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Robust Hybrid MPPT Controller for PV Pumping System

Rafika El idrissi, Ahmed Abbou, Mohcine Mokhlis, Noureddine Skik

***Abstract:** This article suggests a maximum power point tracking (MPPT) method for a photovoltaic (PV) pumping system based on a nonlinear robust method combining the backstepping and the sliding mode techniques, which is referred to us as the BSMC controller. The system's power circuit comprises of a solar panel, a step-up converter and a DC motor feeds a water pump. Two loops are in the control system: the first, provides the reference voltage, that is given by intelligent method based on artificial neural network (ANN), according with the maximum power point (MPP), to the BSMC in the second loop that regulates the PV array voltage in MPP and allows the converter to produce the required power to set the motor at the maximum speed. This is done through adjustment of the DC-DC boost converter duty ratio. The system is, on one side, able to predict the desired optimal voltage quickly by using the ANN, and also to prevent unnecessary calculation and research of the MPP. On the other side, the sliding mode and the backstepping controllers are used to provide good performance and robustness against rapid changes in the insolation and temperature. Also, the system's asymptotic stability is proven by lyapunov's functions. The proposed approach is compared to the method, P&O, IC and the hybrid technique ANN-integral sliding mode controller. Simulation results depict the proposed regulator effectiveness and robustness in relation to rapidly irradiance and temperature changes, using Maltab/Simulink.*

***Keywords**: ANN, BSMC, MPPT, Solar Panels, Step-up Converter.*

I. INTRODUCTION

In latest years, worldwide demand for energy has been growing. For this reason, it is indispensable that renewable energy systems are used. In particular, Photovoltaic (PV) power systems have now been commonly used [1]. Specially, standalone photovoltaic pumping systems have become an appropriate solution for the supply of water in rural areas without access to an electrical grid.

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***** Correspondence Author

Rafika El idrissi*, Electrical Engineering Department, Mohammadia School of Engineers, Mohamed V University, Rabat, Morocco. Email: rafika.elidrissi@gmail.com.

Ahmed Abbou, Electrical Engineering Department, Mohammadia School of Engineers, Mohamed V University, Rabat, Morocco. Emails: abbou@emi.ac.ma,

Mohcine and Mokhlis, Electrical Engineering Department, Mohammadia School of Engineers, Mohamed V University, Rabat, Morocco. Emails: mohcine1mo@gmail.com,

Noureddine Skik, Electrical Engineering Department, Mohammadia School of Engineers, Mohamed V University, Rabat, Morocco. Emails: noureddine.skik@gmail.com.

Various studies have been performed regarding electric motors selection and pumps for water pumping systems [2] - [3]- [4]. In the past, DC engines employed mainly to drive PV-based water pumps with great effectiveness and easy control strategies [5]- [6].

The permanent magnet and independently agitated DC engines were discovered to be better suited to PV panel water pumping systems [7]- [8]- [9]. The energy generated by the PV panel relies on the temperature and radiation circumstances. Therefore, under particular circumstances each PV module has only one operating point for MPP.

To achieve the MPP and regulate PV output voltage, a DC / DC converter must be added to the panel output. This combines the PV panel and the optimal position of the motor pump. Various DC / DC converter topologies are available [10]- [11]. A boost converter has been applied here.

A sufficient digital DC / DC switch control enables the input voltage o the converter to set the required value for MPPT to be received. In this situation a permanent magnet DC engine feeds a centrifugal pump with the converter output voltage. Different control algorithms can actually perform the MPPT to attain the highest possible power in all conditions [12]. Some of them are based on online techniques, such as perturb and observe (P&O) [13]- [14]- [15], incremental conductance [16]- [17], ANNs [18]- [19], fuzzy logic [20]- [21], That are the most common literary techniques. Unfortunately, these algorithms provide nearly MP only if the PV module undergoes non-uniform insolation and do not provide exact convergence. Other MPPT hybrid techniques [22]- [23] are designed to solve this dilemma using a double loop control. The first loop actually delivers the MP voltage and the second ensures a control of MP voltage. A DC-DC converter which works on the appropriate MPP is necessary to adjust the impedance between the PV array and the load. The parameters' disruptions influence the control manner, since the tracking performance is closely linked to the second loop. A two - loop hybrid method is recommended in [24] to track MPP more efficiently. An incremental conductance method is used to estimate MPP in the first part. Terminal sliding mode controller to adjust the system to the MPP reference search is used in the second part.

This article suggests a new method for controlling MPPT PV pumping system by means of a boost converter. The MPP is being tracked with the help of an off - line ANN via the nonlinear backstepping sliding mode method. The ANN offers the photovoltaic output reference voltage for distinct radiations and temperatures, forcing the PV pump system to perform the projected MPP by operating on the DC / DC step-up converter duty ratio. The proposed approach is compared with the direct methods, P&O, IC, and the hybrid one, which combines the ANN and the integral sliding mode controller [25] to demonstrate its effectiveness and tracking performances.

Having regard to these ideas, the remain of this paper is described in the following way. The second gives a configuration of the whole system overview. Section three, presents the system modelling. The MPPT proposal is presented in the fourth section with a detailed procedural design. The fifth part presents simulation results and discussions, which are followed up by conclusions in the final section.

II. CONFIGURATION OF THE WHOLE SYSTEM

The overall scheme of the PV pumping system employed to study controller performance is illustrated in the fig 1. The solar radiation is converted in electrical energy by the PV modules that power a DC motor through a DC/DC step-up converter. Therefore, the step-up converter associated with a MPPT control can reasonably track the MP of the PV panel regardless of the environmental conditions, and feeds it to the DC motor. Finally, the group DC motor-centrifugal pump convert the mechanical energy into hydraulic energy.

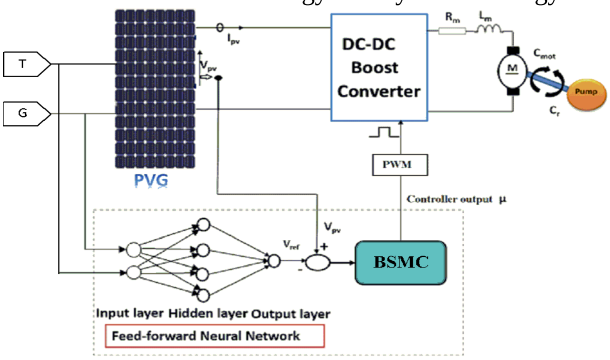


Figure 1. The whole system configuration.

III. THE PROPOSED SYSTEM MATHEMATICAL MODEL

A. *PV panel modelling*

Solar panels based on photovoltaic effects convert light into power. The electric circuit of the PV cell, as shown in Fig 2 [26]- [27]- [28], consists of a source current (I_{ph}), that reflects photon produced current, a diode, a current-leak shunting resistance (R_{sh}) and an ohmic loss modeling series resistance (R_s). Gathering the solar cells form a photovoltaic module. The parallel connection between the modules increases the current value and the voltage value increases by series connection, leading to a PV generator or a PV panel. During the simulation in this paper SM55 PV module is considered. It is a series of 36 solar cells that can supply maximum 53.32W of energy.

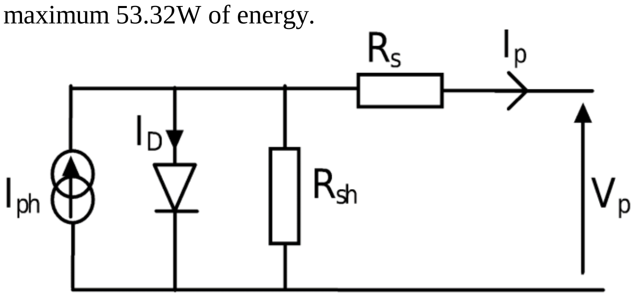


Figure 2. The electric circuit of the PV cell.

Since R_s is small and R_{sh} is high, both may be overlooked to simplify the research. The PVG displays a nonlinear insolation-dependent voltage–current characteristic, mathematically expressed as follow [29].

$$I_{pv} = N_p I_{ph} - N_p I_0 \left[\exp\left(\frac{qV_{pv}}{nN_s KT} \right) - 1 \right] \tag{1}$$

I_{pv} [A] and V_{pv} [V] mean the output current and the voltage of the PVG respectively. N_p and N_s are the parallel and the series connected cells respectively, q = 1.6 × 10^{-19} [C] is the charge of electron, K = 1.3805 × 10-23 J/K is the constant of Boltzmann, y is the p-n junction ideality factor and T [K] is the temperature of the cell.

The saturation current of the cell depends on temperature according to the following equation:

$$I_0 = I_{0r} \left(\frac{T}{T_r} \right)^3 \exp\left(\frac{qE_g}{K\Upsilon} \left[\frac{1}{T_r} - \frac{1}{T} \right] \right) \tag{2}$$

Where E_g = 1.1 [eV] is the energy used in the cell in the semiconductor range and T_r [K] means the nominal operating temperature of the cell.

The saturation current of the cell I_{0r} at T_r is defined as follows:

$$I_{0r} = \frac{I_{scr}}{\exp\left(\frac{qV_{oc}}{N_s \Upsilon KT} \right) - 1} \tag{3}$$

Where I_{scr} [A] means the short-circuit current of the cell at reference temperature and radiation. V_{oc} [V] means the open circuit voltage.

I_{ph} [A] is associated with the following relation with solar sunlight and the temperature of the cell:

$$I_{ph} = \left[I_{scr} + K_i \left(T - T_r \right) \right] \frac{E}{1000} \tag{4}$$

Where K_i [A/K] means the coefficient of the temperature of short-circuit current and E [W/m2] is the sun radiation. Table 1 gathers the Main identifications of the simulated PVG at standard conditions:

Table 1. PV generator's electrical parameters

Parameters	Names	Values
N_s	Cell number linked to the series	20
N_p	Number of cells linked parallel	5
γ	Factor of ideality	1.7404
I_{scr}	Short-circuit current at the cell temperature reference	3.45A
I_{0r}	The cell Reverse saturation current	4.842μA
K_i	Temperature coefficient of short-circuit current	4x10^{-4}A/K
T_r	The cell reference temperature	298.15 K

For distinct sun radiations E and temperatures T values the I-V and V-P features of PVG are shown in figures 3 and 4. These figures show that the atmospheric situation has an important impact on MP. When solar radiation is continuous, the strength of the PVG reduces with growing temperature.

The increase in cell temperature decreases the open circuit voltage linearly and rises the current slightly**.** PVG energy is reduced as solar irradiation drops at a steady cell temperature. When the sunlight decreases slowly the short-circuit current increases and the open circuit voltage decreases.

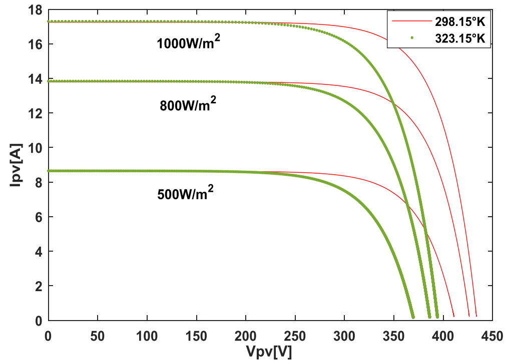


Figure 3. Vpv – Ipv at various sunlights and cell temperatures.

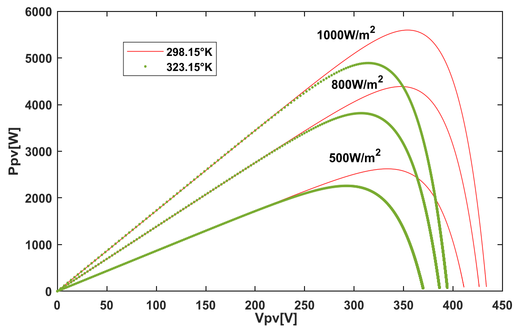


Figure 4. Ppv - Vpv at various sunlights and cell temperatures.

B. *DC-DC step up converter modelling*

The converter controls the PVG output voltage (V_{pv}), which extracts the maximum energy from the PVG. Between the PVG and the DC engine the boost converter is used for corresponding PVG Output Features to the DC Engine Input Features. Circuit topology of a step-up converter is shown in Figure 5:

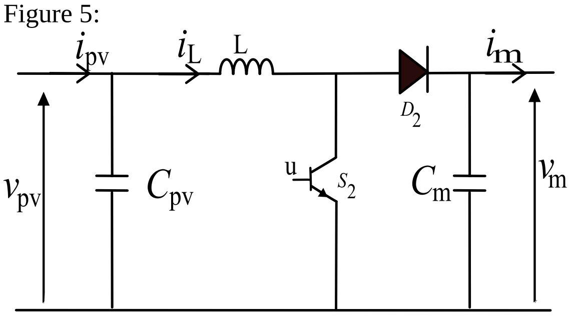


Figure 5. DC-DC step-up converter

According to [30], the step-up converter dynamic equations are listed here:

$$\begin{cases} \dfrac{dV_{pv}}{dt} = \dfrac{1}{C_{pv}}\left(I_{pv} - I_L\right) \\ \dfrac{dI_L}{dt} = \dfrac{1}{L}\left(V_{pv} - (1-u)V_m\right) \\ \dfrac{dV_{pv}}{dt} = \dfrac{1}{C_m}\left(-I_m + (1-u)I_L\right) \end{cases} \quad (5)$$

Where V_{pv}, I_L and V_m are the PVG output voltage, the inductor current and the converter output voltage respectively; u is the duty ratio; and I_{pv} means the average state of output current of the PVG.

This averaged state space model is then used to pursuit the reference peak voltage.

C. *DC motor and Centrifugal pump dynamic model*

The motor and the pump can be dynamically modelled by the following set of equations:

$$V_m = R_m i_m + L_m \frac{di_m}{dt} + K_e w \quad (6)$$

The system mechanical equation is given by the following:

$$J\frac{dw}{dt} = K_m i_m - K_r w^2 \quad (7)$$

ω and J respectively are the the speed of rotation and the group inertia moment, K_m is the electric couple constant , L_m is the led rolling-up inductance, R_m is the engine resistance, K_r is the proportionality coefficient and K_e is the constant force versus electrometrical.

IV. PROPOSED CONTROLLER FOR MPPT

The control system suggested is splitted into double loops, following the method of [31], as illustrated in Fig.1. The first is to produce the reference voltage based on intelligent method. The second, a BSMC controller is suggested to force the"V_{pv}" track"V_{ref}"and to provide the duty cycle μ so that the PVG is exploited optimally under gradually changing of irradiation and temperature.

A. *ANN based suggested MPPT control*

ANNs are considered an alternate way to deal with nonlinear issues. They can learn from examples and manage inadequate information. they can predict quickly [32]- [33]. The PVG has a unique MPP for each irradiance and temperature measurement. ANN is a three-layer feedforward network that MPPT controller is based on, as illustrated in the fig 1. The structure of the ANN is determined by the number of layers, the number of neurons per layer, the type of activation function in each layer and the connection between them. This structure is chosen to boost the precision of the acquired neural network after several trials.

Through the two input layer neurons the irradiance and temperature input variables are transferred to the hidden layer. The hidden layer contains 5 hidden neurons with the sigmoid activation feature. Therefore, the resulting activation of the neurons in the concealed layer is calculated accordingly:

$$x = f_s\left(\sum w_s\left[GT\right] + b_s\right) \quad (8)$$

The neurons of the concealed output layer have their characteristics in the weight matrix, indicated by w_s , w_0 respectively and the bias vector indicated by b_s , b_0 , respectively. The sunlight G and the temperature T are the input.

The output layer includes a neuron with a linear activation feature, which is shown as follows:

$$f_s(x) = x \quad (9)$$

This neuron has the following connection to the calculated MPP voltage V_{mp} :

$$\hat{V}_{mp} = f_0\left(w_0 x + b_0\right) \quad (10)$$

The neural network database should include a broad variety of measures to enhance the predictive precision. The database is based on the simulation of the PV module above.

The neural network is trained offline with the backpropagation Bayesian regularization, which minimizes the MSE. This is how the MSE is computed:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(V_{mp}(i) - \hat{V}_{mp}(i)\right)^2 \quad (11)$$

Where "V_{mp}" is the target ith and its estimated output is "$\hat{V}_{mp}$" . Figs 6 and 7 demonstrate respectively the development of the error of performance for the ANN based MPPT approach and a comparison between the ANN calculated outputs and the goals.

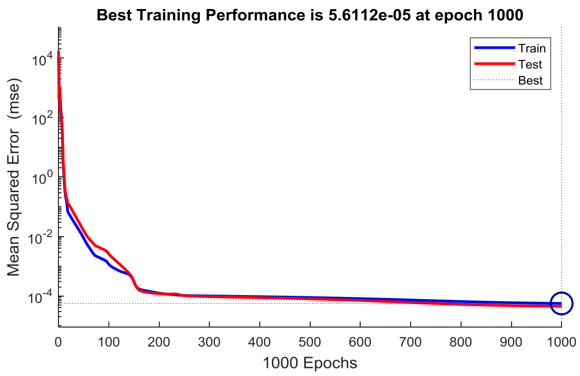


Figure 6. The MSE evolution during training.

Following the training phase, the ANN-based MPPT controller should provide MPP voltage in all weathers. One advantage of this controller is that a large number of iterations are not necessary to find the MPP, thus reducing oscillation around the MP and increasing efficiency. The data used to train the ANN offline is depicted in fig.7

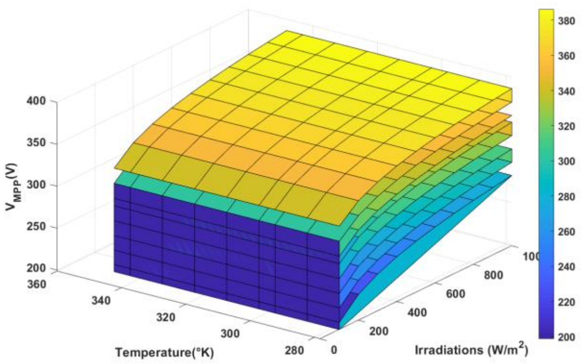


Figure 7. the optimal PV voltage according to the environmental conditions changes

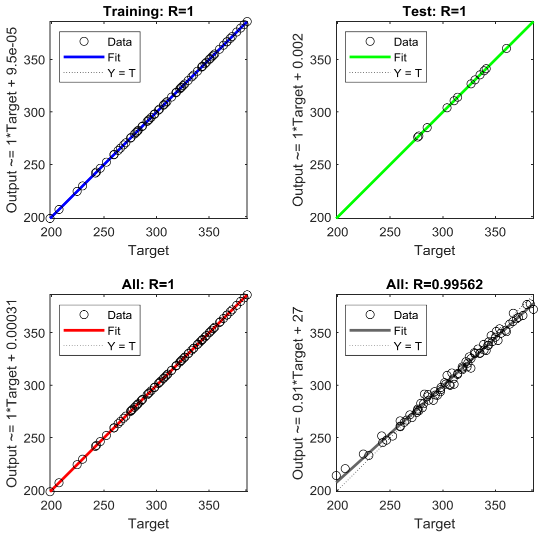


Figure 8. The ANN predicted outputs and targets during the learning stage.

B. *Proposed backstepping-sliding mode controller design*

In this part, the backstepping and sliding mode are combined to design the BSMC controller. This controller development is aimed at finding a proper control law that converges the tracking error to zero and ensures a stable closed loop system.

There are two phases to the design approach. A Lyapunov function first builds a virtual control input. A valid control is then achieved.

The process of design is as follows:

Step1: e_1 (x) is the state variable tracking error which is defined as follow:

$$e_1 = V_{pv} - V_{ref} \quad (12)$$

Where "V_{ref}" denotes the reference signal provided by the ANN . the controller aim is to verify that system output accurately track the reference signal.

The goal is to converge the error signal e_1 to zero, taking the time derivative of Eq. (12) and simplifying using Eq. (5), we get:

$$\dot{e}_1 = \dot{V}_{pv} - \dot{V}_{ref} = \frac{1}{C_{pv}}\left[i_{pv} - i_L\right] - \dot{V}_{ref} \quad (13)$$

A first Lyapunov function candidate is chosen as follow, for checking the convergence of e_1 to zero:

$$V_1 = \frac{1}{2}e_1^2 \quad (14)$$

Its time derivative, using Eq. (13), yields:

$$\dot{V}_1 = e_1\dot{e}_1 = e_1\left[\frac{1}{C_{pv}}\left(i_{pv} - i_L\right) - \dot{V}_{ref}\right] \quad (15)$$

So that the Lyapunov function to be negative, let:

$$\frac{1}{C_{pv}}\left[i_{pv}-i_L\right]-\dot{V}_{ref}=-K_1e_1 \quad (16)$$

Where K1 is a positive definite, so, $\dot{V}_1$ becomes:

$$\dot{V}_1=-K_1e_1^2 \quad (17)$$

Considering iL as a virtual control, we get:

$$\alpha=i_L=K_1C_{pv}e_1+i_{pv}-C_{pv}\dot{V}_{ref} \quad (18)$$

Step2: Another error e_2 is defined to track i_L to α:

$$e_2=i_L-\alpha \quad (19)$$

Replacing i_L by $e_2+\alpha$ in Eq. (15), we get:

$$\dot{V}_1=-\frac{e_1e_2}{C_{pv}}-K_1e_1^2 \quad (20)$$

In Eq. (20), the first term is negatively definite, but we are unsure of the second term.

Now, to guarantee the convergence of both e_1 and e_2 to zero, a second Lyapunov function is selected whose time derivative should be defined negative so that our system can reach the MPP.

$$V_2=V_1^2+\frac{1}{2}S^2 \quad (21)$$

Where S is the chosen sliding surface:

$$S=e_2 \quad (22)$$

The derivative with respect to time of the Lyapunov function is obtained through the following equation:

$$\dot{V}_2=\dot{V}_1+S\dot{S}=-K_1e_1^2+S\left[-\frac{e_1}{C_{pv}}+\dot{S}\right] \quad (23)$$

We put:

$$\left[-\frac{e_1}{C_{pv}}+\dot{S}\right]=-K_2S-\rho\sin(S) \quad (24)$$

The expression for the control input deduced from Eq. (24), as follow:

$$u=\frac{L}{V_m}\left[-K_2S-\rho\sin(S)+\frac{e_1}{C_{pv}}+\frac{1}{L}\left(V_m-V_{pv}\right)-\dot{\alpha}\right] \quad (25)$$

Which conducts to:

$$\dot{V}_2=-K_1e_1^2-\left(K_2S^2+\rho\sin(S)\right)<0 \quad (26)$$

Therefore, that proves the stability of e_1 and e_2 to zero, Which leads consequently to the convergence of V_{pv} to V_{ref}, K_2 and ρ should be positive definite.

V. SIMULATION RESULTS AND DISCUSSION

An SM55 PVG evaluated the tracking performance of the developed controller. The MPP PV generator voltage is considered as V_{ref}. For each change in solar irradiation or temperature it is calculated off-line with the ANN. Tables 2 and 3 respectively collect the boost converter, controllers, and DC motor parameters.

Table 2: The boost converter & the controllers' parameters

Parameters	Values
Cpv	500 µF
L	1.5 mH
Cm	4700 µF
K_1	3.2217e+03
K_2	3.2200e+03
K_3	178.8396

Table 3: Electrical and electromechanical of DC motor parameters (ABB DMI B180)

Parameters	Names	Values
V_{mn}	Nominal voltage of the Motor	400 V
I_{mn}	Nominal current of the Motor	12.2 A
w_n	Nominal rotation speed of the Motor	104.7rad/s
L_m	Inductance of the Motor	0.12 H
R_m	Resistance of the Motor	9.84Ω
K_e	Electromechanical coupling constant	2.674 VS/rad
K_m	Electric couple constant	2.541 N m/A
J	Motor total inertia	0.03 kg m^2
K_r	Proportionality coefficient of resistant torque	2.8 x 10^{-3}N m s^2/rad^2

The proposed control technique is compared in equal conditions firstly to the direct methods such as the P&O and the incremental conductance methods. Then with the hybrid method ANN-integral sliding mode controller. The scheme under study is evaluated for rapid modifications in sunlight and temperature as depicted in fig.9.

First, the initial irradiance is maintained at 600 W / m2, which is suddenly changed to 700 W / m2 after 5 s, to test the controller proposed in fast variable circumstances. Likewise, it's changed to 800 W/m2 after 7.5 s then to 1000 W / m2 after 11 s. While the initial temperature of the PV array is first kept at 298.15°K, that is then increased to 308.15°K after an interval of 14s and after 18s, the temperature is sharply decreased to 288.15°K.

The fig. 10 shows the dynamic response of the PVG voltage and the reference of the proposed controller. As it can be observed the ANN provides the reference voltage within a short period of time, while the BSMC rapidly tracked this reference. The performances of this controller are compared to the direct methods, P&O and IC, as illustrated in fig. 11a,b,c. It is clearly obvious that the proposed approach more accurate than these methods.

To assess more the proposed ANN-BSMC strategy performances, a comparative analysis with the hybrid method ANN- integral sliding mode controller is considered. The results of voltage, power curves responses are shown in fig. 12,a,b. as can be seen, the ANN produces successfully the tracking peak voltage that both controllers have tracked.

However, we can say from the fig12-a and fig12-b that the proposed controller outperforms the integral sliding mode controller in term of tracking speed with very low oscillation and stability.

A zoomed part of the oscillation around the MPP using the integral sliding mode controller is presented in fig12-a. It's clearly obvious that the output voltage ripples of the proposed controller is much lower than the ISMC controller. According to environmental conditions changes, the suggested BSMC reveals its robustness, which reduces the chattering phenomenon.

Fig.13,a,b,c depict the dynamic response of motor, voltage, speed and current of the proposed method. It can be illustrated from those figures that the proposed control succeeds to maximize the speed of the motor.

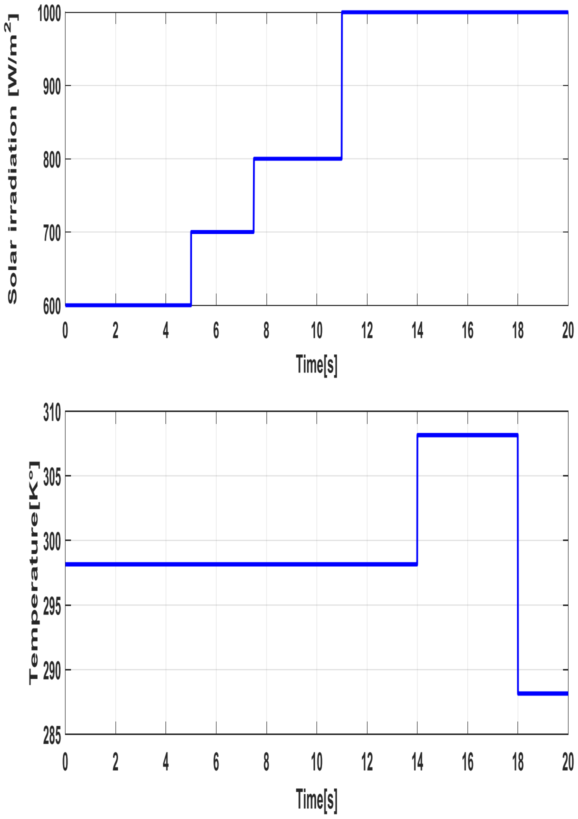


Figure 9. the proposed environmental conditions changes

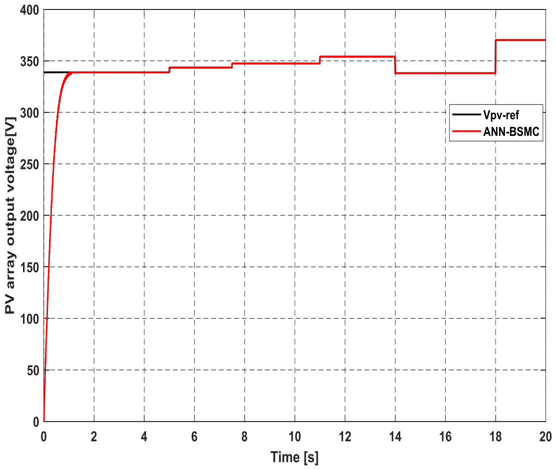
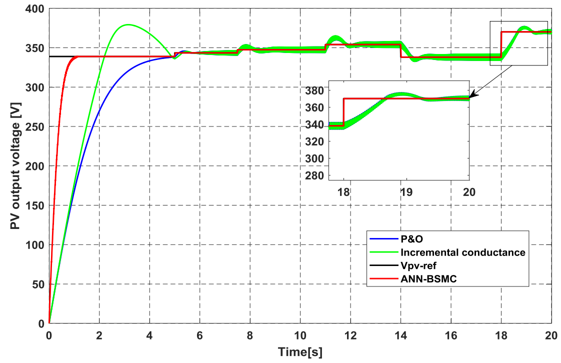
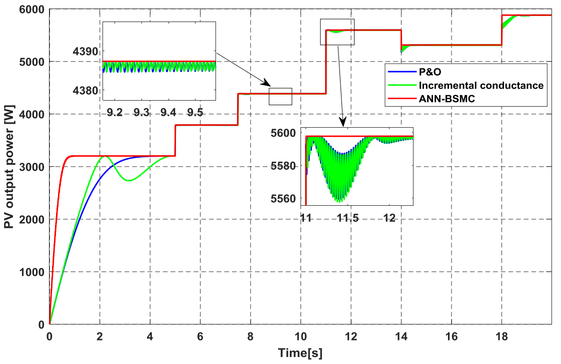


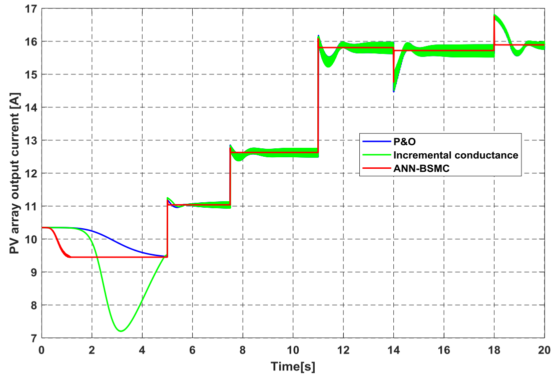
Figure 10. the measured MPP voltage generated by the ANN loop and the PV voltage using BSMC loop.



(a)

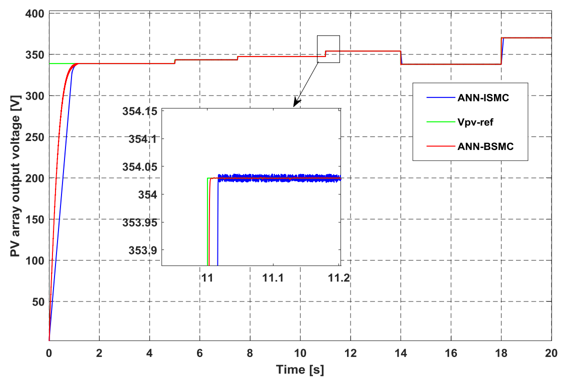


(b)

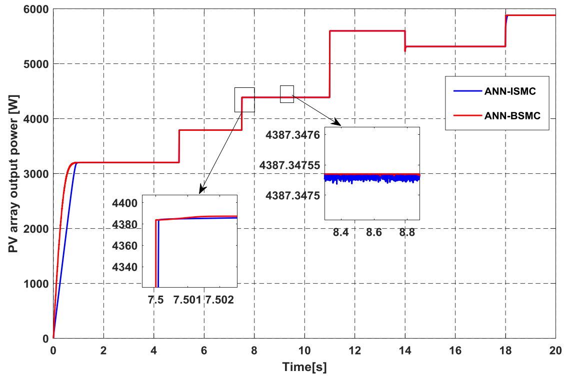


(c)

Figure 11. PV array: a) voltage, b) power and c) current generated using P&O, IC and the proposed method

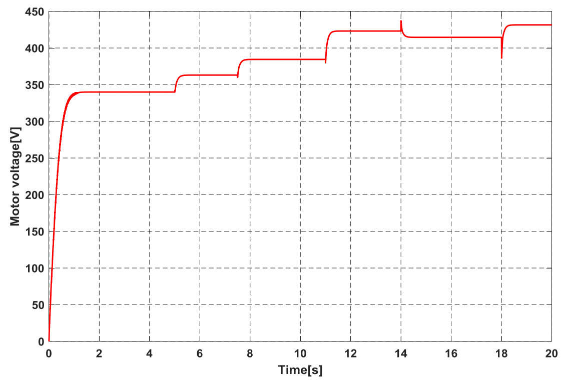


(a)

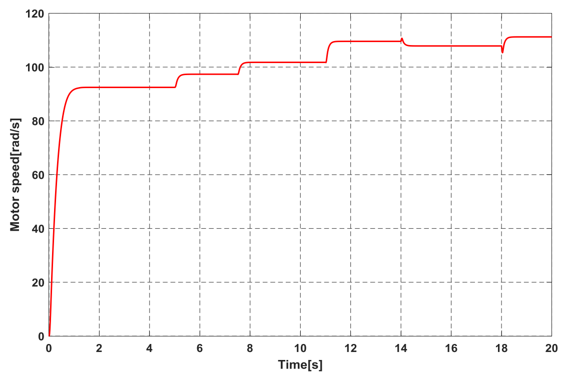


(b)

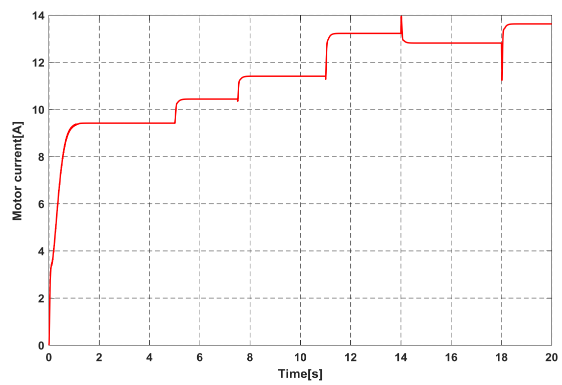
Figure 12. PVG: a) voltage, b) power of the proposed approach compared to the integral sliding mode controller.



(a)



(b)



(c)

Figure 13. The motor: a) voltage, b) speed and current using the proposed controller.

VI. CONCLUSION

This work includes a thorough assessment and design, using a hybrid method composed of the backstepping and the sliding mode techniques, of the MPPT solution. This solution aim is performing a fast MPPT in PV pumping systems and operates the motor pump at the best rate. In term of PV systems nonlinear characteristics, that are based on the atmospheric conditions, an ANN supplies the measured voltage to the step-up converter, this one is attributed to the system rapidity. Also by applying this loop in the PV system, it has perfectly predicted and generated the reference signal of the optimal voltage. Following the delivery of reference voltage by ANN. It was suggested that the BSMC controller regulate the DC / DC step-up converter by acting on the duty ratio. The proposed controller is compared firstly with the direct methods, P&O and IC, then with the hybrid ANN-ISMC method in order to validate its performances. The simulation results depict that the proposed method succeeds to track the reference voltage more effectively compare to other methods. The ANN-BSMC controller not only achieved steady state faster but also achieved a small SSE and it demonstrated a very low oscillation around MPP, it succeeded to reduce the chattering phenomenon of the sliding mode controller. Simulations either during temperature changes or during different solar radiations were examined for the developed approach efficiency. The results showed that the combination of the two controllers, which are the backstepping and the sliding mode, the system response is improved in term of tracking speed, SSE and the MPP's oscillation.

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AUTHORS PROFILE

Rafika El idrissi was born in Sidi Bennour, Morocco, in 1990. She received the B.S. degree in Electronics and Industrial Computing and M.S. degree in Information processing from Hassan II University, Casablanca, Morocco, in 2012 and 2014, respectively. She is currently pursuing her PH.D. in Electrical Engineering department at Mohammadia School of Engineers, Mohamed V University, Rabat, Morocco. Her research interests include nonlinear control theories, Power Systems, and photovoltaic systems.

Ahmed ABBOU: He received the B.E. degree from ENSET in Rabat, the M.E. degree from Mohammed V University in Rabat and the Ph.D. degree from Mohammed V University in Rabat, in 2000, 2005 and 2009, respectively, all in electrical engineering. Since 2009, he has been working at Mohammadia School of engineers, Mohammed V University in Rabat, Department of electric Power Engineering, where he is a Professor of Power Electronics and Electric drives. He published numerous papers in scientific international journals and conferences proceedings. His current research interests include induction machine control systems, self-excited induction generator, power electronics, sensorless drives for AC machines and renewable energy (PV and wind energy).

Mohcine Mokhlis was born in Casablanca, Morocco, in 1992. He obtained the B.S. in Electronic, Electro-technical and Automatic in 2014, and M.S. degrees in Automatic, Signal Processing and Industrial Informatics in 2016, from the Faculty of Science and Technology (FSTS), Settat, Morocco. He is currently working toward on the Ph.D. degree in electrical engineering at Mohammadia School of Engineers (EMI), Rabat, Morocco. His current research paper concerns the photovoltaic system.

Noureddine Skik received the M.S. degree in industrial electronics from the Faculty of Sciences-Fez, in 2014. He is currently pursuing his Ph.D. in Electrical Engineering department at Mohammed V University, Mohammadia School of Engineers, Rabat, Morocco. His research interests include static converters, power electronics, power systems, Smart Grid, Renewable Energy and Artificial Intelligence.