

## Research Article

# Power Management Controller for Microgrid Integration of Hybrid PV/Fuel Cell System Based on Artificial Deep Neural Network

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Nowadays, the power demand is increasing day by day due to the growth of the population and industries. The conventional power plant alone is incompetent to meet the consumer demand due to environmental concerns. In this present situation, the essential thing is to be find an alternate way to meet the consumer demand. In present days most of the developed countries concentrate to develop alternative resources and invest huge money for its research and development activities. Most renewable energy sources are naturally friendly sources such as wind, solar, fuel cell, and hydro/water sources. The results of power generation using renewable energy sources only depend on the availability of the resources. The availability of renewable energy sources throughout the day is variable due to fluctuations in the natural resources. This research work discusses two major renewable energy power generating sources: photovoltaic (PV) cell and fuel cell. Both of them provide foundations for power generation, so they are very popular because of their impressive performance mechanisms. The mentioned renewable energy-based power generating systems are static devices, so the power losses are generally ignorable as compared to line losses in the main grid. The PV and fuel cell (FC) power systems need a controller for maximum power generation during fluctuations in the input resources. Based on the investigation report, an algorithm is proposed for an advanced maximum power point tracking (MPPT) controller. This paper proposes a deep neural network- (DNN-) based MPPT algorithm, which has been simulated using MATLAB both for PV and for FC. The main purpose behind this paper has been to develop the latest DNN controller for improving the output power quality that is generated using a hybrid PV and fuel cell system. After developing and simulating the proposed system, we performed the analysis in different possible operating conditions. Finally, we evaluated the simulation outcomes based on IEEE 1547 and 519 standards to prove the system's effectiveness.

## 1. Introduction

Right now, power generation and transmission require substantially large quantities of fossil fuels. The fossil fuel-based power generation systems cannot meet the consumer demand in future due to limited availability of fuel. Further, environmental considerations will limit their usage as they emit more greenhouse gases. This leads to warning levels and climate change, and the availability of fossil fuels is now limited. Nowadays, many counties are concentrating on alternate sources, replacing fossil fuels with greener and ecofriendly fuels. Presently, the combination of solar and fuel

cells is a promising renewable energy (RE) source [1–5]. The power, which is extracted out of a PV module, is substantially vulnerable to environmental factors, natural fluctuations, and differences in operating conditions [6–8]. It is a fact that when the requirement for power is critical, solar energy fails to generate sustainable power. To fulfill the power demand, many processes and devices have been introduced. For instance, for understanding the energy demand in the peak periods, such as at night, a hybrid system consisting of a fuel cell and a PV was developed without power storage. It has a few drawbacks such as the issue of integrating a microgrid, and besides, such a system is difficult to operate under

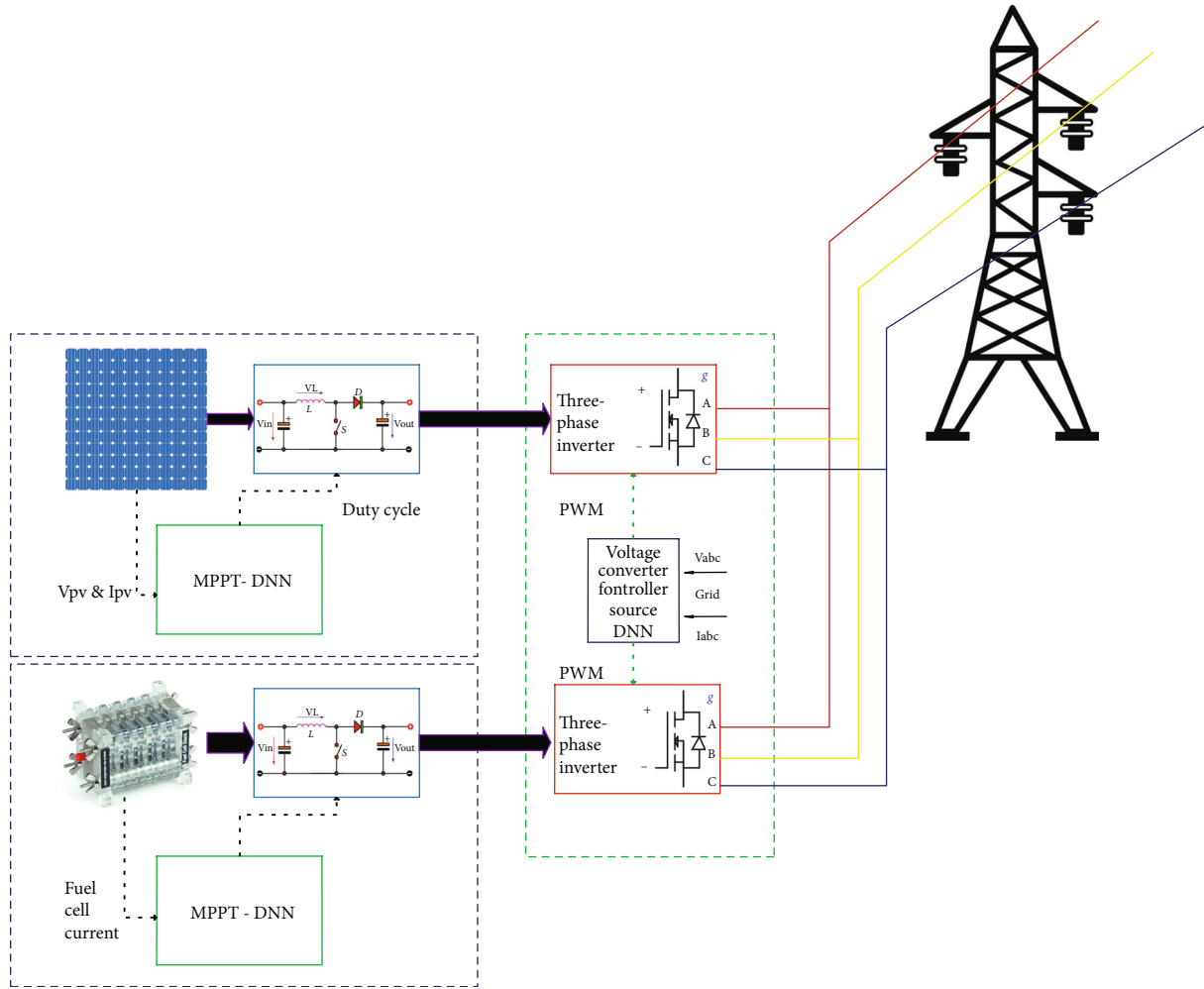


FIGURE 1: Block diagram of the proposed microgrid system and its controller.

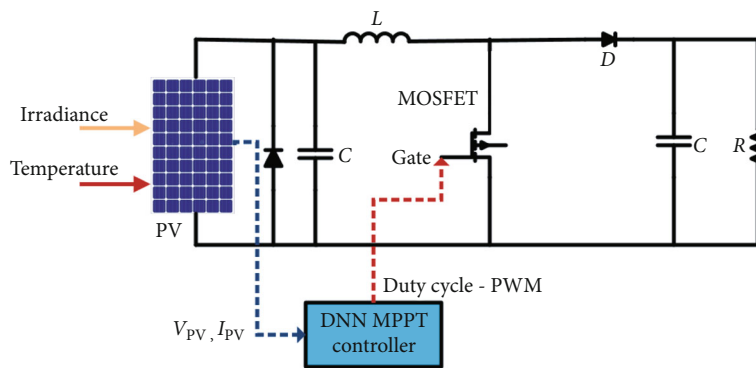


FIGURE 2: Proposed DNN-based MPPT algorithm.

unstable conditions or has irregular, unmanageable, stochastic, and highly variable sources. To be precise, researchers focused on the following area such as high penetration level to the microgrid or when there are issues such as poor load following, load discrepancy, frequency deviation, voltage variability, reliability problems, and poor power quality.

Based on the literature reports, various algorithms such as the Whale Optimization Algorithm (WOA), Water Cycle Algorithm (WCA), Moth-Flame Optimizer (MFO), and Hybrid Particle Swarm-Gravitational Search Algorithm (PSOGSA) have been both developed and applied for designing the optimized microgrid and analyzing power quality

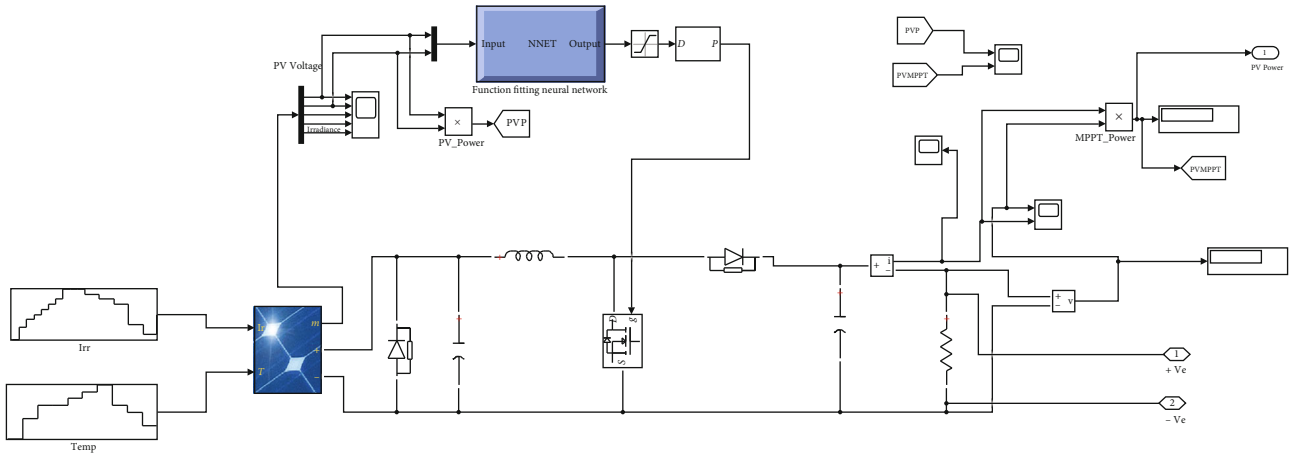


FIGURE 3: Simulation model of DNN-based MPPT algorithm for PV systems.

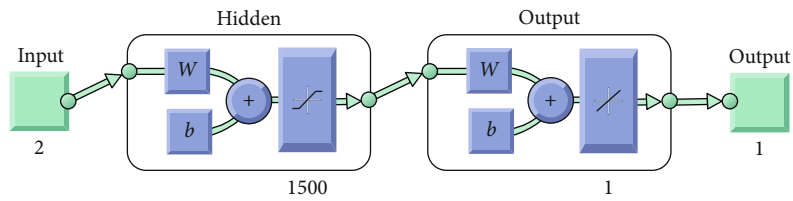


FIGURE 4: DNN model for PV MPPT system.

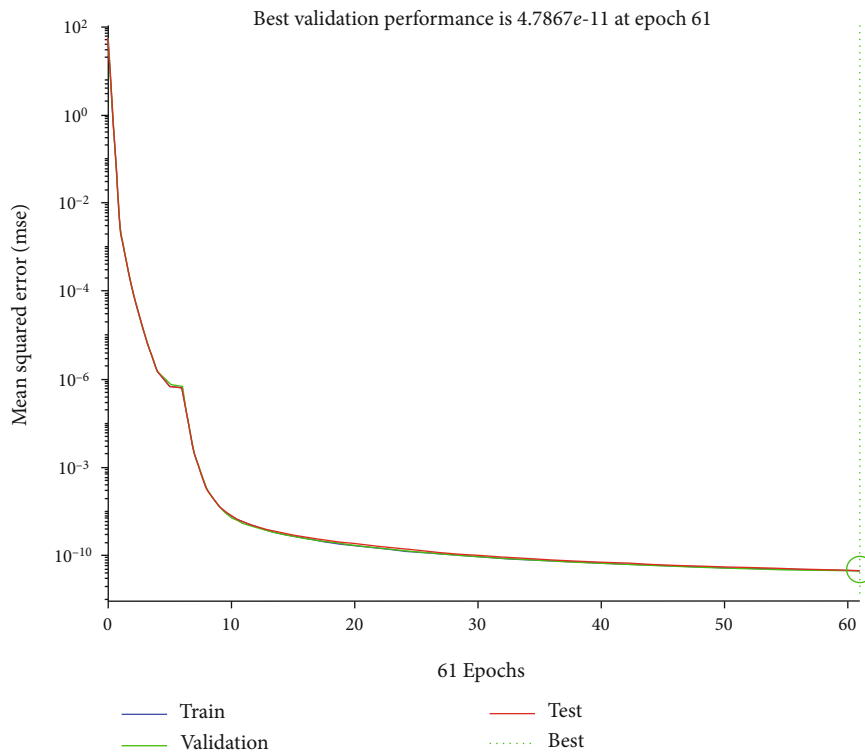


FIGURE 5: DNN-PV MPPT controller showing best validation performance.

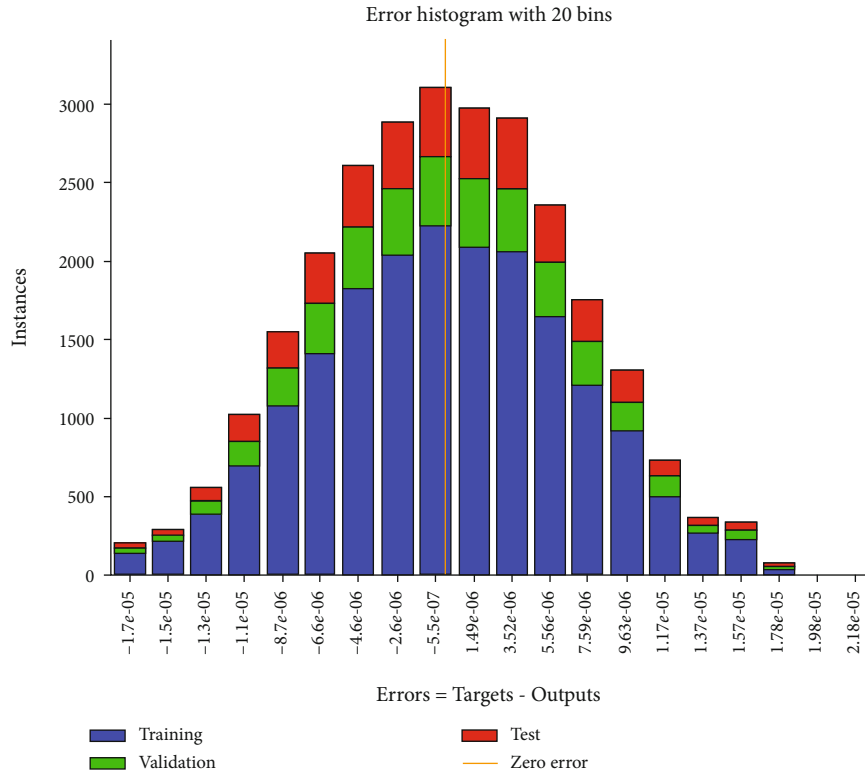


FIGURE 6: DNN-PV MPPT controller error histogram.

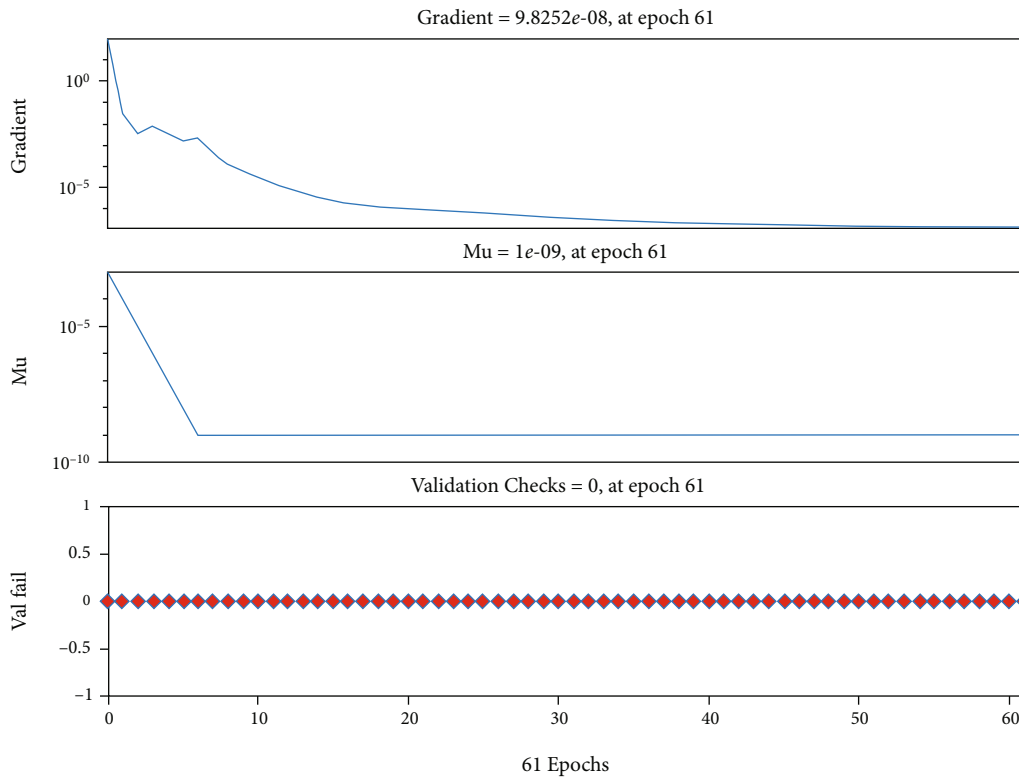


FIGURE 7: DNN-PV MPPT controller with training data.

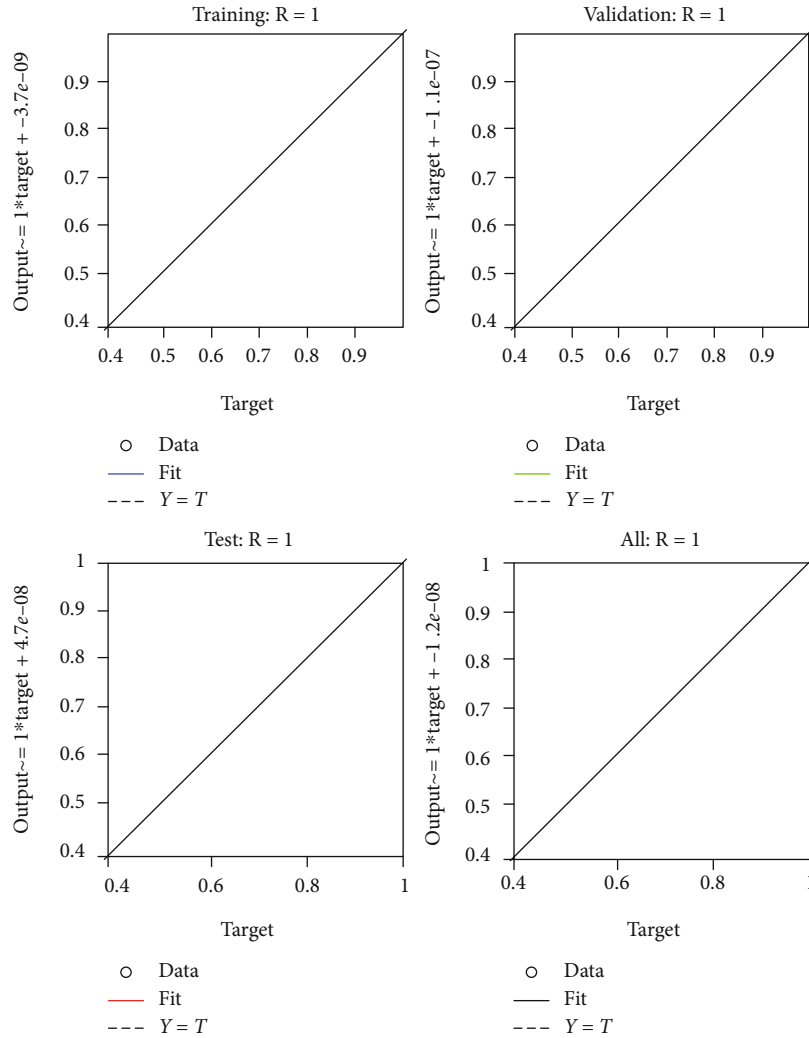


FIGURE 8: DNN-PV MPPT controller showing best regression.

issues [9]. Another important factor of the hybrid renewable energy system is optimization of net present cost (NPC), fuel cost, operation cost, and cost of energy (COE) of the hybrid. The optimization of the key performance indicators of the hybrid power system is done by using the hybrid optimization model for electric renewables (HOMER) [10]. The energy flow is from the energy source to the electrical system for a residential application in conjunction with an intelligent demand management control strategy [11]. The real and reactive power controller is challenging role in hybrid renewable energy systems. An adaptive Lyapunov-based rapid terminal sliding mode control is superior over the traditional PI control because of its faster error tracking capability and robustness. A Q-V-based inverter control is employed to interface the single phase grid and the hybrid system [12]. The optimal power flow (OPF) formulation includes the forecasted active power generation of WT and PV as dependent variables, whereas the voltage magnitude at WT and PV buses is considered as control (decision) variables [13].

The hybrids of Renewable Energy Sources (RESs) deal with optimal performance in cost consideration, emission,

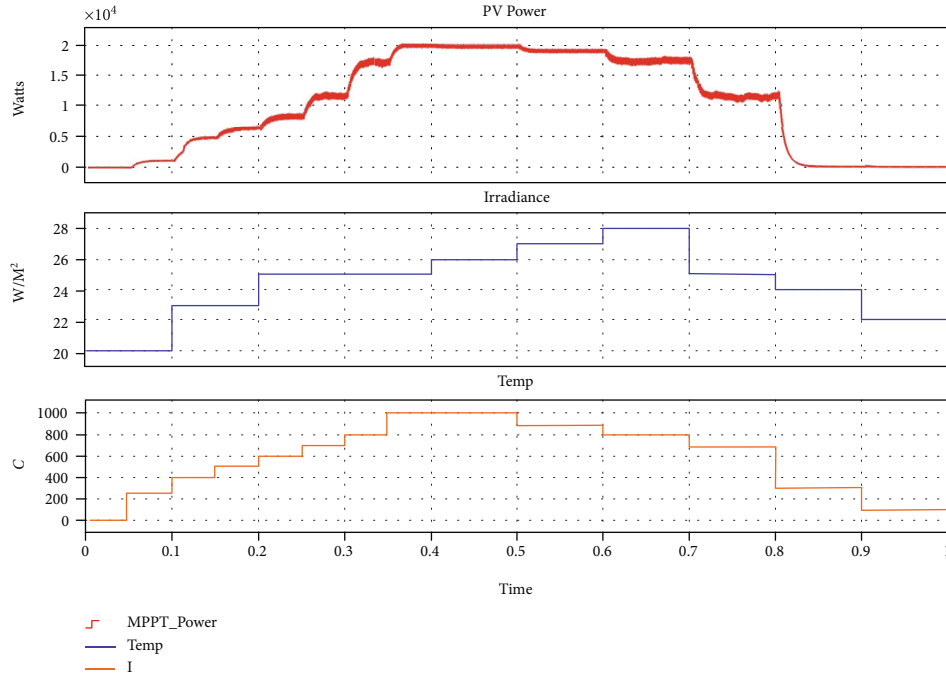
TABLE 1

(a) DNN data of MPPT controller for PV systems

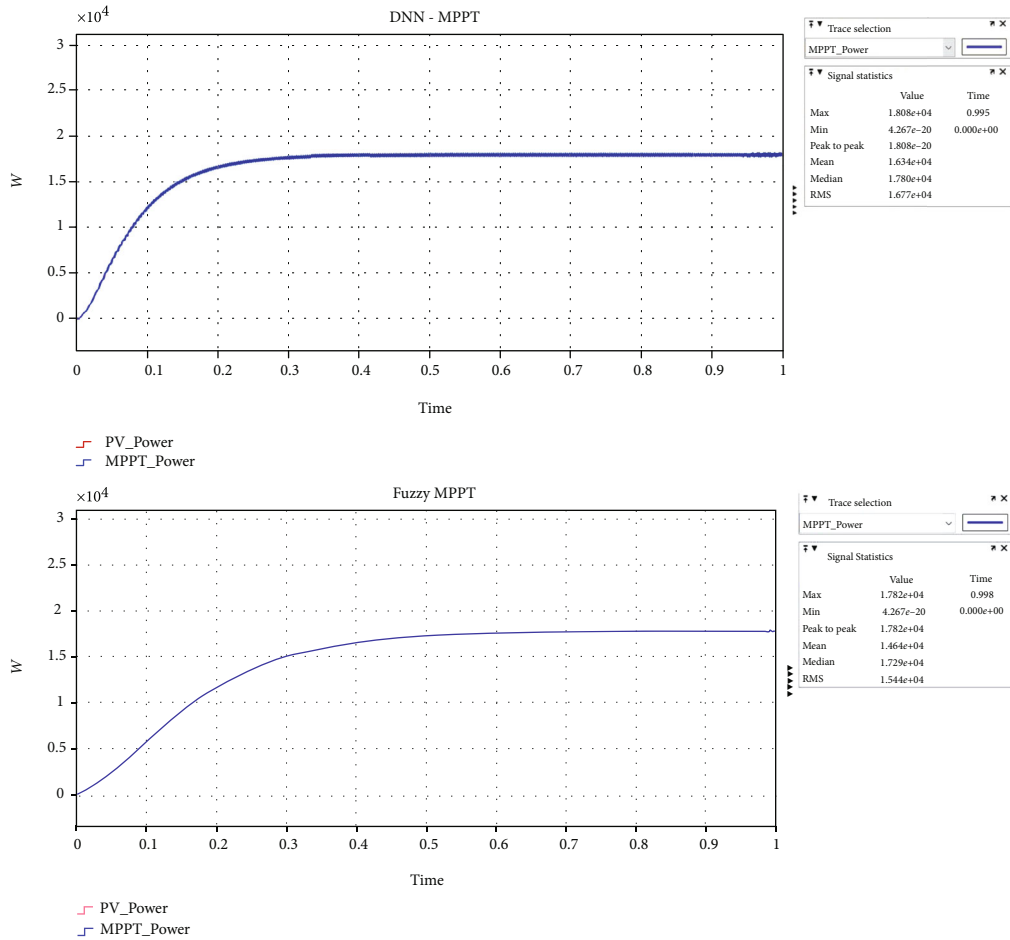
DNN-FC MPPT	Values
Best validation	4.7867e-11
Mu	1e-09
Gradient	9.8252e-08
Training	1
Validation	1
Test	1
Overall regression	1

(b) Comparative analyses of MPPT controller for PV systems

Controller	Fuzzy	DNN
PV	17820 W	18080 W



(a)



(b)

FIGURE 9: (a) Simulation results of DNN-PV MPPT power with respect to irradiance and temperature. (b) Comparison of fuzzy- and DNN-based MPPT controller.

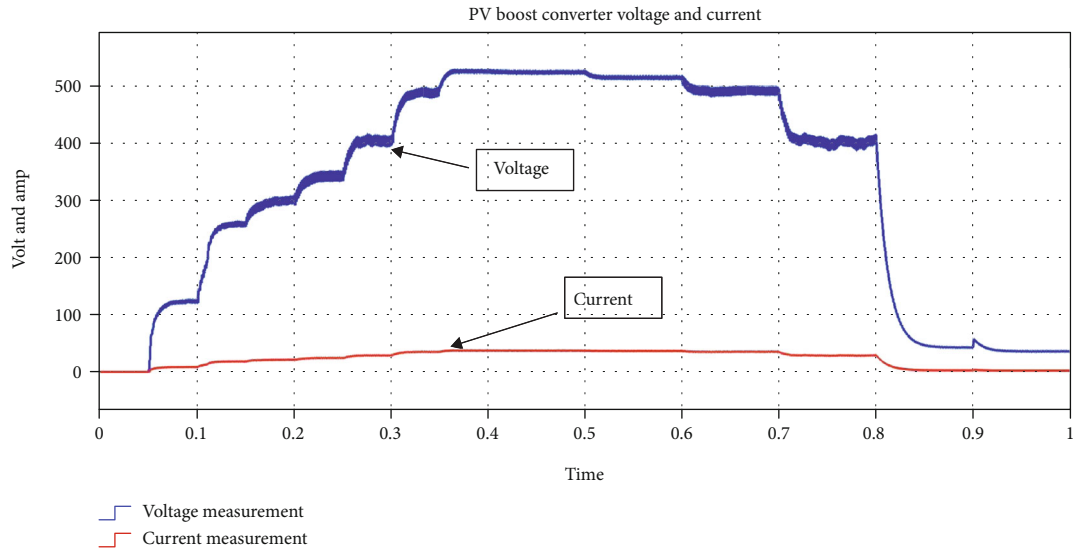


FIGURE 10: Simulation results of DNN-PV MPPT boost converter voltage and current with respect to irradiance and temperature.

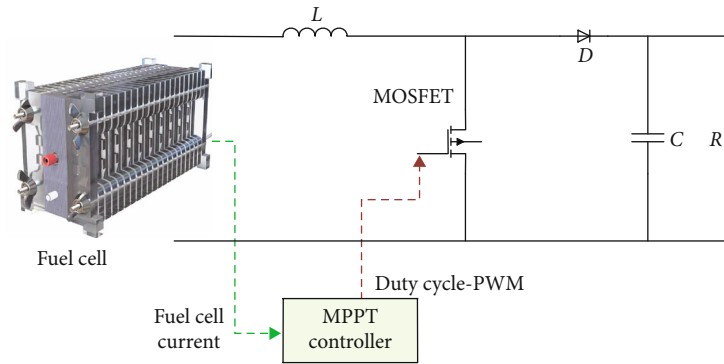


FIGURE 11: Proposed DNN-based optimum fuel flow algorithm for the fuel cell power system.

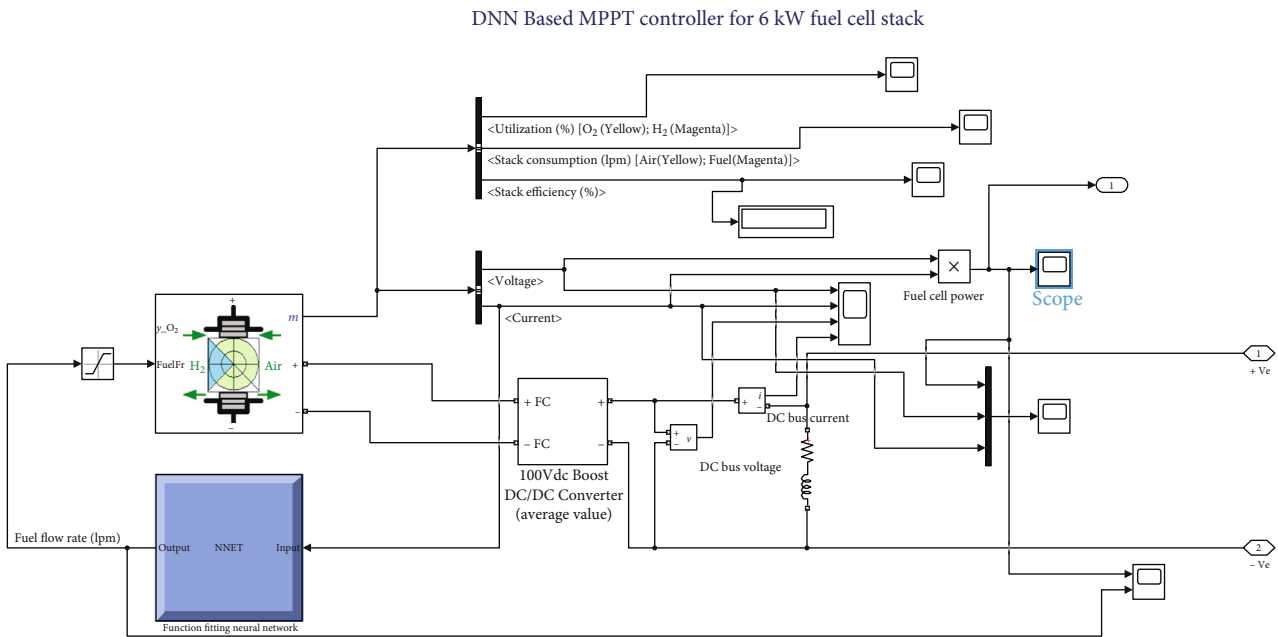


FIGURE 12: Simulation model of the DNN controller-based optimum fuel flow algorithm for a fuel cell power system.

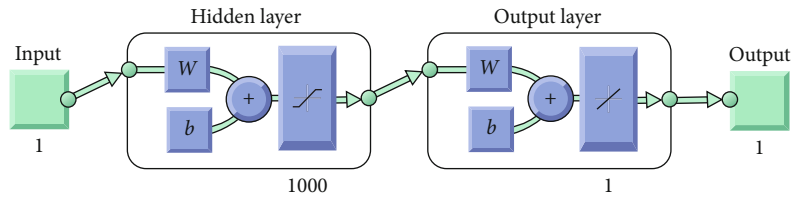


FIGURE 13: DNN model for fuel cell MPPT system.

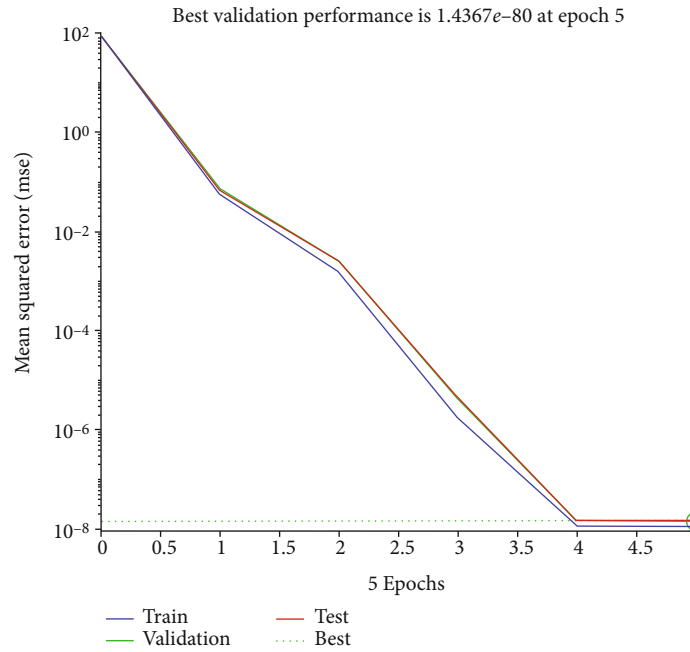


FIGURE 14: DNN-based fuel flow controller showing best validation performance.

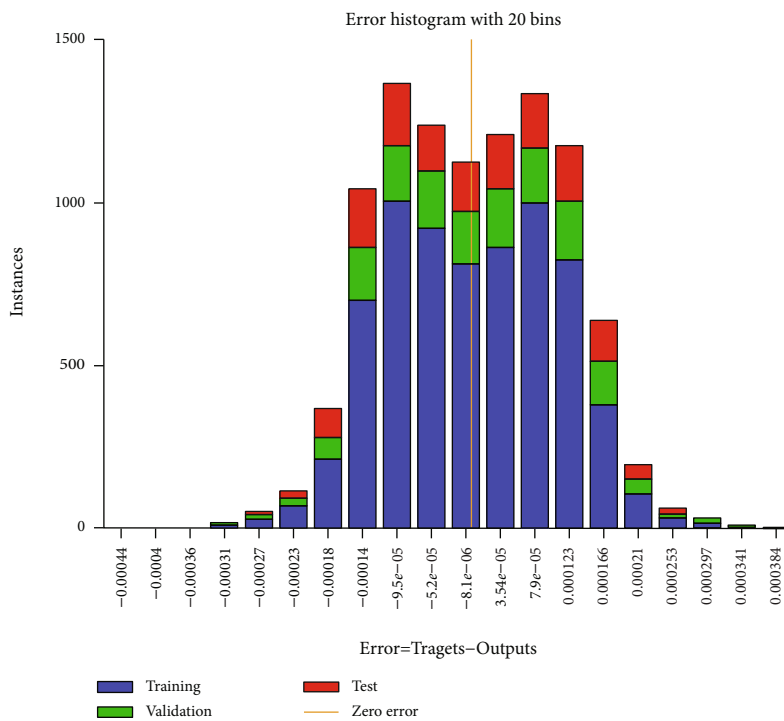


FIGURE 15: Error histogram of the DNN-based fuel flow controller.



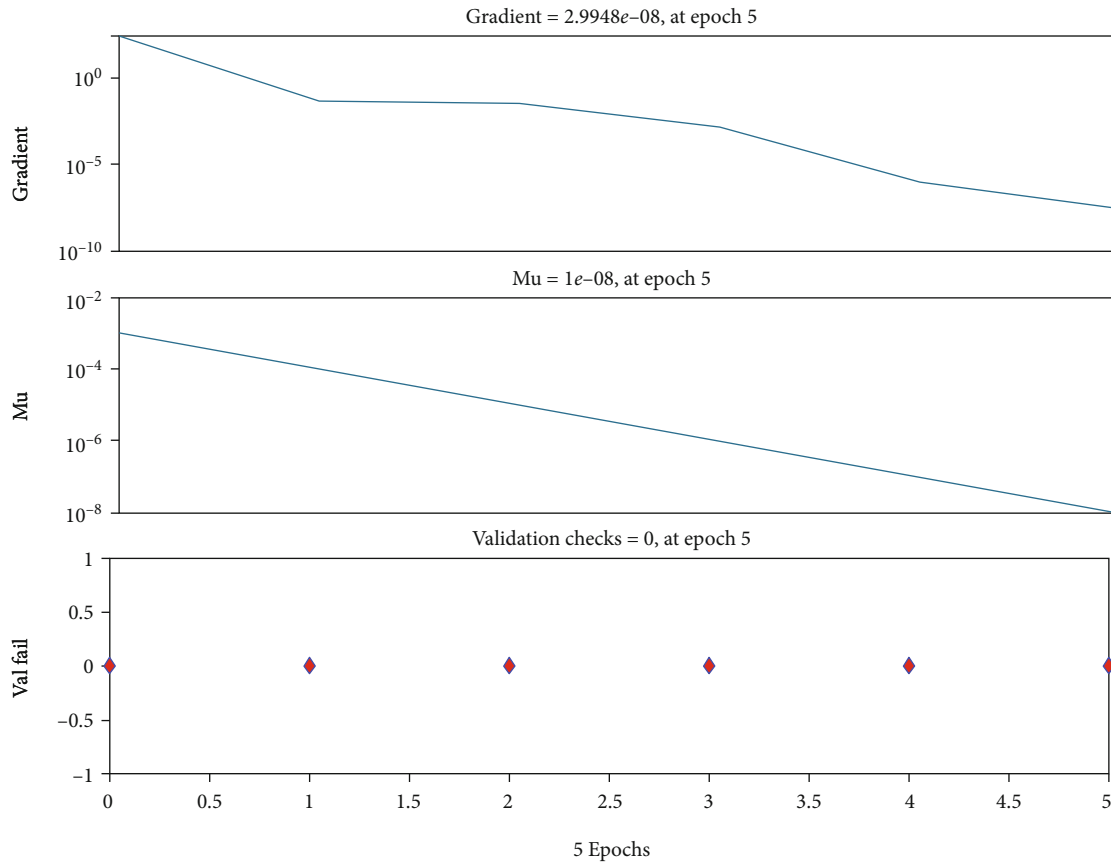


FIGURE 16: Training data of the DNN-based fuel flow controller.

space management and adequate reliability in power generation, and power quality and optimum power utilization [14].

Hence, novel and innovative technologies based on feasible ideas are needed to deal with the mentioned issues so as to increase the RE sources' penetration in the power grid.

This paper has proposed a novel and deep neural network algorithm to solve the power system issues with integrated PV and FC generators. This system is represented in Figure 1. The main contributions of this work include the following:

- (1) Design and model the MPPT controller for PV and fuel cells using DNN and analyze its performance under various weather conditions
- (2) Design and develop a hybrid PV-fuel cell energy system and model a smart inverter for microgrid integration of a hybrid system
- (3) Design a DNN-based voltage source controller that is synchronous with the microgrid and hybrid PV and fuel cell energy system
- (4) The proposed DNN-based smart inverter helps to reduce harmonics and improves the power quality and its stability

The organization of this paper is as follows: the DNN-based MPPT algorithm for a PV system is given in Section 2. This section also analyzes the proposed algorithm's performance under various weather conditions. The DNN-based MPPT algorithm for fuel cell energy system and performance analysis under various fuel pressures and its results are explained in Section 3. The proposed DNN-based microgrid-integrated hybrid PV and fuel cell power system are explained in Section 4. In Section 5, the DNN-based smart inverter controller is modelled, and its performance is explained. The results for simulation are given in Section 6 while Section 7 includes the final conclusions.

## 2. Deep Neural Network-Based MPPT for PV

In the present situation, renewable energy sources are required to make the maximum power point tracking algorithm generate maximum power under various weather conditions [15]. The researchers have been focused to create different MPPT algorithms, including the incremental conductance, P&O, feedback voltage and current, fuzzy, ANN, PSO ANFIS, and other controllers [16–18]. This paper throws light on a new advanced MPPT algorithm called a Deep Neural Network (DNN) controller for photovoltaic systems. The proposed DNN-based MPPT algorithms were

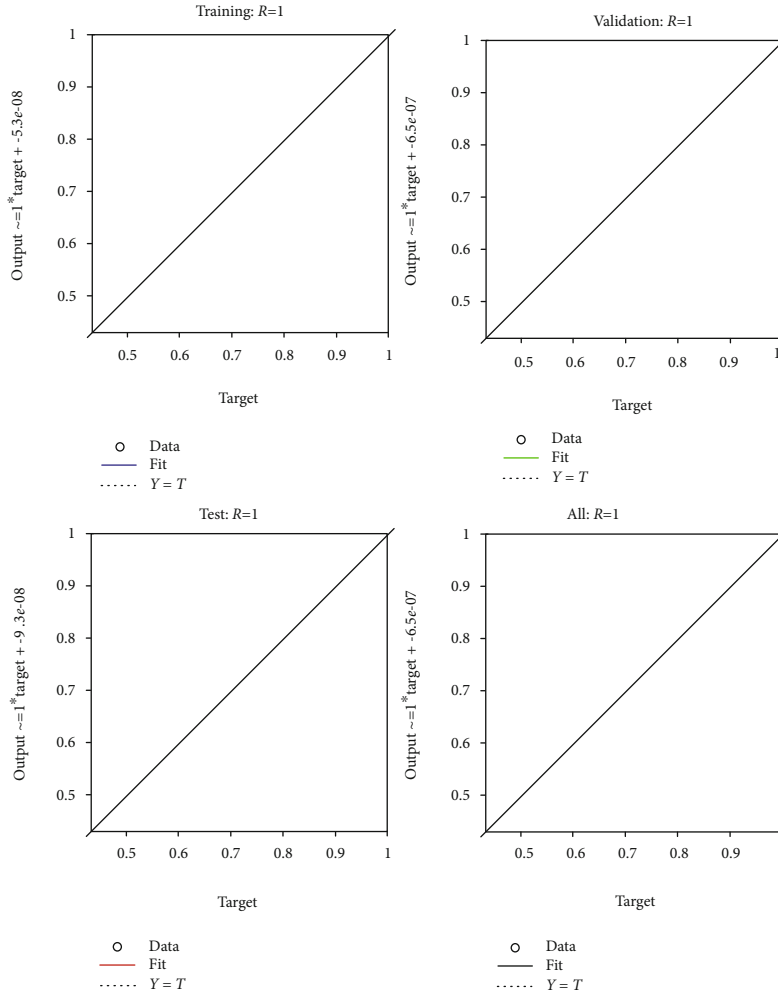


FIGURE 17: Training and validation of the DNN-based fuel flow controller.

developed using 75,000 data entries, such as PV voltage, current, and its corresponding duty cycle, as Figure 2 shows. The MPPT algorithm of a PV system simulation model has been developed and modelled with MATLAB, illustrated in Figure 3. The proposed simulation was performed using a 50 kW model PV array, which is connected with a boost converter, and it is controlled by the proposed MPPT algorithm. The developed DNN algorithm has 2 inputs, including a PV current and voltage, and besides, 1500 hidden layer neurons are used between the input and output layers, as Figure 4 indicates. The proposed MPPT algorithm’s output generates a duty cycle for a PV-connected boost converter. This DNN layer has been used for training the MPPT network using the data, such as input (PV voltage, PV current) and output in the form of a duty cycle of a converter.

The best validation performance of the proposed DNN controller is presented in Figure 5. The following details are observed while training the DNN for the MPPT controller such as the error (targeted output) histogram data of the proposed DNN controller being very small, which is obvious in Figure 6. The gradient and validation checks of the proposed DNN trained network are presented in Figure 7. Finally, the

TABLE 2

(a) DNN data of the MPPT controller for the FC system

DNN-fuel cell MPPT	Values
Best validation	1.4367e-8
Mu	1.00e-8
Gradient	2.9948e-8
Training	1
Validation	1
Test	1
Overall regression	1

(b) Fuel cell efficiency comparison: fuzzy and DNN

Controller	Fuzzy	DNN
Efficiency	57.01%	57.09%

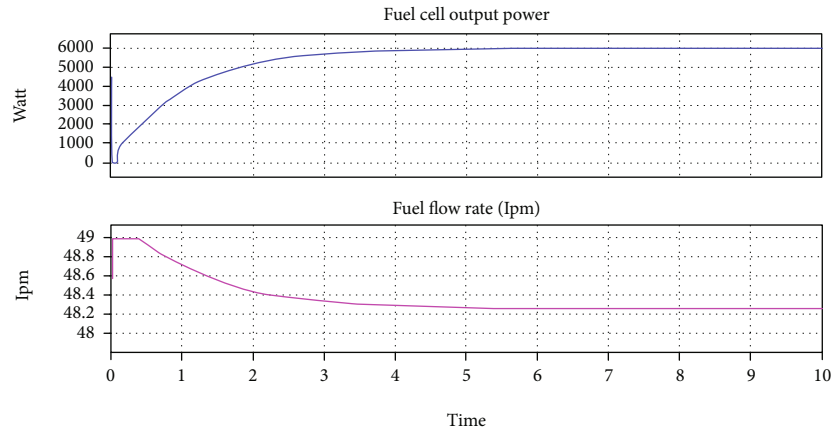


FIGURE 18: Simulation results for the DNN-fuel cell power with respect to optimum fuel flow.

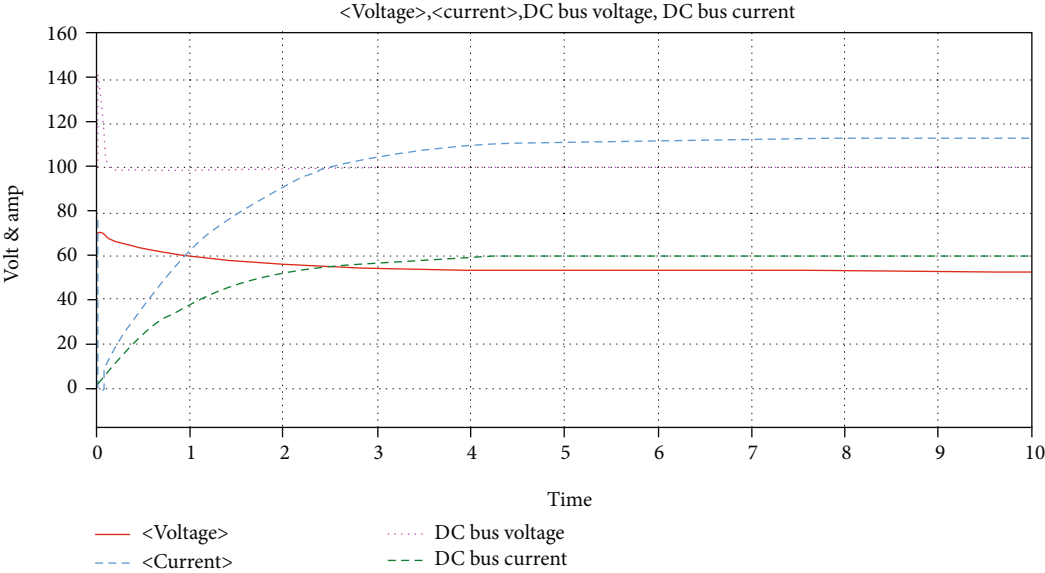


FIGURE 19: Simulation results for DNN-fuel cell converter voltage and current as well as DC bus voltage and current.

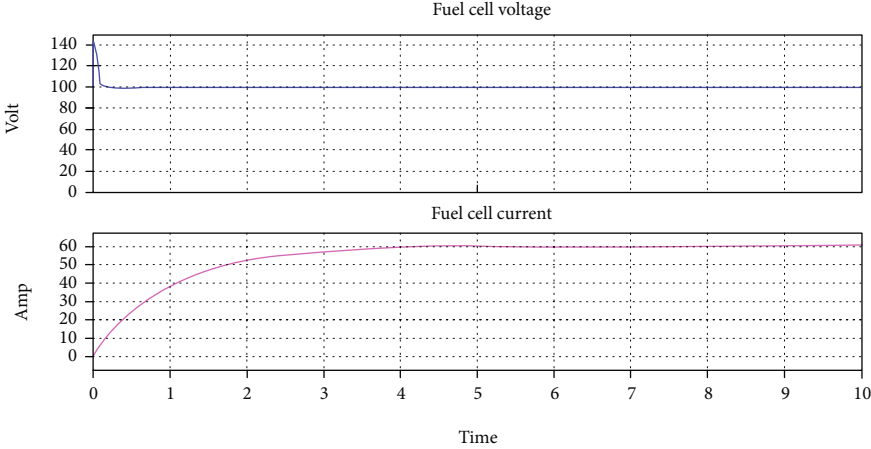


FIGURE 20: Fuel cell voltage and current waveform.

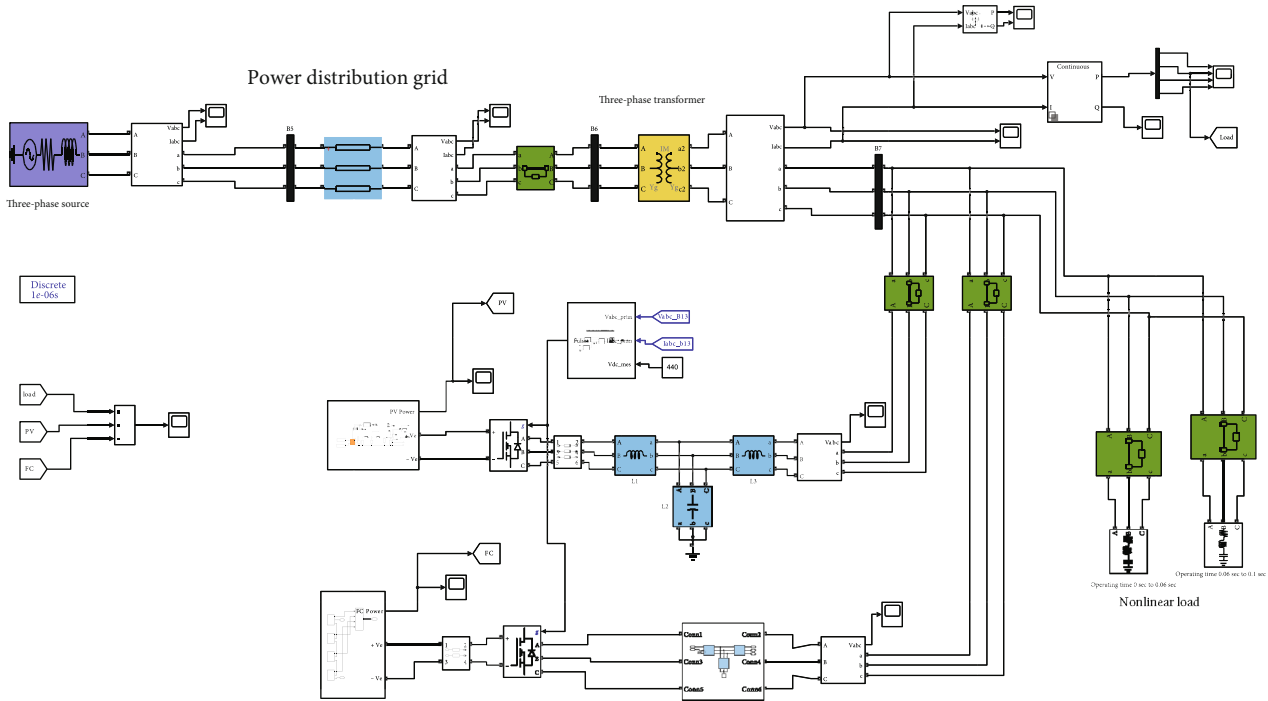


FIGURE 21: The proposed simulation model of a DNN-based controller with a microgrid integrated with a hybrid PV and a FC energy system.

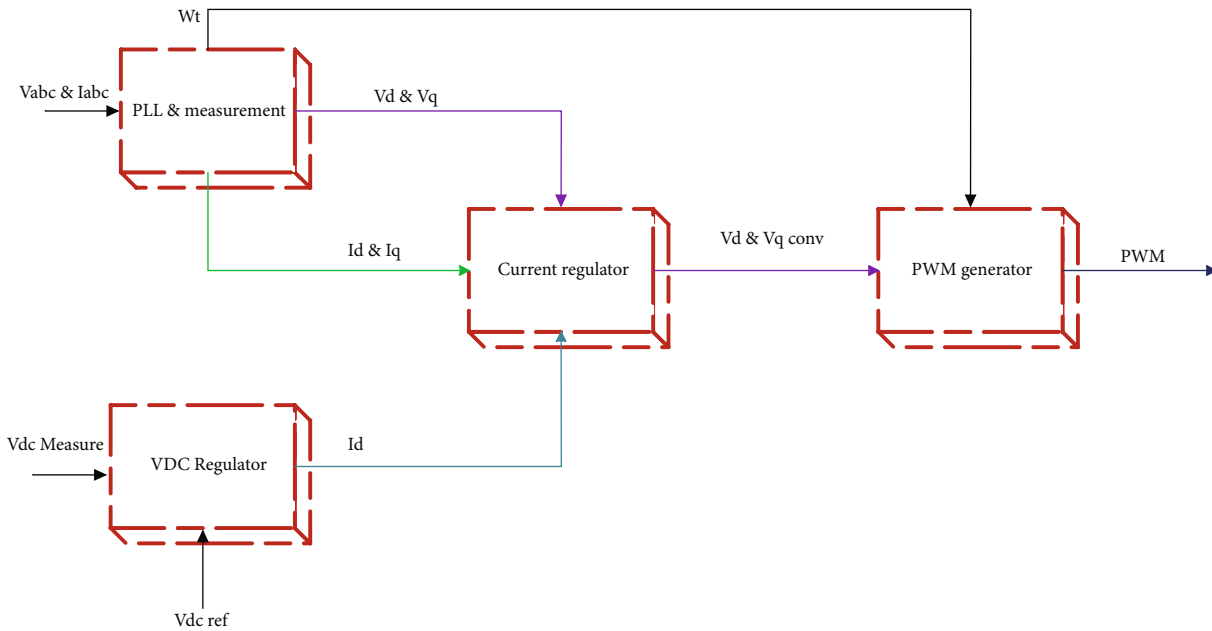


FIGURE 22: DNN controller-based voltage source controller for smart inverters.

proposed DNN-based MPPT algorithm has been developed and is presented with its best regression for training data, test data, validation data, and overall performance data in Figure 8. The overall DNN data are presented in Table 1.

The proposed 50 kW PV system has been simulated in MATLAB, and the proposed DNN-based MPPT algorithm was applied. The proposed simulation model has been simulated under various weather conditions, and its performance

was analyzed in various operating conditions. The 50 kW PV system's simulation results are illustrated in Figure 9(a), which also shows various solar irradiance values with respect to the corresponding PV output power and MPPT controller-based PV output power. The comparative analyses of the PV MPPT with fuzzy and DNN is presented in Figure 9(b) and Table 1(b); the boost converter's current waveform and output voltage are illustrated in Figure 10.

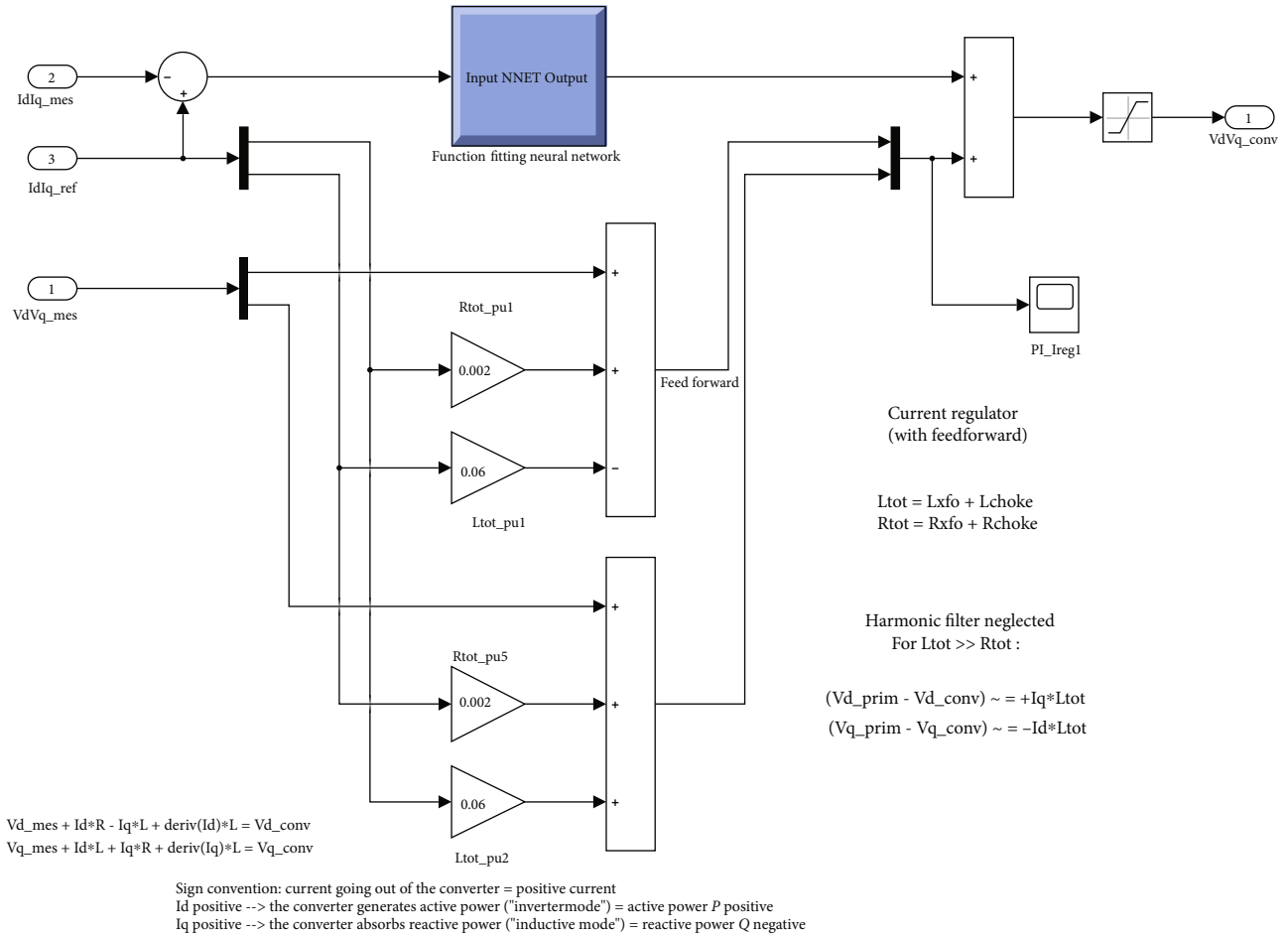


FIGURE 23: DNN-based current regulator for smart inverter.

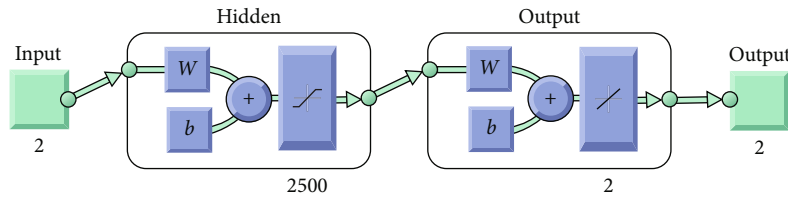


FIGURE 24: DNN model for the current regulator of a smart inverter.

### 3. Deep Neural Network-Based MPPT for Power System Using a Fuel Cell

The DNN controller develops rules and limits to assure optimum fuel flow for a fuel cell system, as shown in Figure 11. For the DNN learning rule, 44,000 entries of data were used to develop the optimum fuel flow rule. The simulation model of the projected algorithm-based fuel cell system has been simulated using MATLAB, as Figure 12 illustrates. A 6kW fuel cell power system was simulated, and a boost convertor was employed for stepping up voltage-supported optimized fuel flows [19]. The control of fuel flow will lead to the fuel cell's current limitation as

well reduce hemic losses in the fuel cell, which helps to increase fuel cell operating efficiency. In Figure 13, the DNN layer has been illustrated. This layer has a single input, which is the fuel cell current, and there are a thousand hidden layers between the input and the output. It only has a single output, which is the fuel flow pressure.

The best validation performance of the proposed DNN controller is presented in Figure 14. The following information is observed and noted such as the error (target – output) histogram data of the proposed DNN controller being very small, as shown in Figure 15. The gradient and validation checks of the proposed DNN-trained network are presented in Figure 16. Finally, the

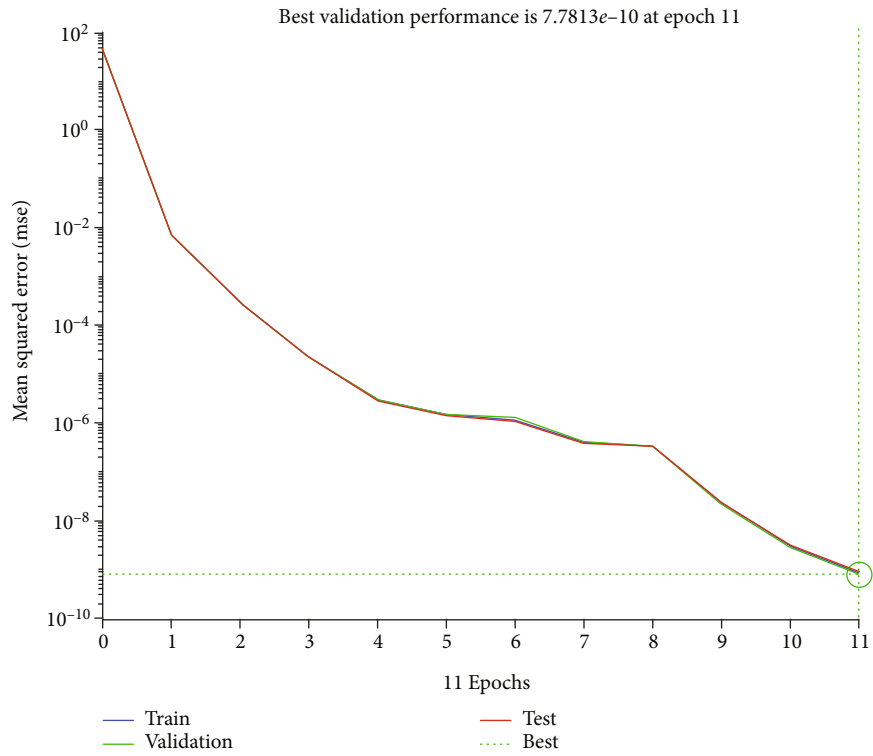


FIGURE 25: DNN-current regulator showing best validation performance.

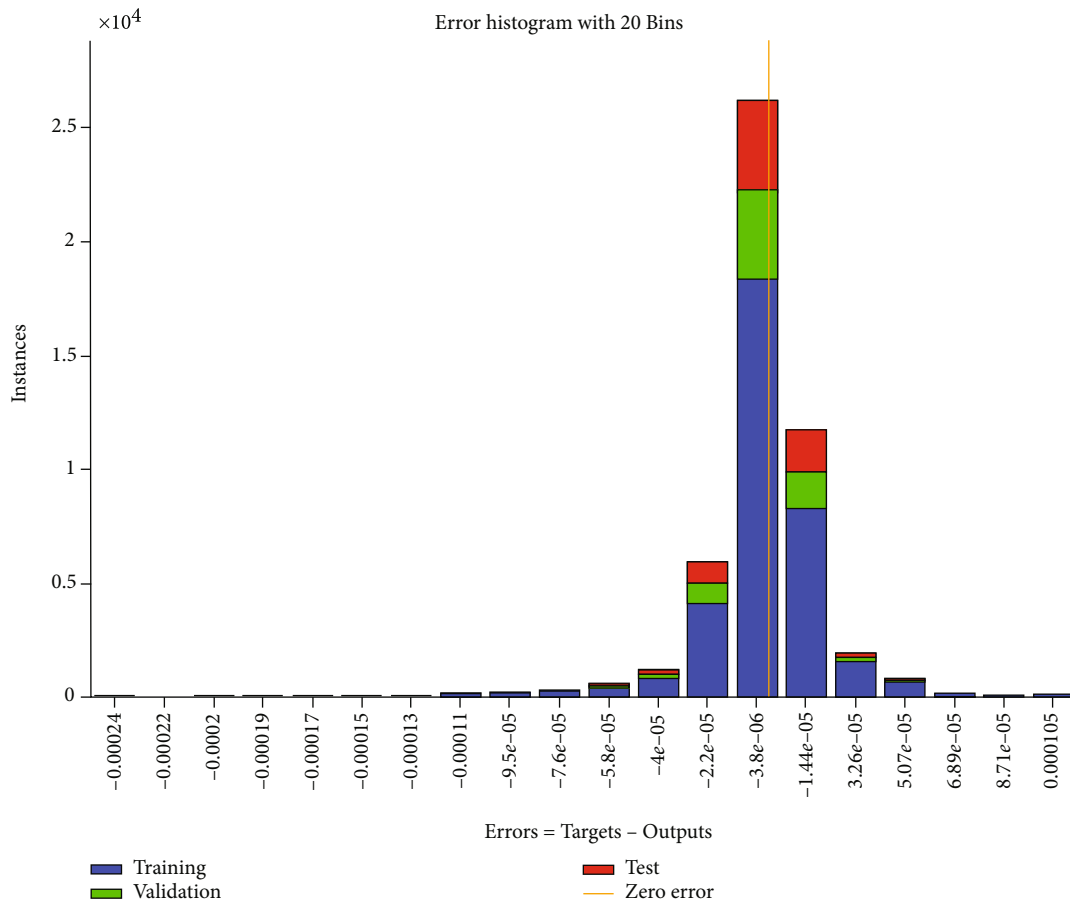


FIGURE 26: Error histogram of a DNN-based current regulator.

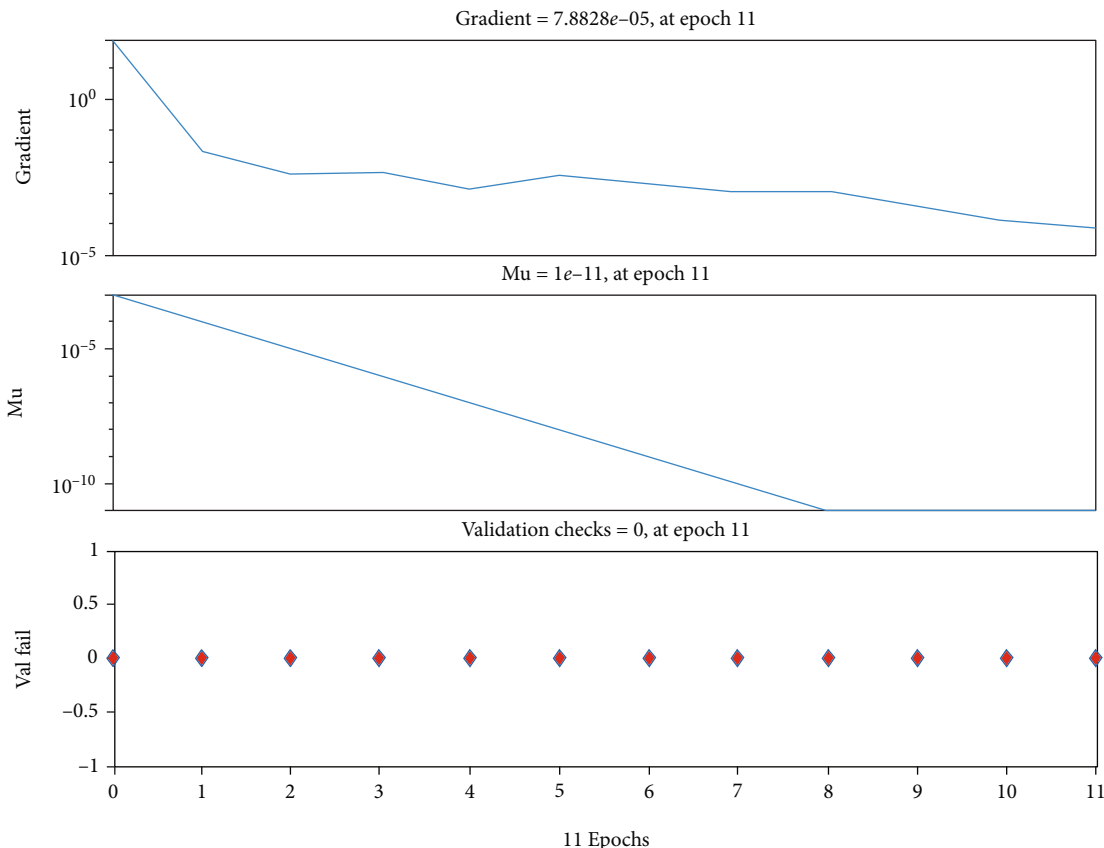


FIGURE 27: Training data of a DNN-based current regulator.

proposed DNN-based fuel flow control algorithm has been developed that showed best regression for training data, test data, validation data, and the overall performance data, as seen in Figure 17. The overall design and DNN data are presented in Table 2.

We applied the proposed DNN-based MPPT algorithm to a 6kW fuel cell power system and simulated it in MATLAB environment. The proposed fuel flow controller system has been analyzed under various fuel pressures. Figure 18 illustrates a power system that uses a fuel cell to generate power at various fuel flow pressures. The current waveform and output voltage of a boost converter are shown in Figure 19, and for the fuel cell, they are presented in Figure 20. Table 2(b) shows the comparative analyses of fuel cell efficiency with fuzzy and DNN controller.

#### 4. Integration of Microgrid with Hybrid PV and Fuel Cell Power Systems

In this section, we will discuss how a microgrid is integrated with a hybrid power system, its components like fuel cells or PVs, and how it is controlled by a DNN-based MPPT algorithm. The detailed simulation model is presented in Figure 21. In this simulation model, a 74kW hybrid PV (50kW) and a fuel cell ( $6 \times 4 = 24$  kW) energy system are integrated into a power microgrid with the support of a smart inverter, which is controlled by a DNN-based voltage source controller [15, 20, 21] as shown in Figure 22. In this control-

ler, there are three major subcontrollers, which are designed including a voltage regulator, a phase lock loop, and a current regulator. Finally, the PWM signals will be generated through the current regulator for the smart inverter through a synchronous connection between the hybrid 74kW PV/fuel cell and the microgrid system.

#### 5. Deep Neural Network Controller-Based Grid-Integrated Smart Inverter

A Deep Neural Network (DNN) controller can regulate the current in a grid-connected hybrid PV and FC energy system with the help of an exploitation sensing inverter. During this DNN learning, the algorithmic rule is used with 75,000 data items for providing training to develop roles to run a current regulator algorithm. The simulation model of the projected current regulator-based grid-connected smart inverter has been simulated using MATLAB, as Figure 23 indicates.

The projected simulation model, the 74 kW hybrid PV (50 kW), and the fuel cell ( $6 \times 4 = 24$  kW) energy system have been used for microgrid integration. The DNN layer that consists of a pair of input neurons, 2500 hidden-layer neurons, and two output neurons is shown in Figure 24. This DNN layer has been used for guiding the current regulator network used in the subsequent data like input (direct axis and quadrant axis current) while the output is a PWM signal for a grid-integrated smart inverter.

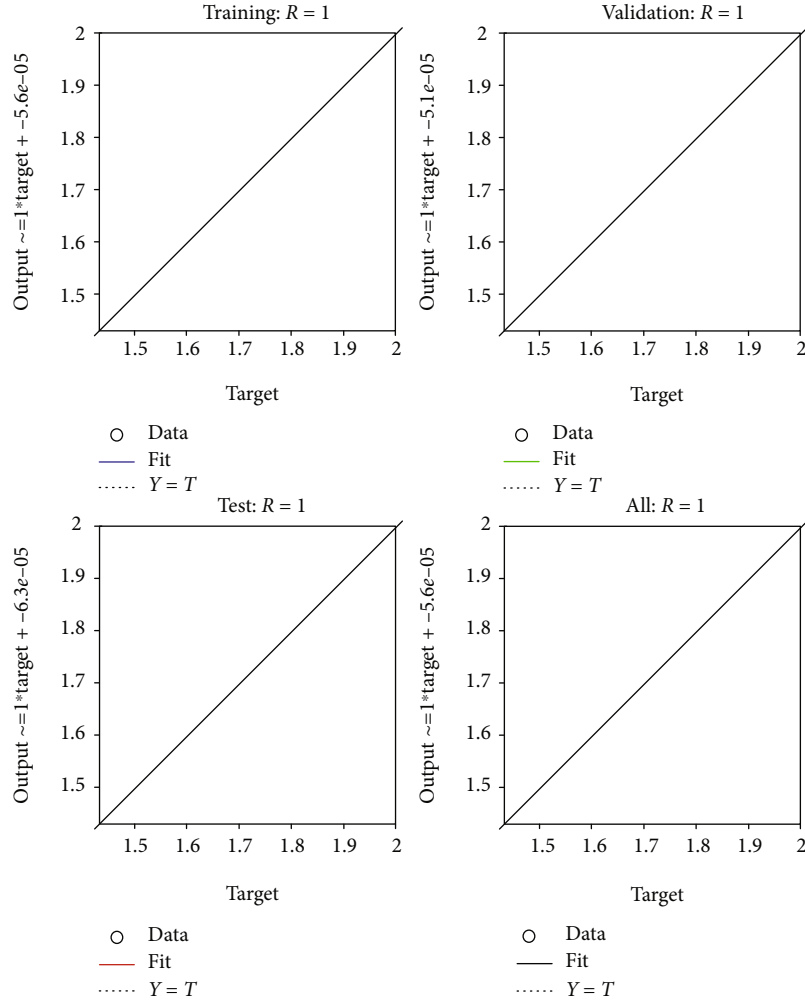


FIGURE 28: DNN-based current regulator—training, test, and validation.

The DNN controller has been trained using the above system, and its best validation performance has been presented in Figure 25. The proposed DNN controller error (target – output) histogram data is presented in Figure 26. The proposed DNN-trained network gradient and validation check is presented in Figure 27. Finally, the proposed DNN-based current regulator algorithm has been developed and is presented with its best regression for training data, test data, validation data, and overall performance data in Figure 28. The regression predicts an output variable (PWM) as a function of the inputs (observed direct and quadrant axis current). The overall DNN data are given in Table 3.

### 6. Results and Discussion

The proposed system has been developed and simulated under varying operational conditions using the MATLAB atmosphere. The simulation model, the simulation results, and the subsequent information were determined. Figure 29 shows the load of real power consumed by the consumers from the microgrid network, which was 110kW. The reac-

TABLE 3: DNN data of a controller for the grid system.

DNN grid	Values
Best validation	7.7813e-10
Mu	1e-11
Gradient	7.8828e-5
Training	1
Validation	1
Test	1
Overall regression	1

tive power is consumed by the consumer’s load from the microgrid, which is approximately 170kVR, as shown in Figure 30. Figure 31 depicts that the full power (74 kilowatts) was generated by combining a PV and a fuel cell in a hybrid power generation system. The most important objective of this analysis is to maintain the microgrid grid voltage and current with no or negligible oscillations. Figure 32 shows the microgrid voltage and current



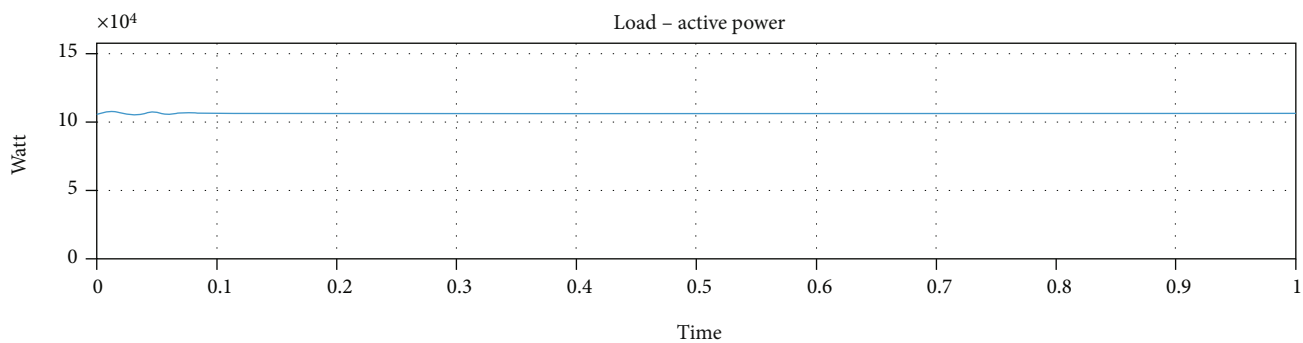


FIGURE 29: Real power consumed by load.

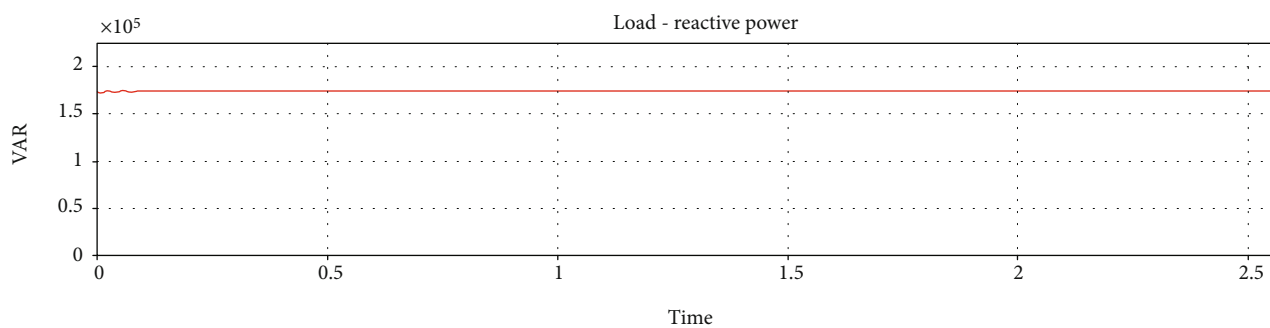


FIGURE 30: Reactive power consumed by the load.

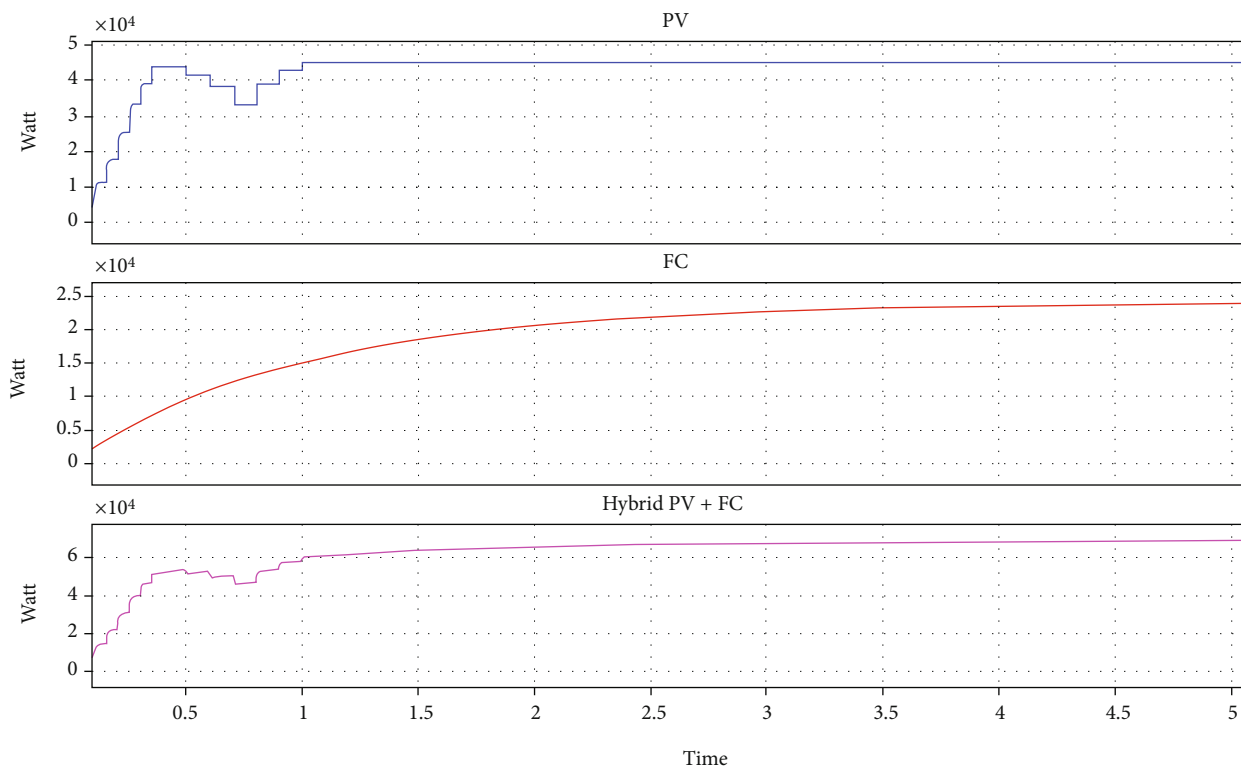


FIGURE 31: Total power generated by hybrid PV and FC energy system.

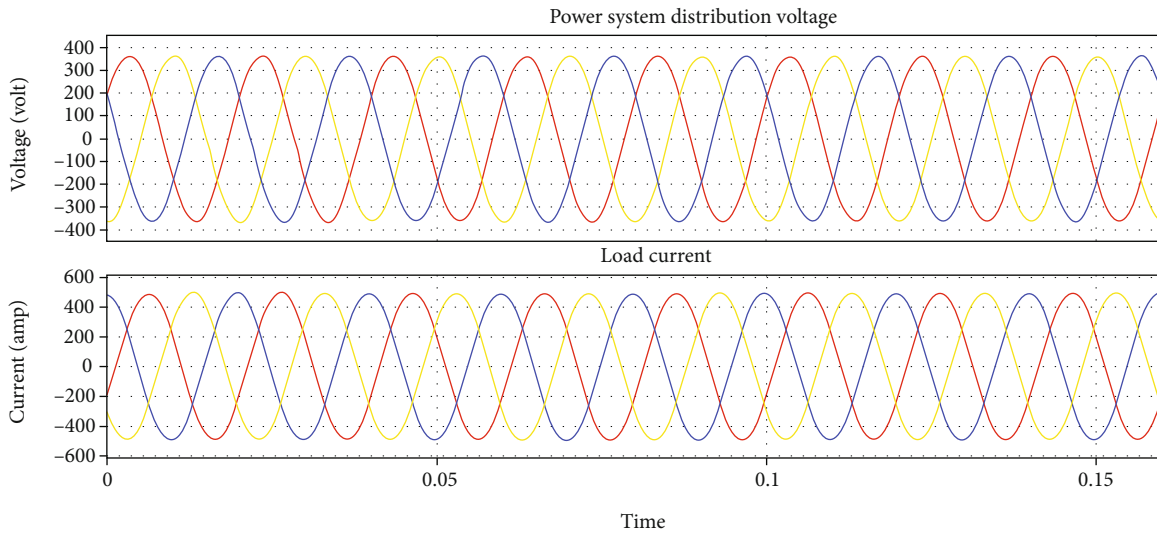


FIGURE 32: Waveform of the microgrid voltage and current.

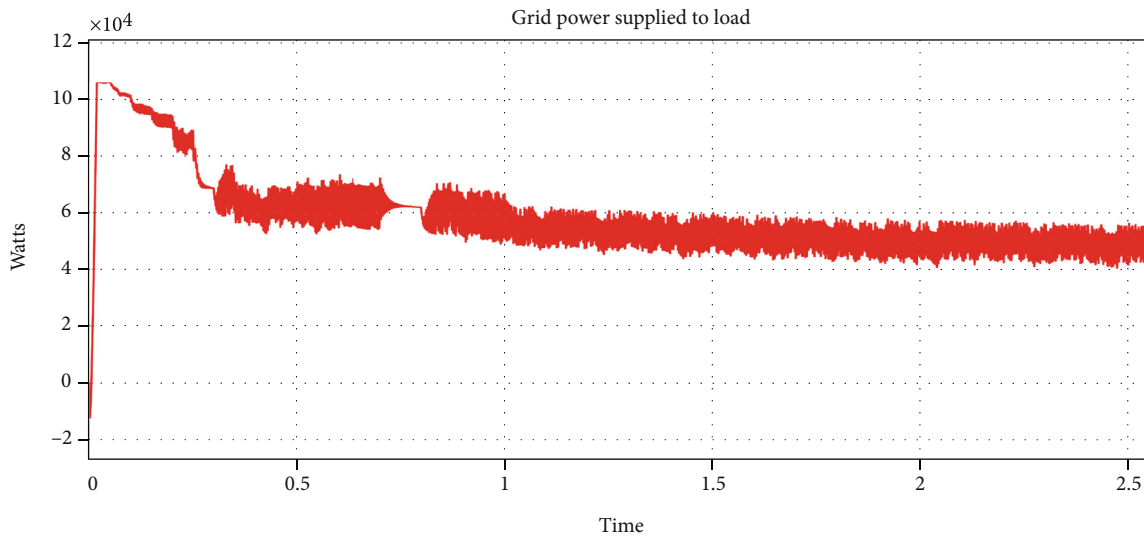


FIGURE 33: Grid-supplied power to the load.

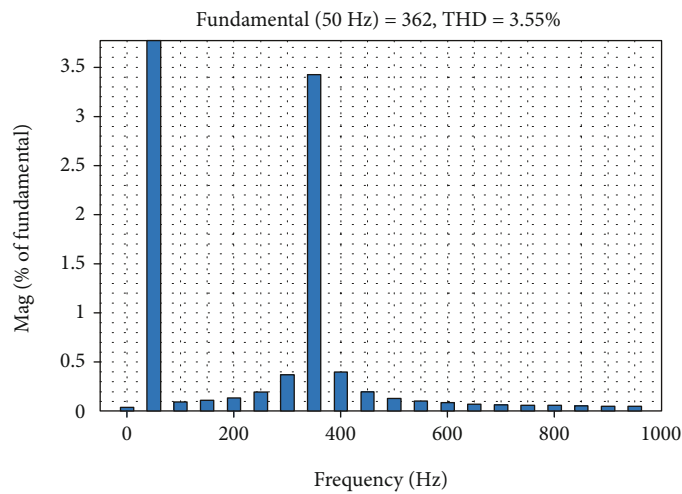


FIGURE 34: THD values for PV system voltage.

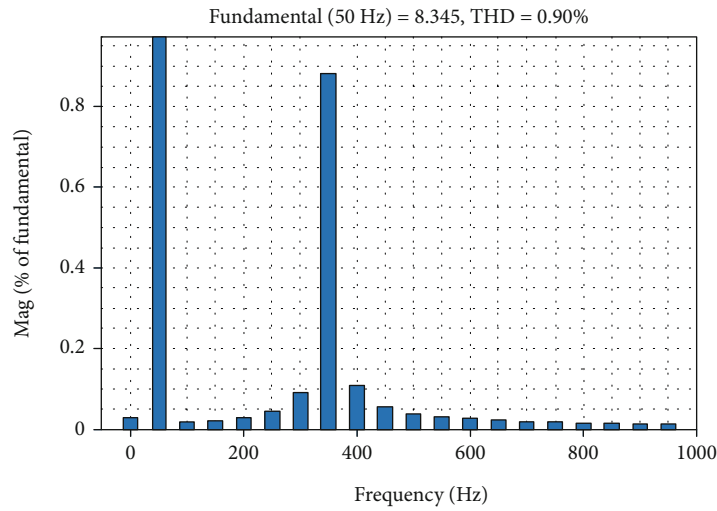


FIGURE 35: THD values for PV system current.

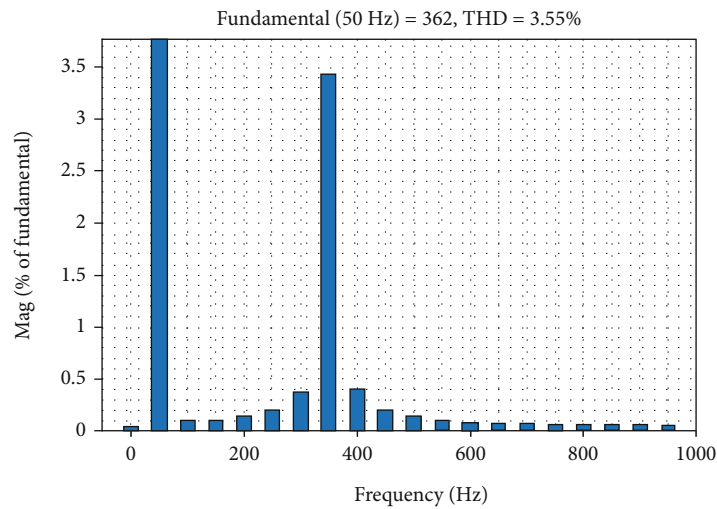


FIGURE 36: THD values for FC voltage.

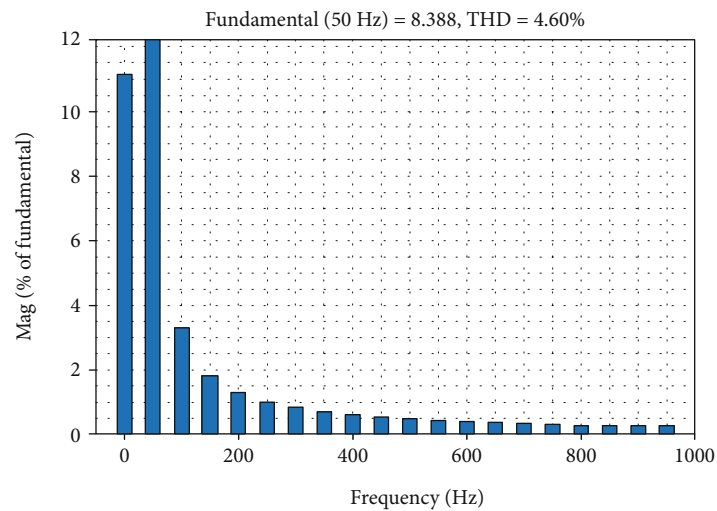


FIGURE 37: THD values for FC current.

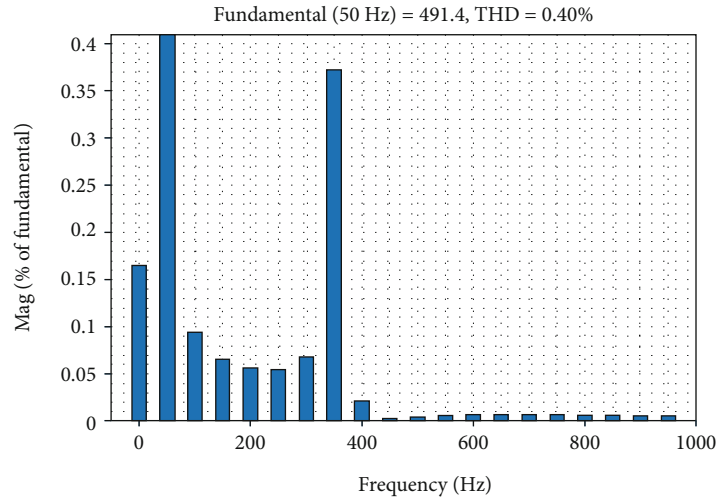


FIGURE 38: THD values for microgrid current load.

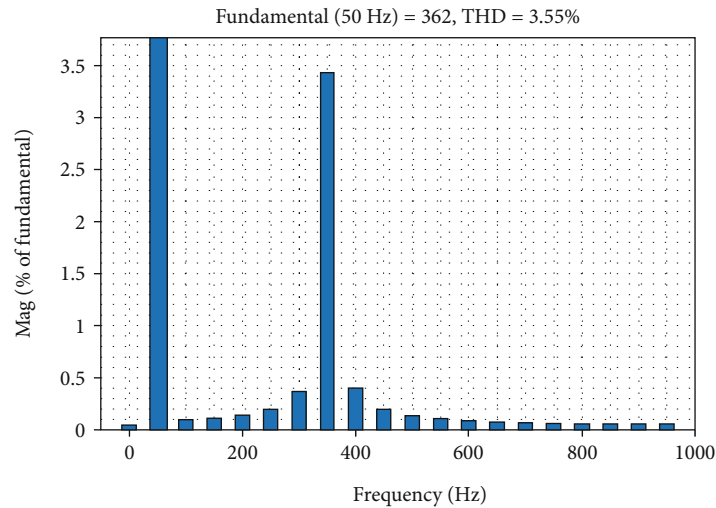


FIGURE 39: THD values for microgrid voltage load.

waveform in the grid-integrated nonlinear supply of power through a hybrid power generation system that is equipped with a PV and a fuel cell. Power management is one of the main tasks of a power generating station because it must meet the clients' demand. In the projected model, the hybrid PV/FC generated around 74 kilowatts of power. The microgrid alone provided the power to the buyer's load, which is given in Figure 33. During this analysis, the other major task is to boost the power quality and to cut back on the THD value at the point of common coupling. This simulation deeply analyzes the THD value of all the generating sources and the microgrid. The PV system's THD values for the voltage and the current are given in Figures 34 and 35, respectively. The next two Figures 36 and 37 present the FC energy system's THD values for current and voltage, respectively. Finally, the microgrid load, voltage, and current THD values are analyzed and given in Figures 38 and 39, respectively. The THD values are presented in tabulated form in Table 4.

TABLE 4: THD comparative values for grid, fuel cell, and PV.

Profile	Voltage-THD	Current-THD
Grid	3.55%	0.4%
FC	3.55%	4.46%
PV	3.55%	0.9%

## 7. Conclusion

This paper has been written after detailed investigation and development of an advanced DNN controller-based MPPT controller algorithm for PV, which has been analyzed in various atmospheric conditions. The PEM cell system has been developed to manage the fuel flow pressure by DNN, which is primarily based on the algorithm to enhance the fuel cell efficiency. Furthermore, the simulation results were evaluated and analyzed in different weather changes and fuel flow fluctuations to make sure that the proposed controller

algorithm is effective. The proposed MPPT results are compared with a fuzzy logic controller and prove the proposed controller effectiveness. The projected grid integration of the hybrid PV and fuel cell energy system has been developed and simulated in the MATLAB atmosphere. The target of this analysis is implementing a simulation model of a smart inverter-based microgrid, which was integrated with a hybrid PV and the fuel cell energy system using the DNN algorithm in MATLAB atmosphere. The projected system has been simulated in various operational conditions, and the results are reported in this paper. The improvements in the power quality are the second most significant purpose of this research. This objective was achieved through finding the THD values of the PV, fuel cell, distributed grid voltage, and current profile. The proposed system THD values are less than 5% according to the IEEE 1547 and 519 standards. The projected system and DNN controller effectively improved the power quality and the environmental surroundings.

### Data Availability

All time available.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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