

Power Management of a Solar-Battery based Stand-Alone System using Adaptive Neuro Fuzzy Inference System based Controller

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Abstract: - This paper presents the performance of a solar-battery based stand-alone power system under the variation of load at the load side. This system consists of three converters namely, (i) Boost converter for solar PV system, (ii) Bi-directional boost converter for battery and (iii) three phase inverter to connect DC side with AC load side. Three control schemes are required for these three converters to manage the power flow among solar energy system, battery system and load. Therefore, Adaptive Neuro Fuzzy Inference System (ANFIS) based control schemes are designed for DC side boost converters i.e. for controlling of solar and battery system. The overall study system with all controllers is implemented in MATLAB/Simulink environment. Simulation results of the system with proposed controllers are obtained under variation of loads and constant (rated) solar irradiation and all results are analyzed in details. Results obtain with proposed controllers are compared with that of obtained with classical PI controller. Result shows that the proposed controller based on ANFIS gives better responses than classical PI controller.

Key-Words: Solar-Battery System, Power Management, Boost converter, Inverter, Control Scheme, ANFIS.

1 Introduction

Recently, the demand of electric energy is gradually increasing with increase in population and rapid industrialization. In addition to the environmental issues, the sources of fossil fuels are limited and depleting quickly. These are causing a large focus on the use of renewable energies [1]. In particular, for consumers that are far from the transmission lines or main power plants and small customers for whom sending energy using transmission lines is not economical, use of distributed generations (DGs) are recommended. Most DG units use renewable energies such as solar-photovoltaic (PV), wind and small hydro as their sources [2-3] and the choice of which is based on availability, location, amount of power needed, and feasibility. As renewable energy is typically unpredictable and uncontrollable, power electronic converters are used to control their output voltage and power, and also to connect either with the main grid or in feeding local loads [4]. In this paper, the main focus is made on solar PV, as a DG unit, based stand-alone system with battery unit to manage the power flow between the source and demand sides. There are mainly four type of topologies used in solar-PV power generation systems as reported in

[5] and Multi-string and AC module topology are more common [6]. In Multi-string topology, a DC/AC converter and many DC/DC converters are required as per the application. DC/DC converters are connected between DG units and common DC-link bus and DC/AC converter is connected between DC-link bus and either with main grid and load. Also, the energy storage devices, like battery, super capacitor etc, and local multifunctional power converters are needed. All units of multi-string are integrated in such way that storage devices can used as a backup for solar PV generation systems [7]. In [8-9], PV power generation units and batteries are coordinated to supply utility power grid or plug-in hybrid electric vehicle loads, but the islanding operation is not considered. In the control of output power and load sharing of DG units, different control schemes are reported in [10-12]. The output of the inverter (DC/AC converter) depends on the droop control based control scheme of inverter and parameters of the system [13-14]. In [15-16], various droop control methods are presented for controlling the inverters in both grid connected and islanding modes. The load sharing capability of the droop control method may be degraded if the load or line impedance changes. But, most of the control

schemes of stand-alone system are designed based on classical PI controllers and hence, they suffer from many problems like more settling time, oscillations etc.

In this paper, ANFIS based control schemes are proposed for PV and battery units to overcome the drawbacks associated with classical PI controllers. ANFIS is a hybrid controller method which uses knowledge of fuzzy logics and training of neural networks to obtain more efficient results. ANFIS has lots of advantages as compare to other methods like more efficient, less convergent, good dynamic performance, less oscillation etc [17-22].

2 Solar-Battery based Stand-alone System

Fig.1 shows a solar PV and battery based stand-alone system. It is connected to the load/consumer end via DC/DC converter, common DC-link capacitor (C_{dc}), three phase inverter, and filter circuits. A boost DC/DC converter is connected between PV unit and common DC-bus capacitor to boost the magnitude of PV output voltage, and hence, regulates the output power of the PV source unit. A bidirectional boost DC/DC converter connects between battery unit and common DC-bus and it is controlled to maintain the constant DC link voltage by charging and discharging the battery unit. The DC link voltage is controlled for achieving maximum power point operation of the solar energy system. Three phase inverter converts common DC bus voltage to AC voltage and it also controls the magnitude and frequency of the load. Filter circuits (RL and C) are used to eliminate the load voltage fluctuations.

In stand-alone power system, PV system cannot always operate to its maximum power mode for balancing the power flow between source and load. As the PV operating point varies based on the solar potential, the nonlinear characteristics of the input source must be considered while designing the control of the system [23] in order to fulfill consumer/load demand requirements which may be an amalgamation of nonlinear and linear loads. On the other hand, there should be another source, like an energy storing device (super capacitor or battery), to retain system operation at the PV maximum/rated power extraction policy. Under this situation, the steady state operation area of the stand-alone system at various loading conditions, which define the currents, will be affected.

In order to manage the power flow of the system, three control schemes are required for three power

converter circuits. The details of those control schemes are illustrated in the next section.

2.1 Control Scheme for Inverter

Fig.2 shows the block diagram of inverter control scheme [15]. Vector control scheme is used to design this control scheme. To implement vector control scheme, dq axis components of three-phase parameters are required and, therefore, all three phase parameters (voltage and current) of the study system are transformed into two phase (dq) components. PLL is used to obtain the reference frequency and angle of the load voltage and that load angle is used for axis transformation i.e. from three phase to two phase and vice versa.

The synchronously rotating (qd) reference frame model of 3-phase inverter, as demonstrated in Fig.1, can be computed by using equation (1), where M_{q1} and M_{d1} are modulation indices of the inverter in qd-axis.

$$\left. \begin{aligned} \frac{d}{dt}(I_{sq}) &= \frac{1}{L_s} (M_q \frac{V_{dc}}{2} V_{mq} - R_s I_{sq} - L_s \omega_s I_{sd}) \\ \frac{d}{dt}(I_{sd}) &= \frac{1}{L_s} (M_d \frac{V_{dc}}{2} V_{md} - R_s I_{sd} + L_s \omega_s I_{sq}) \end{aligned} \right\} \quad (1)$$

The dq-axis of the reference load voltage (V_{dm}^* & V_{qm}^*) are computed using droop control method [14]. Both the components are compared with their respective actual components to calculate the dq-axis load voltage errors. Those errors are passed through the PI controllers to generate dq-axis controlled currents. Thereafter, decoupling terms and dq-axis components of load currents are added with those controlled currents to obtain reference components of inverter output current in dq-axis.

The inverter reference current components (I_{sd}^* & I_{sq}^*) are compared with the actual inverter current to get current errors in dq-axis and those errors are processed through the PI controllers to obtain the controlled voltages. The cross-coupling terms of RL filter are added with the controlled voltages to compute the final control voltage signals in dq-axis. Those signals are used to get the modulation index of the inverter in dq-axis, as shown in Fig.2. The dq-axis modulation indices are transformed into three phase components and pass through the PWM generator to generate six pulses for three phase inverter.

2.2 ANFIS based Control Scheme for DC/DC Converter

In this section, two control schemes are designed for DC/DC converters of PV and Battery units, as shown in Fig.3 and Fig.4 respectively. Both the control schemes are designed on the basis of ANFIS approach. ANFIS is a method for mapping of specified input and output data set from a single input or multi inputs to a single output. This is attained by using the fuzzy logic and artificial neuro networks. ANFIS builds a Fuzzy Inference System (FIS) with the use of specified input-output data sets. The parameters of fuzzy membership function are regulated by using hybrid learning method which is a combination of least square error and back propagation methods [18]. A gradient vector is used to make their adjustment which offers a measure of how well the FIS is modeling the input/output data for a specified set of parameters. In order to reduce the error between reference and actual outputs, any type of optimization methods can be used for adjusting the system parameters after getting the gradient vector. This permits the fuzzy system to learn from the data.

To obtain good dynamic responses at different operating conditions of a particular system, the different gains of the controllers require to be adjusted based on system operating conditions. An ANFIS can be used to adjust the PI controller gains of DC/DC converters. In order to design an ANFIS based controller for a particular system a set of target and training data is needed. This type of data set is computed from classical controller based system. This data set and the hybrid learning algorithm are used to train the adaptive neuro network and hence, the structure of an adaptive network is generated as shown in Fig.5. This is functionally equivalent to a Sugeno fuzzy model, as shown in Fig.6. The followings are detailed information for the proposed ANFIS controllers:

- Number of nodes: 16
- Number of linear parameters: 3
- Number of nonlinear parameters: 9
- Total number of parameters: 12
- Number of training data pairs: 500001
- Number of fuzzy rules: 3

2.2.1 ANFIS based Control Scheme for Battery

Fig.3 shows the block diagram of ANFIS based control scheme for bidirectional boost converter. This control scheme is designed by using equation (2) [15] and ANFIS controllers. In this control scheme, DC-link voltage error, obtained by subtracting actual DC-link voltage from reference DC-link voltage, is passed through ANFIS

controller to generate battery reference current (I_2^*). This reference current is compared with the actual battery current (I_2) to generate the current error and that error is processed through ANFIS controller to compute the pulse signals (S_2 & S_3) for DC/DC converters of battery as shown in Fig.3. This control scheme has two ANFIS controllers i.e. inner and outer ANFIS controllers. Triangular membership functions are chosen for both ANFIS based controllers. Fig.7 and Fig.8 show the membership functions for inner and outer loops of the bidirectional boost converter.

$$\left. \begin{aligned} C_b \frac{d}{dt}(V_b) &= I_b - I_2 \\ L_2 \frac{d}{dt}(I_2) + R_2 I_2 &= V_b - S_2 V_{dc} \\ C_{dc} \frac{d}{dt}(V_{dc}) &= (1-S_1)I_1 + S_2 I_2 - I_{in} \end{aligned} \right\} \quad (2)$$

2.2.2 ANFIS based Control Scheme for PV System

Fig.4 illustrates the block diagram of the ANFIS based control scheme for boost converter of PV unit. Equation (3) [15] and ANFIS controllers are used to design control scheme for PV boost converter.

$$\left. \begin{aligned} C_{pv} \frac{d}{dt}(V_{pv}) &= I_{pv} - I_1 \\ V_{pv} &= L_1 \frac{d}{dt}(I_1) + R_1 I_1 + (1-S_1)V_{dc} \end{aligned} \right\} \quad (3)$$

In this control scheme, maximum power point tracker (MPPT) is used to find out the reference PV voltage and current (V_{pv}^* & I_{pv}^*). The PV voltage error is computed by subtracting V_{pv} from V_{pv}^* and that error is processed through ANFIS controller to obtain the actual PV current (I_{pv}). The reference current (I_1^*) of PV boost controller is calculated by deducting I_{pv} from I_{pv}^* . The I_1^* current is compared with the actual boost converter current (I_1) and the result is passed through ANFIS controller for generating the control signal (S_1) for PV boost converter, as shown in Fig.4. Like battery control scheme, this control scheme has also two ANFIS controllers i.e. inner and outer ANFIS controllers. Triangular membership functions are considered for both ANFIS based controllers of PV system. Fig.9 and Fig.10 show the membership functions for inner and outer loops of boost converter.

3 Simulation Results and Discussion

To verify the effectiveness of proposed ANFIS controllers, the simulink model of study system is implemented in MATLAB/Simulink environment. The simulink model consists of a Microgrid with two different sources, a nonlinear PV source and a battery source. Time domain responses of the system are obtained under load variation with classical PI controller and also with proposed controllers. System parameters and classical PI controller values are taken from [15]. The responses of the system with classical controllers and ANFIS controllers are presented in (Figs.11 & 12) and (Figs.13 & 14) respectively. It is considered that the PV system works at its rated power (2300W) level and load is varied from 1500W to 2900W and back to 1500W, as shown in Fig.11 (a) and Fig.13(a). The DC/DC converter of battery tries to maintain constant voltage across common DC-bus (300V) irrespective of load variation and also control the battery charge or discharge currents at its maximum limit.

During 0-0.4 sec and 0.8-1 sec: The load power is considered 1500W, as shown in Fig.11(a) and Fig.13(a). As the total load demand power is less than the nominal power of PV generation system, excessive power is fed to the battery unit via bi-directional DC/DC converter and hence, battery gets charge (-ve power flow) as shown in Fig.11(a) and Fig.13(a). Battery charging voltage and current are shown in Fig.12 (a,b) and Fig.14 (a,d) for Classical and ANFIS controllers respectively.

During 0.4-0.8 sec: The load power is increased to 2900W from 1500W during this time interval, as shown in Fig.11(a) and Fig.13(a). As the total load demand power is more than the nominal generating power of PV generation system, the battery gets discharge during this interval (+ve power flow) and therefore, the battery feeds power to the load for fulfilling the load/consumer demand, as shown in Fig.11(a) and Fig.13(a). Battery voltage and current are shown in Fig.12 (a,b) and Fig.14 (a,b), during discharging conditions, with classical and ANFIS Controllers.

- It is observed, from Fig.11(b) and Fig.13(b), that the dc-link voltage across common DC-link capacitor is maintained constant irrespective of the load variation.
- It can be notice, from Fig.12(b) and Fig.14(b), that the battery current gets negative during charging condition i.e. battery current flows from common DC-link to battery to store energy. During discharging condition, battery current becomes positive i.e. battery current flows from battery side to common DC-Bus for releasing the power.
- Three-phase inverter voltage is shown in Fig.12 (c,d) and Fig.14(c,d) without and with ANFIS controller respectively.
- From Fig.11(d) and Fig.13(d), it is observed that the both control schemes are enough capable to maintain islanding load voltage to its rated value.

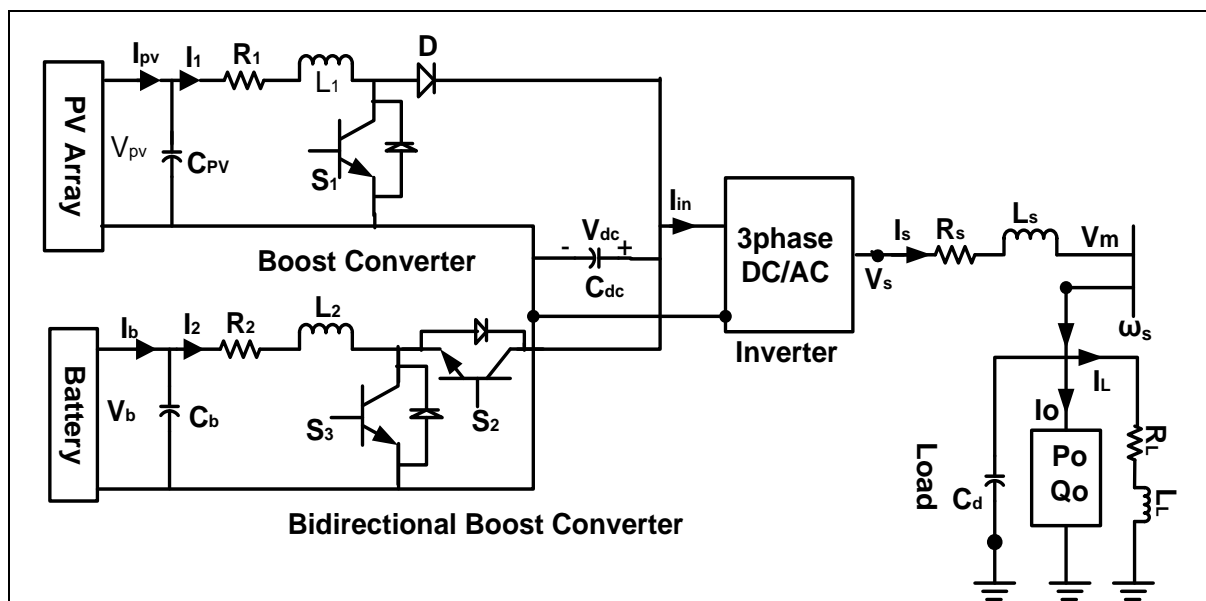


Fig. 1. Block diagram of a Stand-alone System with PV and Battery Units [15].

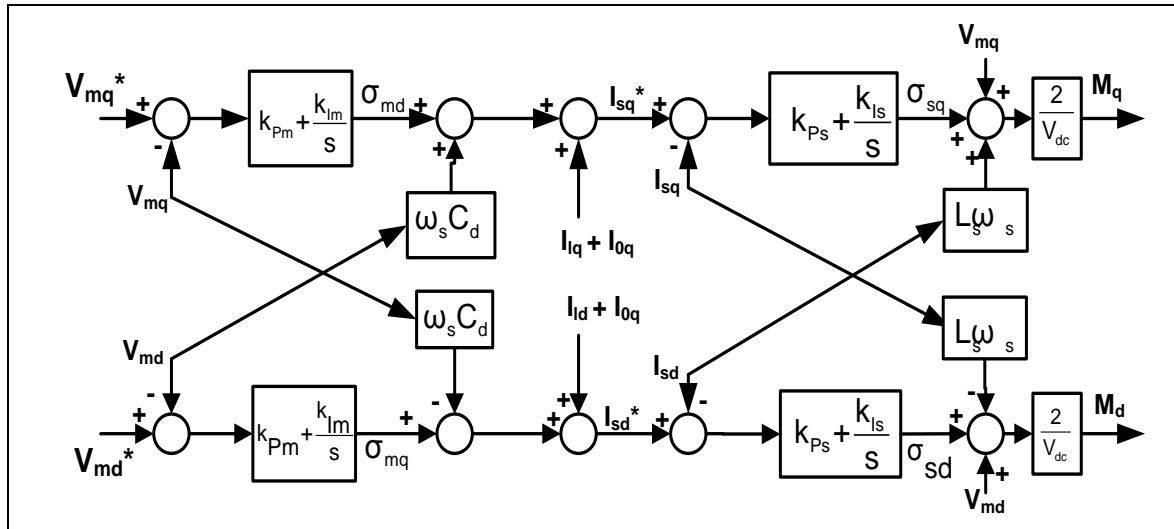


Fig. 2. Block Diagram of Control Scheme for DC-AC 3-phase Converter [15].

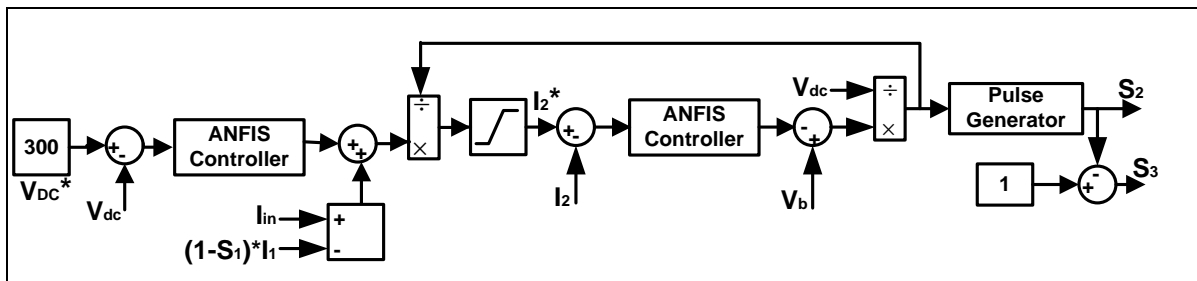


Fig. 3. ANFIS based Control Scheme for DC/DC Bi-directional Boost Converter of Battery Unit.

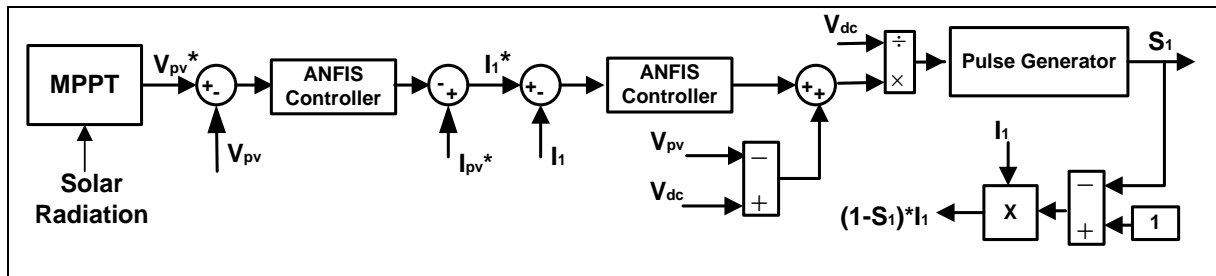


Fig. 4. ANFIS based Control Scheme for DC/DC Boost Converter of PV Unit.

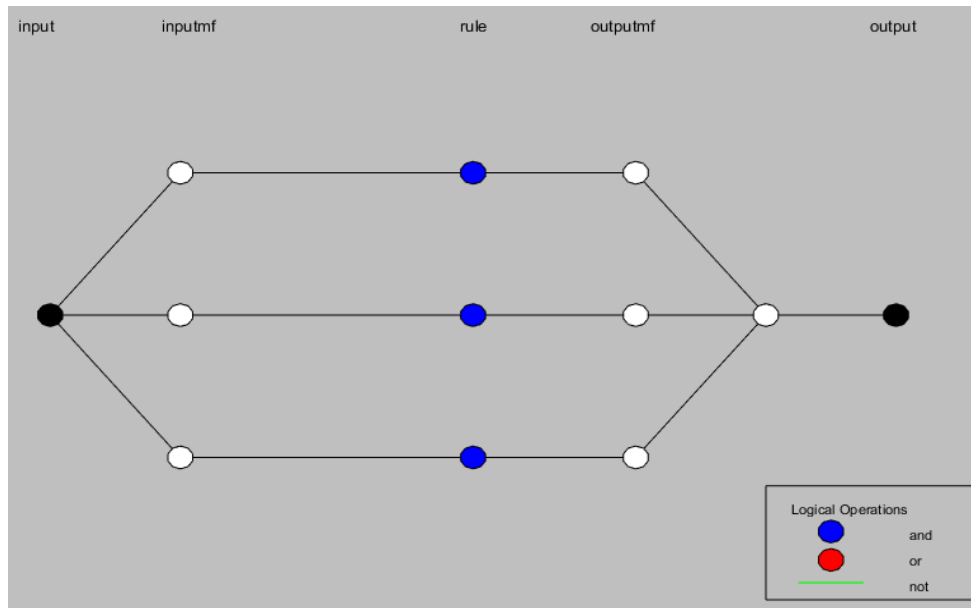


Fig. 5. Structure for Adaptive Network.

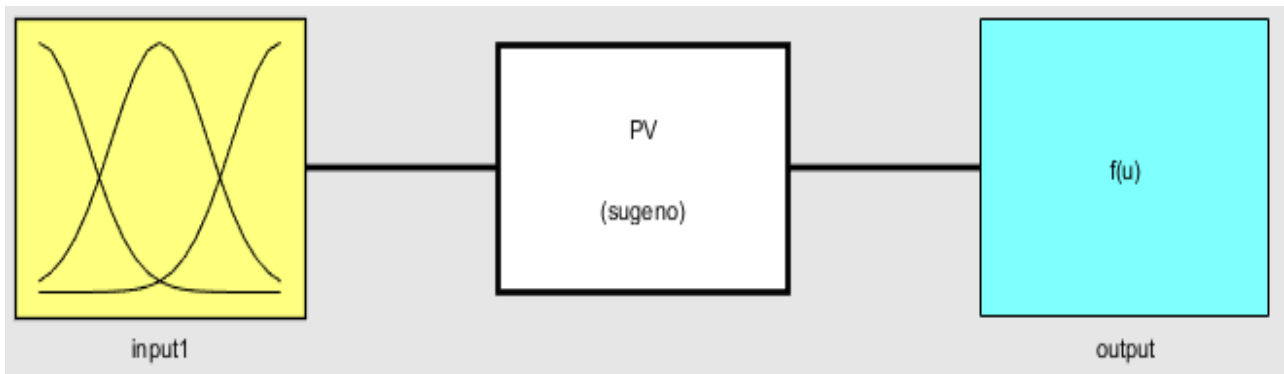
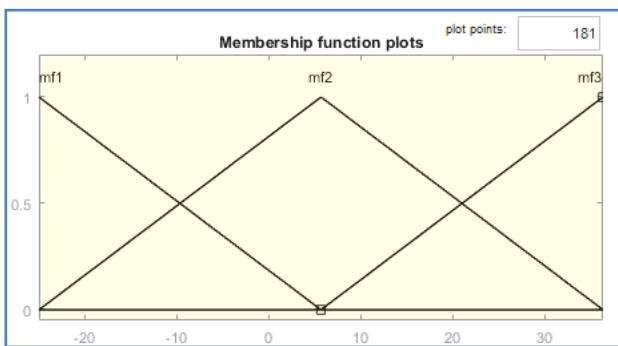
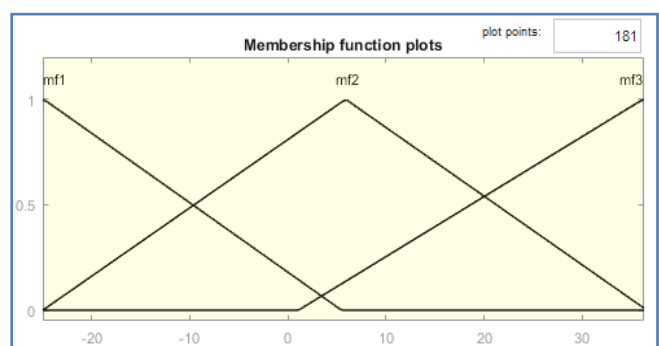


Fig. 6. Structure for ANFIS.

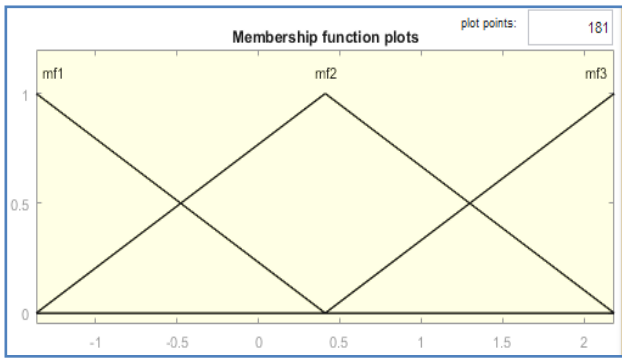


Before Training

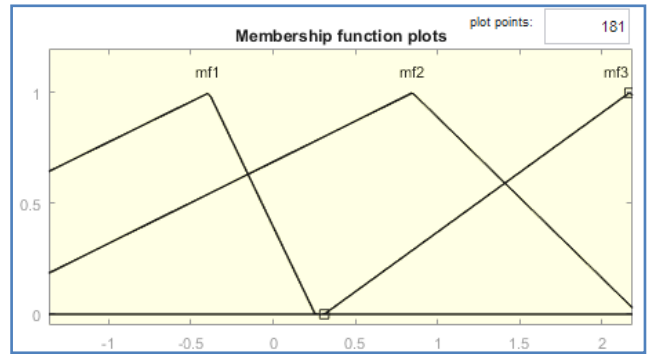


(b) After Training

Fig. 7. Membership Function for Inner Control Loop of battery Control Scheme.

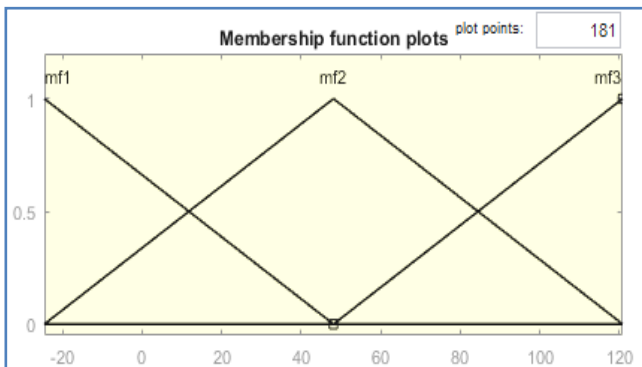


(a) Before Training



(b) After Training

Fig. 8. Membership Function for Outer Control Loop of battery Control Scheme.

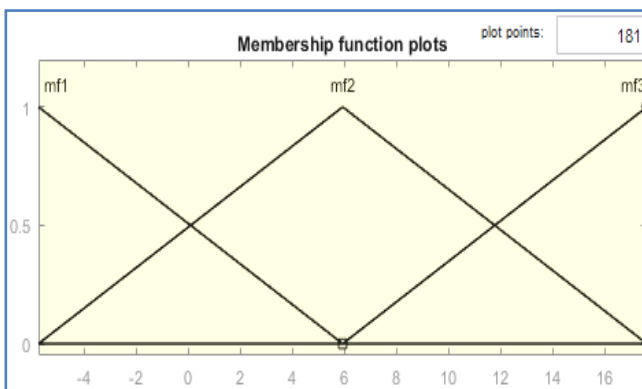


(a) Before Training

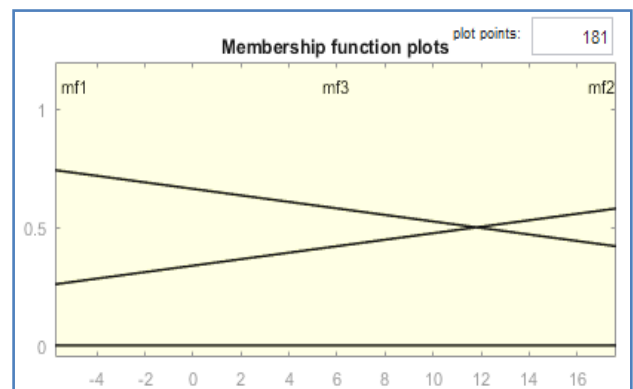


(b) After Training

Fig. 9. Membership Function for Outer Control Loop of PV Control Scheme.



(a) Before Training



(b) After Training

Fig. 10. Membership Function for Inner Control Loop of PV Control Scheme.

4 Comparison of System Responses Obtained with Proposed and Classical PI based Control Schemes

Time responses of the system with classical PI controller as well as those with ANFIS controller have been presented in section-3. The results

obtained in section-3, using the two types of controllers, are listed in Table-I along with comments on the responses for comparison.

Table-1: Comparison of System Responses with Classical PI & Proposed ANFIS controllers

Variables	Figure No		Comments on system responses at varying loads and constant irradiations.
	With Classical PI Controller	With ANFIS Controller	
Power	Fig.11(a)	Fig.13(a)	It can be noted that both the controllers are capable of managing the power flow of a solar-battery based stand-alone system for satisfying the load end demands. When compared, it can be seen that response of battery power during discharging interval are oscillated with classical PI controller. But, there is no oscillation observed with ANFIS controllers.
DC-link voltage	Fig.11(b)	Fig.13(b)	Both the controllers have perfectly tracked the reference values of V_{dc} and kept it fixed to its rated level. But, the dc-link voltage obtained with ANFIS controller is smoother than that of obtained with classical PI controllers.
Battery voltage and Current	Fig.12(a) and Fig.12(b)	Fig.14(a) and Fig.14(b)	It is observed that the battery voltage and current, obtained with classical PI controller, are more oscillatory in nature than that of using ANFIS controller. Therefore, it can be concluded that ANFIS controller based control schemes give better responses as compare to classical controller based control schemes.

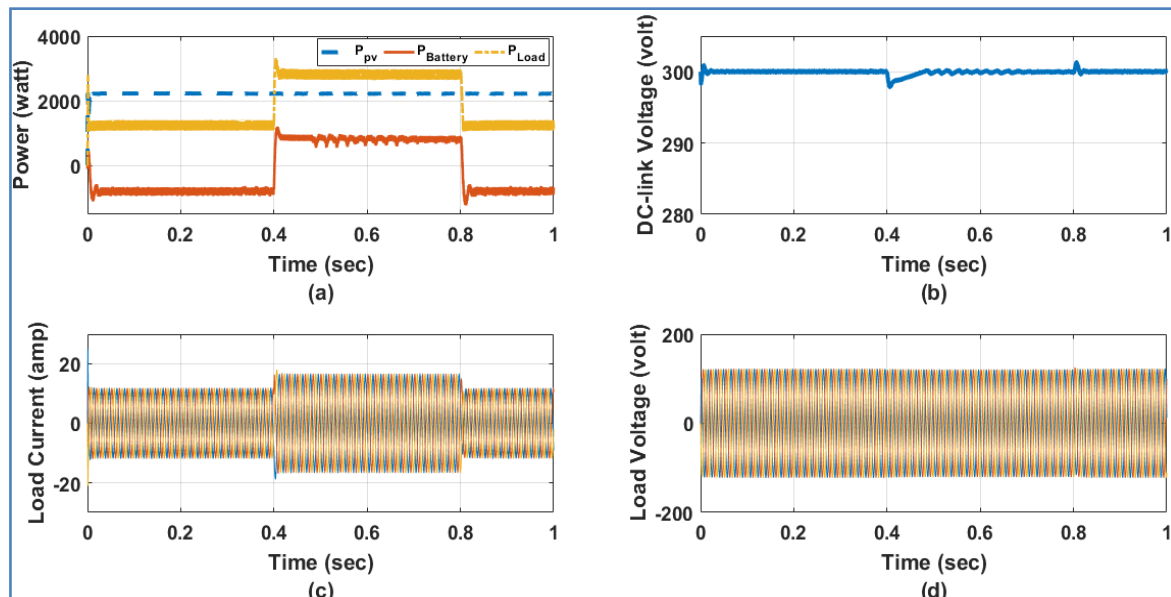


Fig. 11. (a) Power (watt), (b) DC-link Voltage (volt) (c) Load current (amp) and (d) Load voltage (volt) (With Classical PI Controller)

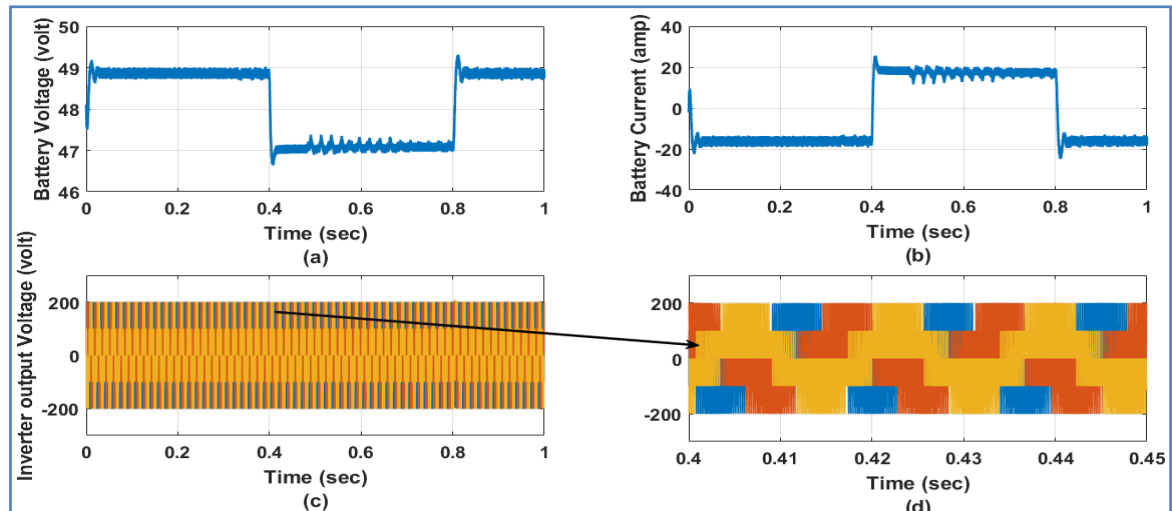


Fig. 12.(a) Voltage of Battery (volt), (b) Current of Battery (amp) (c) Output Voltage of 3-phase Inverter (volt), and (d) Zoom viewed of Inverter Output Voltage(volt) (With Classical PI Controller).

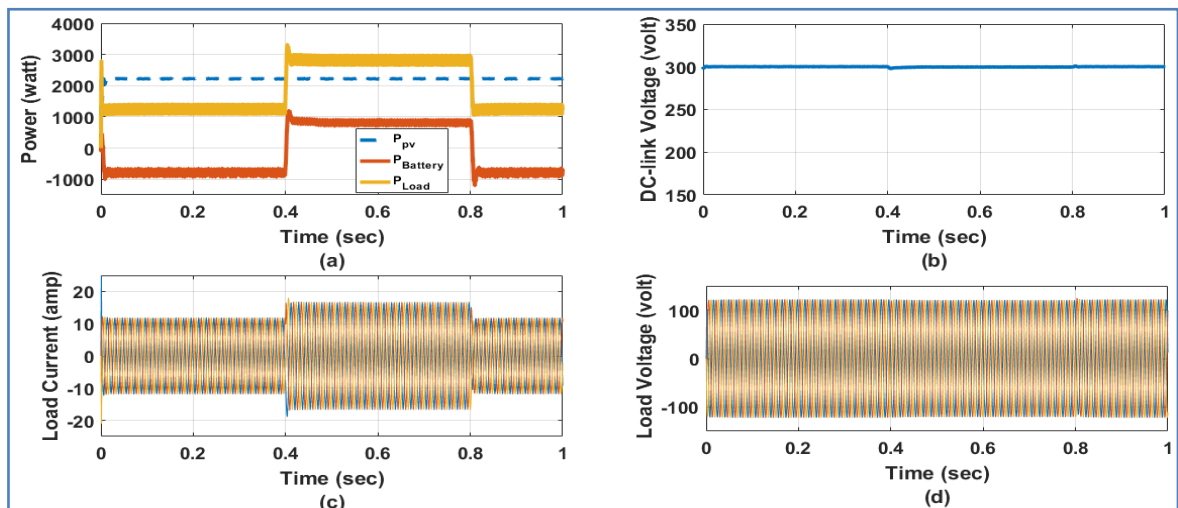


Fig. 13. (a) Power (watt), (b) DC-link Voltage (volt) (c) Load current (amp) and (d) Load voltage (volt) (With ANFIS Controller).

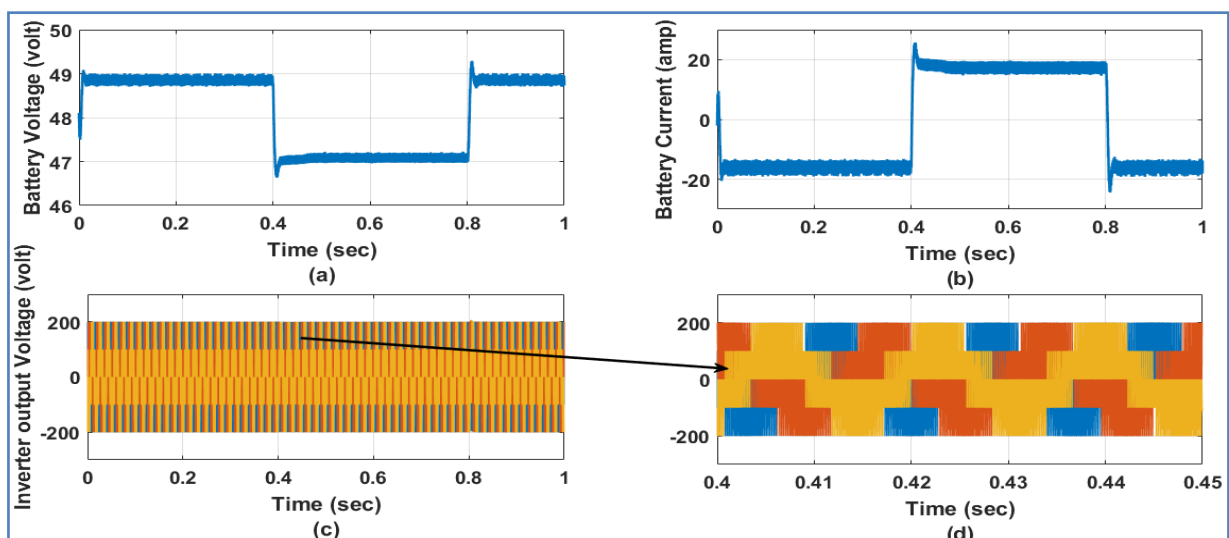


Fig. 14.(a) Voltage of Battery (volt), (b) Current of Battery (amp) (c) Output Voltage of 3-phase Inverter (volt), and (d) Zoom viewed of Inverter Output Voltage(volt) (with ANFIS Controller).

5 Conclusion

In this paper, a simulink model for solar-PV and battery based stand-alone power system is implemented in MATLAB/simulink environment. The performances of the system are studied by varying loads and at constant (rated) solar irradiation (1pu). ANFIS based control schemes are designed for PV and battery units of the study system for balancing the power flow between source and load with lower oscillation during both transient and steady state conditions. Simulink results obtained with ANFIS controller are compared with that of classical PI controllers. From simulink results, it can be observed that ANFIS based control schemes give better responses as compare to classical control schemes.

The advantages of using ANFIS are that they provide better alternative as compared to classical conventional system; they exhibit a faster converging speed, good performance, less oscillation under steady-state conditions.

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