Experimental validation of Neuro-fuzzy energy management for a DC electrical micro-network

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Abstract— Energy management is an important component for the profitability of energy production systems in a context where the use of photovoltaic (PV) systems with storage is expanding. It allows to control the power generated by the PV and at the same time to supervise the storage system. In this paper, a Hybrid Particle Swarm Adaptive Neuro-Fuzzy Inference System (HPSANFIS) is presented for the Energy Management System (EMS) of a Hybrid PV Battery (HPVB) system. The proposed EMS consists of two parts. A part concerning the optimization of the power produced by the PV module (PVM) and a part concerning the supervision of the battery. The same hybrid method is used for both separate applications. The methods are validated under a dSPACE DS1202. The obtained results show that the proposed EMS makes the autonomous HPVB system capable of working normally by tracking Maximum Power Point (MPP), charging and discharging battery whatever the meteorological conditions.

Keywords: **Energy management, hybrid system, ANFIS, PSO, photovoltaic**

I. INTRODUCTION (*HEADING 1*)

In a context of immeasurable energy demand and depletion of fossil resources, the use of renewable energies is still in transition [1]. Indeed, renewable energies remain our greatest hope for the fight against climate change and its disastrous effects on the environment. Among them, solar photovoltaic energy is widely used. This is due in large part to its accessibility almost everywhere on the globe, but also its availability, low maintenance and its non-polluting character [2]. The residential and building sector is the most energy intensive sector. The use of solar photovoltaic (SPV) energy in these two key sectors therefore remains confronted with the problem of the intermittence of the solar source [3]. Recourse to the storage system then becomes a necessity in order to continuously supply these sectors. An efficient EMS will then be a challenge to satisfy the energy demand of the residential and building sectors [4]. The EMS must both allow to produce a maximum power from PVM by using maximum power point tracking techniques (MPPT) and protect battery against overcharge and deep discharge by supervision techniques.

Many works deal with the EMS of SPV systems. They focus on several techniques such as smart EMS where authors show the efficiency of the methods whatever the variations of climatic conditions.

Conductance (InC), soft-computing methods based on artificial intelligence (AI) or Bio-Inspired (BI) algorithms and hybrid methods.

AI algorithms are inspired by human intelligence. Among these latter algorithms, there are artificial neural networks (ANN) and fuzzy logic (LF) [5]–[9]. BI or evolutionary algorithms are inspired by the theory of evolution, nature and gregarious relationships in animals. Mention may be made, among others, of Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) [7], [10]. The last category of MPPT methods consists for the most of one evolutionary algorithm to optimize the structure of another algorithm of different class (AI or conventional) [11]. In [12], the authors provide a comparative and comprehensive review of the 17 most famous and efficient MPPT techniques. The obtained results show that the conventional MPPT techniques especially InC and P&O followed by HC are efficient, accurate and reliable to track the unique MPP under uniform conditions (un-shaded) but they failed to track the optimum global power (OGP) and stuck at the first MPP whatever it is OGP or optimum local power (OLP) under partial shading conditions in terms of tracking speed, convergence speed, ability to track true maxima and efficiency. Thus, the implementation of techniques based on AI and BI is expected to reduce the oscillation of the operating voltage and hence minimize the power loss in the PV system [13],[14]. In [15], five MPPT controllers have been developed. The MPPT techniques which will be described are based on: Proportional-Integral-Derivative (PID), FL, ANN, and GA PSO. The obtained results show that ANN is a perfect choice when a high efficiency MPP tracking is needed. It shows high performance and gives better results thus outperforming all other controllers. It's following respectively by FL, PSO, GA and PID. In [16], a novel ANFIS-based MPPT algorithm is proposed and compared with techniques based on FL, InC and P&O algorithms. The deviation from the MPP, as observed with the conventional techniques, did not occur. More- over, it provides a very fast response under rapidly changing environmental conditions. This made the efficiency of the proposed ANFIS based MPPT to be above 99%.

In addition, EMS also includes a supervision part which will mainly protect the storage system (battery) against deep charges and discharges.

In ref [17], authors proposed an EMS based on fuzzy logic (FL) algorithm which allows us to optimize the management of the storage system. The results show that that the FL control maintains the battery voltage almost stable at the end phase of charge. They obtained a very short transition time between the charging and discharging mode with the use of FL comparing to the other techniques used in this field. In ref [18], an adaptive neuro fuzzy inference system (ANFIS) is used for controlling the charging process of a battery. It is found that the proposed ANFIS smart controller has helped improve for optimum usage of batteries and for saving the battery life time. In ref [19], an intelligent control technique based on ANFIS is presented. This approach is simultaneously used for tracking maximum power point (MPP) and battery supervision. The obtained results show the effectiveness of the proposed ANFIS control strategy. In [20], a supervision and control power system for PV system with battery storage is presented. The control power system is based on FL. Authors proposed a supervision algorithm for the charging and discharging process of the battery. The obtained results show that the proposed strategy presents high performances whatever the meteorological conditions.

The problems related to all these EMS techniques are for the most part: the intermittence or the severe variation of the climatic conditions (conventional techniques), the complexity of implementation and the choice of certain parameters such as MsF and inputs (AI techniques).

The objective of this paper is to develop an EMS which will make it possible to overcome the problem linked to the intermittence of the PV source through a power optimization technique and a storage system supervision technique. Furthermore, this paper introduce a novel EMS based on HPSANFIS which can predict and track the maximum power point of PV system under rabidly changing environmental conditions in short time with minimum error and low oscillations. The remainder of the paper is organized as follows: In Section 2, modelling and complete simulation of the overall PV system under Matlab/Simulink environment is presented. Section 3 describes in detail the developed EMS. In Section 4, a simulation of the EMS is carried out to verify the validity of the developed EMS under various scenarios in weather conditions. Thereafter, a comparative study is given based on comparative analysis between simulations and experimental validation under dspace DS1202. Finally, the main conclusion and recommendations about EMS are made in the last section.

II. DYNAMIC MODELING

The topology of the Hybrid PV-Battery (HPVB) system is shown in fig.1. The hybrid power source consists of a PV panel and a battery providing a load is proposed to make the system highly efficient and reliable. It also composed by a boost converter (BC), a DC bus, and a bidirectional converter (BdC). The battery is connected to the DC bus via the BdC while the DC bus is powered by the photovoltaic system via its BC which maintains the bus voltage at its reference value.

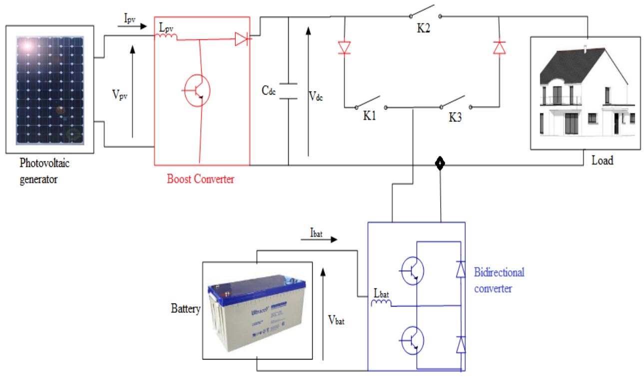

Fig.1. HPVB system configuration

A. PVM modeling

The equivalent circuit of the solar cell is given in [20],[19]. A single photovoltaic cell produces an output voltage of less than 1 V, about 0,6 V for crystalline-silicone (SI) cells. The relationship between the current and the voltage of the PVM is given by equation (1). This latter represents the current delivered by the PV cell.

$$I_{pv} = I_{ph} - I_0\left[\exp\left(\frac{q(V_{pv}+R_S I_{pv})}{A*n*k*T_c}\right) - 1\right] - \frac{V_{pv}+R_S I_{pv}}{R_p} \quad (1)$$

B. BC modeling

BC is used to increase the PVM voltage. It is modeling by using the laws of Kirchhoff (equation (3)).

$$\begin{cases} L_{pv}\frac{dI_{pv}}{dt} = V_{pv} - V_{bat}(1-D) \\ C_{dc}\frac{dv_{bat}}{dt} = i_{pv}(1-D) - \frac{V_{bat}}{R} \end{cases} \quad (3)$$

Equations (4) to (6) describe the BC parameters.

$$V_{pv}=(1\text{-}D)V_{dc} \quad (4)$$

$$C_{dc} = \frac{I_{pv}}{2f_c\Delta V_{dc}} \quad (5)$$

$$L_{pv} = \frac{V_{dc}}{4f_c\Delta I_{pv}} \quad (6)$$

Iph: photo-current;
Io: saturation current;
q: charge of an electron;
A: non-linear impact of irradiation;
K: Boltzmann's constant;
n: ideality factor of the diode;
Rs, Rp: Serie, Parallel resistance
Lpv: BC inductance;
Cdc: output capacity of the BC.
fc: switching frequency of the Mosfet.
D: duty cycle.
ΔV: voltage ripple.
ΔI: current ripple.

C. BdC and Battery modeling

The BdC is used for charging and discharging the battery. The presentation of the operation of this type of converter by mathematical equation (7) must be performed taking into account the state of the switch k.

$$\begin{cases} L_{bat}\frac{di_{bat}}{dt} = \alpha V_{pv} + V_{bat}(1-\alpha) \\ C_{bat}\frac{dv_{bat}}{dt} = -i_{bat}(1-\alpha) - \frac{V_{bat}}{R} \end{cases} \quad (7)$$

The voltage of the battery (Vbat) is given by equation (8).

$$V_{bat} = E_{bat} - z * \frac{\int I_{bat}dt}{Q_d} - R_{bat} * I_{bat} \quad (8)$$

Ebat: Vacuum voltage (Open Circuit voltage) of the battery;

Rbat: Internal resistance of the battery;

$\frac{\int I_{bat}dt}{Q_d}$: models the discharge status of the battery;

z: constant that depends on the type of the battery.

Equation (9) gives the capacity of the battery (Cbat) as a function of a reference capacitor C10. It serves as a reference for determining the State of Charge (SOC) of the battery [20].

$$C_{bat} = C_{10}\frac{1{,}76(1+0{,}005*\Delta T)}{1+0{,}67*\left(\frac{I_{bat}}{I_{10}}\right)} R_b I_{bat} \quad (9)$$

ΔT is the temperature difference.

The power of the battery (Pbat) and the load (Pload) can be expressed as a function of the power delivered by the PVM (Ppv) (equation (10)). They are linked by a factor S (switching state of the Mosfet switch of BC) [21].

$$P_{load}(t) = S_3 * P_{bat}(t) + S_2 * P_{pv}(t) \quad (10)$$

The sign of Pbat depends on the process charge of the battery.
$P_{bat} < 0$: discharging; $P_{bat} > 0$: charging
The SOC (%) of the battery can be written (equation (11)):

$$SOC = 100\left(1 - \frac{Q_d}{C_{bat}}\right) \quad (11)$$

With
Qd the amount of charge missing to the battery, given by equation (12).

$$Q_d = t * I_{bat} \quad (12)$$

t is the operating time of the battery with an Ibat current.

III. Energy Management System strategy proposed for HPVB

In this part, the MPP search and the battery supervision are performed using two HPSANFIS algorithms. The difficulty encountered with the use of ANFIS is related to the choice of membership functions (MsF) during the learning phase. Indeed, the MsF have a considerable impact on the performance of the algorithm [2]. To overcome this problem, an evolutionary optimization algorithm of the PSO type is chosen for an optimal choice of its parameters. Indeed, the choice of membership functions is very important in the learning process of ANFIS. This choice concerns the number of MsF and their type. These functions are very important since they constitute the Fuzzy Inference System (FIS). They therefore constitute the interpretation capacity of ANFIS [22], [23].

A. *MPPT based on HPSANFIS algorithm*

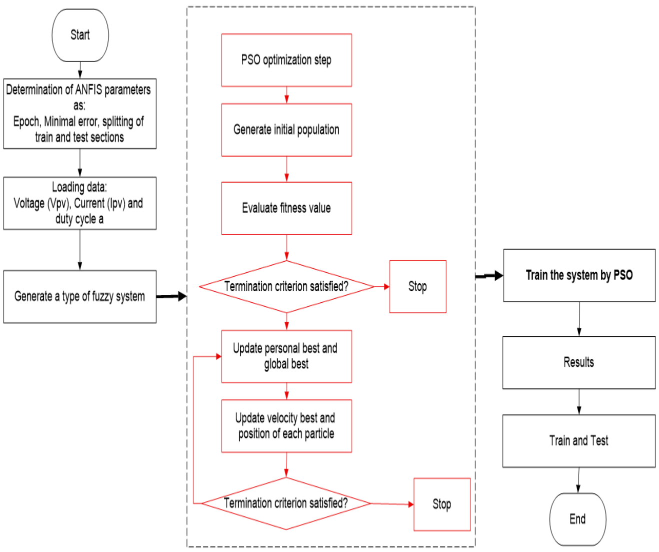

Fig.2. HPSANFIS MPPT flowchart

The MPPT technique proposed in this paper consists of two inputs and one output. The inputs are represented by the voltage and current, and the output by the duty cycle D. The inputs and the output are linked by equation (13).

The equations (16) and (17) model the fitness function (F) for each input with the use of PSO. This function optimizes the error between the average value and the instantaneous value of the input. The Standard deviations (σ) are modeled by equations (14) and (15).

$$D = \sum_i \left\{ \frac{\exp\left[-\left(\frac{V_{pv,i}-\bar{V}_{pv}}{\sigma(V_{pv})}\right)^2 - \left(\frac{I_{pv,i}-\bar{I}_{pv}}{\sigma(I_{pv})}\right)^2\right]}{\sum_i \exp\left[-\left(\frac{V_{pv,i}-\bar{V}_{pv}}{\sigma(V_{pv})}\right)^2 - \left(\frac{I_{pv,i}-\bar{I}_{pv}}{\sigma(I_{pv})}\right)^2\right]} * (p_i * V_{pv} + q_i * I_{pv} + r_i) \right\} \quad (13)$$

$$\sigma(V_{pv}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(V_{pv,i} - \bar{V}_{pv})} \quad (14)$$

$$\sigma(I_{pv}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(I_{pv,i} - \bar{I}_{pv})} \quad (15)$$

$$F_{Vpv} = \int (V_{pv,i} - \bar{V}_{pv}) \quad (16)$$

$$F_{Ipv} = \int (I_{pv,i} - \bar{I}_{pv}) \quad (17)$$

(pi, qi, ri): output parameters (consequents), determined during the learning process;

σ: Standard deviation;

$\bar{V}_{pv}$: Average of the PVM voltage;

$\bar{I}_{pv}$: Average of the PVM current;

N: size of the database.

B. *Supervision of the charge and discharge of the battery*

The main decision factors for the supervisory strategy are PVM supplied power (Ppv) and battery charge status (SOC). The use of the supervisor makes it possible to produce maximum power from the PVM, to protect the batteries against overloads and deep discharges and essentially to satisfy the energy needs. The same ANFIS algorithm as that of the MPP search is used. The system has several possible modes of operation depending on the switches that are operated.

Mode 1 (M1): the available power to the PVM (Ppv ≥0) is totally enough to power the load and charge the batteries.

Mode 2 (M2): The power supplied by the PVM is insufficient (0 <Ppv <Pload); in this case, the power of the batteries is added to satisfy the power demand. It's the compensation mode.

Mode 3 (M3): No energy is supplied by the PVM (Ppv <0), so the batteries only feed the load.

Mode 4 (M4): The PV power is sufficient and the batteries are fully charged, the disconnection of batteries is then necessary for their protection.

Mode 5 (M5): No production of the PVM and the batteries are discharged. The load is then disconnected.
The logic states of the relays are given in Table 1.

Table 1: Logic states of the relays for the differences modes of operation

Switches	Operating modes				
	M1	M2	M3	M4	M5
S1	ON	OFF	OFF	OFF	OFF
S2	ON	ON	OFF	ON	OFF
S3	OFF	ON	ON	OFF	OFF

From the energy management model presented in Figure1, we can determine the logical equations of: load (14), discharge

(15), charge/discharge (16) and load in functions of the control switches (S1, S2 and S3). The different powers (Pi) (equations ((14) to (17)) can be expressed in terms of different switches considered as Boolean values (0 or 1).

- Battery charge power (S1 high)
  $$P_1 = S_1.S_2.\bar{S}_3 \quad (14)$$
- Battery discharge power (S3 high)
  $$P_2 = \bar{S}_1.S_2.S_3 + \bar{S}_1.\bar{S}_2.S_3 \quad (15)$$
- Charging / discharging power of the battery (S1 and S3 in high state)
  $$P_3 = S_1.\bar{S}_2.\bar{S}_3 + \bar{S}_1.\bar{S}_2.S_3 \quad (16)$$
- Load power (S2 high)
  $$P_4 = S_1.S_2.\bar{S}_3 + \bar{S}_1.S_2.S_3 + \bar{S}_1.S_2.\bar{S}_3 \quad (17)$$

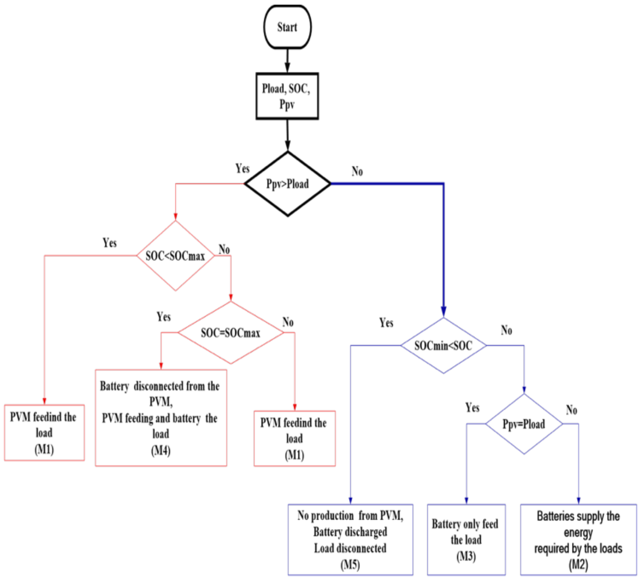

Fig.3. Supervision strategy

IV. EXPERIMENTAL RESULTS

The programs were implemented via Matlab/Simulink through the interface of the dSPACE DS1202 real-time toolbox. The figure 4 illustrates the experimental test bench carried out at the laboratory of the Paris East Cretail University (France). The main characteristics of each component will be provided in the following. The system used for validation consists of a PV emulator, a variable load and a battery. The BC and BdC are driven by the signals generated by the dSPACE board.

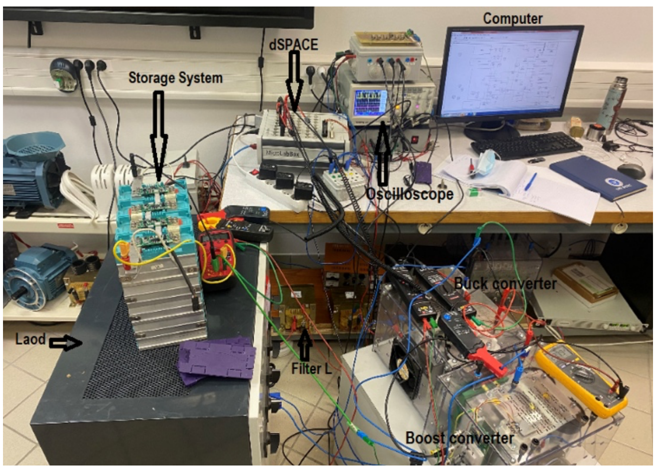

Fig.4. Experimental bench

To test the effectiveness of the proposed EMS applied to the HPVB system the simulation under matlab/simulink through dSPACE DS1202 over a period of ten hours (between 08h to 18h) has been performed.

The profiles of solar irradiation and temperature are shown in figure 5. They are considered to verify the ability of the proposed EMS under different conditions.

Figure 6 shows the variation of the duty cycle of the BdC depending on whether the converter is in boost or buck mode. Thus, the following phases can be distinguished according to figures 7 and 8. They represent the current and power curves respectively.

Phase 1 (between 8H and 9H): The PV power is lower than the load power. The battery power will be added to satisfy the load. This is the compensation mode (M2) where switches S2 and S3 are closed and S1 is open. This operating mode is characterized by negative battery power.

Phase 2 (between 9H and 12H): the power delivered by the PVM is again higher than that of the load. The PVM therefore supplies the load and the batteries are fully charged. Switches S2 is closed while switch S1 and S3 are open: this is function M4.

Phase 3 (between 12H and 17H): There is a good irradiation of 1000W/m² and a temperature of 25°C. The EMS detects that the PV power is higher than the load power. The PV feeds the load and the batteries are fully charged, the disconnection of batteries is then necessary for their protection. Switches S2 is closed and switch S3 and S1 remains open: M4.

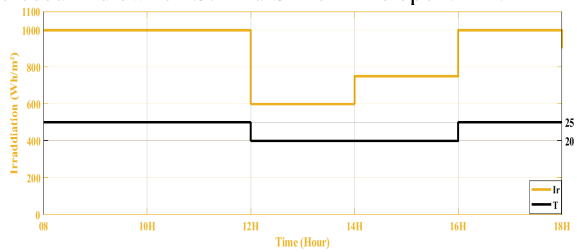

Fig.5. Profiles of solar irradiation and temperature

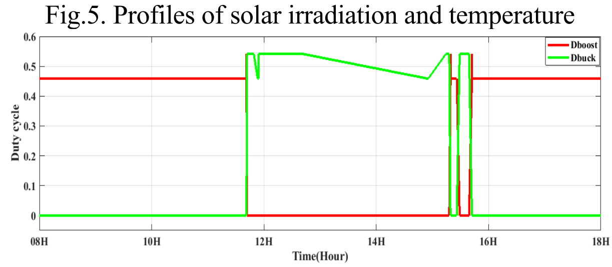

Fig.6. Variation of duty cycle of the BdC

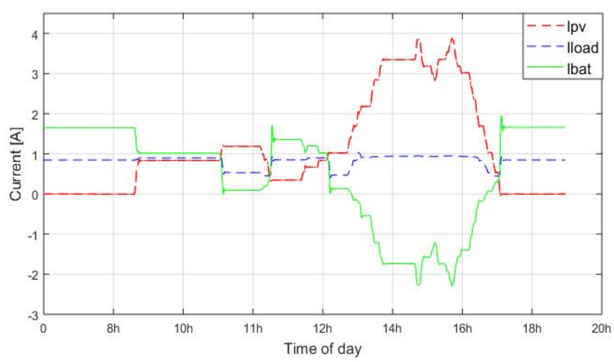

Fig.7. Current waveforms between 08H and 20H

V. Conclusion

In this paper, EMS based on HPSANFIS of HPVB has been presented. This technique is validated in real time by implementation in dSPACE D1202. The obtained results show good performances and the load is at any time satisfied by the different sources. The proposed EMS allows an optimal operation of the whole system with high performances of the PVM whatever the meteorological conditions.

References

[1] F. Chekired, Z. Smara, A. Mahrane, M. Chikh, and S. Berkane, “An energy flow management algorithm for a photovoltaic solar home,” Energy Procedia, vol. 111, no. September 2016, pp. 934–943, 2017.

[2] E. M. Ndiaye, A. Ndiaye, and M. Faye, “Experimental Validation of PSO and Neuro-Fuzzy Soft-Computing Methods for Power Optimization of PV installations,” in 8th IEEE International Conference on Smart Grid, 2020, pp. 189–197.

[3] E. M. Ndiaye, A. Ndiaye, M. Faye, M. A. Tankari, and G. Lefebvre, “Adaptive Neuro-Fuzzy Inference System Application for The Identification of a Photovoltaic System and The Forecasting of Its Maximum Power Point,” 7th Int. IEEE Conf. Renew. Energy Res. Appl. ICRERA 2018, vol. 5, pp. 1–7, 2018.

[4] M. Traore et al., “Supervision of a PV system with storage connected to the power line and design of a battery protection system,” Wirel. Networks, 2018.

[5] B. Bendib, H. Belmili, and F. Krim, “A survey of the most used MPPT methods : Conventional and advanced algorithms applied for photovoltaic systems,” Renew. Sustain. Energy Rev., vol. 45, pp. 637–648, 2015.

[6] T. H. Kwan and X. Wu, “High performance P & O based lock-on mechanism MPPT algorithm with smooth tracking,” Sol. Energy, vol. 155, pp. 816–828, 2017.

[7] M. Kermadi and E. M. Berkouk, “Arti fi cial intelligence-based maximum power point tracking controllers for Photovoltaic systems : Comparative study,” Renew. Sustain. Energy Rev., vol. 69, no. February 2016, pp. 369–386, 2017.

[8] T. Radjai, L. Rahmani, S. Mekhilef, and J. P. Gaubert, “Implementation of a modified incremental conductance MPPT algorithm with direct control based on a fuzzy duty cycle change estimator using dSPACE,” Sol. Energy, vol. 110, pp. 325–337, 2014.

[9] A. Ndiaye, L. Thiaw, and G. Sow, “Application of new modeling and control for grid connected photovoltaic systems based on artificial intelligence,” J. Electr. Electron. Eng. Res., vol. 7, no. 1, pp. 1–10, 2015.

[10] M. Elloumi, R. Kallel, and G. Boukettaya, “A comparative study of GA and APSO algorithm for an optimal design of a standalone PV/Battery system,” 15th Int. Multi-Conference Syst. Signals Devices, pp. 1104–1109, 2018.

[11] Y. K. Semero, J. Zhang, D. Zheng, and S. Member, “PV Power Forecasting Using an Integrated GA-PSO-ANFIS Approach and Gaussian Process Regression Based Feature Selection Strategy,” CSEE J. POWER ENERGY Syst., vol. 4, no. 2, pp. 210–218, 2018.

[12] A. M. Eltamaly, H. M. H. Farh, and M. F. Othman, “A novel evaluation index for the photovoltaic maximum power point tracker techniques,” Sol. Energy, vol. 174, no. September, pp. 940–956, 2018.

[13] H. Bounechba, A. Bouzid, K. Nabti, and H. Benalla, “Comparison of perturb & observe and fuzzy logic in maximum power point tracker for PV systems,” Energy Procedia, vol. 50, pp. 677–684, 2014.

[14] B. Talbi, F. Krim, S. Mekhilef, and A. Laib, “A high-performance control scheme for photovoltaic pumping system under sudden irradiance and load changes,” Sol. Energy, vol. 159, no. June 2017, pp. 353–368, 2018.

[15] M. Kermadi and E. M. Berkouk, “Artificial intelligence-based maximum power point tracking controllers for Photovoltaic systems: Comparative study,” Renew. Sustain. Energy Rev., vol. 69, no. June 2015, pp. 369–386, 2017.

[16] M. A. Enany, M. A. Farahat, and A. Nasr, “Modeling and evaluation of main maximum power point tracking algorithms for photovoltaics systems,” Renew. Sustain. Energy Rev., vol. 58, pp. 1578–1586, 2016.

[17] F. Chekired, A. Mahrane, M. Chikh, and Z. Smara, “Optimization of energy management of a photovoltaic system by the fuzzy logic technique,” Energy Procedia, vol. 6, pp. 513–521, 2011.

[18] M. M. Ismail and A. F. Bendary, “Smart Battery Controller using ANFIS for Three Phase Grid Connected PV Array System,” Math. Comput. Simul., 2018.

[19] E. M. Ndiaye, A. Ndiaye, M. Faye, and S. Gueye, “Intelligent Control of a Photovoltaic Generator for Charging and Discharging Battery Using Adaptive Neuro-Fuzzy Inference System,” Int. J. Photoenergy, vol. 2020, 2020.

[20] F. Zaouche, D. Rekioua, and J. Gaubert, “Supervision and control strategy for photovoltaic generators with battery storage State of Charge,” Int. J. Hydrogen Energy, pp. 1–20, 2017.

[21] Z. Roumila, D. Rekioua, and T. Rekioua, “ScienceDirect Energy management based fuzzy logic controller of hybrid system wind / photovoltaic / diesel with storage battery Fuzzy logic Control,” Int. J. Hydrogen Energy, pp. 1–11, 2017.

[22] J. R. Jang, “ANFIS : Adaptive-Network-Based Fuzzy Inference System,” IEEE, vol. 23, no. 3, 1993.

[23] E. M. Ndiaye, M. Faye, and A. Ndiaye, “Comparative study between three methods for optimizing the power produced from photovoltaic generator,” Adv. Sci. Technol. Eng. Syst., vol. 5, no. 6, pp. 1458–1465, 2020.