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Design of Efficient Storage Unit and EP-ANFIS Controller for On-grid and Off-grid Connected PV-WT System

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Abstract

The controllers developed so far for the on-grid and off-grid operation is based on frequency regulation at grid and have yield poor switching by inducing oscillation. Hence to solve this problem in this paper, the switching between the on-grid and off-grid are made by the Emperor penguin based Adaptive fuzzy neuro inference system (EP-ANFIS) controller, which works based on the energy supplied to the load. To serve the transient load condition the hybrid storage unit is modelled by social-ski driver algorithm (SSD) that will schedule the energy supplement between the grid and generator. The proposed controller model provides stable operation during the switching process that is without the transient oscillation the switching is smooth. The error in data selection for the ANFIS is reduced by the Emperor penguin optimization (EPO) as 0.1 for the test data. The proposed work is implemented in Matlab/Simulink platform. The results are compared with the existing works in terms of voltage, current, power, and THD. When examining for transient load condition the settling time for the controller to the steady state is 0.78 s which is comparatively low with PID, PI, ANFIS, and ANFIS-PSO controllers. The THD is reduced to 9.11% from the existing methods by maintain the fundamental frequency of 50 Hz.

Keywords

ultracapacitor, fuel cell, power generation, on-grid system, off-grid system, energy scheduling, Emperor penguin optimization, social ski-driver optimization

1 Introduction

The use of RES is rapidly increasing all over the world for the electricity production. The inherent and intermittency nature of the RES (wind system) in the power grid harms its operation [1], which requires an improvement in the energy quality. Solar energy resources is a RES which has a negative correlation with wind energy resource [2]. The EMS monitors the power generated from the hybrid generator, which fulfills the load and the power stored in the storage device [3]. The battery is the most widely used storage device but, suffer from self-discharge and high maintenance cost [4].

The need for a power system is the transmission of generated power to the load in a highly efficient way without wasting energy and low-cost transmission. To overcome the high voltage problem the control system is used in the grid, which absorbs the active power [5]. The RES can operate in both grid modes but the problem is when to make the transition. To operate grid modes, several controllers are used by varying the considerations by the researchers. To have a frequency control on the grid side VSGA [6], droop controller [7] and sliding model controller [8] is used to adaptively switch between the on and off-grid modes based on the frequency but it have poor stability and failed for stable switching operation. Later, the basic controllers like PD, PI, PID controllers, adaptive controller, and fuzzy-neural control strategy are utilized for the same problem [9, 10]. The PD and PI controller provide poor stability, large transport delay, and noise present throughout the process whereas, the PID overcome these disadvantages. But it is not possible to change the grid mode in PID [11]. The above methods are stated for frequency deviation, none of the methods have used the power rise at the load side.

The ANFIS based controllers are used in the estimation of heating value [12] in biomass, mobile robot control [13], and also in many motor operations [14, 15]. The ANFIS controller is proving to a stable operation in discrete optimization. Due to the advantage of stable operation, the

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ANFIS is used for maximum power tracking [16] involving maximum power tracking.

To set the controller coefficients accurately, optimization techniques are required. PSO and GA [17] are the optimization techniques that provide premature convergence when designed with the controllers with high computational efficiency [18]. To reduce the high-power supply directly to the load a controller on the grid is essential, which works for the automated switching on the grid at high speed so that the high-power penetration on load is minimized. Along with this, the controller serves better under transient load condition. The power generated by the PV and wind system is unstable; hence a peak power may get generated traditional methods will manage the generated peak power by having complex circuitry, which leads to delay and high-power loss. Hence this paper presents a faster switching of grid connection when the generated voltage level oscillates.

In this paper, the EMS for RES is proposed by hybridizing the UC and FC, which stores the energy for efficient utilization by the consumer during off-grid and on-grid modes of operation. The microgrid is controlled by a novel Emperor Penguin based Adaptive Neuro-Fuzzy Inference System (EP-ANFIS) controller model where the data selection is performed by Emperor Penguin Optimization (EPO). The existing controllers like PI and PD have the problem of high overshoot and unable to response during the disturbance hence a controller that adaptively changes the grid mode based on the load demand with switching and stable operation is proposed. The paper is contributed as follows:

- Initially, to generate the power, a hybrid RES is utilized. Even though there are huge fluctuations in the generated power, it is essential to store the generated power so that it can be used during energy scarcity or when the load demands more power. By reducing the self-discharge and high maintenance cost of the existing storage unit a novel hybrid storage system is proposed.
- For efficient storage and to make scheduled energy charging and/or discharging ratio, an optimization algorithm is used. The algorithm describes how the generated energy is charged in the storage system and similarly, discharging to the distributed grid.
- Then, a novel EP-ANFIS controller is used at the grid to control the heavy power flows directly to the load. The designed controller will avoid the flow of high power on the load, which affects the devices or equipment that are connected to the power supply on the load side.
- Based on the fuzzy logic the controller performs switching between the modes of the grid, thereby conserving the power at grid, and reducing the energy wastage.

The rest of the paper is organized as follows. Section 2 explains the recently developed techniques related to the presented work. The proposed work is clearly explained in Section 3, and the corresponding result analysis is done in Section 4. Finally, the work is concluded in Section 5 with future suggestions.

2 Related works

In Section 2, a brief description of the works that are relevant to the presented work in terms of RES power generation system, storage units, grid controllers, and ANFIS controller are presented.

Das et al. [19] and Thounthong et al. [20] utilized a hybrid wind, PV power generation system with the FC for storing the energy. A dc-dc converter controlled the FC to satisfy the load when the generator failed to meet the load power. Hence and an auxiliary storage device is used.

By focusing on the grid-based control for energy management, Moafi et al. [21] presented the FFOPID. It can analyze and simulate the dynamic behavior in grid-connected microgrids. The FFOPID controller was designed to reduce the frequency fluctuation and transient load effect. Based on FFOPID, the energy storage unit injects the active power to control frequency by balancing production and consumption. So, the microgrid was set with a limited frequency thereby reducing the power fluctuation, the FFOPID controller reduces the error occurrence in the system. The utilized controller does not work for the changes in grid-connected modes; hence for that problem, Basaran et al. [22] used the PV-WT as the power generation system to operate on both off-grid and on-grid systems. The gel batteries are used to store the energy generated from the hybrid generator and to deliver the energy stored to the load. The hybrid system operates in the on-grid and off-grid mode using the control unit named FLC. That model was efficient and had annual energy of about 2500 kWh/year, but there was a harmonic in the voltage and current at the output power.

On the goal of having regulated frequency control on the grid, Mishra et al. [23] proposed various controller schemes. Initially, the hybrid FOFPID and LQG controller with the MVO algorithm were employed. For the operation of a multi-microgrid system, the power sources like PV-WT and synchronous power generator are utilized with the integration of hybrid battery and flywheel energy storage devices. The optimized controller design has reduced the fluctuation of system frequency in the presence of load. This FOFPID-LQG with the MVO was compared with the PSO and GA. Secondly, a model for the frequency regulation-based control of microgrids using a 2dof PID controller [24] was designed. The supplement to the microgrid is provided by the PV, WT, and diesel generator, where the energy was generated and stored in the hybrid storage system consisted of BES and flywheel. Under stochastic disturbance, the frequency of the grid was controlled by the hybrid dragonfly and pattern search optimization algorithm. Then to control the inertia on the grid at islanded mode by regulating the system frequency was presented by Mishra et al. [25]. The model employs the virtual inertia control technique and for the selection of the inertia gain, the SSA was used. Then the model is used with the PID-based islanded mode control of the microgrid.

To analyze the effectiveness of the ANFIS controller, Suleymani and Bemani [12] utilized the ANFIS controller for the estimation of heating values in biomass, a RES. The HHV was predicted by the volatile matters, carbon, and ash content obtained during the burning process. The ANFIS controller was used with the PSO algorithm due to the local optima problem related to the PSO, the controller yields poor HHVs. Then Benhalima et al. [26] used the ANFIS controller to control the DC-DC boost converter. The boost converter was interfaced with the PV power generator to yield the maximum power. To have a faster response without the saturation in the DC and AC voltages the controller was used with perturb and observe technique. The controller has several number of parameters, but there was no optimum design of parameter, which makes the model complexity during analysis. The ANFIS controller has benefits not only with PV and biomass but on WT power generators. To control the blade pitch on WT against the wind velocity fluctuations Elsisi et al. [27] employed the ANFIS controller. The data to the ANFIS controller was tested and trained by the MOA, which would reconstruct the whole data used for the control strategy. The robustness of the controller was verified by the Hermite-Biehler theorem. But the optimized controller faced the issue of maximum setting time, which leads to the use of another system model in it tending to the complexity issue. The Table 1 gives the comparison of State-of-the-art techniques.

Although many controllers are designed to control the generated power supply to the load with the storage device, they faced the problem of poor data setting process as well as the unsuitable use of controller technique that tends to complexity related issues. When the system operated on RES, the power generated is not constant like the load. As per our knowledge, none of the work has considered the issue of grid connection with the load during high power supply from the generation side, which makes a huge impact on the load and considered as the optimization problem. It is known that the grid will control the high-power flows to the load but on off-grid connection, the high power from the source has-to be solved. Hence this paper solved the issue which occurs during high power supply from the source at off-grid connection by switching it to the on-grid mode.

The switching between the grid modes is essential to reduce the wastage of energy thereby, reducing cost issues also, the switching makes a stability problem in the power system. When the hybrid power system is working for grid connection the switching between off-grid and on-grid is based on the available energy; since the power from the RES system is not continuous similarly, the load is not constant. To formulate these issues, a controller with aforementioned constraints is designed such that the controller can provide energy when the available energy is comparatively smaller than the load as well as the available energy is higher than the load. The controller will test energy on both sides and accomplish the load.

3 Design model

3.1 Power generation

Here, the hybrid energy sources that are used to generate power are PV and WT. The PV system can be modeled by arranging the PV modules to form a PV array. Here every PV module is subjected to the radiation of 1000 W/m². The generated power in the solar system depends on the cell temperature. The power in the PV system is given by:

$$P_{\mathrm{PV}} = P_{\mathrm{PV,rated}} \times I/1000 \times \eta. \tag{1}$$

The power in the WT is given by the velocity of the wind. With the changes in wind velocity the power generated from the WT will get affected. The power in the WT is expressed as:

$$P_{\mathrm{WT}} = \frac{\rho A V^3 C}{2}. \tag{2}$$

Equation (2) is satisfied when the velocity of the wind is between the cut-in and cut-out velocity unless the power is nullified.

Table 1 Comparison of State-of-the-art techniques

Author	Method	Optimization	Objective	Grid connection	Generators used	Description
Moafi et al. [21]	Fuzzy fractional-order proportional-integral-derivative controller	-	Frequency stabilization	Islanded microgrid	WT	Model works only in microgrid system. The controller fails when the high-power supply is connected.
Basaran et al. [22]	Fuzzy logic controllers	-	RES power management	On-grid and off-grid mode	PV and WT	Highly deviated frequency at grid.
Mishra et al. [23]	Fractional order fuzzy PID-linear quadratic Gaussian	Multi-verse optimization	Load frequency control	On grid mode	PV, WT and synchronous generator	The quadratic function does not support when there is a disturbance
Mishra et al. [24]	Two-degree-of-freedom PID	Hybrid dragonfly and pattern search optimization	Frequency regulation	On-grid	PV, WT and diesel generator	Highly distorted signal in on-grid (high THD)
Mishra et al. [25]	Virtual inertia control	Salp swarm optimization	Frequency regulation	Islanded microgrid	PV, WT and diesel generator	The control model requires separate inertia setting so not suitable for utility connection
Benhalima et al. [26]	Adaline based adaptive neuro fuzzy interference system	-	Power quality improvement	On-grid	PV	Can be able to handle small power generation system.
Elsisi et al. [27]	Adaptive neuro fuzzy interference system	Mayfly optimization	Stability at wind speed fluctuation	On-grid	WT	Highly stabilized output. Have not justified the off-grid connection.
Suleymani and Bemani [12]	Adaptive neuro fuzzy interference system	Particle swarm optimization	Estimation of heating value	-	Biomass generator	Accurate estimation and control.
Proposed	Adaptive neuro fuzzy interference system	Emperor penguin optimization	Stability improvement	On-grid and off-grid	PV and WT	Stabilized at both on and off-grid with very low harmonics. Adaptable to multi-generating system.

3.2 Optimization of storage device using Social Ski-Driver (SSD) method

SSD is a metaheuristic-inspired optimization technique that mimics the path taken by ski drivers downhill. Consider the storage device UC and FC with the capacity U_i and F_i having maximum fitness value. FC's capacity is 600 to 2160 Wh/day, whereas the capacity of carbide-derived carbon UC is 10.1 Wh/Kg for 3500 F capacitance. The device with high capacity will get the first energy flow, i.e., $U_i > F_i$ then the energy charged in the UC, until $U_{i+n} = 0$ when this condition is satisfied, the energy gets flows into the FC. By using a Social Ski-Driver optimization algorithm, we have better exploration capabilities. Whereas, the other optimization algorithm has a local optima problem also, many of the optimization algorithms have faced problems in discrete operational condition, which is not found in the presented SSD algorithm. The energy flows to the storage unit and grid are always discrete not continuous, the optimization problem can be solved only by the discrete optimization algorithm. The fitness of the proposed model is given by:

$$\text{fitness function} = E/E_{\max} . \tag{3}$$

Assuming that we can store the energy as per the capacity of the device, hence the State of Charge (SOC) is a constant one. The capacity of the storage device (C_i) is the storage devices capacity which is used to calculate the amount of energy that have been stored in the device. Current capacity (C_c) is the fitness value for the device capacity which is calculated by a fitness function. The fitness value is compared with the current capacity, and the storage unit's available capacity is loaded.

$$M = \frac{C_i + C_c}{2} \tag{4}$$

Energy flow (E_i): the storage device capacity is uploaded by subtracting the energy flow:

$$C_i^{t+1} = C_i^t - E_i^t. \tag{5}$$

E_i is expressed as:

$$E_i = P_{\text{PV}} + P_{\text{WT}}. \tag{6}$$

In SSD, the capacity of the storage device is initialized, and the number of the storage device is defined by the user (here the storage units are 2, UC, and FC).

The proposed model's flow is given in Fig. 1 at which SSD-based energy management is given in proper flow. Initially, the storage capacity of UC and FC is compared to each other. If the UC contains high capacity than the FC, energy will initially be stored in the UC. If the incoming energy is greater than UC's capacity, remain energy will be stored in FC.

The energy flow into the storage devices is not unidirectional, which gives the SSD algorithm more exploration capabilities. The SSD algorithm will optimize the storage capability of the storage unit which will make efficient scheduling of power to the load by the controller.

3.3 Emperor Penguin based Adaptive Neuro-Fuzzy Inference System (EP-ANFIS)

The overall processing steps in the proposed design is briefly provided in Fig. 2. At PV and wind terminals a regulator is used to regulate the voltage obtained from RES. UC and FC are used to store the energy, and its energy management is performed with the help of the SSD algorithm.

Since the load is transient, the heavy power demanded by the load is stopped suddenly at that time the grid has to provide low energy from the already delivered energy level. This requirement on the power system is fulfilled by the novel EP-ANFIS controller. The power supplied to the grid is controlled by means of switching operation of controller. The energy level to the grid is processed by the EPO and the off-grid and on-grid selection are made by the ANFIS controller. The sudden switching between the grid modes may induce the stability problem, but the proposed controller makes smooth switching with a high degree of convergence.

For better data selection, EPO is used, and to train and test the selected data based on the set of ANFIS rules, EPO is modeled with ANFIS. The EPO will give the optimum

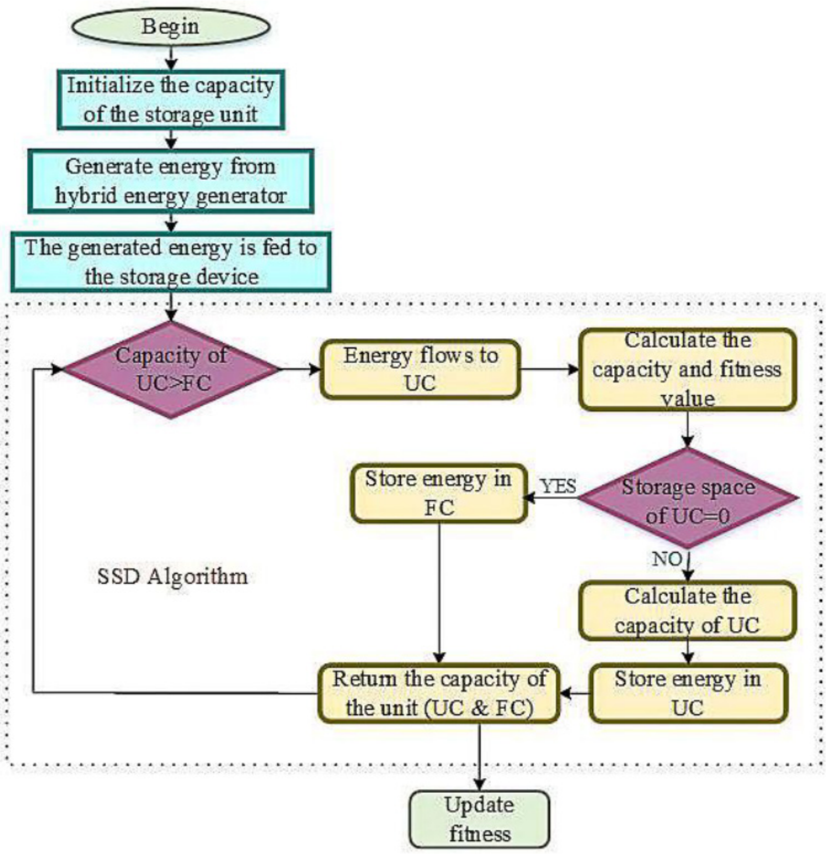


Fig. 1 Flowchart of SSD in energy storage

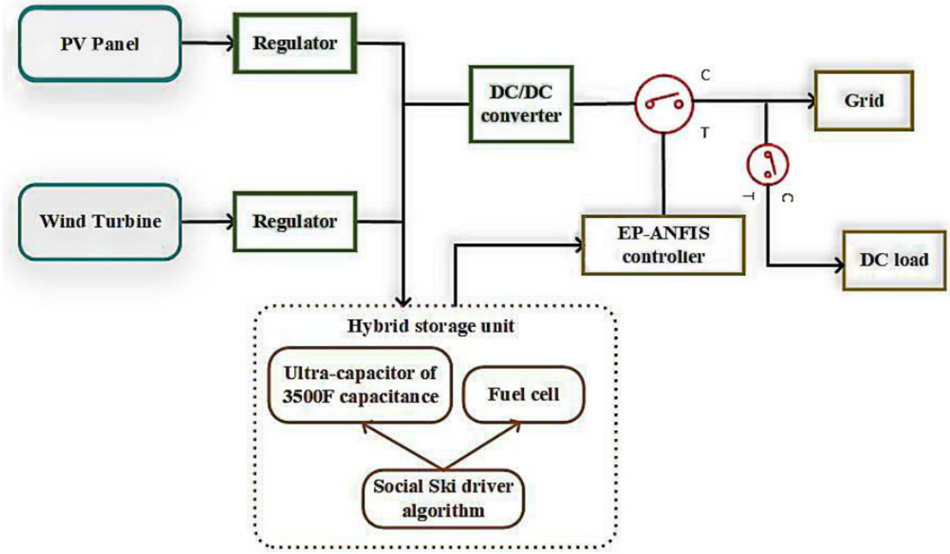


Fig. 2 Block diagram for the hybrid power system with SSD and EP-ANFIS controller

input data, and ANFIS will control the data and train it to acceptable by the grid. It is a hybridization of EPO and ANFIS; hence the name Emperor Penguin based Adaptive Neuro-Fuzzy Inference System (EP-ANFIS).

EPO is used for the data selection process since the EPO works on the life-saving process of the emperor penguin. Here, the error rate is null, which is a primary requirement for the data reconstruction process. But on other algorithm, the noise will get added into the data, which makes the controller operate in the worst condition. The input data values are calculated to find the best solution to the ANFIS. Based on the current optimal solution the other data will get update their voltage, which is defined as:

$$D_b = S * r * P_{opt}(n) - c * P_d(n). \tag{7}$$

The next voltage of input is given by:

$$P_{opt}(n+1) = P_d(n) - A * D_b. \tag{8}$$

The fitness function is given by:

$$I_d = P_{\max} - \frac{\text{Max}_{\text{iteration}}}{n - \text{Max}_{\text{iteration}}}. \tag{9}$$

ANFIS is an intelligent hybrid system with the fusion of neural networks and fuzzy reasoning to make a multi-dimensional description. The ANFIS can solve the nonlinear characteristic of a process hence the model is used for the control over nonlinear behavior of load. The faster convergence properties make the model more useful for the present work i.e., the faster switching will be obtained by the ANFIS controller. During the transient load condition, the controller performs better than the other basic controllers like PI, and PD. Consider the system with two inputs a and b as voltage and current, having one output e as power. Based on Takagi-Sugeno fuzzy model:

- *Rule 1*: if a is $A1$ and b is $B1$, then $f_1 = P_1 a + Q_1 b + R_1$;
- *Rule 2*: if a is $A2$ and b is $B2$, then $f_2 = P_2 a + Q_2 b + R_2$;
- *Layer 1:* The two inputs a and b are given to the layer 1 node to find the membership function with $i = 1,2$. The membership function can be given by:

$$L_i^1 = \delta_{Ai}(a), \tag{10}$$

$$\delta_{Ai}(a) = \frac{1}{1 + \left(\frac{a - z_i}{x_i}\right)^{2y_i}}. \tag{11}$$

We choose the membership function of the fuzzy logic is the bell-shaped function i.e. when the value is maximum, then on-grid and for minimum value is off-grid. The parameters $\{x_i, y_i, z_i\}$ are the premise parameter set.

- *Layer 2*: In this layer, the membership function of two inputs (voltage and current) with the i^{th} node is multiplied, which means it multiplies the incoming signals and return the product one.

$$W_i = \delta_{Ai}(a) * \delta_{Bi}(b), \tag{12}$$

where $i = 1,2$. The output of this layer represents the degree of fulfilment.

- *Layer 3*: In this layer, the degree of fulfilment at a particular node to the sum of all degree of fulfilment rules is calculated.

$$M_i = \frac{W_i'}{W_1 + W_2} \tag{13}$$

The output of this layer is the normalized degree of fulfilment.

- *Layer 4*: The parameter is the consequent parameters. By Takagi-Sugeno type output:

$$L_i^4 = M_i * f_i, \tag{14}$$

$$L_i^4 = M_i * \left(P_i a + Q_i b + R_i\right). \tag{15}$$

- *Layer 5*: The output of this layer is the power for the supply of on-grid and off-grid. It is the summation of the output of all nodes.

$$z = L_i^5 = \sum M_i * f_i \tag{16}$$

$$z = L_i^5 = \frac{\sum W_i' * f_i}{\sum W_i} \tag{17}$$

$W_i = \delta_{Ai}(a) * \delta_{Bi}(b)$ is the membership function of inputs. The rules to check whether the control unit (EP-ANFIS) is connected to on-grid or off-grid is given by.

The EPO data undergoes ANFIS, where the energy that has to be given to the on-grid and off-grid is tested and then selected for transmission. The above-shown Table 2 does this process of selection. In off-grid mode, only low load power can be transmitted, whereas high power can be transmitted in on-grid. Thereby, the energy that wants to be delivered by the on-grid and off-grid is controlled by the EP-ANFIS controller. Hence the proposed system provides low computational time and high efficiency.

4 Result analysis

Proposed work is implemented in Matlab Simulink working platform. In Section 4, the grid mode selection is analysed in terms of voltage power and current, along with the harmonics present in the power delivered to the load. The proposed controller model is compared with the PI, PID and ANFIS-PSO controller. Then at last, the transient characteristics of the controller during the switching of grid modes are also evaluated.

Table 2 For Grid selection

Voltage	Current	Grid connection
High	High	ON-Grid
High	Low	ON-Grid
Low	High	ON-Grid
Low	Low	OFF-Grid

4.1 Simulation settings

Fig. 3 (a) and (b) indicates SSD-based energy management and EP-ANFIS controller for both off-grid and on-grid system. In on-grid conditions, the grid is connected to the entire set-up, and the analysis of voltage, power, and current is performed. Likewise, voltage, power, and current analysis are performed for off-grid conditions in which the grid is not connected to the Simulink block. The parameter illustration of the Simulink model is given in Table 3.

The power stored in the hybrid storage unit is represented in Fig. 4. The energy generated from the PV-WT is stored in the storage unit. When the more demand is accessed by the load then the energy from the storage unit will get the dropped depending on the power production and vice versa for the low demand time.

4.2 Analysis of off-grid and on-grid mode

The voltage and power delivering rate on both on, and off grid mode is illustrated in Section 4.2. Figs. 5 and 6 represent the voltage, current, and power analysis of proposed work under off-grid and on-grid mode, respectively. Here, the voltage, current, and power curves are not smooth in Figs. 5 and 6, which is the reason for THD and this effect can be reduced with the help of an EP-ANFIS controller.

Here the Table 4, gives the comparison of voltage, current, and power levels in off-grid and on-grid mode by the PI, PID, and ANFIS-PSO method with the proposed EP-ANFIS controller. Here, PID, PI and ANFIS-PSO optimized controllers are taken for the controller comparative methods and the PSO, GA, and MOA are used to compare the data selection for the operation of the controller.

The frequency deviation during the switching between the grid-mode is given in Fig. 7. At 0.45 to 0.5 s, the switch is connceted to grid with the voltage level of 2×10^4, this is a slight change in voltage value before 0.45 s hence there is a fine deviation in frequency. While heavy fluctuation is seen at the interval of 0.7 s due to the switching from on-grid to off-grid. In contrast, this switching is varied heavily for other controllers due to the lack of disturbances handling capacity.

Fig. 8 gives the comparison of the data selection made by the optimization algorithms for the ANFIS controller. During the data selection, the other algorithms like GA [23], PSO [17], and MOA [23] makes more error when compared to the training data. Hence the total output will get affected but in the used EPO method the error produced after training the test data is approximately zero,

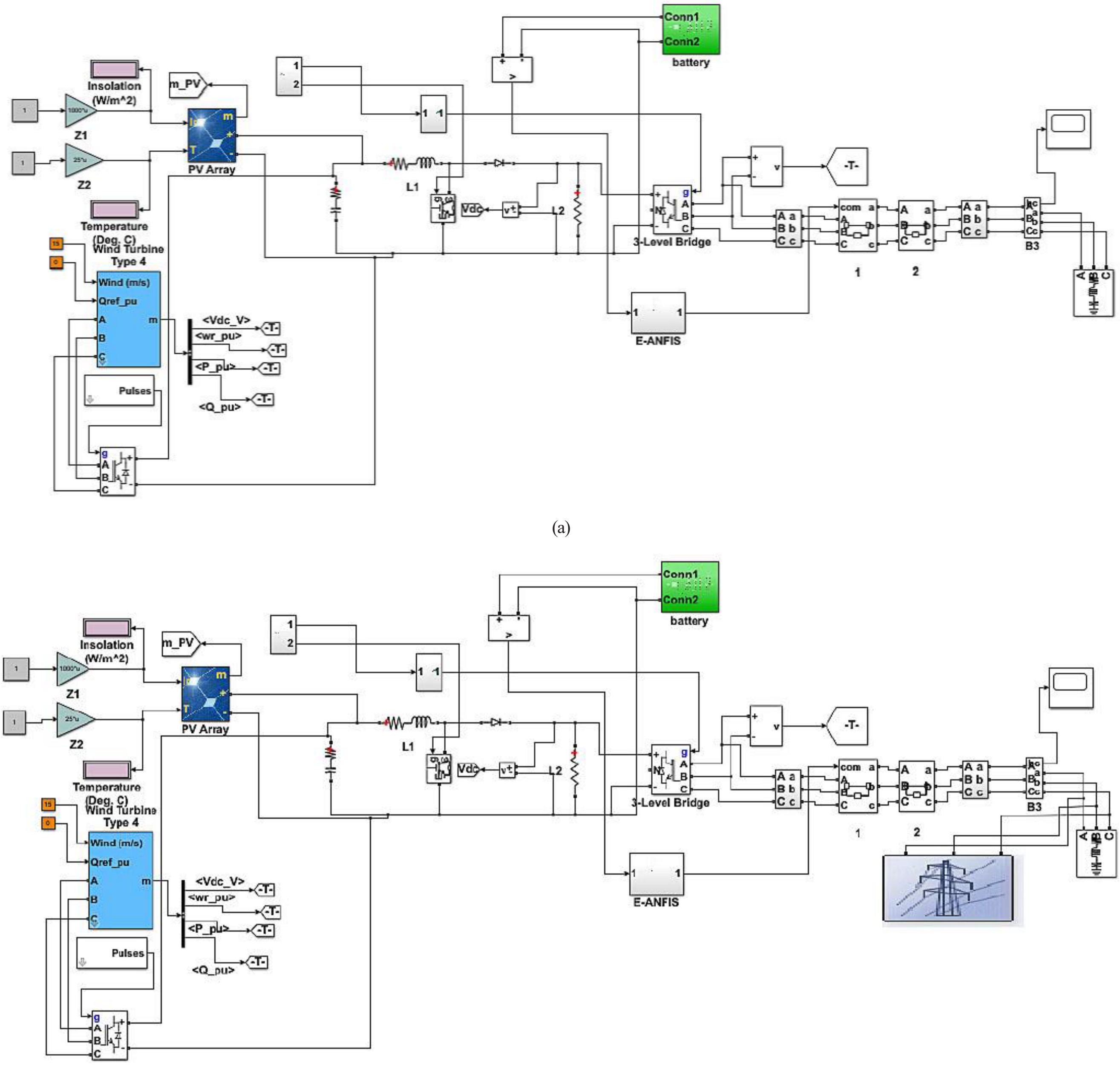


Fig. 3 Proposed Simulink Block; (a) off-grid; (b) on-grid

Table 3 Simulation parameters

Parameters	Specification
PV Irradiation and Temperature	1000 W/m^2 and 25 °C
Wind Speed	15 m/s
Active power of RLC Load	500 W
Inductive Reactive power of RLC Load	100 W
Capacitive Reactive power of RLC Load	100 W
Grid Voltage	600 V
Grid Power	0.42 × 10^4 W
Maximum load power	4.3 × 10^5 W
Minimum load power	5025 W

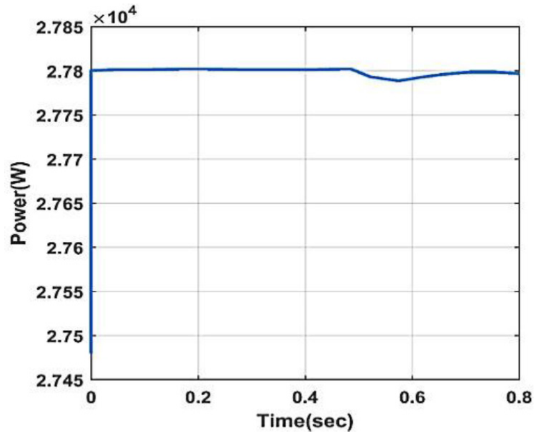


Fig. 4 State of energy in hybrid storage unit

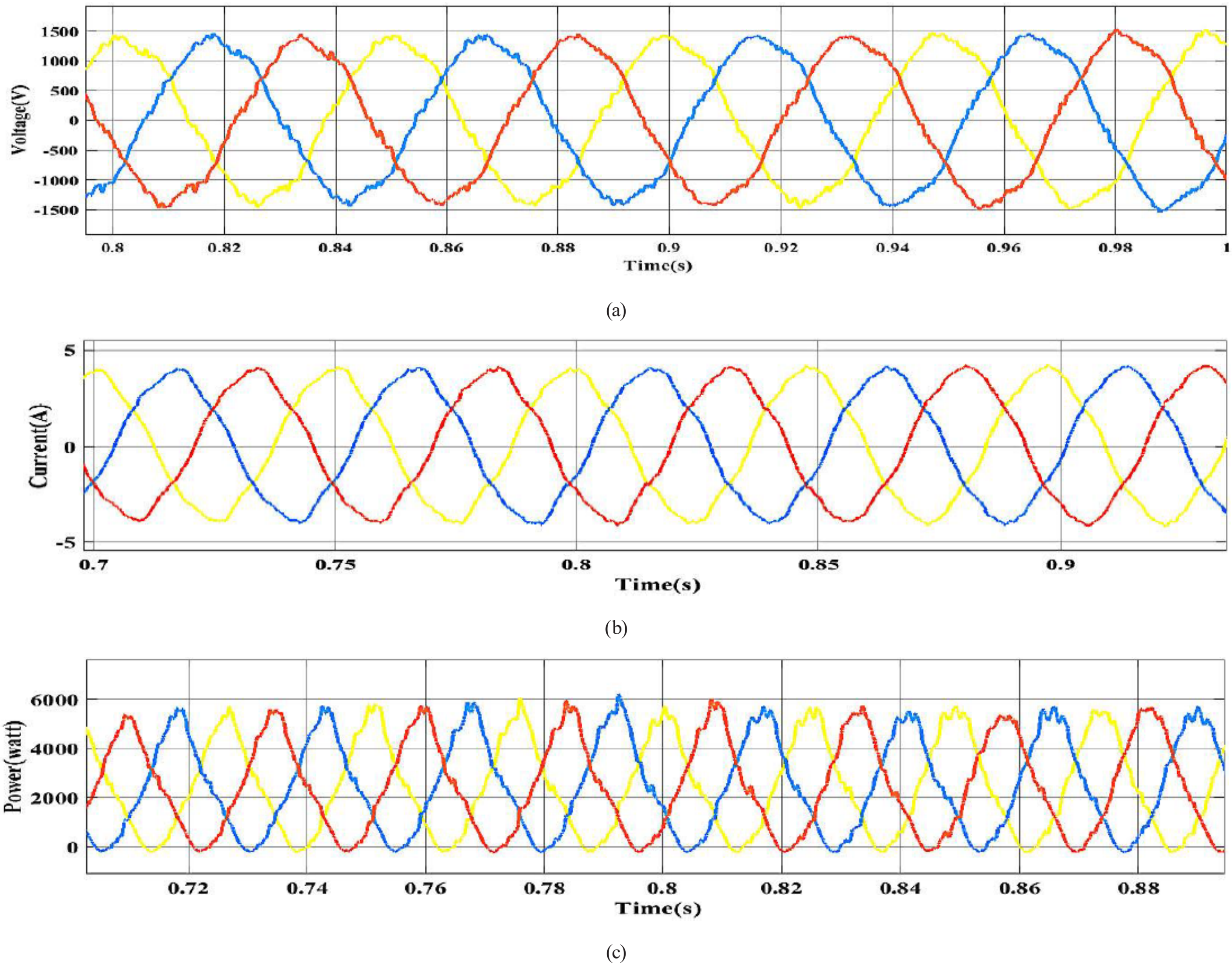


Fig. 5 Parameter Analysis of Off-grid mode; (a) Off-grid voltage; (b) Off-grid current; (c) Off-grid power

which indicates better data selection for the process made by the ANFIS controller.

The error comparison of different controller is given in Table 5. The error data such as ITAE, ITSE, IAE and ISE are calculated for proposed as well as the extant controllers and the validated values are provided. From the tale it is clear that the proposed controller has a very low error of 0.02 ITAE, 0.04 ITSE, 0.05 IAE and 0.0025 ISE are perceived.

4.3 Total Harmonic Distortion analysis

The analysis of THD for proposed and exiting methods are given in Fig. 9. The THD of the proposed controller is compared with the ANFIS-PSO, PID and PI. From this THD analysis, it is proved that the proposed work gives 9.11% reduced THD than other comparative methods.

Here, PID, PI and ANFIS-PSO optimized controllers are taken for the controller comparative methods and the PSO, GA, and MOA are used to compare the data selection for the operation of the controller. The fundamental frequency of the power is maintained as 50 Hz by the proposed controller which will enhance the performance in the off-grid connection. The harmonic distortion is taken between frequency and magnitude for the existing work. It is analyzed between magnitude and harmonic order for the proposed work. From this result analysis, it is proved that the proposed work works better than the previous models in terms of THD analysis.

4.4 Transient characteristics

To analyze the transient stability of the controller, initially considering the power delivered to the load is through on-grid with the power of 4.2×10^5. When the transient load is detected, the supply to the load is made through the off-grid mode at 0.7 s at this particular time the transient response of the controller is represented by the Fig. 10.

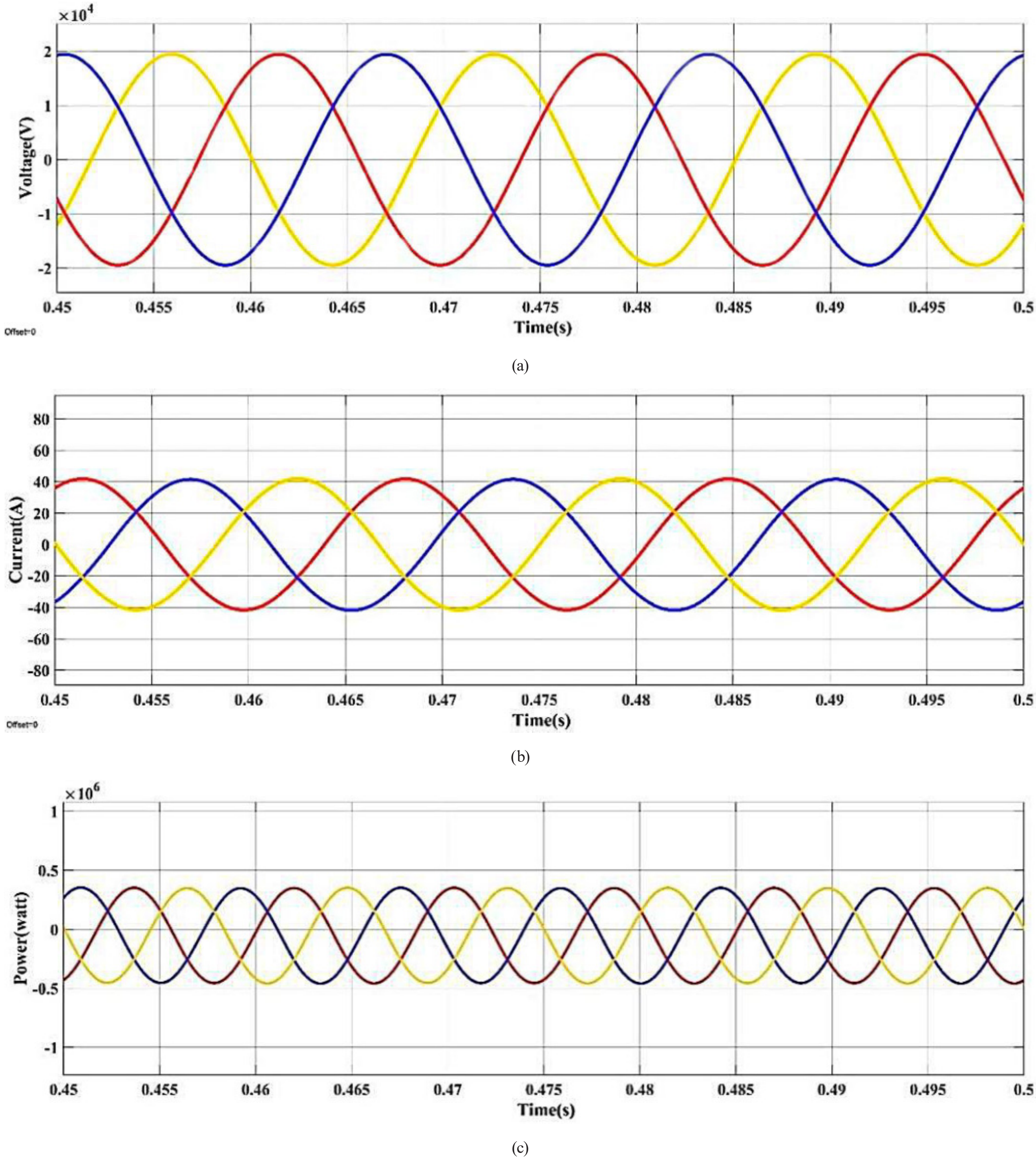


Fig. 6 Parameter Analysis for On-grid mode; (a) On-grid voltage; (b) On-grid current; (c) On-grid power

Table 4 Numerical analysis for Off-grid and On-grid mode

Techniques	Off-grid mode			On-grid mode		
	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
PI	1398	2.8	3875	1.29×10^4	19.8	2.01×10^5
PID	1450	4	4718	1.72×10^4	24	3.2×10^5
ANFIS-PSO	1423	3.8	4524	1.68×10^4	23.8	2.8×10^5
EP-ANFIS	1500	4.2	5000	1.9×10^4	40.3	4.2×10^5

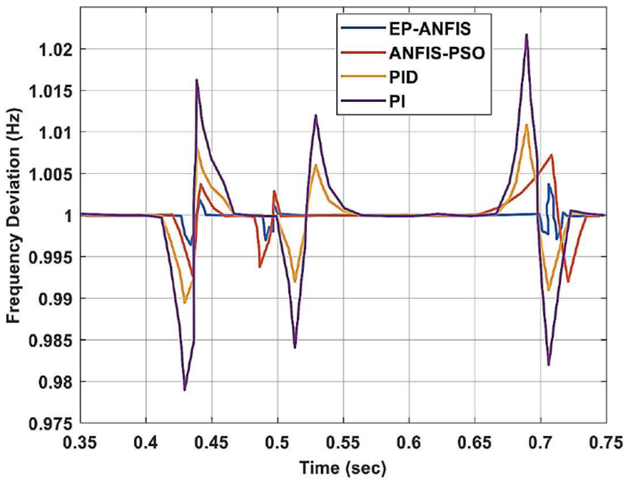


Fig. 7 Frequency deviation during switching

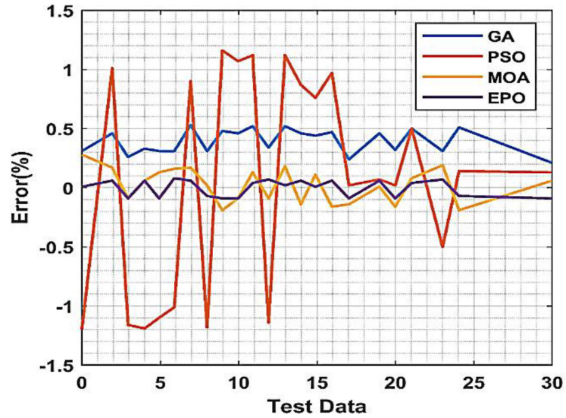
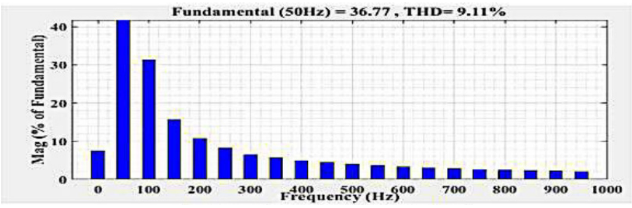


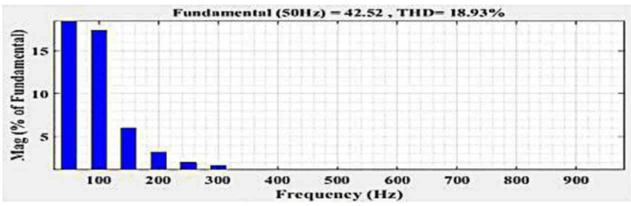
Fig. 8 Error on test data after training data

Table 5 Comparison of ITAE, ITSE, ISE and IAE

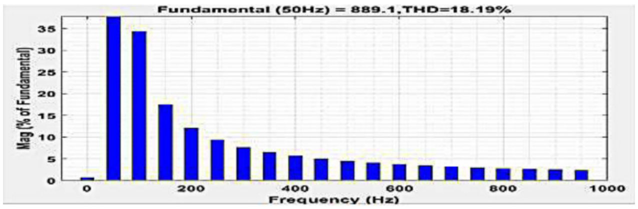
Techniques	ITAE	ITSE	IAE	ISE
PI	0.66	0.09	0.72	0.008
PID	0.58	0.086	0.64	0.0072
ANFIS-PSO	0.53	0.034	0.58	0.0031
EP-ANFIS	0.02	0.04	0.5	0.0025



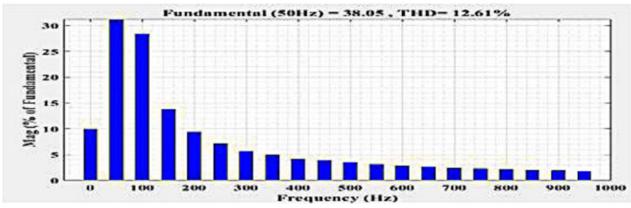
(a)



(b)



(c)



(d)

Fig. 9 Analysis of Total Harmonic Distortion (THD) (a) proposed method (b) PID controller (c) PI controller (d) ANFIS-PSO controller

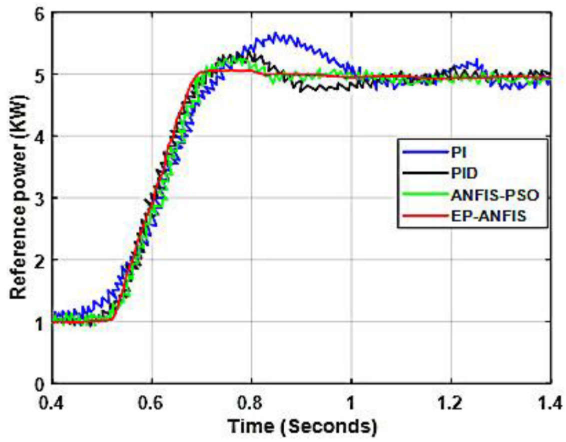


Fig. 10 Transient response of the Controller

Table 6 Transient analysis of the Controller

Controller	Maximum power (W)	Minimum power (W)	Peak time (s)	Rise time (s)	Settling time (s)	Maximum Overshoot (%)
PI	2.01×10^5	3875	0.896	0.23	1.275	5.529
PID	3.2×10^5	4718	0.782	0.21	1.04	5.367
ANFIS-PSO	2.8×10^5	4524	0.763	0.16	1.12	5.188
EP-ANFIS	4.2×10^5	5000	0.759	0.13	0.965	5.048

Here, in Table 6 the maximum overshoot power delivered to the load during the transient is 5.529% for the proposed method with time for achieving peak power is 0.759 s. The transiency of the controller during the switching is stable with the settling time of 0.965 s. This timing closure is better than any other controller.

5 Conclusion

Based on the energy constraints between the load and power generator the grid operation was different for RESs. Hence to serve the transient power at load SSD optimized storage unit was employed with EP-ANFIS controller, which controls grid operation based on energy flows into it. Through the comparative analysis, the proposed work offers 9.11% of reduced THD with PI, PID and ANFIS-PSO, which proves that the proposed system was highly efficient and reliable. The switching by the proposed controller was much better than the existing controllers by providing smooth switching and stability with a minimum period of 0.965 s. Thus, the proposed controller has the benefit of low switching error, decreasing complexity and stable operation under transient characteristics.

In the future, the work is extended by applying the grid-connected controller model in any specific load such as in any kind of motor for an application or examine an electric vehicle in off-grid and on-grid modes.

Nomenclature

RES	Renewable Energy Source
EMS	Energy Management System
PD	Proportional Derivative
PI	Proportional Integral
PID	Proportional Integral Derivative
ANFIS	Adaptive Neuro Fuzzy Interference System
PSO	Particle Swarm Optimization
EPO	Emperor Penguin Optimization
VSGA	Virtual Synchronous Generator Algorithm
GA	Genetic Algorithm
FFOPID	Fuzzy Fractional-Order Proportional-Integral-Derivative controller
FLC	Fuzzy Logic Controller
FOFPID	Fractional Order Fuzzy PID
LQG	Linear Quadratic Gaussian
MVO	Multi Verse Optimization
2d of F	Two-degree-of-freedom PID
SSA	Salp Swarm Algorithm
HHV	Higher Heating Value
UC	Ultracapacitor
FC	Fuel Cell
ITAE	Integral of Time weighted Absolute Error
IAE	Integral Absolute Error
ITSE	Integral Time Squared Error
ISE	Integral Squared Error
SOC	State of Charge
SSD	Social Sci-Driver algorithm
THD	Total Harmonic Distortion
MOA	Matfly Optimization Algorithm
P_{PV}	Power generated by the PV panel
I	Incident radiation
$P_{\mathrm{PV,rated}}$	Rated power of the PV panel
P_{WT}	Power generated by the WT generator
ρ	Air density
A	Frontal area
V	Velocity of the wind
C	Power coefficient
E	Capacity of storage device
$E_{\max}$	Maximum amount of stored energy
C_c	Current capacity
C_i	Initial capacity
E_i	Total power generated from the PV-WT generators
D_b	Difference between the input and the best data of optimization
n	Ongoing iteration
r and c	Data collision avoidance parameter in optimization
P_{opt}	Best optimal solution
$P_d(n)$	Voltage at the current input data
S	Force to move from one solution to other
$P(n+1)$	Updated voltage for next iteration
$A1$, $A2$, $B1$ and $B2$	Linear parameters in ANFIS

P_1, P_2, Q_1, Q_2, R_1 and R_2	Polynomial parameters in ANFIS
$\delta_{Ai}(a)$	Membership function of fuzzy system
W_i'	Degree of fulfilment with $i = 1, 2$
a and b	Input of ANFIS

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