this paper; PSO [12], ACO [13], ABC [14], NA [15], FA [16], ST [17], GA [18], BAT [19].

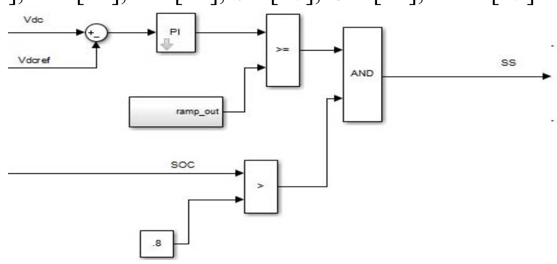

Fig. 10 – Dump load controller.

To clearly understand the energy management; see the flowchart which is depicted in Fig. 11.

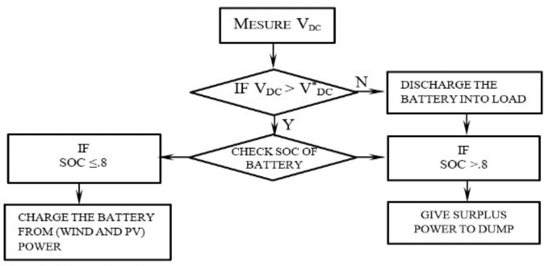

Fig. 11 –Energy management algorithm.

Figure 12 represents another ac load connected to the inverter; this part has not been treated in our work.

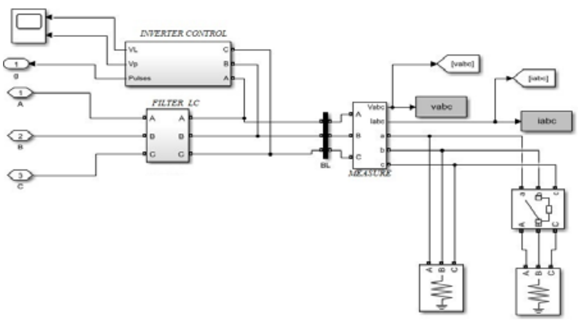

Fig. 12 – Ac load connected to the inverter.

4. DIGITAL SIMULATION

The pumping system is built using MATLAB/SIMULINK. The doubly fed induction machine parameters used in this simulation are listed in Table 4. The centrifugal pump performances used in this work for a speed of 2900 rpm are $Q = 30$ m^3/h, $H = 80$ m.

Tables 2 and 3 represent the characteristics of the PV module and wind generator respectively. The number of PV solar panels used to supply the desired load is 11.

Table 2

The characteristics of the PV 200 W

The nominal open-circuit voltage	32.9 V
The nominal short-circuit current	8.21 A
The voltage at the MPP	26.42 V
The maximum experimental peak output power	200 W
Parallel resistance R_s	0.2172 Ω
Serie resistance R_p	951.9319 Ω
Numbers of cells in module	54

Table 3

Parameters of PMSG

Power	6 kW
Poles	5
Stator resistance	0.425 Ω
Stator inductance	8.4 mH
Magnet flux linkage	0433 Wb
Rated speed	153 rad⁄s

Table 4

Doubly fed induction motor parameters

Power	1.5 kW
Stator resistance	1.75 Ω
Rotor resistance	1.68 Ω
Inertia	0.01 kg·m^2
Frequency	50 Hz
Stator inductance	0.295 H
Rotor inductance	0.104 H
Mutual Inductance	0.165 H
Poles	2

5. DISCUSS RESULTS

Figures 13 and 14 represent simulation results of the PV connected to resistance as dc load. MPPT-PSO is used to control the duty cycle of the switching transistor. Figure 13 represents the duty cycle, voltage, current, and power PV responses, with one module.

According to the simulation results (Fig. 14), it can be seen clearly that the dc voltage and duty cycle responses based on PSO are better than those obtained by GWO [20], in this figure, we use 11 modules to get 500 V needed to feed our DFIM motor via an inverter.

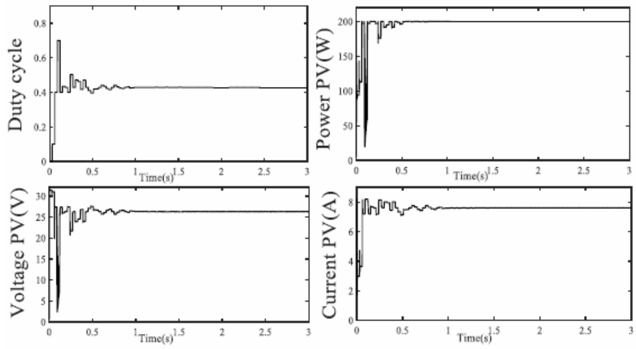

Fig. 13 – PV responses of the first proposed system (one module).

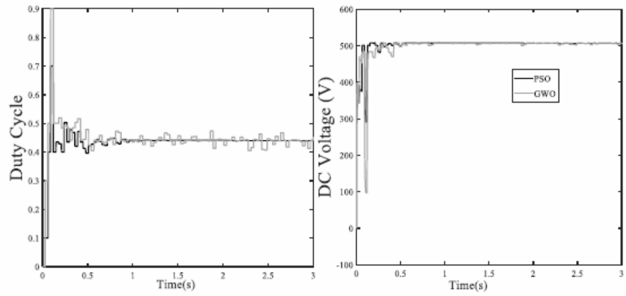

Fig. 14 – Duty cycle and dc voltage response of the first proposed system with 11 modules.

Figures 15 to 19 represent simulation results of PV/wind-Battery system (as source) connected to ac load (DTC-Inverter-DFIM as load). The boost of the PV is controlled by MPPT-PSO. The PI-dc voltage controller and PI rotor speed controller are also based on PSO as explained in Section 3. Figure 15 represents the dc voltage response by using PSO, BAT, GA, and classical techniques. It can be noticed, according to Table 1 and this figure, that PSO can give us better performance compared to the other methods.

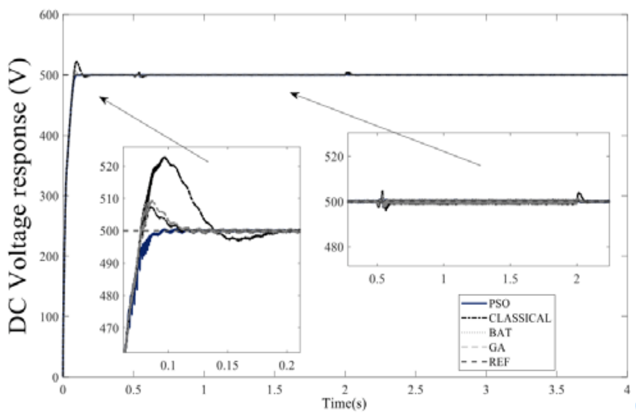

Fig. 15 – Dc voltage response by using PI controller based on GA, BAT and PSO.

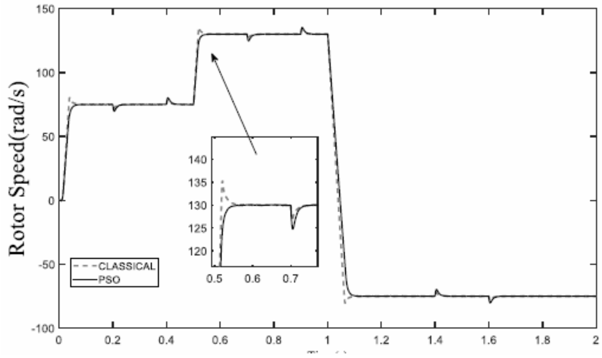

Fig. 16 – Rotor speed response by using PI based PSO.

Figure 16 shows the rotor speed response of the DFIM regulated by the PI controller based on the PSO and the conventional PI controller.

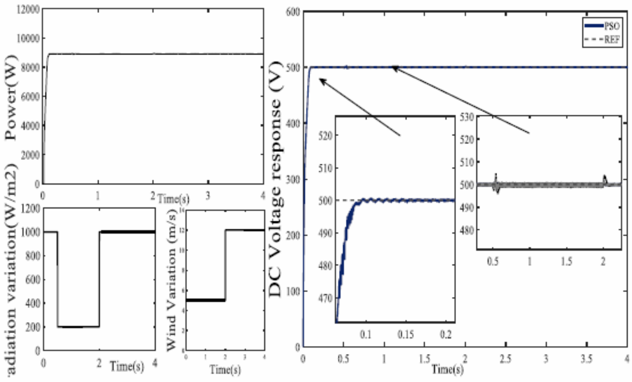

Fig. 17– Dc voltage and power responses under weather conditions.

A load torque equal to 10 N.m is applied throughout the simulation. It can be observed, from the results obtained, that the performances of the DFIM using the PI regulator based on the PSO are better compared to the conventional PI regulator.

Figure 17 represents duty cycle and power responses under weathers changes (irradiation "1000-200-1000 W/m^2" and wind speed change "5-12-7 m/s") at 0.5 s, 2 s and 5 s. It is clear from this figure that the PI controller based on PSO gives satisfactory results under weather condition variation.

From Fig. 18 it can be noticed that estimated values (stator flux, torque, dc voltage, rotor speed) tack their references (1.1 Wb, load torque applied 10 N$\cdot$m in each variation of speed *w*/2, *w* and –*w*/2 with *w* = 130 rad/s, 500 V) by using PSO.

These results are obtained from system not related to pump, to show the effective of using PSO by varying the speed (*w*/2, *w* and inverse speed –*w*).

The next figure (Fig.19) presents rotor speed, current, torque, flux, dc voltage, and water flow responses under a variety of weather conditions and load torque. These results are obtained now from the system related to pump.

From Fig. 19, during the starting up with no load, the speed and dc voltage quickly reach its references values without overshoot and the command quickly rejects the disturbance by using PSO.

Figure 20 represents nearly all the blocks used in this proposed work.

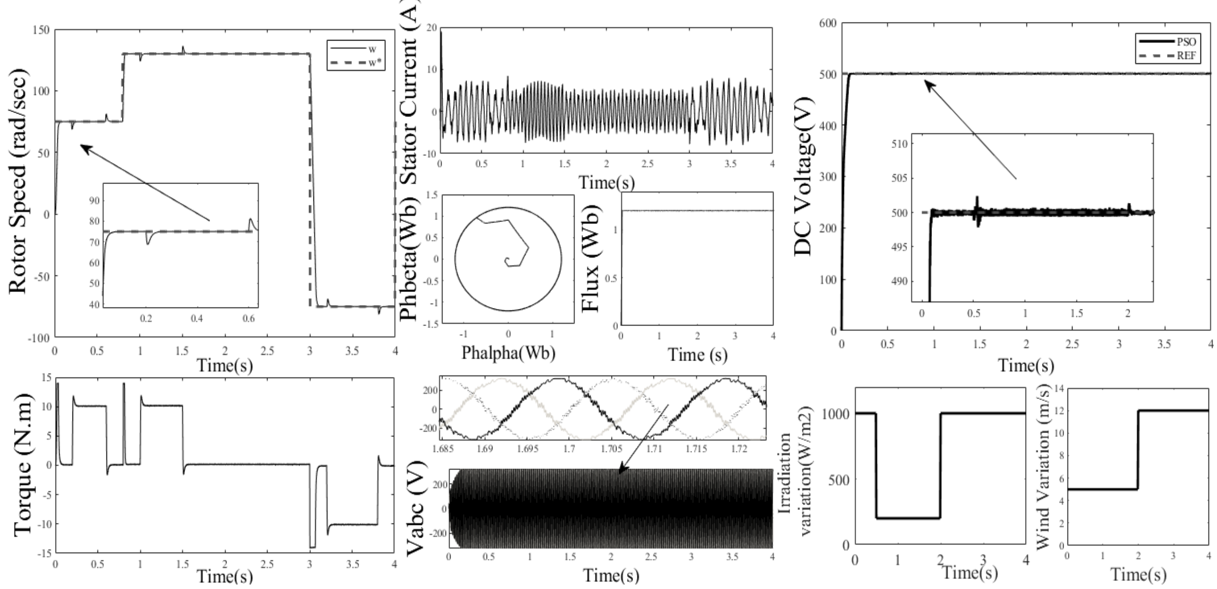

Fig. 18 – Direct torque responses with their inputs under weather (irradiation and wind speed) and load torque variation based on PSO

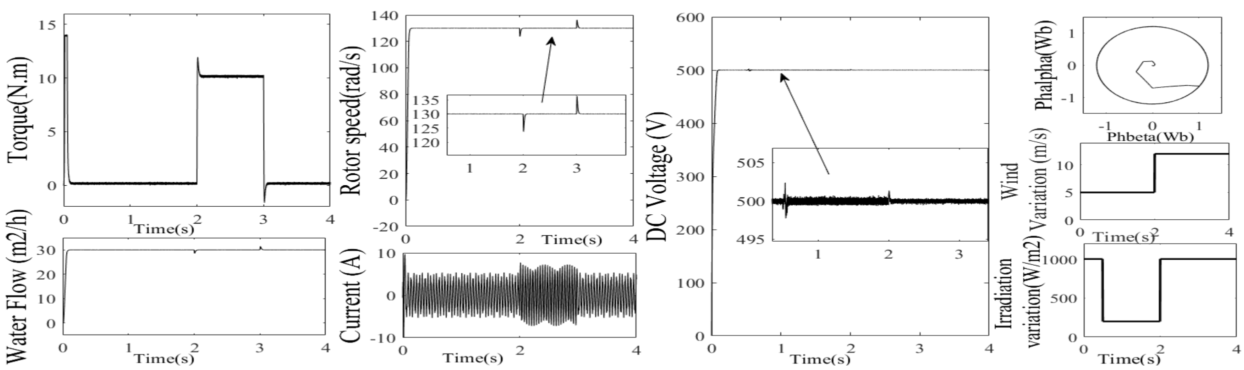

Fig. 19 – Pumping system connected to the hybrid renewable energy system and based on PSO.

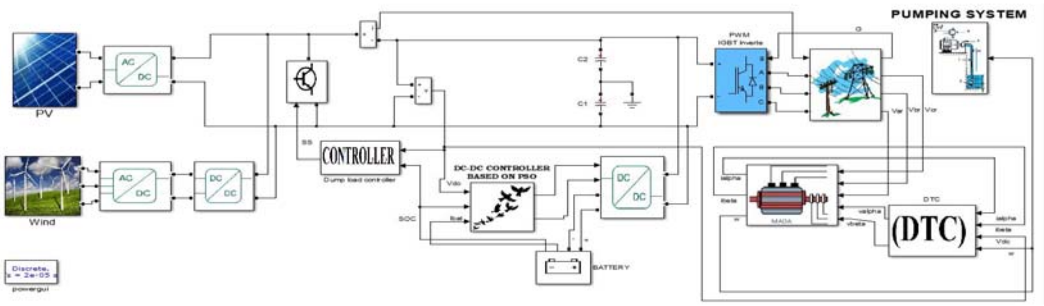

Fig. 20 – Standalone hybrid renewable energy system based on PSO.

6. **CONCLUSION**

The objective of this paper was first to apply a meta-heuristic MPPT controller based on particle swarm optimization (MPPT-PSO) to maximize the efficiency of a PV system connected to a dc load. This MPPT-PSO controller allowed us to regulate the duty cycle of the dc/dc converter. A comparative study was carried out between two meta-heuristic algorithms namely PSO and GWO to demonstrate the efficiency of the proposed approach. The simulation results revealed that the PSO is better than the GWO. Secondly, we were interested in the dynamic behavior of the dc/ac inverter. We have chosen to study the command which controls the dc link voltage (Vdc) required to supply the inverter. As we were also interested in rotor speed control of DFIM. These loops are controlled by PI controllers. The gains values of the PI regulators are adjusted by meta-heuristic methods (PSO, GA, BAT). A comparative study was carried out between the proposed techniques. The simulation results showed that PSO is the most efficient compared to the other meta-heuristic techniques proposed in terms of efficiency, speed, and stability.

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