Available online at www.sciencedirect.com
ScienceDirect
Mathematics and Computers in Simulation 167 (2020) 104–118
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Original articles

Smart battery controller using ANFIS for three phase grid connected PV array system

Mohamed M. Ismail*, Ahmed F. Bendary

Department of Electrical Power and Machines, Faculty of Engineering, Helwan University, Egypt

Received 31 August 2017; received in revised form 25 February 2018; accepted 16 April 2018
Available online 3 May 2018

Abstract

This paper presents 60 MW grid connected three phase hybrid systems. The proposed model contains two stages of conditioning energy conversion power unit, while a Nickel–Cadmium battery is used for DC power saving generated from the (PV) array. The 9 bus IEEE grid is used in this article as an example. The basic contribution of this article is the best utilization of batteries as an additional source to increase the generated power based on demand. Two (ANFIS) controllers are desired for this purpose. one is used for organizing the battery charging process and the other is used for on/off battery switching to grid in case of incensement of load. The system is designed and studied using MATLAB/Simulink.

Keywords: Photovoltaic array; 9 bus IEEE grid; ANFIS and battery storage

1. Introduction

The demand of electricity in the world is increasing rapidly. The great challenge is to meet this demand with no effect on the climate and the environment. The main source of power production today is the petroleum fuels.

One of the promising techniques in electric power generation is the solar power energy, which is one of the most available resources worldwide; however, it is still among the expensive sources due to high investment costs. Although the prices have steadily decreased in some countries, grid connected solar panels are currently economically feasible.

In places with adequate of solar radiation and a weak existing power grid, specifically for off-grid locations and standalone systems, hybrid system integrated model and the strategy for power management in solar power is because some cost-effective solutions [3,18,21,22,25,34,38]. Renewable systems have a high chance as a new means of power generation to reduce gas emission from the conventional electric power generation [11,19].

Among all the various DG technologies, solar systems are rapidly growing in electricity markets because of the declining cost of PV modules [14,36], improving its efficiency, manufacturing-technology enhancements. However,

* Corresponding author.
E-mail address: m_m_ismail@yahoo.com (M.M. Ismail).

https://doi.org/10.1016/j.matcom.2018.04.008
0378-4754/

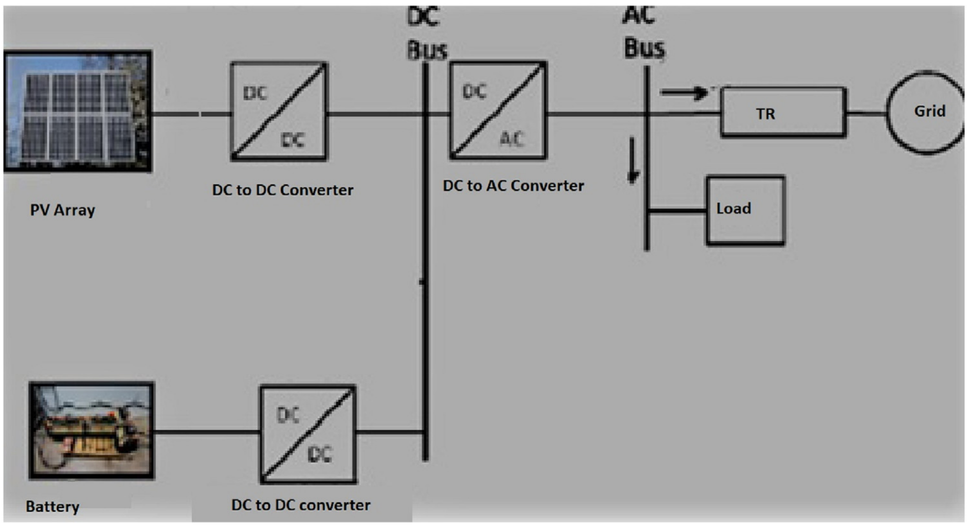

Fig. 1. PV array system with charging batteries grid connected.

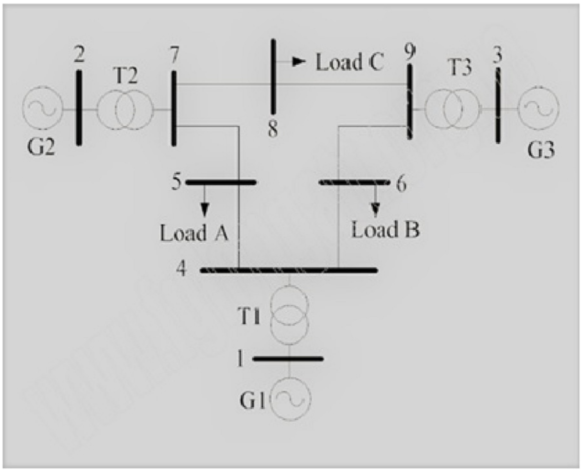

Fig. 2. Modified 9 bus IEEE grid with additional loads connected.

increasing the levels of penetration of solar energy systems into the grid has given rise to relevant problems of potential relating to power quality and PV performance [8,24,37].

Standalone solar system is greatly required in urban areas where there is no access to national grid [5]. The solar system performance is affected based on the amount of sun radiation [23]. Many techniques of the VSI are implemented on the PV grid connected systems [13,17,33].

The successful use of PV energy systems depends on their performance, efficiency, power quality, stability and reliability. Furthermore, from investment point of view, the Return of Investment estimation and the profitability of grid connected solar systems need information about its performance. In that way, several studies have been carried out for improvement and optimizing of solar systems applications.

Fuzzy logic is among the important techniques used for PV grid connected system [1,2,7,12,28,30,35]. Some other AI techniques are implemented for improving the performance of PV integrated systems [29]. In the past, ANFIS technique was implemented on the solar system for MPPT improvement [4,15,16,31,32] or for enhancing the behavior of VSI [9,26]. A new scheme of control is introduced for controlling the power sharing between batteries and super capacitors [20].

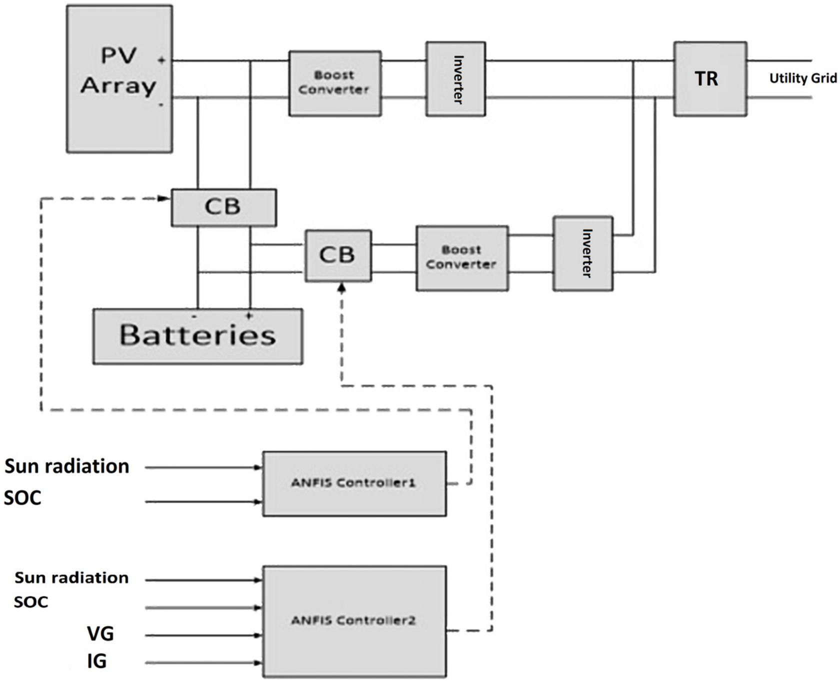

Fig. 3. The new proposed PV array system with ANFIS.

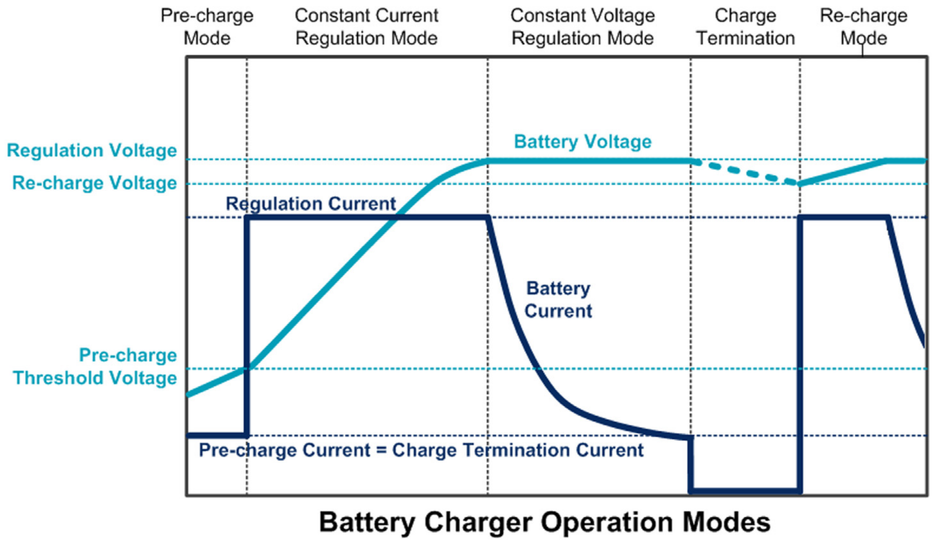

Fig. 4. Battery characteristics.

Recently, new researchers use fractional order PI to achieve enhancement in the behavior of the on-grid solar system [27]. Some improvement has been reached using PV battery charger [6], and from the literature review, it is found that the smart controllers designed in this article are not introduced before. In this article, two ANFIS techniques are implemented: one for controlling the process of charging and the other for switching the batteries as another power source to grid based on load change. The simulation is implemented on 60 MW grid integrated solar system based on MPPT technique. It is found that the online AI techniques such as fuzzy logic (FL), neural network (ANN) and

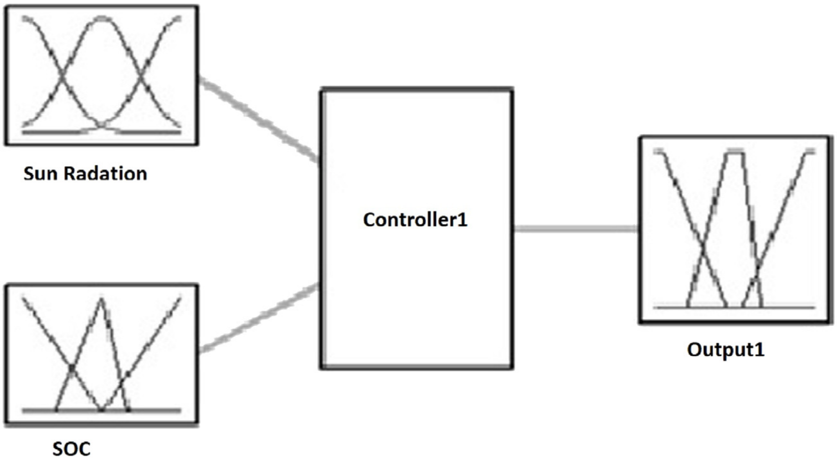

Fig. 5a. ANFIS controller 1 structure.

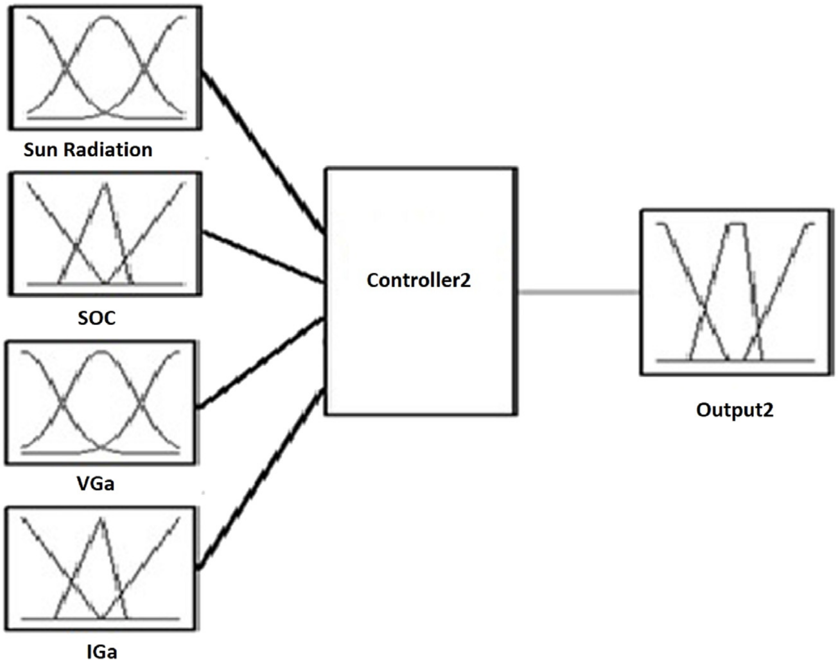

Fig. 5b. ANFIS controller 2 structure.

ANFIS controllers are the most suitable techniques to be adopted as smart controller than the offline methods. The fuzzy system is more difficult to be used in complex systems as that used in this article than ANFIS controller. ANFIS controller is a combination of fuzzy logic (FL) and (ANN) neural network, and it is more effective to be used as smart controller. The system is tested at different conditions using MATLAB/Simulink to demonstrate the behavior and efficiency of the new technique.

2. The proposed system

In this article, the assembly of PV model connected to 9 bus IEEE standard grid while a modification is done by increasing the loads on the grid is indicated in Figs. 1 and 2.

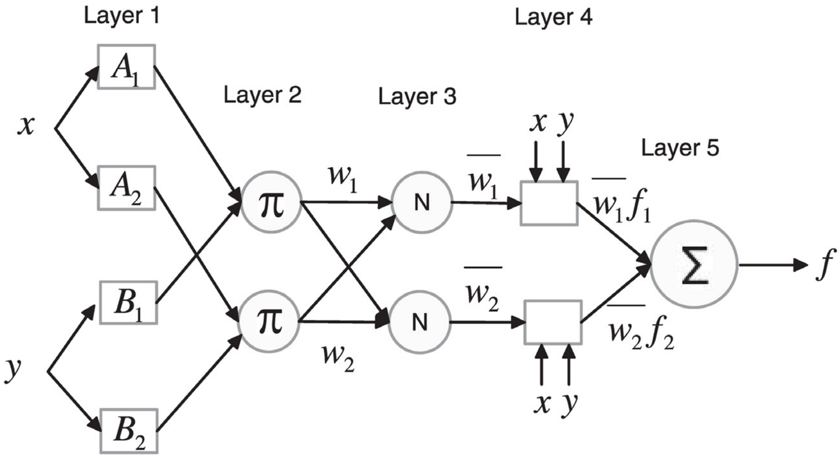

Fig. 5c. ANFIS architecture for a two-input system.

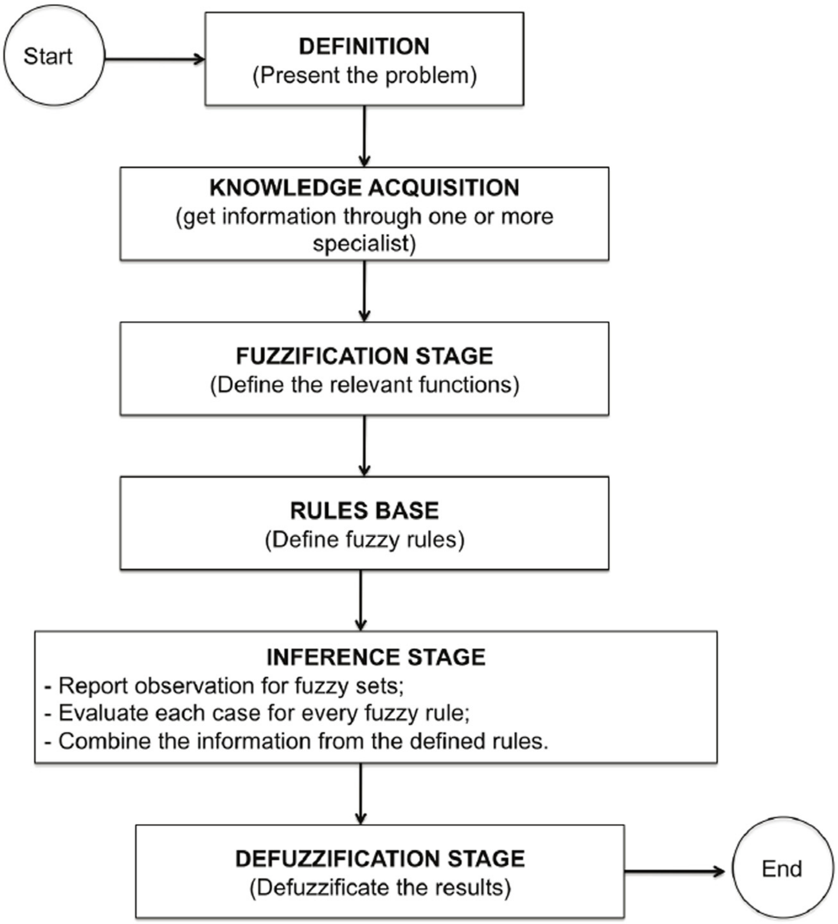

Fig. 5d. Basic diagram of ANFIS computation.

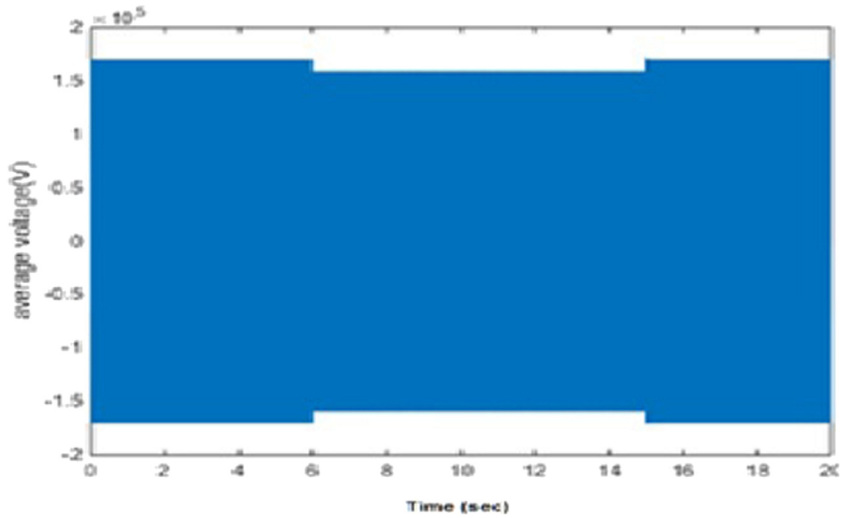

Fig. 6. Effects of sudden increase of load on voltage.

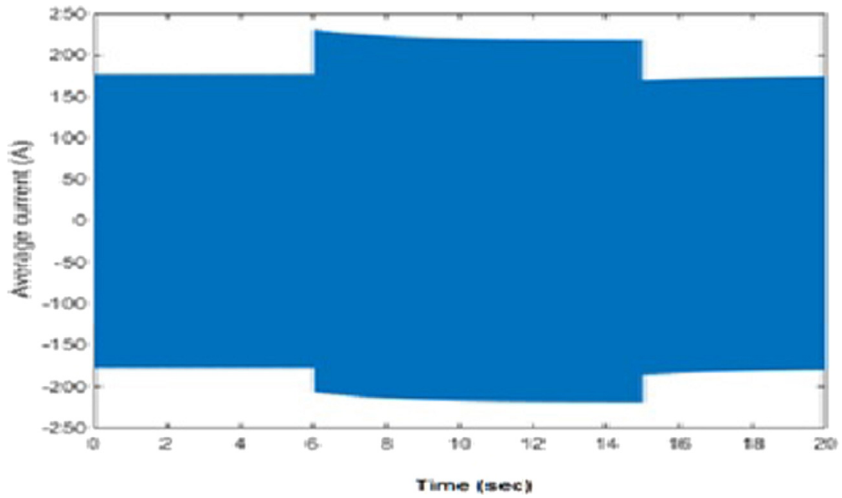

Fig. 7. Effects of sudden increase of load on current.

Two ANFIS controllers are desired as indicated in Fig. 3: one for smart battery charging and the other for automatic battery switching to grid as an additional source.

3. Battery State of Charge (SOC)

One of the important parameters that should be considered in battery technology is its SOC. The main problems for the batteries are over charging or draining the batteries. Knowledge of SOC require control over the charging and discharging processes to increase the battery life time. SOC is defined as the ratio of the available battery capacity to the rated capacity of the battery. The current integration starts at $\mathrm{SOC}(t) = 100\%$ at $t = 0$.

The mathematical definition of SOC can be defined as follows [10]:

$$\mathrm{SOC}(t) = \frac{Ah_{\mathrm{nom}} - \int_0^t I(t)dt}{Ah_{\mathrm{nom}}} \tag{1}$$

where $I(t)$ is the current of the battery, and Ah_{nom} is the nominal capacity of the battery.

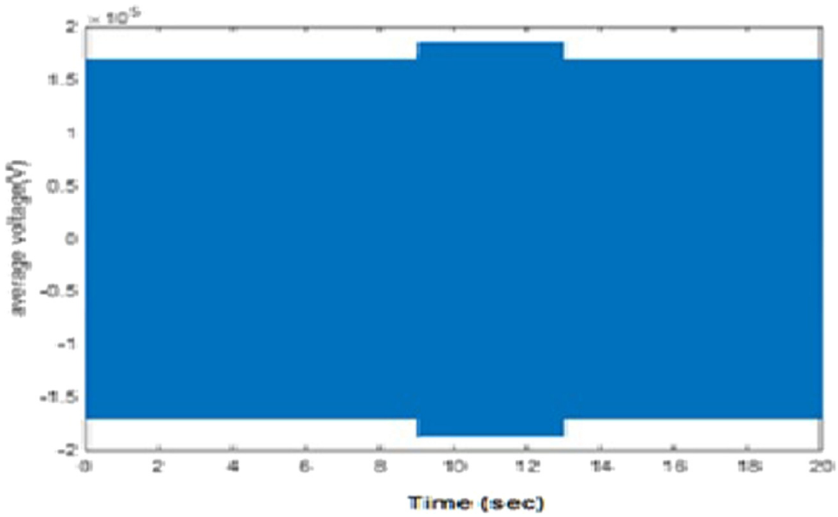

Fig. 8. Voltage effect of switching on the battery to the grid.

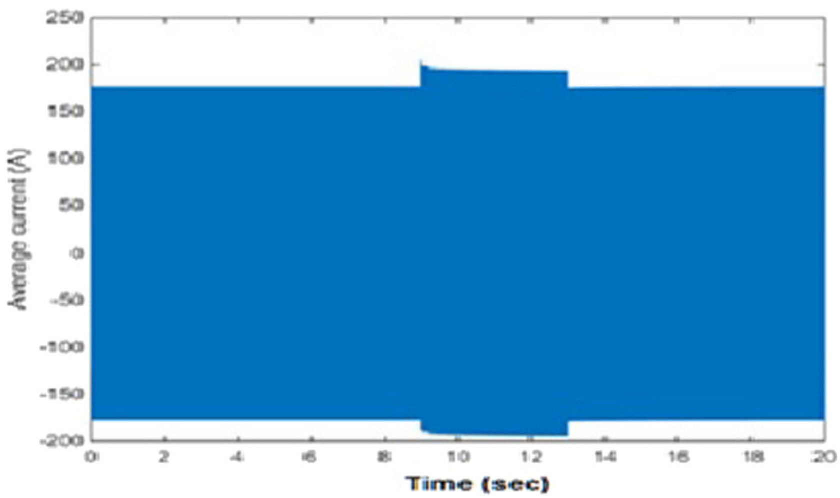

Fig. 9. Current effects of switching on the battery to the grid.

The losses in battery capacity are the reason that creates complexity in computing an accurate SOC. The capacity of any battery is the free charge amount generated by active material at negative electrode and consumed by the positive electrode at 100% state of charge. It is expressed in Ampere-hour (A h). The characteristics of the selected type of the battery used in the simulation model is indicated in Fig. 4.

The battery voltage at different charging conditions is indicated; the battery voltage is varied based on the percentage of SOC. Therefore, the measurement of the battery voltage is an effective factor to identify the percentage of battery charge during the operation.

4. ANFIS controller

In this article, the application of Adaptive Neuro-Fuzzy Interference System (ANFIS) is presented.

The ANFIS controller that can be generated by using fuzzy logic toolbox in MATLAB allows Sugeno fuzzy inference system generation. Two ANFIS techniques are used in simulation modeling: the first ANFIS technique is

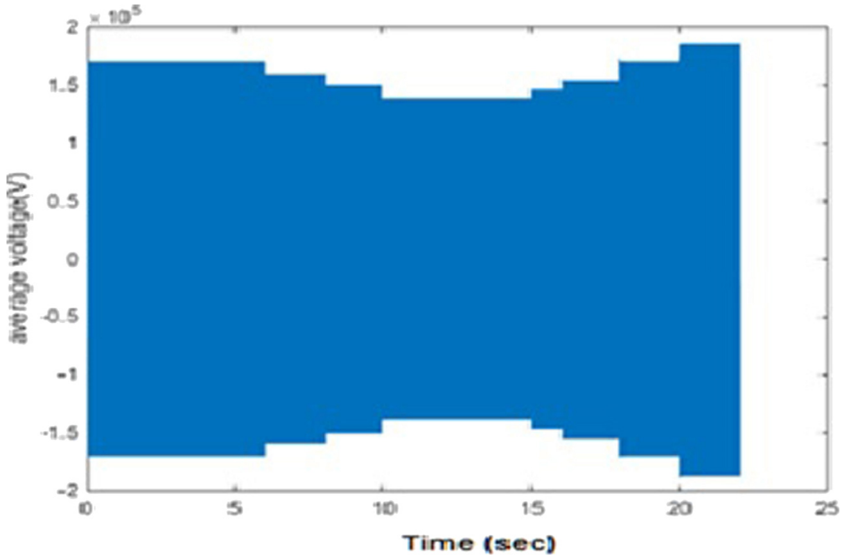

Fig. 10. Effects of gradually load switching on the voltages.

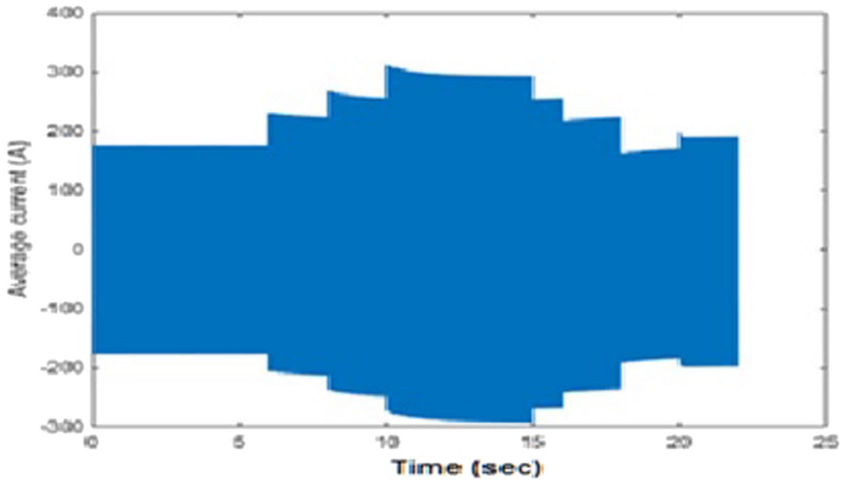

Fig. 11. Effects of gradually load switching on the currents.

used as a smart battery charger for organizing the battery charging; whereas, the second ANFIS controller controls the switching methodology of the batteries with the power grid, as an extra power source based on demand is to be supplied according to the philosophy in Tables 1 and 2.

L is low radiation (less than 200 W/m^2), and H is high radiation (greater than or equal 200 W/m^2). E is empty battery (SOC is less than 50%), and F is full battery (SOC is greater than or equal 50%). Normal is the value of voltage and current at normal loading condition. The value of normal value of voltage is 1700 kV, and the normal value of current is 170 A. The change in voltage and current indicates increase or decrease in the normal value. Increase or decrease in grid voltage or current definition is that the value is higher or lower than the normal value.

The structure of the ANFIS controllers is indicated in Fig. 5. The first controller operates with an inputs describe both the sun irradiation changes synchronizing with the battery charging status, the controller output permit or prevent battery charging based on SOC, also the second controller operates with four inputs describes sun irradiation changes,

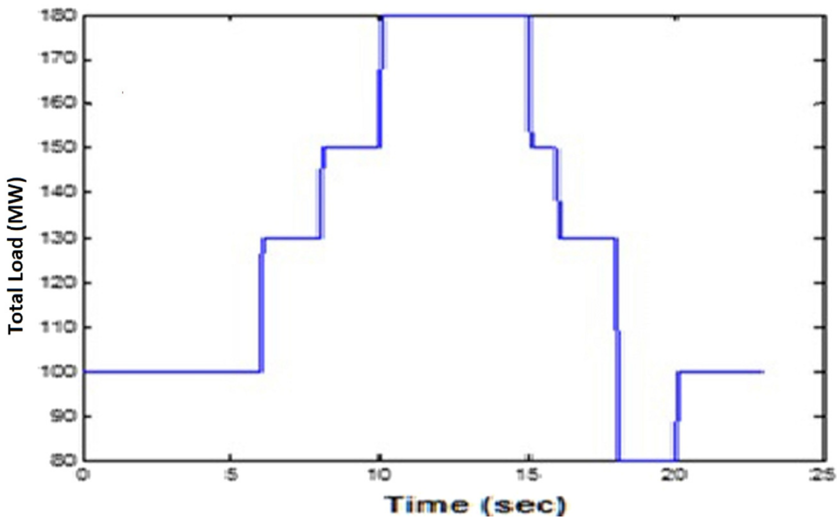

Fig. 12. Gradually load increment.

Table 1
Training rules for the first ANFIS controller.

Input 1 Radiation (W/m^2)	Input 2 SOC %	Input 3 Average voltage (V)	Input 4 Average current (I)	ANFIS2 output
L	F	Normal	Normal	1
L	E	Normal	Normal	0
H	F	Normal	Normal	0
H	E	Normal	Normal	0
H	F	Change	Normal	0
L	F	Change	Normal	0
H	F	Decrease	Increase	1
H	E	Decrease	Increase	0
L	F	Decrease	Increase	1
L	E	Decrease	Increase	0

Table 2
Training rules for the second ANFIS controller.

Input 1 Radiation (W/m^2)	Input 2 SOC %	ANFIS1 output
>200	<10%	1
>200	>10%	0
<200	<10%	0
<200	>10%	0

battery charging status, average value of voltage and current of the grid, the second controller output permit or prevent battery switching to power grid. The concept of the rules for the first and second controller is illustrated in Tables 1 and 2, respectively.

Fig. 5c shows the ANFIS network that is composed of five layers. Each node in the first layer is a square (adaptive) node with a node function. The basic diagram computation in ANFIS is shown in Fig. 5d. The structure of the network is composed of a set of units (and connections) arranged into five connected network layers, via. l1–l5 as shown in Fig. 4.

The ANFIS structure is tuned automatically by least-square estimation as well as the back-propagation algorithm. The algorithm shown above is used in the next section to develop the ANFIS technique to control the various parameters of the induction motor. The average value of the voltage or current is the average of the three-phase

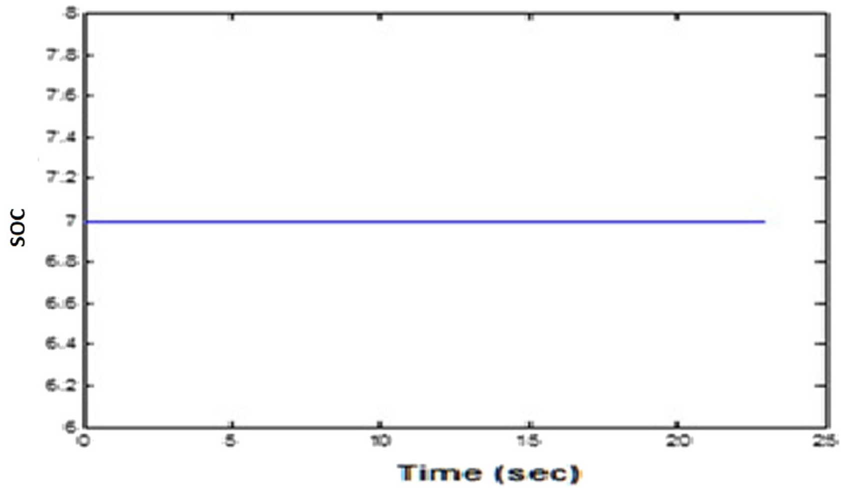

Fig. 13. State of battery charging.

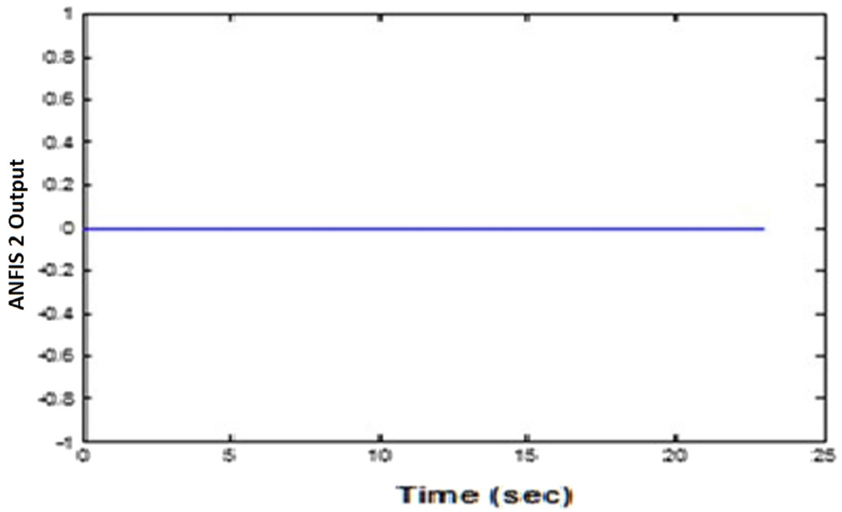

Fig. 14. Second controller output.

value. The average value is used with the ANFIS controller to ensure accurate detection of signal variation based on the three-phase value of voltage or current. The fuzzy logic membership functions for the input and output are turned using neural network method which is well known in MATLAB program as ANFIS structure. The parameters of the controllers are selected such that, optimization method is hybrid, the no of epochs are 1000, the membership function output is linear, the membership function is gbellmf, error tolerance was chosen to be 0. 01, MF type is gbellmf, grid partitions, the inputs of the grid partitions are the number MFS are 3, the outputs is MF type defined to be constant.

5. Simulation results

The simulation is done at different conditions by varying the load gradually and suddenly and with different SOCs for battery. First 60 MW and 50 MVAR load is sudden switched on and off to the grid after 6 s and 15 s, respectively,

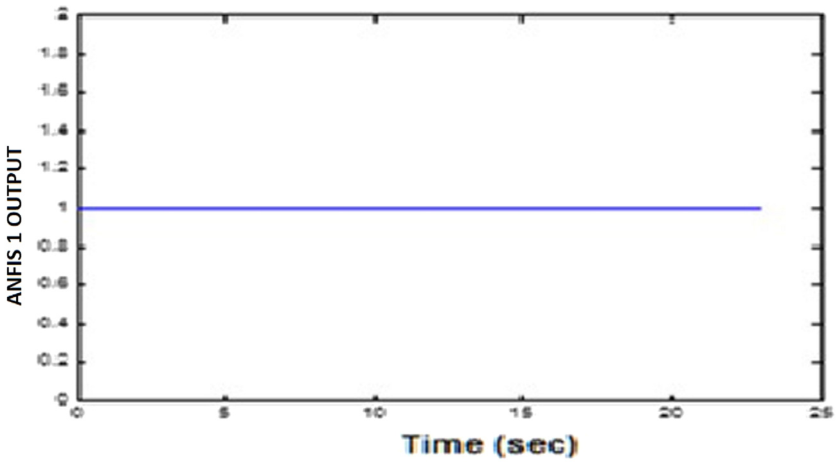

Fig. 15. First controller output.

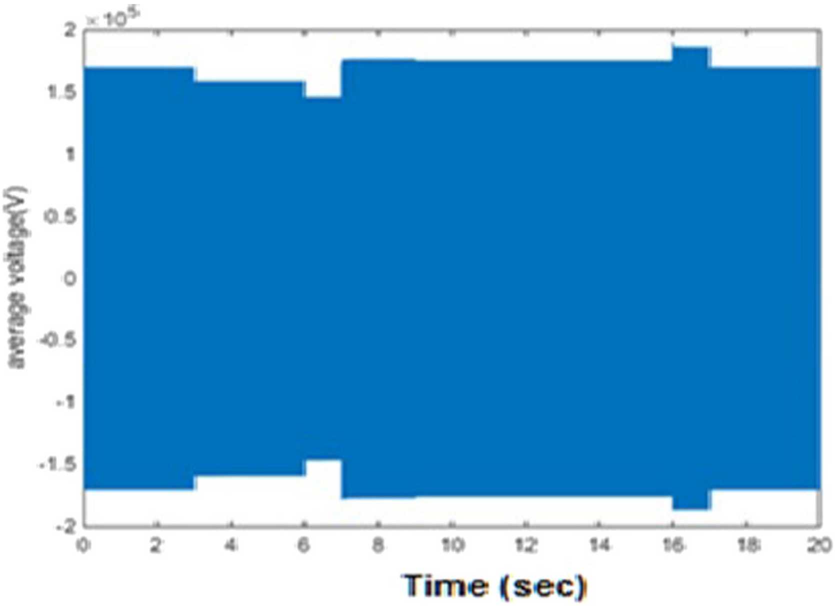

Fig. 16. Grid voltage behavior when using the smart controllers during load variation.

as indicated in Figs. 6 and 7. It is found that the grid voltage decreased and the current increased than the normal value during the duration between 6 and 15 s and then returned to their normal value after 15 s. From the simulations, it is found that the measurement of voltage and current gives a direct indication about any change in the loads of the grid as the value of voltage and current is changed immediately with respect to the load increasing as well as returning to their nominal values when the extra load is switched off. Another test is done by switching on the batteries to the grid after 9 s as an extra source without load change and switched off after 13 s. Figs. 8 and 9 show the results. It is found that both voltage and current increased than the normal value during the duration between 9 and 13 s. The results can be useful to the controller to indicate that there is no need of batteries in this case as an extra source such that the loads are not increased.

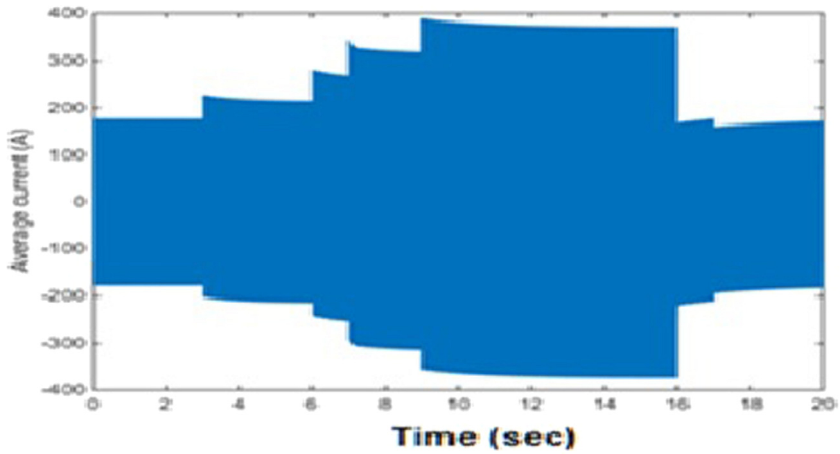

Fig. 17. Grid current behavior when using the smart controllers during load variation.

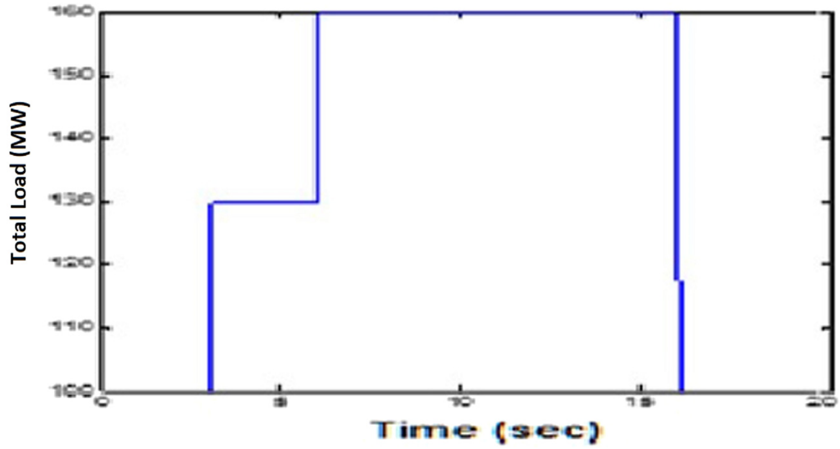

Fig. 18. Load variation during simulation.

Figs. 10 and 11 present the voltages and current effect of gradually increasing of load in steps after 6, 8 and 10 s and decreased gradually again at 15, 16 and 18 and at 20 s the extra load is completely removed. The measurement of current and voltage gives a direct and sensitive indication about any small changes in the loads.

Finally, the presented results in the pre-described figures show the robustness of the presented model.

The test is repeated when the two ANFIS controllers are added and the load is gradually increased and decreased in steps indicated in Fig. 12. The percentage of SOC is 7% (L). It is found that the second controller prevents the batteries to be switched to the grid although the load is increased due to low SOC to increase the life time of the battery while the first controller is switching the battery to the charging process. The results presented in Figs. 13–15are considered as detailed application for the training rules for the first and second ANFIS controllers described in Tables 1 and 2.

Another validation of the smart controllers modeling is done by repeating the simulation through sudden switching of extra 60 MW load at bus 1 after 3 s and at bus 2 after 6 s when the SOC of batteries was 80%. The controller responds to the load variation by switching the battery to the grid after 7 s as extra source. The transformer T1 is switched off from the grid due to up normal conditions after 9 s that lead to increasing and decreasing in grid current and voltage, respectively; then the extra load is completely switched off after 16 s; the measured average voltage is higher than the normal value, and the controller takes action by switching off the batteries after 17 s while there was no output from the first controller because the batteries were not in need of charging as indicated in Figs. 16–20. The

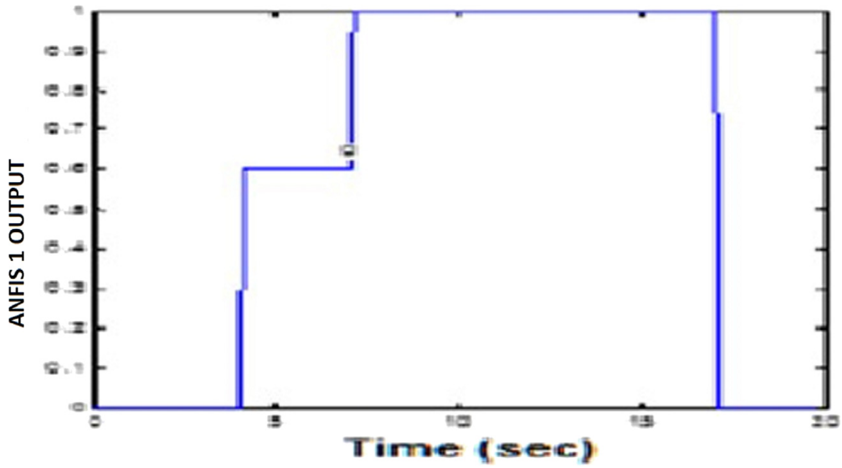

Fig. 19. First ANFIS controller output during simulation.

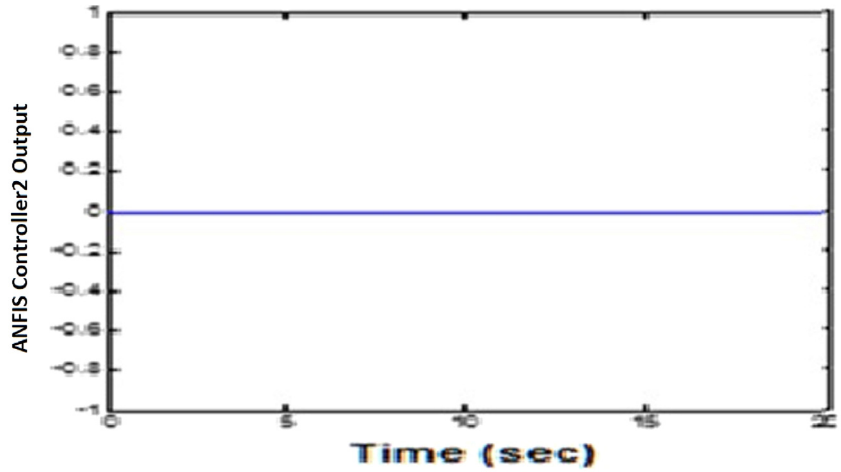

Fig. 20. Second ANFIS controller output during simulation.

SOC in the simulations assumed to be forced as constant value as indicated in Fig. 13 due to long deterioration time in MATLAB.

From the above simulations, it is found that the smart controllers are effective for controlling the battery charging and for optimal usage of batteries as an extra source on demand.

6. Conclusion

This article presents 60 MW grid connected three phase photovoltaic systems. A Nickel–Cadmium battery is used as a DC power saving connected to the PV array. The 9 bus IEEE grid is used in this article. Two ANFIS controllers are implemented: one for organizing the battery charging and the other for switching on or off the batteries as an extra source to grid in case of incensement of load.

This paper solves the problem of load increment than the generation capacity of the utility by switching the battery on to the grid in case of high SOC level and by preventing the battery from switching to the grid in case of low SOC level to increase its life time, and the sequence of battery charging is more reliable by considering the percentage of SOC and the percentage of sun irradiation. It is found that this article succeeds to design an efficient smart controller for optimum usage of batteries and for saving the battery life time (see Table 3).

Table 3
List of symbols.

Parameter	Description
PV	Photovoltaics
VSI	Voltage Source Inverter
FL	Fuzzy Logic
ANN	Artificial Neural Network
SOC	State of Charge
ANFIS	Artificial Neural Fuzzy Interface System
Ah_{nom}	is the nominal capacity of battery
L	low radiation (less than 200 W/m^2)
H	high radiation (greater than or equal 200 W/m^2)
E	empty battery (SOC is less than 50%)
F	full battery (SOC is greater than or equal 50%).
Normal	the value of voltage and current at normal loading condition
MW	Mega Watt
MF	membership function

References

[1] I. Abadlia, T. Bahi, H. Bouzeria, Energy management strategy based on fuzzy logic for compound RES/ESS used in stand-alone application, Int. J. Hydrogen Energy (2016) 6705–6717.

[2] M.N. Ali, M.F. El-Gohary, M.A. Mohamad, M.A. Abd-Allah, Grid connected photovoltaic power plant controlled by using FLC and CR with DC-DC Boost converter, Int. J. Sci. Res. Eng. Technol. (IJSRET) 3 (6) (2014).

[3] Ashmi, M. Kumar, S. Soni, Performance analysis of a standalone PV-wind-diesel hybrid system using ANFIS based Controller, Int. J. Comput. Appl. 147 (13) (2016) 18–23.

[4] A. Bin-Halabi, A. Abdennour, H. Mashaly, An accurate ANFIS-based MPPT for solar PV system, Int. J. Adv. Comput. Res. 4 (15) (2014) (ISSN (print): 2249-7277 ISSN (online): 2277-7970).

[5] M.A. Elgendy, B. Zahawi, D.J. Atkinson, Comparison of directly connected and constant voltage controlled photovoltaic pumping systems, IEEE Trans. Sustain. Energy 1 (3) (2010) 184–192.

[6] H. Fakham, Di Lu, B. Francois, Power control design of a battery charger in a hybrid active PV generator for load following applications, IEEE Trans. Indust. Electron. 58 (1) (2011) 85–94 TIE-09-1370.

[7] S. GanaVara, A. Chandrapati, N.K., L. Prasanth, Fuzzy logic controlling of a single phase seven-level grid-connected inverter for photovoltaic system, Int. J. Eng. Res. 3 (5) (2014) 299–304.

[8] H. Haeberlin, L. Borgna, M. Kaempfer, U. Zwahlen, New test at grid-connected PV inverters: Overview over test results and measured values of total efficiency, in: 21th European Photovoltaic Solar Energy Conference, Dresden, Germany, Sept. 2006.

[9] P. Hunoor, S. Savanur, Design and analysis of ANFIS controller to control modulation index of VSI Connected to PV Array, Eur. J. Adv. Eng. Technol. 2 (5) (2015) 12–17.

[10] M.M. Ismail, M.A.M. Hassan, The state of charge estimation for rechargeable batteries based on artificial neural network techniques, in: International Conference on Control, Decision and Information Technologies (CoDIT), 2013, 733–739.

[11] S. Jena, B. ChittiBabu, S.R. Samantaray, M. Mohapatra, Comparative study between adaptive hysteresis and SVPWM Current Control for Grid-connected Inverter System, in: Proceedings Of IEEE Students Technology Symposium, 2011, pp. 310–315.

[12] P. Jose, P. Rani Jose, Grid connected photovoltaic system with fuzzy logic control based MPPT, Int. J. Eng. Innov. Technol. (IJEIT) 3 (8) (2014).

[13] J. Kim, O. Yang, Design of a high-efficient grid-connected three-phase three-level T-Type PV power system, Int. J. Control Autom. 7 (10) (2014) 65–78.

[14] A.S. Khalifa, E.F. El-Saadany, Control of three phase grid connected photovoltaic power systems, in: Proceedings of IEEE 14th International Conference on Harmonics and Quality of Power (ICHQP), 2010, pp. 1–7.

[15] R.K. Kharb, M.F. Ansari, S.L. Shimi, Design and implementation of ANFIS based MPPT scheme with open loop boost converter for solar PV module, Int. J. Adv. Res. Electr. Electron. Instrum. Eng. 3 (1) (2014).

[16] Ahmet Afşin Kulaksiz, ANFIS-based estimation of PV module equivalent parameters application to a stand-alone PV system with MPPT controller, Turk. J. Electr. Eng. Comput. Sci. 21 (2013) 2127–2140.

[17] S. Kumar, G. Ravikumar, A seven-level grid connected inverter for photovoltaic system, Int. J. Comput. Eng. Res. Trends 1 (6) (2014).

[18] C. Li, D. Zhou, W. Yu, H. Wang, D. Zhu, G. Li, Performance of off-grid residential solar photovoltaic power systems using five solar tracking modes in Kunming China, Int. J. Hydrogen Energy (2017) 1–9.

[19] Y. Liu, Z. Hu, Z. Zhang, J. Suo, K. Liang, Research on the three-phase photovoltaic grid-connected control strategy, Energy Power Eng. 5 (2013) 31–35.

[20] Víctor Manuel Miñambres Marcos, Miguel Ángel Guerrero-Martínez, Fermín Barrero-González, María Isabel Milanés-Montero, A grid connected photovoltaic inverter with battery-supercapacitor hybrid energy storage, J. Sensors (2017) 1–18.

[21] A. Maroufmashat, M. Fowler, S. Khavas, A. Elkamel, R. Roshandel, A. Hajimiragha, Mixed integer linear programing based approach for optimal planning and operation of a smart urban energy network to support the hydrogen economy, Int. J. Hydrogen Energy (2016) 7700–7716.
[22] N.J. Mhusa, G.N. Nyakoe, E. Mgaya, V power management in photovoltaic-wind hybrid system based on artificial intelligence, J. Multidiscip. Eng. Sci. Technol. (JMEST) 2 (1) (2015) ISSN: 3159-0040.
[23] C. Mounika, C. Sampath Kumar, S. Khamuruddin, Implementation of sustainable DC grid connected PV system during day & night, Int. J. Innov. Res. Electr. Electron. Instrum. Control Eng. 2 (8) (2014).
[24] S.S. Mujawar, G.M. Karve, Control of grid connected inverter system for sinusoidal current injection with improved performance, Int. J. Innov. Eng. Res. Technol. 1 (2) (2014).
[25] S. Nasri, S. Salama, I. Yahyaoui, B. Zafar, A. Cherif, Autonomous hybrid system and coordinated intelligent management approach in power system operation and control using hydrogen storage, Int. J. Hydrogen Energy (2017) 1–13.
[26] P.L. Pugalhanthi, R. Parthasarathy, An overview of ANFIS based quasi Z source inverter for photovoltaic power generation, Int. J. Adv. Comput. Commun. Syst. (IJACCS) 1 (2) (2014).
[27] H.S. Ramadan, Optimal fractional order PI control applicability for enhanced dynamic behavior of on-grid solar PV systems, Int. J. Hydrogen Energy (2017) 4017–4031.
[28] K. Ramalingeswara Rao, K.S. Srikanth, Improvement of power quality using fuzzy logic controller in grid connected photovoltaic cell using UPQC, Int. J. Power Electron. Drive Syst. (IJPEDS) 5 (1) (2014) 101–111.
[29] A. Rezvani, M. Gandomkar, Maziarizadbakhsh, S. Vafaei, Improvement of grid-connected photovoltaic system using artificial neural network and genetic algorithm under different condition, Int. J. Soft Comput. Math. Control (IJSCMC) 3 (4) (2014).
[30] Y. Santhosh, Kurva Mallikarjuna, Design and analysis of fuzzy logic control current source inverter for grid connected PV system, Int. J. Electr. Electron. Eng. 1 (9) (2014).
[31] T. Shanthi, A.S. Vanmukhil, ANFIS controller based MPPT control of photovoltaic generation system, in: International Conference on Innovations in Intelligent Instrumentation, Optimization and Signal Processing (ICIIIOSP-2013).
[32] T. Shanthi, A.S. Vanmukhil, Photovoltaic generation system with MPPT control using ANFIS, Int. Electr. Eng. J. (IEEJ) 4 (3) (2013) 1105–1115.
[33] V. Sureshkumar, S. Arun, Three phase current source inverter using space vector pwm for grid connected applications, The International Journal of Engineering and Science (IJES) 3 (2) (2014).
[34] P. Trivino, L. Fernandez, A. Mena, F. Iborra, F. Jurado, Optimized operation combining costs, efficiency and lifetime of a hybrid renewable energy system with energy storage by battery and hydrogen in grid-connected applications, Int. J. Hydrogen Energy (2016) 23132–23144.
[35] T. Vigneysh, N. Kumarappan, Autonomous operation and control of photovoltaic/solid oxide fuel cell/battery energy storage based microgrid using fuzzy logic controller, Int. J. Hydrogen Energy (2016) 877–891.
[36] M.G. Villalva, J.R. Gazoli, E.R. Filho, Comprehensive approach to modeling and simulation of photovoltaic arrays, IEEE Trans. Power Electron. 24 (5) (2009) 1198–1208.
[37] Z. Yao, L. Xiao, J.M. Guerrero, An improved control strategy for the three-phase grid-connected inverter, IET Renew. Power Gener. (2015).
[38] H. Zhang, H. Zhou, J. Ren, W. Liu, S. Ruan, Y. Gao, Three-phase grid-connected photovoltaic system with SVPWM current controller, in: Proceedings of IEEE 6th International Conference on Power Electronics and Motion Control IPEMC, May 2009, pp. 2161–2164.