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ANFIS Based Real-Time Power Reference Generator for PV Applications

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Abstract: In this study, a real-time power estimation of a 250Wp solar panel is performed by using a commercial product SIS01-TC-T PV reference module and STM development board. Power estimation was carried out with Adaptive Neuro-Fuzzy Inference System (ANFIS). During the training process, the actual values of the Photo Voltaic (PV) panel with a 250Wp power were used. ANFIS training was accomplished with the hybrid learning algorithm. The power estimation process can be used as a reference power for various applications. The estimated power value can be used in real-time power monitoring for remote monitoring systems or optimum angle control applications for solar tracking mechanisms. It can also be used as a reference value for hybrid Maximum Power Point Tracking (MPPT) control applications or Proportional, Integral, and Derivative (PID) control. In addition, with this reference power value, the Pulse Width Modulation (PWM) signal required by various power electronics stages can be generated.

Keywords: ANFIS, PV Panel, Real-Time Power Estimation

FV Uygulamaları için ANFIS Tabanlı Gerçek Zamanlı Güç Referans Üreteci

Öz: Çalışma ile ticari bir ürün olan SIS01-TC-T PV referans modülü ve STM geliştirme kartı kullanılarak 250Wp'lik güneş panelinin gerçek zamanlı güç tahmini yapılmaktadır. Güç tahmini Uyarlamalı ağ tabanlı bulanık çıkarım sistemi (ANFIS) ile gerçekleştirilmiştir. Eğitim sürecinde 250Wp güce sahip FotoVoltaik (PV) panele ait gerçek değerler kullanılmıştır. ANFIS eğitimi hyrib öğrenme algoritması ile gerçekleştirilmiş. Yapılan güç tahmini, çeşitli uygulamalar için referans güç olarak kullanılabilecektir. Elde edilen tahmini güç değeri; uzaktan izleme sistemleri için gerçek zamanlı güç izleme veya güneş takip mekanizması için optimum açı kontrolü vb. gibi uygulamalarda kullanılabilir. Diğer bir kullanım alanı olarak hibrit yapılı Maksimum Güç Noktası Takibi (MPPT) kontrol uygulamaları veya Oransal-İntegral-Türevsel denetleyici (PID) için referans değer olarak kullanılabilir. Ek olarak bu referans güç değeri ile çeşitli güç elektroniği katlarının ihtiyaç duyduğu Darbe Genişlik Modülasyonu (PWM) sinyalinin üretilmesi sağlanılabilir.

Anahtar Kelimeler: ANFIS, FV Panel, Gerçek Zamanlı Güç Tahmini

1. Introduction

Renewable energy sources offer alternative solutions to the current energy crisis and the most popular of these sources is solar energy [1-4]. It can be directly converted into electrical energy thanks to PV cells using the photovoltaic effect [5]. Solar energy is used extensively in production, transportation, health and living areas [6]. Like other renewable energy sources, solar energy has an uncertain nature [7]. In this respect, since the instantaneous value of the energy obtained from the sun will change depending on atmospheric conditions [8], studies are continuing to make maximum use of solar energy and maximize production [9], [10]. These studies are methods called maximum

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power point tracking. Many methods have been proposed for maximum power point tracking for PV systems [11], [12]. Solar and wind energy has a nonlinear and irregular power output, MPPT algorithms can overcome this irregularity and make it efficient [13], [14]. Optimum use of electrical energy produced from PV panels can be achieved with traditional MPPT algorithms that work by monitoring various parameters of the panel (panel current, voltage, power, etc.). In addition, there are hybrid MPPT techniques that include traditional methods and can detect the maximum power point (MPP) even in cases such as partial shading [15]. Maximum power point tracking algorithms using traditional methods approach the MPP of the PV with a fixed or variable step [16]. Efficient use of energy can also be achieved by measuring the produced energy accurately or estimating it with the use of various methods. Electricity generation from PV panels is highly affected by atmospheric changes such as temperature and solar radiation [17], [18]. Considering this situation, estimating the energy to be obtained from the panels with these two parameters is of great benefit. Forecasting energy production for real-time, daily, weekly, or monthly periods can be made with approaches such as mathematical, Fuzzy Logic (FL), and ANFIS [19]. In addition, the geographic location (latitude and longitude) can be used in addition to temperature and solar radiation in the instantaneous power estimation of the PV panel (Sinha, 2020). Studies using the estimated values obtained as a result of ANFIS training can give better results than traditional methods [20]. Estimated power values and control signals needed by simple structured power electronics circuits such as direct current to direct current (DC-DC) converters [21] can be produced. While voltage source converters (VSC) can be recommended for irregular operating conditions [22], power modules fed by PV panels and capable of producing AC directly can be driven by ANFIS [23]. The control of building-integrated PV modules, which have become popular today, can also be done by ANFIS [24], [25]. With a feedback structure to be added to the system, maximum power can be obtained from the PV system. Another study to make maximum use of PV Panels is the systems that follow the sun mechanically. These systems can be provided to increase power generation and efficiency by automatically adjusting the PV panels [26]. Power estimation using real-time changing atmospheric data can also be used as a reference value for other application areas. Examples of energy management studies [27], [28] for maintaining the balance between load and source or hybrid energy sources can be given. Similarly, approaches such as Artificial neural network (ANN) and ANFIS can also perform the function of integrating various energy sources into the existing system [29] and contribute to smart grid applications [30].

2. Experimental Methods

In this section, information will be given about the design and implementation phases of real-time power estimation using the Reference PV cell.

2.1. Modeling of PV Cell

PV cells consist of P-type and N-type semiconductors. As a result of exposing the junction point of P-type and N-type semiconductors to photon radiation, an electron flow is provided through the external circuit, this phenomenon is called the photovoltaic effect. As a result of this event, an electric current is generated. PV cells behave as a current source. The electrical model of the PV cell is shown in Figure 1.

The model given in Figure 1 is called the single diode model and is the model with the most general use. The current generation of the PV cell varies with solar radiation (G) and cell temperature (T). Equation 1 is used to calculate the output current over the electrical model of the PV cell. The current produced by the PV cell depending on solar radiation and temperature is calculated by Equation 2.

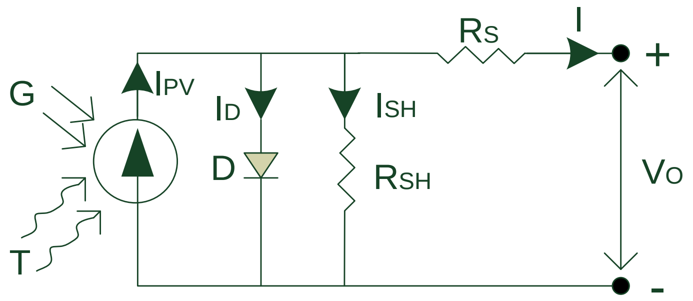

Figure 1. Single diode equivalent circuit model of PV cell.

$$I = I_{pv} - I_0\left[exp\left(\frac{q(V+IR_s)}{\alpha KT}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \tag{1}$$

$$I_{pv} = I_{sc} + K_i\left(T - T_{ref}\right)\frac{G}{G_{ref}} \tag{2}$$

Where I is PV cell output current, V is PV cell output voltage, I_{pv} is light-generated current, $I_0$is cell reverse saturation current, I_{sc} is cell short circuit current, $T_{ref}$is reference temperature in Celcius, T is cell temperature in Celsius, K_i is short circuit current/temperature coefficient, G is solar radiation, G_{ref} is reference solar radiation in W/m^2, R_s is series resistor resistance, R_{sh} is shunt resistor resistance, K is Boltzmann's constant, respectively.

In the study, electrical data of STP250S-20/Wd product of Suntech company, which is a commercial product, was used. By taking the electrical data of the panel into the simulation environment, graphics were tried to be obtained under the changing solar radiation and temperature values. The electrical data of the simulated panel are given in Table 1.

Table 1. Electrical data of the simulated solar panel within the scope of the study.

Parameter	**Value**	**Unit**
Maximum Power (*Ppv*)	250	W
Maximum Power Voltage (*Vmp*)	30.4	V
Open Circuit Voltage (*Voc*)	37.4	V
Maximum Power Current (*Imp*)	8.15	A
Short Circuit Current (*Isc*)	8.63	A
Number of Cell	60	Pieces
Module Efficiency	15.2	%

The data in Table 1 were provided by the manufacturer, the values written on the information sheets, and were obtained under 1.0 kW/m^2 and 25 °C temperature. The current-voltage characteristic of the simulated panel using the data within the scope of the study is given in Figure 2.

The graph was created under a constant temperature of 25 °C and according to the variation of solar radiation between 0.2 kW/m^2-1.0 kW/m^2.

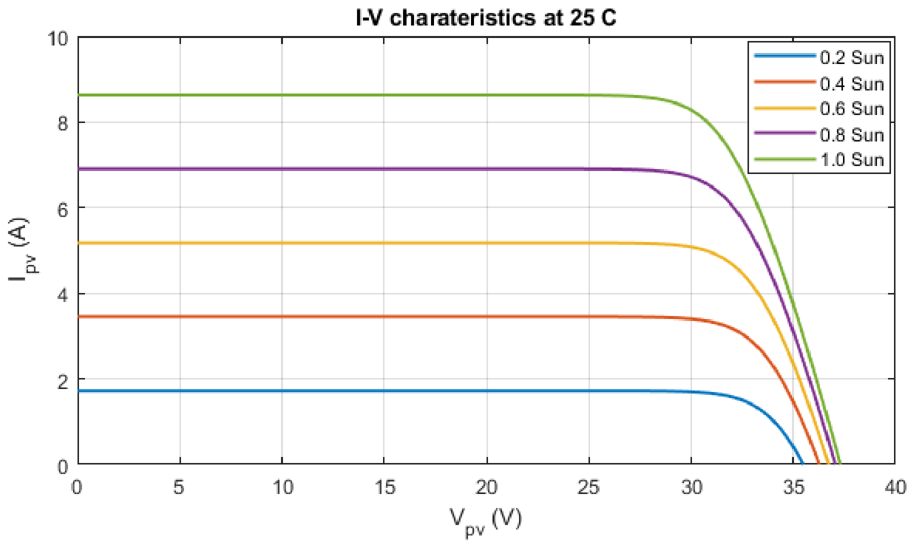

Figure 2. Output current and voltage graph of the PV panel under constant temperature, variation solar radiation.

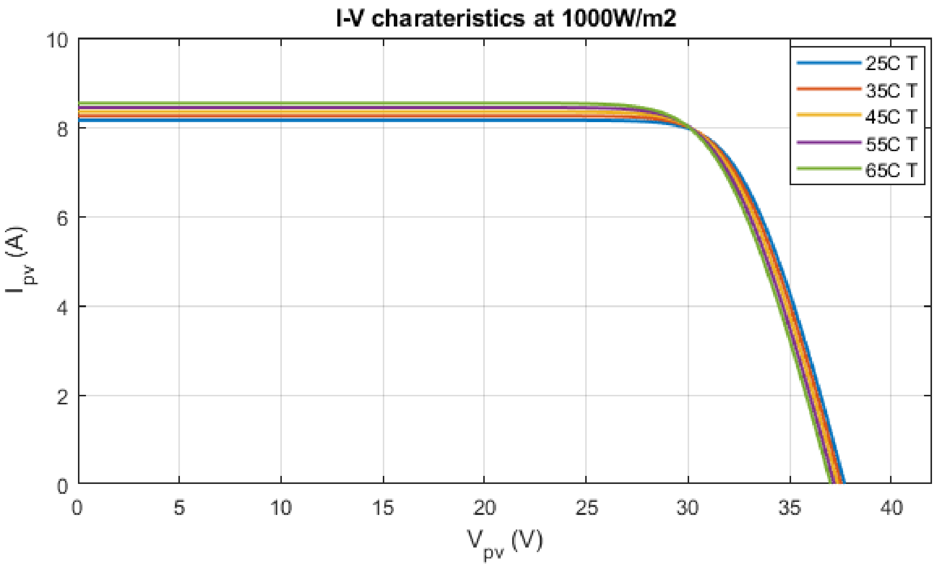

Figure 3. Output current and voltage graph of the panel under constant solar radiation, variable temperature.

In the graph given in Figure 3, the change in the current-voltage characteristic of the same PV panel is drawn this time under 1.0 kW/m^2 constant solar radiation and according to changing temperature values. The temperature variation range in the graph is 25-65 °C.

2.2. Training and Testing Data

In the study, Adaptive Neuro-Fuzzy Interface System (ANFIS) was used to estimate the output power of the solar panel with 250Wp power. ANFIS is a data learning technique that aims to achieve desired results over input data by using multiple artificial neural networks [31], In this respect, it is used in many applications around the world [32]. In this context, the solar panel data of the past was applied to ANFIS, training was provided and the FIS file was produced. The rule relations network and layers of this FIS file are given in Figure 4.

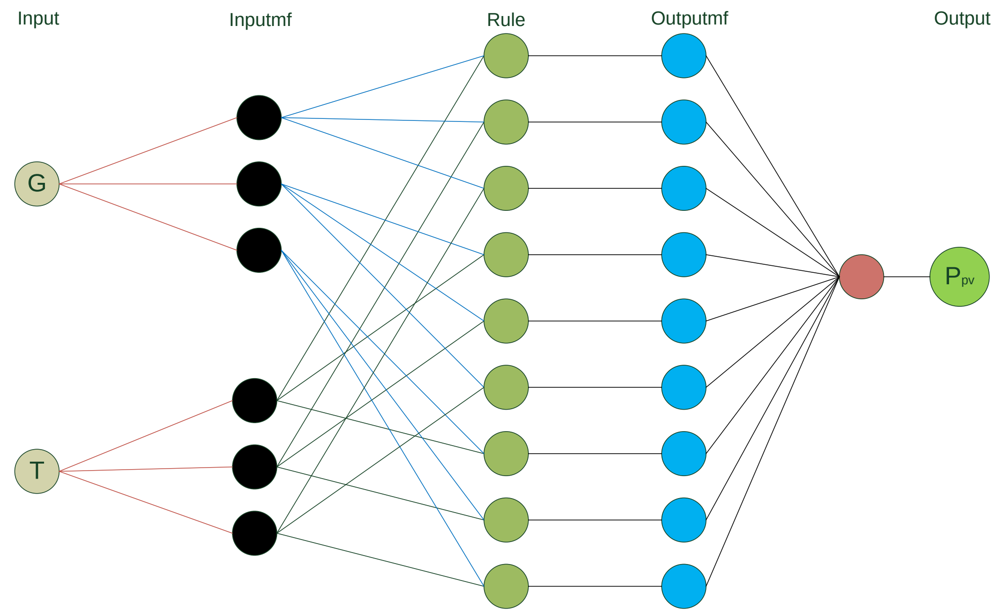

Figure 4. Layer and relationships graph of the FIS file created within the scope of the study.

During the training process, real temperature, radiation, and power data of a real panel were used. The solar radiation (G) graph participating in the training is given in Figure 5.

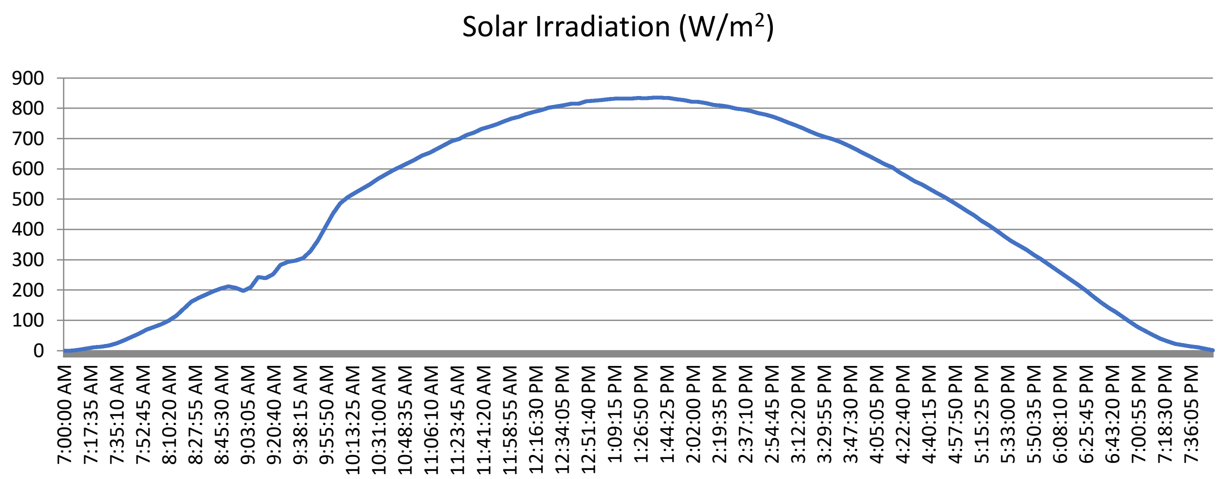

Figure 5. Solar irradiance graph was used to train ANFIS within the scope of the study.

The actual solar radiation graph used in the training is a data stack covering 24 hours, but since the solar panels will not produce energy when the solar radiation is 0 W/m2, the early hours when the sun does not rise and the evening hours when the sun goes down were not used in the education. In this case, the data participating in the training is between 07:00 in the morning and 7:40 p.m. The solar radiation data are from Nevşehir province, in September, and were obtained from a commercial meteorology station. According to the values measured by the solar radiation sensor located within the station, the most intense times of solar radiation are at noon and it is approximately 835 W/m2. In Figure 6, there is a graph created by the air temperature data, which is also composed of real values.

Ambient temperature, like solar radiation, is a 24-hour chunk of data. At the time the data group was selected, the air temperature did not fall to 0 °C, but these data are also between 07:00 in the morning and 7:40 p.m. in order not to disturb the time synchronization.

According to the graph, the temperature change is between 13.3 °C and 29.8 °C.

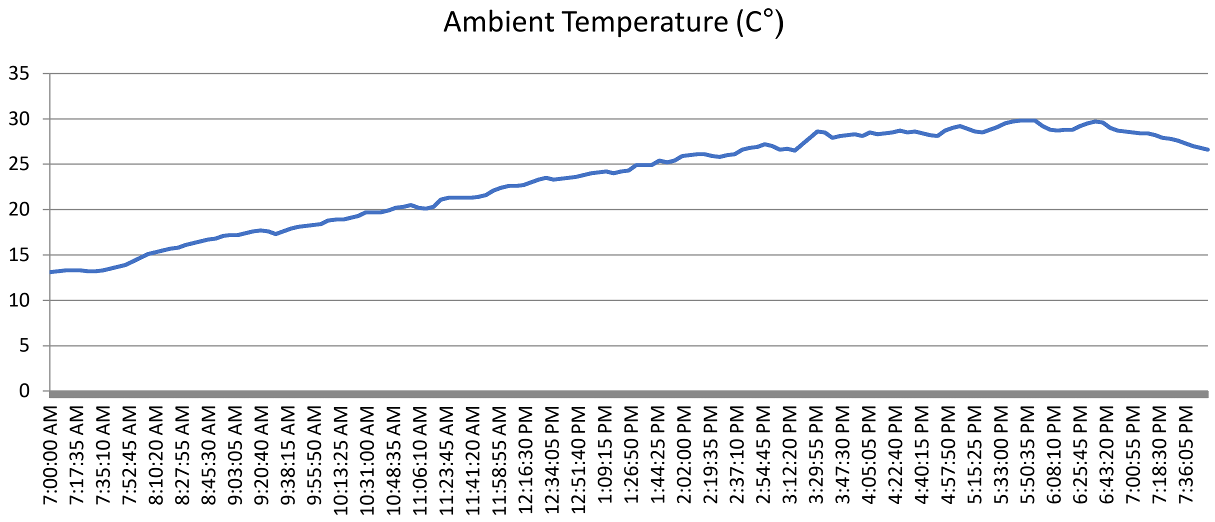

Figure 6. Ambient temperature graph was used for training ANFIS within the scope of the study.

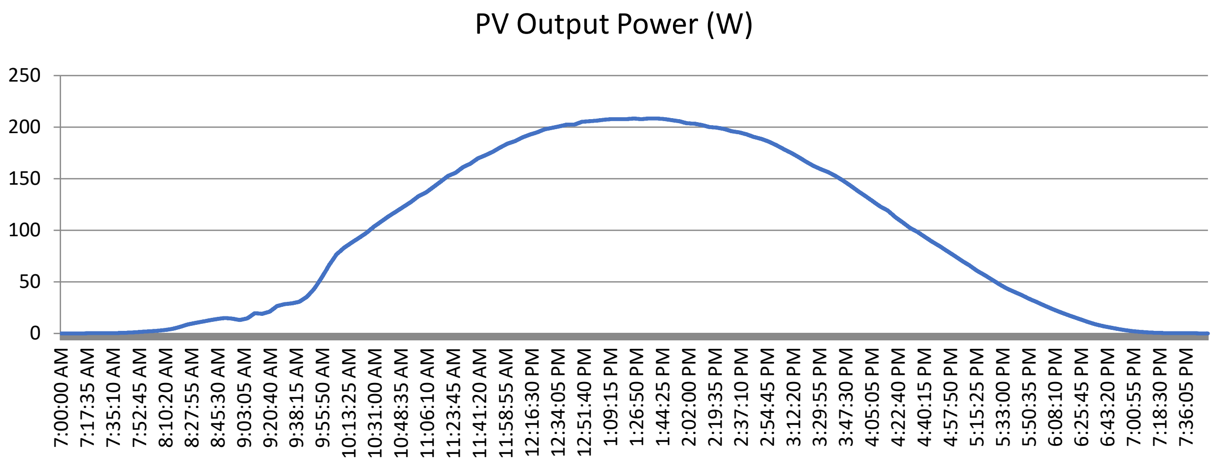

Figure 7. Solar panel output power graph used for training ANFIS within the scope of the study.

The output power graph of the panel is given in Figure 7. The output power value of the panel was obtained by changing the graphic values in Figure 5 and Figure 6. The highest output power of the panel is at the peak of solar radiation, and it is around 210.6 W against the 835 W/m^2 radiation value.

2.3. Proposed System and General Structure

According to the system structure proposed within the scope of the study, it is aimed to estimate the output power of the 250 W solar panel in real-time by using a commercial product SIS01-TC-T PV reference module and STM development board. In the estimation of the power, ANFIS, which is trained by using real data, is used. The training process created for this purpose can be summarized with the block structure given in Figure 8. According to this block structure, solar radiation, air temperature, and output power data of a solar panel operated in previous times were recorded with a data logger and tabulated. This table was later used for ANFIS training and testing.

After the ANFIS training, a FIS file was created that aims to reach the output value against the input data. This created FIS file has been uploaded to the STM 32F072 development board with the embedded system software.

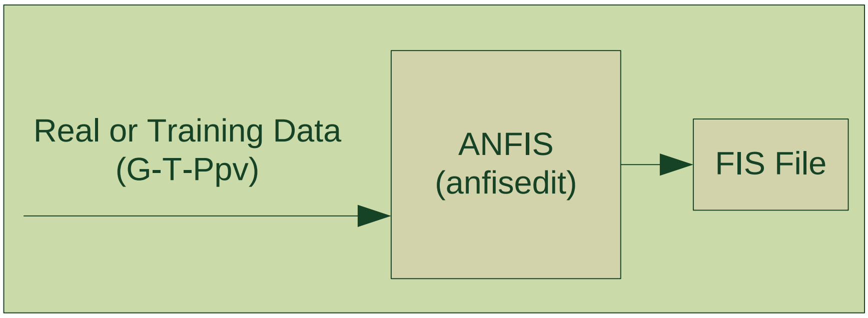

Figure 8. Block diagram of the ANFIS training process.

The block diagram indicating the post-training processes and the scope of the study is given in Figure 9.

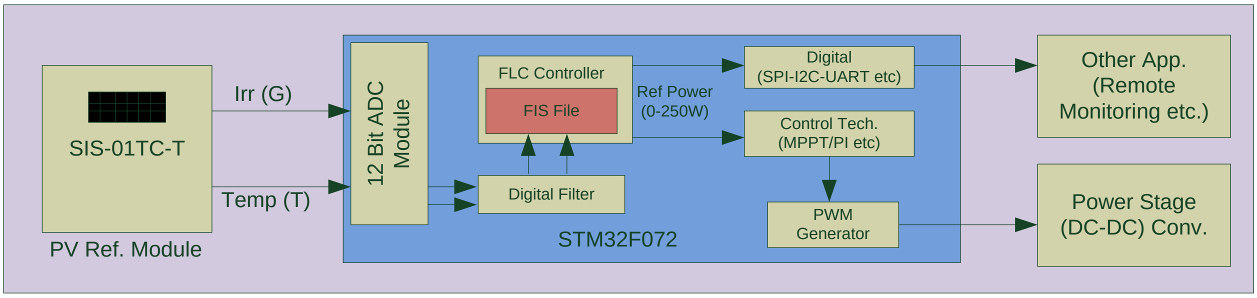

Figure 9. Block diagram of the system created within the scope of the study.

According to the block diagram, the commercial product SIS-01TC-T PV solar cell module generates the current solar radiation value and temperature as an analog signal. The instantaneous solar data (sunlight and cell temperature) obtained are transferred to the STM32F072 development board via the 12Bit ADC module. The analog data applied to the ADC module is transformed into digital data that the fuzzy logic controller (FLC) needs by passing through several digital filters. The FIS file produced at the end of the ANFIS training makes a power estimation with FLC based on the cell temperature and solar irradiance data. The visual of the test setup created is given in Figure 10.

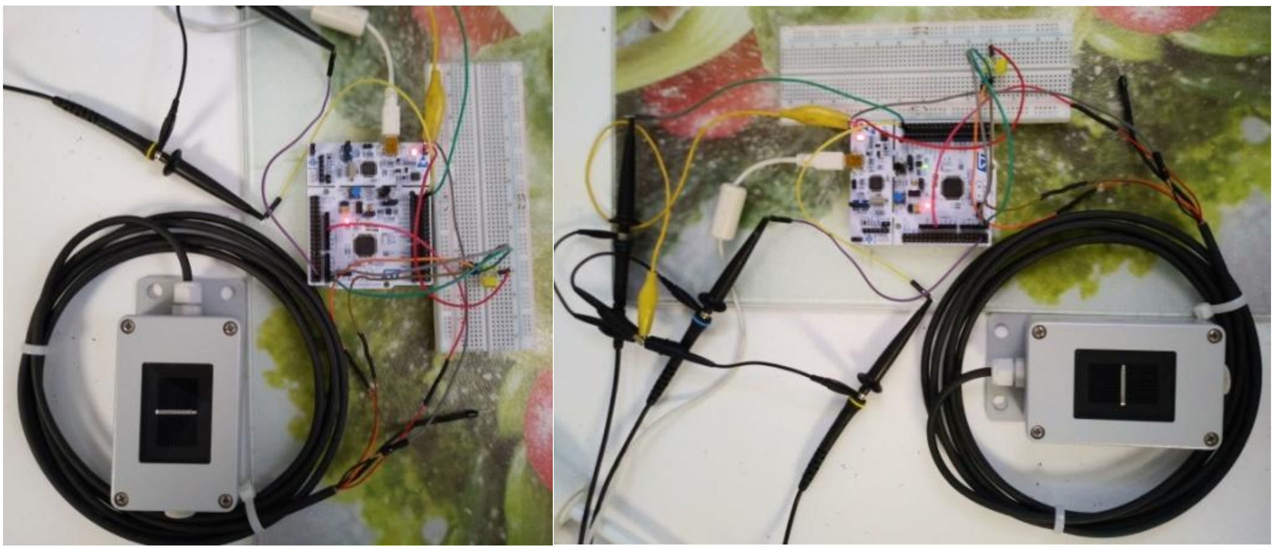

Figure 10. Test circuit created within the scope of the study.

3. Results and Discussion

ANFIS, which was trained on real solar panel data, was then tested on real solar data of September 10, Nevşehir province. The maximum solar radiation value entered into ANFIS as test data with this disruption is 976 W/m^2 and is given in Figure 11.

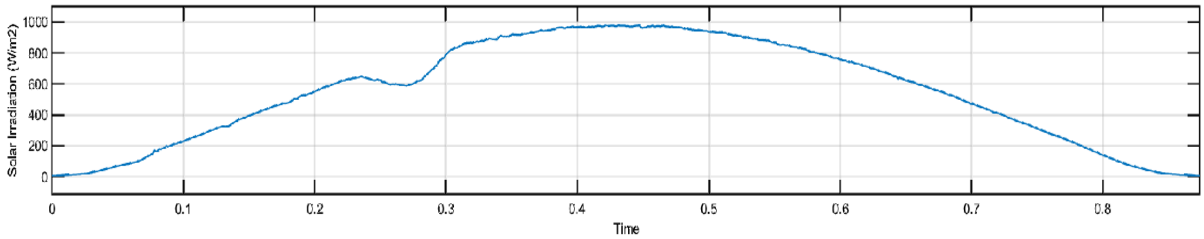

Figure 11. Graph of solar radiation data used for testing.

The solar irradiance value used for the test was cleared from the early morning and evening hours when the irradiance was 0 W/m^2, as in the training data. Another data stack entered into ANFIS as test data is the air temperature of Nevşehir. The outdoor temperature value change range is 16.7 °C to 29.2 °C. The air temperature graph used as test data is given in Figure 12.

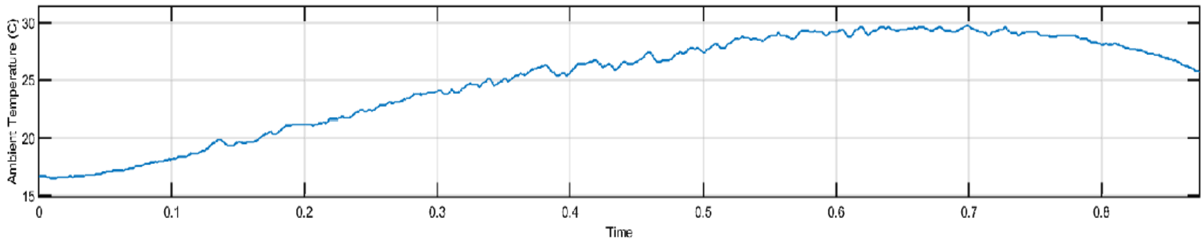

Figure 12. Graph of ambient temperature data used for testing.

As a result of using the graphic data in Figure 11 and Figure 12 as input, ANFIS created the power graph given in Figure 13.

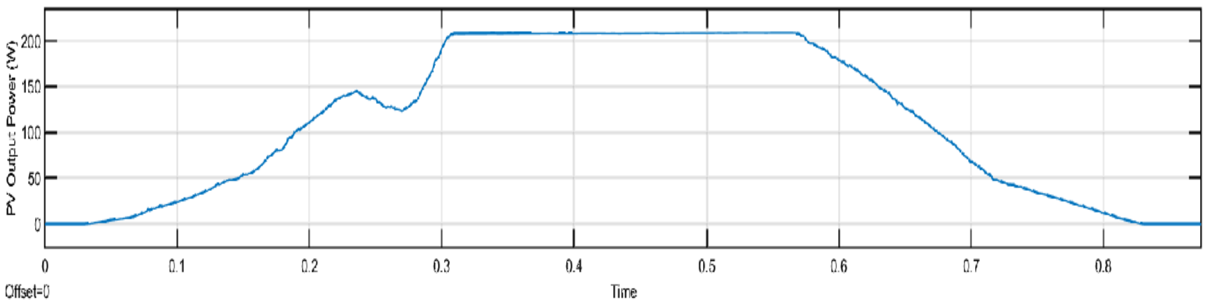

Figure 13. Solar panel output power graph produced by ANFIS versus solar irradiance and air temperature data used for testing.

According to the graph in Figure 12, it is between 0.31 seconds and 0.57. The main reason why the power output is constant between seconds is that the data used in the training of ANFIS is not covered by the test data. Moreover, the power output is constant between seconds is that the data used in the training of ANFIS is not covered by the test data seen in Figure 5. Another reason explaining this situation is that while the maximum solar radiation value used for education is 835 W/m2, the solar radiation increases up to 976 W/m2 in the test data. For this reason, ANFIS behaves as if it is saturated in this interval, since the data received in the training does not include the data taken in the test. In case the training data used for ANFIS includes the test data; it is possible for the output power estimation curve of the panel to appear as the power curve of a real PV panel.

4. Conclusions

With the study, real-time power estimation of a 250 W solar panel was made using a commercial product SIS01-TC-T PV reference module and STM development board. The output power of the panel was estimated by ANFIS. During the training process, real electrical and environmental data of the PV panel with 250 W power were used. The power estimation obtained with the developed and tested system can be used as a reference power for various applications. With the estimated power value, real-time power monitoring can be done for PV panel remote monitoring systems. At the same time, optimum angle control can be made for the solar tracking mechanism created for PV panels with the reference power value, which does not need time and sun angle sensor. As another usage area, the obtained reference power value can be used in hybrid MPPT control applications aiming to obtain optimum power from PV panels. In addition, it can be used as a reference value for PID control applications. Moreover, with this reference power value, the PWM signal required by various power electronics stages is produced. The FIS file obtained within the scope of the study was tested by loading it on the STM 32F4072 board. According to the created test setup, the PV reference module and STM were hardware combined, and real-time power estimation was made. The estimated power value obtained is numerical. Within the scope of the study, no power stage was used like inverter, converter and so on.

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Authors' Contributions

GG is the inventor of the original device and the overall supervisor of the project.

Competing Interests

The authors declare that they have no competing interests.

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