A Novel Energy Management Scheme using ANFIS for Independent Microgrid

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Abstract- In this paper an energy management technique for Hybrid Renewable Energy System (HRES) connected with AC load using Adaptive Neuro Fuzzy Interference System (ANFIS) is proposed. This algorithm is developed with an aim of increasing the power transfer capability between the source side and load side and it offers several benefits like the enhanced predicting capability, degradation in complexity as well as the randomization and so forth. In this work, photovoltaic (PV) system, Wind Generating System (WGS), Fuel Cell (FC), Ultra Capacitor (UC) and the battery are considered as the energy sources. The ANFIS technique is trained with the inputs such as the previous instant energy of the available sources and the required load demand of the current time and the corresponding target reference power of the sources and storage devices. According to the load variation, the proposed method makes the appropriate control signals at the testing time to manage the energy of the HRES. A STATCOM based voltage regulation and harmonic mitigation is introduced. The implementation of the system elements and control method has been done in MATLAB/Simulink and the performance of the proposed method is analysed by using different environmental and load test conditions. The results of the test cases confirms that the proposed control technique is effective in prediction of energy required for the next instant and manages the energy flow among HRES power sources and energy storage devices.

Keywords ANFIS, Energy management, Hybrid power system, Microgrid, STATCOM.

1. Introduction

In near future substantial growth and unexpected challenges in the energy production, transmission and utilization technologies are to be witnessed. Awareness of people about the pollution due to usage of fossil fuel for energy production and initiatives by many countries to scale back environmental pollution has increased the use of green energy sources for power generation [1]. Green energy technologies include renewable energy sources for instance solar PV, Solar Thermal, Wind, biomass, small hydel, wave and tides, geothermal and alternative energy generation for instance microturbine, and fuel cell [2]. The increased usage of renewable energy sources give benefits of reducing transmission losses, forestall dependency on fossil fuels and further improve the system reliability, etc. [3]. Wind and Solar systems are more prominent energy sources and can be used in combination as hybrid power system (HPS) to get reliable power. Anyway, wind and solar energy outputs are depends upon stochastic environmental parameters [4, 5, 6]. Hence energy backup should be provided to increase the energy security. Fuel cell, battery, super capacitor can be used as energy storing devices in an HPS, either as a single device backup or in combinations [7].

Microgrid is nothing but combination of renewable based distributed generating systems of different kind with energy storage systems supplying local loads or connected to grid [8]. Renewable energy based microgrid can be thought as a recently introduced concept called ‘smart grid’, which provides energy management solutions in the distributed generations [9]. MG is a platform to integrate distributed energy resources (DERs) into distribution network which could be a highly promising solution to the problem of depletion of fossil fuels in future. The DERs may include distributed generation (DGs) and distributed storage (DS) [10]. Microgrids are supplying residential communities or industrial consumers in rural or urban areas and are operating in either grid connected mode or islanded mode [11].

Even though renewable energy sources don’t have any pollution, the energy output is random in nature. Hence integration of renewable energy sources creates power quality, stability problems due to mismatch of real and reactive powers between sources and load. To overcome above said issues, suitable energy management control schemes are required in a microgrid [12, 13, 14]. The voltage and frequency regulation in an HPS microgrid have to be achieved by instantaneously matching the load demand and energy generated. So as to realize the energy balance between sources and utilities new control schemes are necessary [15, 16].

In a standalone HRES microgrid, when the loads are switched the voltage profile (voltage sag or swell) and frequency get affected owing to active and reactive power variations. Additionally, when nonlinear loads are connected, current harmonics are introduced in the system on the source side. These power quality issues in a standalone system can be improved by introducing any filter configurations (passive compensation) or FACTS devices (active compensation) on ac bus [17, 18].

Number research works have been published recently in the field of energy management of HPS microgrid. Related recent research works are reviewed here. An energy management scheme for a PV/Fuel cell/Battery HPS have been introduced by Manuel Castaneda et al. The control scheme desiged to i) meet the load demand ii) maintain the hydrogen level iii) maintain SOC of the battery and to extend the life of storage devices [19]. A. Baziar et al. [20] have proposed a 2m Point Estimate Method (2m PEM) based energy management for a microgrid consists of PV, Wind, Microturbine and Fuel cell. This proposed scheme runs 2m times to account m uncertain variables in the system. Wei Gu et al. [21] have presented review of the modelling and energy management of the combined cooling, heating and power (CCHP) micro grid. The performance of a CCHP microgrid are analysed in technical, economical and environmental aspects.

P. Garcia-Trivino et al. [22] have studied the performance of grid-connected PV/Wind/Battery/Fuel cell HPS with PI controllers tuned by particle swarm optimization (PSO) for the inverter power control. The performance of PI controllers with offline and online PSO tuning based on ITAE index, are compared under variable environmental conditions. Kuo-Hao Chang et al. [23] have investigated the use of Monte Carlo simulation, along with simulation optimization techniques, for obtaining the optimal design of HRES in uncertain environments. Their proposed model considers the equipment installation, including PV, WT and diesel generators and the energy storage systems in each power station, and also satisfied the load demand with minimum generating cost.

R. Yumurtaci et al. proposed an neural network controller (NNC) based energy management for a HPS consists of WT, PV system, FC system and Battery. The performance of the controller was examined with different environmental inputs on four different days in summer, winter, autumn, and spring. SOC of the battery and power difference between sources and load is monitored by ANNC and corresponding reference power is generated for FC [24]. ANN is used to achieve MPPT of the PV system in a standalone HPS. Fuzzy logic controllers are employed in HPS to manage the power flow between WT,PV,FC, Battery. Another Fuzzy logic controllers is employed for temperature control of FC, which helps improving the system effciency, and prolong its life [25].

In a PV generating system, an adaptive neuro-fuzzy inference system (ANFIS) based MPPT control is employed to predict voltage for maximum power operation using short circuit current and open circuit voltage as inputs. Root mean square error (RMSE) is used to tune the best membership functions in FIS structure [26]. P. García et al. [27] proposed an ANFIS based energy management system (EMS) for a grid-connected HPS consists of WT and PV as primary energy sources, and energy storage systems (ESS) of FC system and battery. ANFIS-based supervisory control system takes the power demanded by the grid, the available renewable power, the hydrogen tank level and the SOC of the battery as inputs and determines the power that are supplied by/stored in the FC and battery. Another ANFIS-based control is also applied to the three-phase inverter, which controls the power delivered by HPS to grid by controlling the active and reactive power.

Load frequency control of Multi-area power system network is acheived by ANFIS controller. The proposed controller is compared with ANN and fuzzy controller to analyse its superiority [28]. The parameters of the static synchronous compensator (STATCOM) are tuned for proper reactive power requirement and to stabilize voltatge using ANFIS based approach with disturbances in load and power generation of a wind-diesel HPS. The transient responses of HPS are compared under fixed DC link capacitor and dynamic compensation by STATCOM [29].

The review of the recent research work shows that, energy management of hybrid renewable energy, storage devices for microgrids require an intelligent controller. Many techniques are used for the energy management strategies such as fuzzy, neuro-fuzzy and optimization algorithms. Accordingly, a hybrid renewable energy system's control strategies are designed to achieve the goal of meeting load demand, by the use of energy sources optimally and to regulate the voltage and frequency of AC bus. Therefore, an integrated renewable energy system with an intelligent energy management is required for a promising solution to overcome this challenge. ANFIS based EMS is not found applied for standalone HPS in any of the literature.

This paper proposes an energy management system for the standalone HPS using ANFIS technique. The ANFIS technique is trained with the inputs such as the previous instant energy of the available sources, the required load demand of the current time and the corresponding target reference power of the sources are determined. According to the load variation, the proposed method makes the appropriate control signals at the testing time to match the source power and load power. The primary novelties of the control schemes employed in this paper are: 1) the application of ANFIS to the EMS of a standalone HRES, which generates reference powers for ESS (Fuel Cell, battery and UC) that are generated by/stored in the ESS, taking into account previous instant power of the renewable sources and the load demand of the current instant and 2) harmonic mitigation and voltage regulation in ac bus is achieved by the STATCOM.

2. Hybrid Renewable Energy System with Proposed Energy Management Scheme

The HRES structure with proposed methodology is depicted in Fig. 1. The presented HRES is identified as three groups and they are connected to DC bus commonly. The first group consists of the renewable energy sources, solar PV system and WECS, which provides power to the DC bus when there is wind or solar resources available. The second group encompasses the energy storage systems, battery, UC and FC, which offers the durable electrical energy as well as the fast dynamic power regulation. Finally, the VSI delivers the active and the reactive power to the AC load-connected, using the DC bus power. The model of renewable energy sources, energy storage devices and proposed energy management system are described in the following subsections.

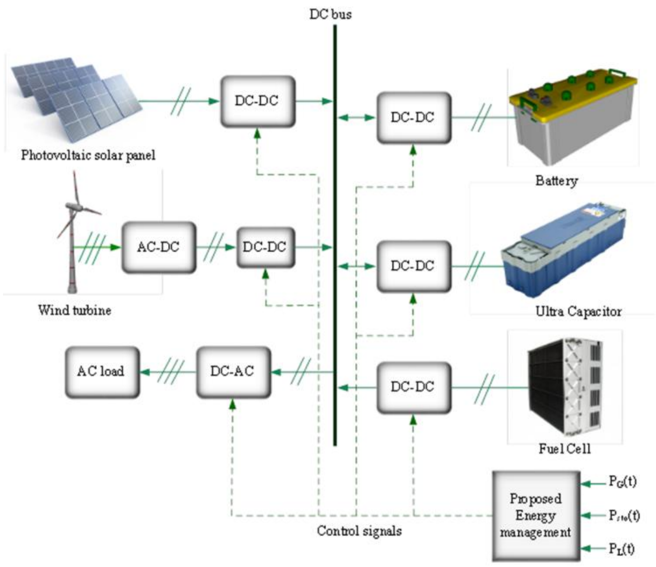


Fig. 1. Structure of the HRES with proposed methodology

2.1. PV System

The PV system constitutes one of the renewable energy sources in HPS, which extort the power from the existing solar energy. The energy management system need to operate at maximum power from the PV system when the load demand is greater than the accessible power generation and need to operate with controlled power from the PV system when the load demand is within the accessible generation power. In this system, the traditional Perturb and Observation (P&O) Maximum Power Point algorithm is elegantly employed. The current of the PV system is described [30, 31] in Eq. (1)

$$I_{pv} = I_g - I_o\left[\exp^{\left(\frac{qv_d}{K_B F T_C}\right)} - 1\right] - \frac{v_d}{R_p} \tag{1}$$

where, I_g represents the light generated current; I_o symbolizes the dark saturation current dependant on the cell temperature; q signifies the electron charge $(1.6\times10^{-19}C)$; K_B indicates the Boltzmann's constant, T_C corresponds to the cell absolute temperature; F relates to the cell idealizing factor; v_d denotes the diode voltage and R_p represents the parallel resistance.

2.2. Wind Generating system

The wind turbine is employed for the purpose of converting the wind energy into mechanical energy. The mechanical power of the wind turbine [30, 32, 33] is expressed in Eq. (2).

$$P_m = \frac{1}{2}\rho A C_p(\lambda,\beta)V_\omega^3 \tag{2}$$

where, P_m represents the mechanical output power of the wind turbine, ρ corresponds to the air density, A symbolizes the area swept by blades, V_ω signifies the wind speed in m/s, β indicates the pitch angle in degree, $C_p(\lambda,\beta)$ is the power coefficient of the wind turbine, The power coefficient is calculated [30, 32, 33] by Eq. (3).

$$C_p = 0.73(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2)e^{-18.4/\lambda_i}$$

$$\text{with } \lambda_i = \left(\frac{1}{\lambda - 0.002\beta} - \frac{0.003}{\beta^3+1}\right)^{-1} \tag{3}$$

where C_p represents a non-linear function of both the Tip Speed Ratio (TSR) λ and the pitch angle β. The power which is accessible from the wind turbine may be utilized for the purpose of meeting the load demand.

2.3. Energy Storage Devices

The energy storage systems presented in the HRES are used to store the surplus of energy generated by the PV and wind sources which support the sharing of the stored energy when the load demand exceeds the energy generated by HPS sources. In the proposed system, the lead-acid batteries and fuel cell are effectively used to furnish the long-term energy backup. Ultra-capacitors are used for the purpose of the fast dynamic power regulation. The FC effectively utilises the hydrogen to generate energy and mitigate the renewable energy shortages. Taking into consideration the safety concerns, the batteries have to be invariably charged or discharged by means of an optimal power tracking system so as to keep aloof the overcharges and discharges.

2.4. Training Dataset Generation

The responsibility of energy management system is to utilize the energy sources of the HRES and control the energy storage devices with the intention of providing the power demanded by the load/grid. The proposed ANFIS technique requires suitable training data set for managing the HRES. The required energy management training dataset has been developed as per the available generation from the sources of HPS and the load demand at particular instant. The training dataset decides the reference power required from the renewable energy sources and the storage devices. The source power can be described by Eq. (4) [31, 34, 35].

$$P_{sour}(t) = P_G(t) + P_{sto}(t) \tag{4}$$

where, $P_G(t)$ represents the total power generated from the available renewable energy sources at time t; $P_{sour}(t)$ symbolizes the total power of the available sources in the HRES at time t and $P_{sto}(t)$ signifies the total power from the storage devices at time t. The renewable energy sources and the storage devices power are described by means of Eq. (5) and Eq. (6).

$$P_G(t) = P_{PV}(t) + P_{WT}(t) \tag{5}$$

$$P_{sto}(t) = P_{BAT}(t) + P_{UC}(t) + P_{FC}(t) \tag{6}$$

where, $P_{PV}(t)$ represents the power generated from the PV system at time t; $P_{WT}(t)$ characterizes the power generated from the wind turbine at time t; $P_{BAT}(t)$ signifies the power required from the battery at time t; $P_{UC}(t)$ relates to the power required from the UC at time t and $P_{FC}(t)$ corresponds to the power required from the FC at time t.

$$P_{sour}^{ref}(t) = P_L(t) \tag{7}$$

$$P_{PV}^{ref}(t) = P_{PV-MPPT} \tag{8}$$

$$P_{WT}^{ref}(t) = P_{WT-MPPT} \tag{9}$$

$$P_{sto}^{ref}(t) = P_G(t) - P_{sour}(t) \tag{10}$$

where, $P_{sour}^{ref}(t)$ relates to the reference power of the available source in the HRES at time t; $P_{PV}^{ref}(t)$ and $P_{WT}^{ref}(t)$ represent the reference power of the both the PV and WT system at time t; $P_{PV-MPPT}$ and $P_{WT-MPPT}$ characterize the MPPT power of both the PV and WT system at time t and $P_{sto}^{ref}(t)$ corresponds to the reference storage power at time t [34, 35]. Based on Eq. (4) to Eq. (10), the training dataset of the ANFIS has been developed, which is given in Eq. (11).

$$\begin{bmatrix} P_G(0), P_L(1) \\ P_G(1), P_L(2) \\ \vdots \\ P_G(t-1), P_L(t) \end{bmatrix} = \begin{bmatrix} P_{ref}(0) \\ P_{ref}(1) \\ \vdots \\ P_{ref}(t) \end{bmatrix} \tag{11}$$

The generated dataset is utilized for training the ANFIS and it manages the energy of the HRES at the testing time. The ANFIS based energy management is explained in section 3.

3. ANFIS based Energy Management Scheme

The ANFIS has emerged as a hybrid soft computing technique, involving the blend of the neural network and fuzzy, utilising superior level reasoning skills and inferior level computational command [26,28]. ANFIS is a powerful adaptive network for modeling complex and nonlinear systems with less input and the output target parameters. The fuzzy interference system is fine-tuned by the neural network learning technique. ANFIS uses hybrid learning procedure, to form input-output relationship based on the human knowledge and input-output data. ANFIS could be employed to model nonlinear functions, identify nonlinear parameters in online control, and to predict parameters in the time series models [36].

Normally, the ANFIS is home to a layered structure, which is well-illustrated in Fig. 2. It embraces five functional nodes such as input, fuzzification, product, normalization and defuzzification nodes. The square nodes are the adaptive nodes and the circle nodes are the fixed nodes. The inputs for ANFIS are the previous instant power generation from the renewable energy sources $P_G(t-1)$ and the load demand $P_L(t)$ and the output target is reference power of the HRES $P_{ref}(t)$. By employing the relative parameters, the novel ANFIS technique is able to generate the rules and tuned efficiently. It has one output, the reference power that must be generated from storage devices. The reference powers for battery, fuel cell, and ultra capacitor are calculated by using SOC limitations for each device and SOC levels.

A common rule set for the first order Takagi-Sugeno interference system with two fuzzy layers is described in Eq. (12) and Eq. (13) [27,36]

Rule 1: If $P_G(t-1)$ is C_1 and $P_L(t)$ is D_1 then

$$f_1 = m_1 P_G(t-1) + n_1 P_L(t) + k_1 \tag{12}$$

Rule 2: If $P_G(t-1)$ is C_2 and $P_L(t)$ is D_2 then

$$f_2 = m_2 P_G(t-1) + n_2 P_L(t) + k_2 \tag{13}$$

where, m_1, m_2, n_1, n_2, k_1 *and* k_2 represent the linear parameters, C_1, C_2, D_1 *and* D_2 characterize the non-linear parameters. The Fig. 3 shows the fuse reasoning of the ANFIS.

Activation levels relating to the fuzzy rules can be calculated by means of the relation $W = X_i(a) \bullet Y_i(b)$, where the logical operator "and" can be optimized by a permanent t-norm. The output of each rule is obtained as a linear blend between parameters of the antecedents of each rule and is furnished by Eq. (14) [27, 36]

$$f_i = m_i P_G(t-1) + n_i P_L(t) + k_i \,,\; i = 1,2\ldots \tag{14}$$

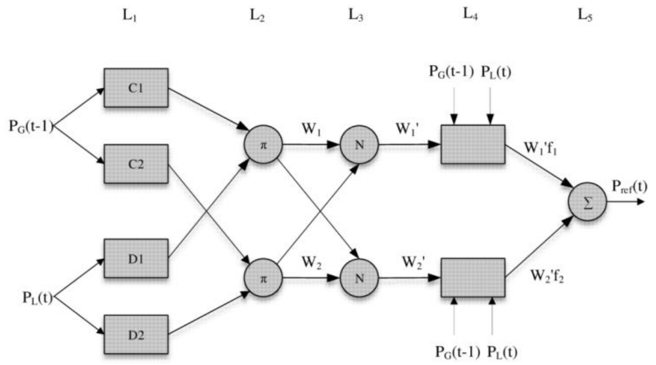


Fig. 2. Structure of the ANFIS

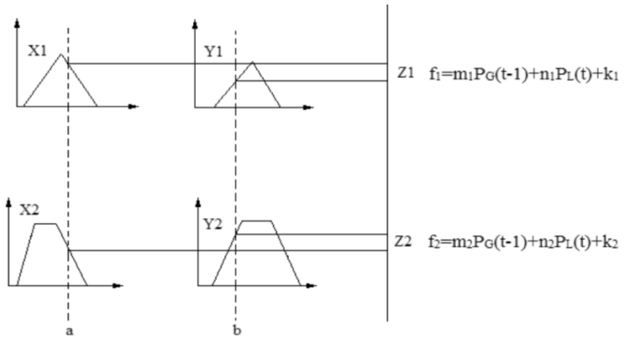


Fig. 3. First order Takagi-sugeno fuse reasoning

The output of the model f [27, 36] is obtained by multiplying the standardized activation degrees of the rules by the individual output of each rule, which is furnished in Eq. (15).

$$f = \frac{\sum W_i' f_i}{\sum W_i} \ , \ i = 1,2\ldots \tag{15}$$

where, W_i represents the normalized value, which constitutes the sum of W_1 and W_2. The ANFIS layer framework is beautifully pictured in Fig. 2 and the related depiction is furnished as follows

3.1. Fuzzification layer

In the fuzzification layer each and every input layer characterizes an input variable which is furnished into fuzzification layer. The generated power at previous instant $P_G(t-1)$ and the load demand at the current instant $P_L(t)$ of nodes are represented by C_1, C_2, D_1 *and* D_2, in which C_1, C_2, D_1 *and* D_2 constitute the linguistic labels of fuzzy theory for dividing the membership functions. The output of the fuzzy layer is furnished in Eq. (16) and Eq. (17) [27, 36].

$$R_{L1,i} = \mu C_i(P_G(t-1)) \, , \ i = 1,2; \tag{16}$$

$$R_{L1,j} = \mu D_j(P_L(t)), \ j = 1,2; \tag{17}$$

where, $R_{L1,i}$ and $R_{L1,j}$ represent the output of the fuzzy layer and $\mu C_i(P_G(t-1))$ and $\mu D_j(P_L(t))$ characterize the membership function of the fuzzy layer.

3.2. Product layer

The product layer gracefully discharges the task of carrying out the logical "and" or product of the input membership functions, which is represented as π. The product layer output signifies the input weight function of the succeeding node. The output of this layer can be described by Eq. (18) and Eq. (19) [27, 36].

$$W_1 = R_{L2,i} = \mu C_i(P_G(t-1).\mu D_i(P_L(t)), \ i = 1,2; \tag{18}$$

$$W_2 = R_{L2,j} = \mu C_j(P_G(t-1).\mu D_j(P_L(t)), \ j = 1,2; \tag{19}$$

Where, W_1 *and* W_2 represent the outputs of the product layer.

3.3. Normalization layer

The normalized layer represents the third layer, where each node is a permanent one which characterizes the IF segment of a fuzzy rule. It is effectively employed to normalize the input weights, and is competent to carry out the fuzzy "and" operation. This layer may be labeled as N and the output of the corresponding layer is expressed in Eq. (20) and Eq. (21) [27, 36].

$$W_1' = R_{L3,i} = \frac{W_i}{W_1 + W_2}, \ i = 1,2; \tag{20}$$

$$W_2' = R_{L3,j} = \frac{W_j}{W_1 + W_2}, \ j = 1,2; \tag{21}$$

Where, W_1' *and* W_2' represent the outputs of the normalized layer.

3.4. Defuzzification layer

The task assigned to this layer is the execution of an adaptive function, which furnishes output membership function in accordance with the preset fuzzy rules. The output of the defuzzification layer is furnished by means of Eq. (22) and Eq. (23)

$$W_1' f_i = R_{L4,i} = \frac{W_i}{W_1 + W_2}\left[m_1 P_G(t-1) + n_1 P_L(t) + k_1\right] \tag{22}$$

$$W_2' f_j = R_{L4,j} = \frac{W_j}{W_1 + W_2}\left[m_2 P_G(t-1) + n_2 P_L(t) + k_2\right] \tag{23}$$

Where, $W_1' f_i$ and $W_2' f_i$ are the outputs of the de-fuzzy layer.

3.5. Total output layer

The output layer characterizes the THEN segment of the fuzzy rule. The sum of the input signals may be calculated, which is furnished as $\sum W_i' f_i$. The total output of the layer is furnished by Eq. (24) [27, 36]

$$f = R_{L5,i} = \sum W_l{}' f_i = \frac{\sum W_i f_i}{\sum W_i} \qquad (24)$$

Where, f represents the total output. When the ANFIS training is finished, it is ready to give the reference power $P_{ref}(t)$ to manage the energy of the HRES. By using the proposed method, the PV, WECS, FC, UC and battery controller are taking decisions and the power exchange between the source and load side is enhanced [37]. The proposed methodology energy management structure is shown in the following Fig. 4. The references for various systems in HRES are generated based on the equations given in Table 1 [31]. The proposed energy management technique is implemented in the MATLAB/Simulink platform and the effectiveness is tested for two different cases.

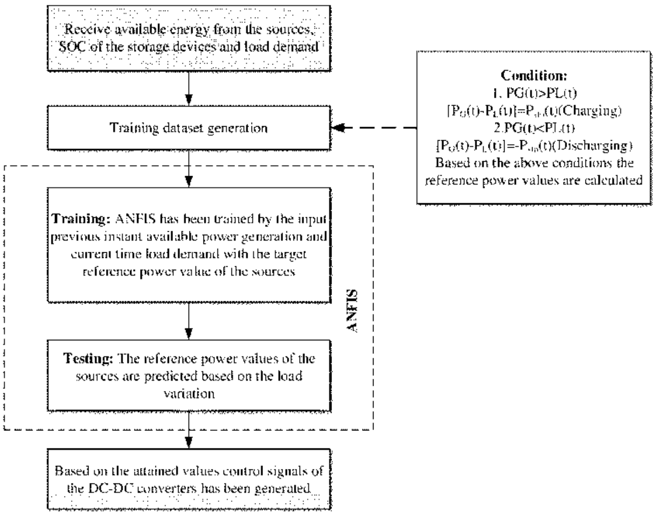


Fig. 2. Structure of the proposed energy management

Table 1. Reference calculations

Power Source	Power control
DC-link	$P_{dc\_ref}(t) = V_{dc\_link} I_{dc\_ref}$
PV	$V_{PV\_ref}(t) = P_{PV\_MPPT} / I_{PV}$ or P_{PV_Limit} / I_{PV}
Wind	$V_{WT\_ref}(t) = P_{WT\_MPPT} / I_{WT}$ or P_{WT_Limit} / I_{WT}
Battery	$I_{BAT\_ref}(t) = P_{BAT\_ref} / V_{BAT}$
Fuel Cell	$I_{FC\_ref}(t) = P_{FC\_ref} / V_{FC}$
Ultra Capacitor	$I_{UC\_ref}(t) = P_{UC\_ref} / V_{UC}$

4. Power Quality Improvement

In this paper a Synchronous Static Compensator (STATCOM) is employed for the voltage regulation and to compensate the harmonics. It is a class of Voltage Source Converter based FACTS device which is a controlled reactive power source consisting of a VSI [38, 39]. It is a shunt connected device used for voltage control, power factor correction, load balancing and harmonics compensation by providing reactive power [40]. In this Paper, for the power quality analysis a diode bridge rectifier with Resistive load is used as a nonlinear load and linear loads of RL loads are switched at different times. The analysis was made to mitigate the harmonics introduced by the nonlinear load.

5. Results and Discussion

This section explains the experimental outcomes of the proposed algorithm implemented in a machine with Intel(R) core(TM) i5 processor, 4GB RAM and MATLAB/Simulink 7.10.0 (R2015a) platform. The proposed energy management is designed for the HRES system in Fig. 1 and the effectiveness of the proposed method is analysed in two test cases. The designed model of the HRES configuration is described in Table 2.

The proposed method predicts the reference power of the sources depending on the load variation. For this purpose, the proposed method requires the previous instant generated power from the energy sources and the current time load demand. The generated power higher than the load demand means, the excess amount of power is allowed for charging of the storage devices. But the generated power lesser than the load demand means, the required power is discharged from the storage devices.

Table 2. Simulation parameters of HPS

Parameters	Values
PV rated power	3.78 kW
PV open circuit voltage	64.2 V
PV short circuit current	5.96 A
WT rated power	1 kW
FC rated power	1.26 kW
FC nominal stack efficiency	55%
Battery nominal voltage	26.4 V
Battery rated capacity	6.6 Ah
UC rated voltage	16 V
UC rated capacitance	500 F

The proposed method's effectiveness is verified through two different test cases like input power generation variation and output load variation. Initially the proposed method is verified through the input power generation variation but the load value is constant 6 kW nonlinear load (diode rectifier with R load). The required reference load demand is described in Fig. 5. According to the first test case, the irradiation of the PV system is shown in Fig. 6. Based on the irradiation level, the output power generated from the PV is described in Fig. 7. The output power of the PV generator is varied between 1.6 kW to 3.6 kW. The maximum power of the PV is extracted at the period 0.25 to 0.85 s and 2 to 3 s. The minimum power generation is attained at the period 1.25 to 1.5 s. At this time, the required load demand is satisfied by utilizing PV, WT output power and storage devices output power. The MPPT of the PV generation system is attained from the traditional P&O technique. The generated power from the WT is illustrated in Fig. 8. The MPPT of the WT is attained by using the traditional P&O MPPT technique.

The FC output power utilized for the testing condition is described in Fig. 9. It shows that the fuel cell power utilization is increased from the period 1.25 to 1.5 s, during which the reduced power generation from the PV system. The FC voltage and current are described in Fig. 10. The UC output power based on the load demand and input available power generation is described in Fig. 11. The maximum power discharged from the UC during the time period 1.25 to 1.5 s and after that constant power only utilized from the UC. The power of the UC is 550 W at 0.25 to 0.85 s and 2 to 3 s. The voltage, current and state of charge (SOC) of UC are described in Fig. 12. It is clearly shows that the SOC of the UC is reduced from the 92% to 90% from the period 0.5 to 3 s. The battery power utilized by the energy management scheme is shown in Fig. 13. The battery SOC, current and voltage are illustrated in Fig. 14. The final power outcome of the available energy sources are depicted in Fig. 15. The required load demand is mentioned as the reference power in Fig. 16. Here, the required load demand is 6 kW, which is satisfied from the available energy sources and storage devices.

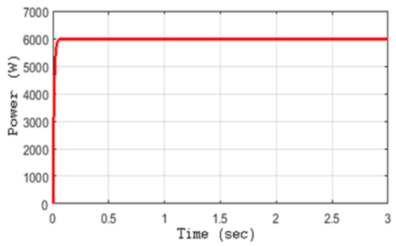


Fig. 3. Load demand of the first test case

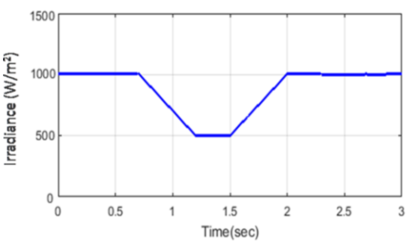


Fig. 4. PV generator irradiation

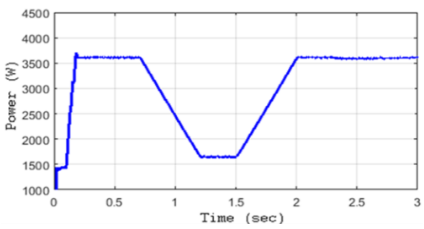


Fig. 5. PV generator output power

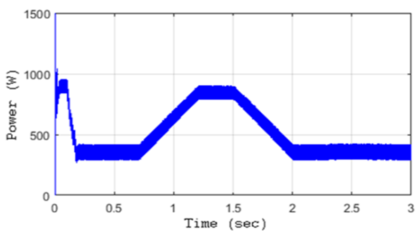


Fig. 6. WT output power

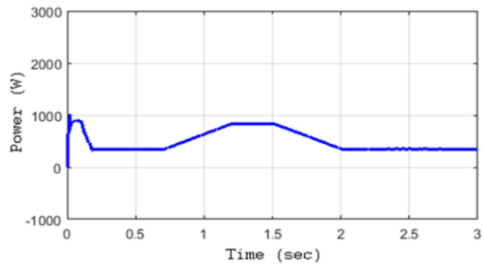
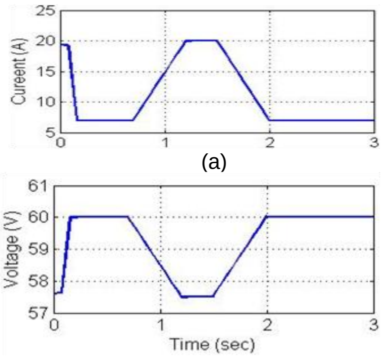


Fig. 7. FC output power



(b)

Fig. 8. FC (a) current (b) voltage

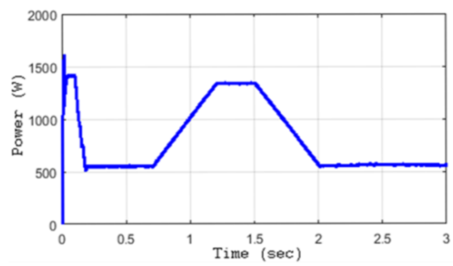


Fig. 9. UC output power

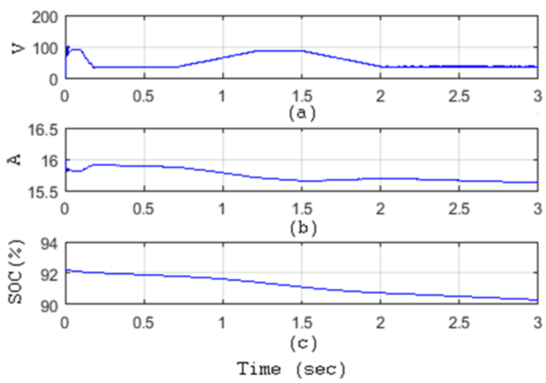


Fig. 10. UC (a) voltage (b) current (c) SOC

The effect of connected nonlinear load (diode rectifier) on the source side current is shown in Fig. 17(b). The current is distorted due to nonlinear load and has a THD content of 29.97%. The current shape is improved by the action of STATCOM which is shown in Fig. 17 (c) and has a THD value of 2.26%. The respective compensation current produced by the STATCOM is shown in Fig. 17 (d). The load demand is constant in this test case, so that the voltage magnitude is not affected. The real and reactive powers for the first test case without STATCOM and with STATCOM are shown in Fig. 18. It can be seen that the reactive power is compensated by the STATCOM, which is shown in Fig. 18(d).

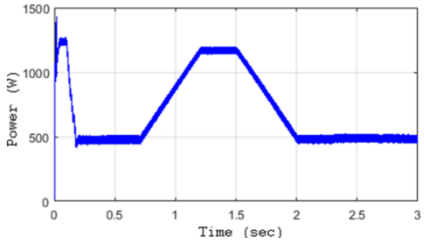


Fig. 11. Battery output power

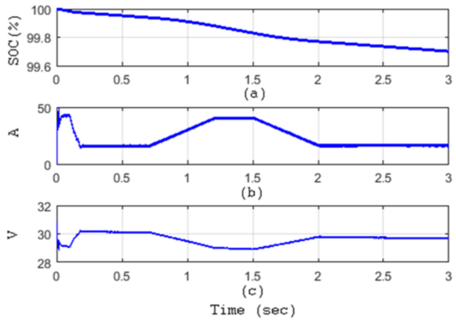


Fig. 12. Battery (a) SOC (b) current (c) voltage

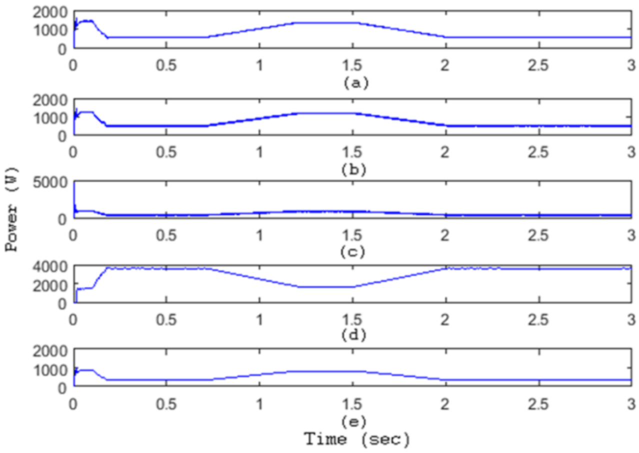


Fig. 13. Power produced from (a) UC (b) Battery (c) FC (d) PV and (e) WECS

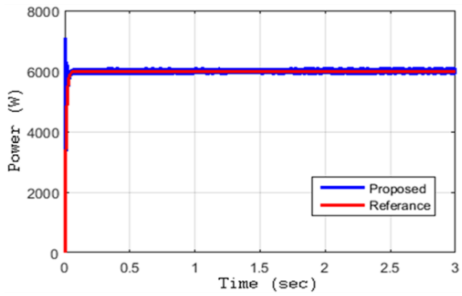


Fig. 14. Total power generation with reference

The second test case has been conducted by using the loads i) 6 kW resistive load connected through a diode rectifier during 0 to 3 s ii) a RL load of 500 W active power is connected during 0 to 1 s and iii) a RL load of 1.3 kW during 2 to 3 s as shown in Fig.19. In that the condition, the constant irradiation and wind power are considered.

In the second test case, the irradiation and PV power is illustrated in Fig. 20 and 21 respectively. The maximum power is extracted from the PV during 0.25 to 1 s. The maximum power extraction is not required at the time period 1 to 2 s because the load value is decreased from the 6.5 kW to 6 kW. At this time the PV power is maintained at 3.5 kW and again the maximum power of the PV has been extracted at the period 2 to 3 s (3.78 kW). The power output of the WECS is shown in Fig. 22. The WECS output power is maintained at 900 W to 910 W. The FC output power extracted using the proposed energy management technique is described in Fig. 23. The voltage and current magnitudes of the FC are illustrated in Fig. 24. The UC power sharing at the second test case using the propose energy management technique is illustrated in Fig. 25. The UC power is 750 W at the time period 0.2 to 1 s. The power consumption from the UC is reduced to 550 W at the time period 1 to 2 s. After that the power extraction from the UC is increased to 900 W because the load value is high at the time period 2 to 3 s.

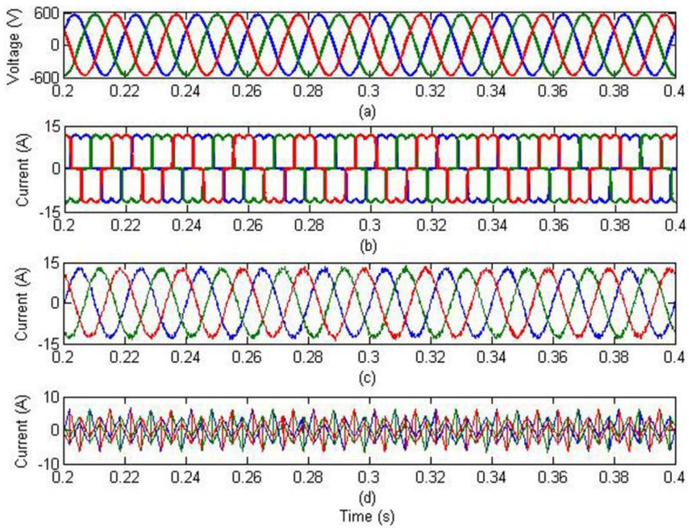


Fig. 17. (a) Inverter Voltage (b) current with diode rectifier load (c) current with compensation (d) Compensating current

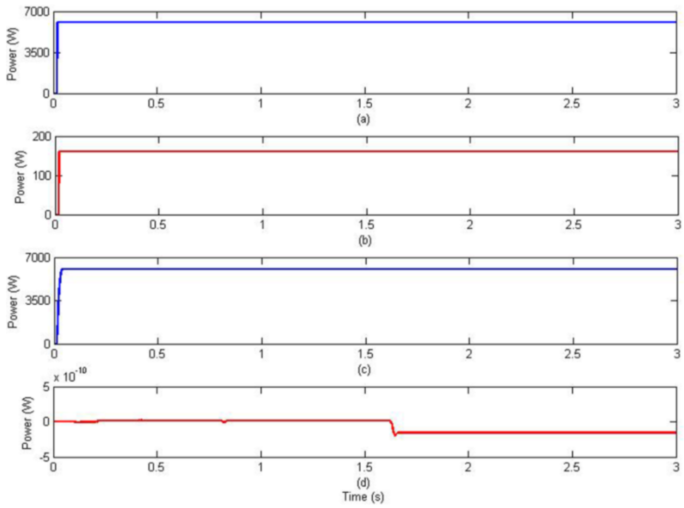


Fig. 18. Real and reactive powers (a), (b) without compensation and (c), (d) with compensation

The voltage, current and SOC of the UC is described in Fig. 26. From the Figure it is understood that the SOC of the

UC is gradually reduced from the 92% to 90% at the time period 0 to 3 s. The battery output power using proposed energy management is shown in Fig. 27. The battery output power utilization depends on the load variation. The battery SOC, current and voltage are depicted in Fig. 28. The power produced from the energy sources and storage devices is shown in Fig. 29. The total power generation by using the proposed energy management technique with the required load demand is illustrated in Fig. 30. The proposed ANFIS technique effectively manages the load demand by properly calculating the reference values for the sources and storage devices. In Fig. 31, the current waveforms without compensation and with compensation for the diode load connected are shown for the period 1.9 s to 2.1 s.

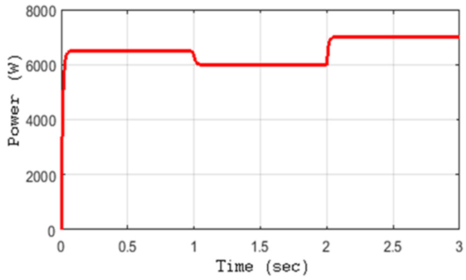


Fig. 159. Load demand of the second test case

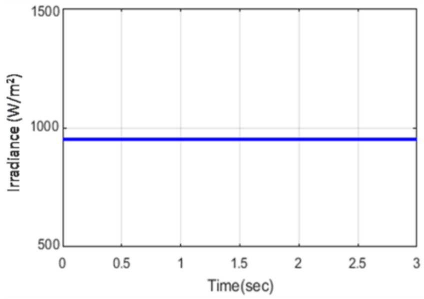


Fig. 20. PV generator irradiation

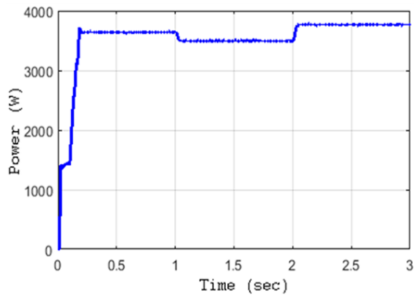


Fig. 21. PV output power

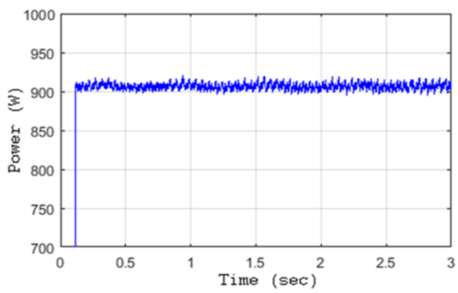


Fig. 162. WT output power

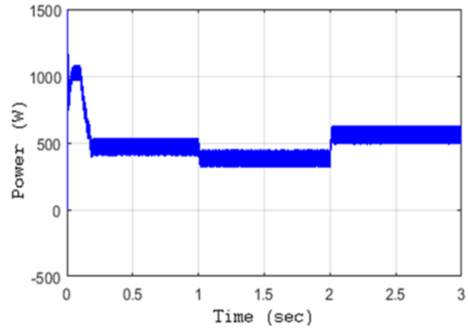


Fig. 23. FC output power

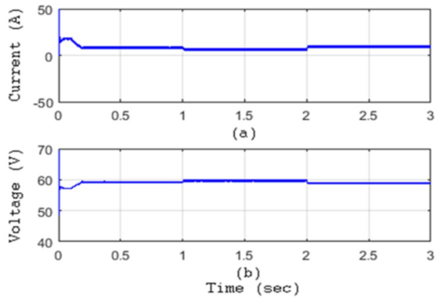


Fig. 24. FC (a) current (b) voltage

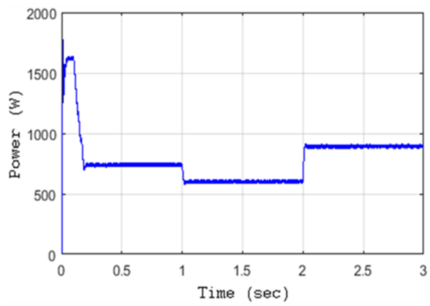


Fig. 175. UC output power

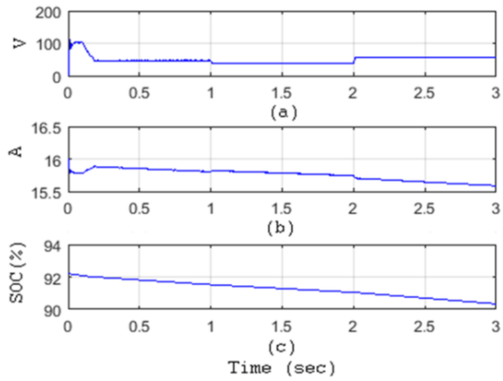


Fig. 186. UC (a) voltage (b) current and (c) SOC

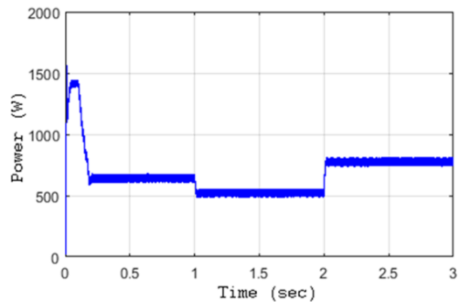


Fig. 27. Battery output power

The current THD without compensation is 27.92% and with compensation is 1.94%. The THD values are lesser than the first test case, because of RL loads connected in second test case. Voltage variations in the microgrid due to inclusion and exclusion of loads are also taken care by the STATCOM. Here the load variations are small, so that the voltage profile is not getting affected much and small variations are compensated by the fast action of STATCOM. The real and reactive power of the system under two cases ie., without STATCOM and with STATCOM for the second test case are depicted in Fig. 32.

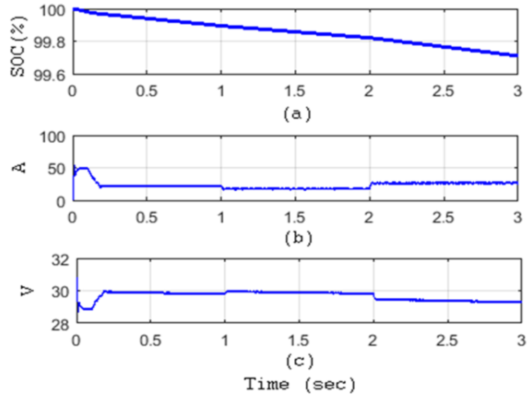


Fig. 28. Battery (a) SOC (b) current (c) voltage

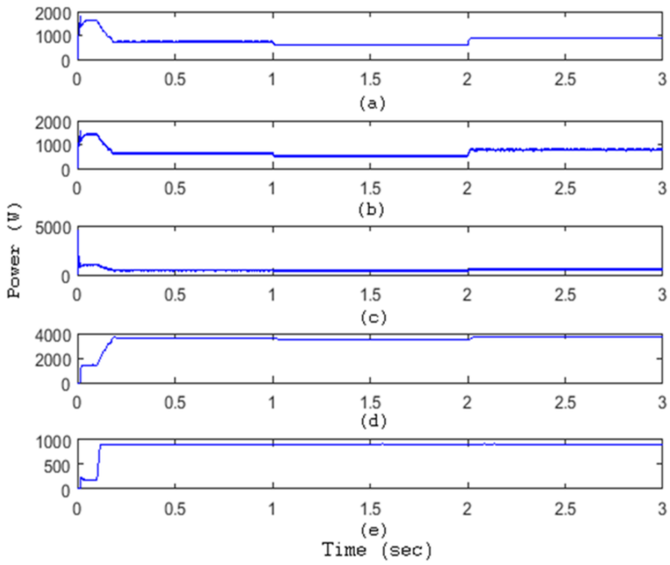


Fig. 29. Power produced from (a) UC (b) Battery (c) FC (d) PV and (e) WECS

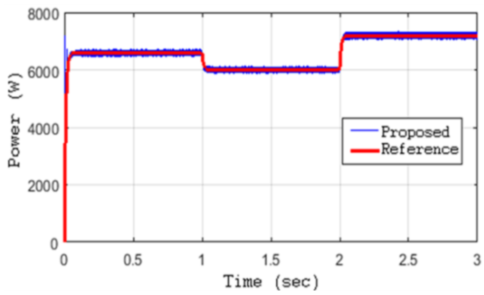


Fig. 30. Total power generation with load power reference

The proposed ANFIS based energy management scheme identifies the power requirement and the available energy generation and finds the reference power values of the sources. Once, the renewable energy sources are failed to produce the required quantity of the power requirement means, the proposed control scheme manages the power requirement by utilizing the storage devices. Power quality issues of standalone HRES system such as harmonics due to nonlinear loads and voltage variations due to sudden switching of loads are also addressed by using the D-STATCOM.

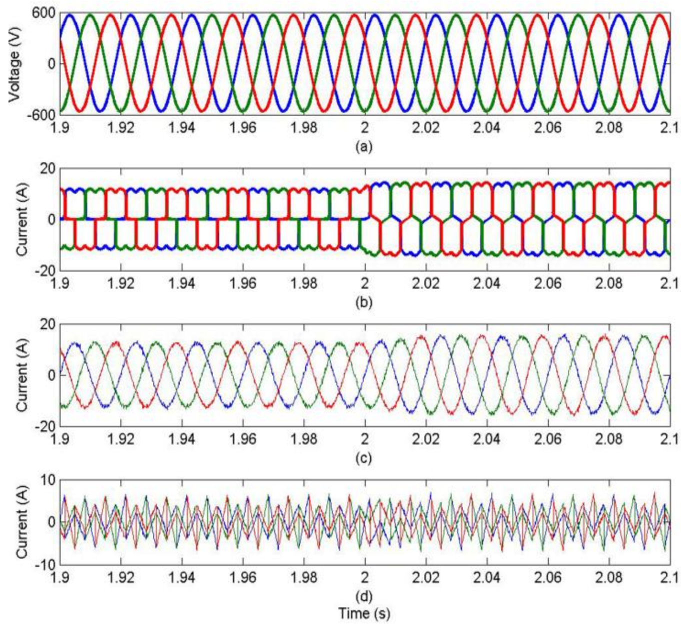


Fig. 31. (a) Inverter Voltage (b) current with diode rectifier load (c) current with compensation (d) Compensating current

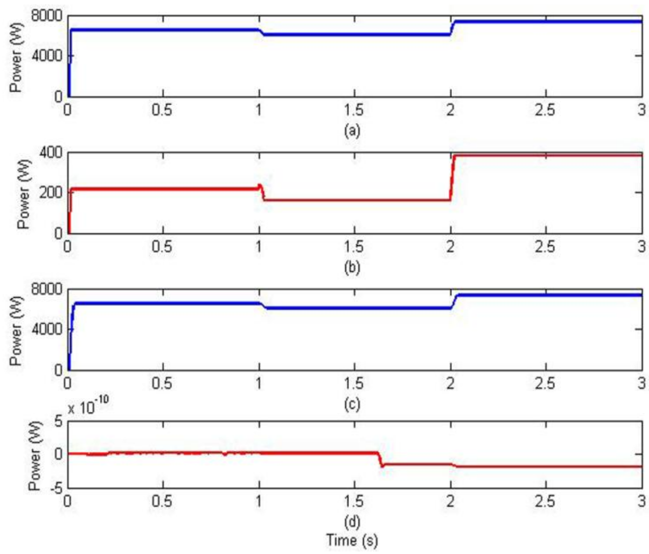


Fig. 32. Real and reactive powers (a), (b) without compensation and (c), (d) with compensation

6. Conclusion

This paper proposed the ANFIS based energy management technique for the HRES connected with the ac load. The benefit of the suggested method includes the improved prediction ability and the lesser complexity in attaining the optimal values. The HRES have been developed with the help of the PV, WT, FC, UC and the battery. The proposed method identified the reference power for the energy sources based on the power values from the sources at previous instant and the load requirement at current instant. The control signals were developed as per the variations of the ac load. Then the proposed method was implemented and the simulated results are presented. The effectiveness of the proposed ANFIS based energy management method have been analysed with continuously varying environmental inputs and load conditions. From the analysis, it is evident that the proposed method effectively managed the power flow among HRES elements, and is proficient.

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