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Integration of Wind and Solar Hybrid Power Generation Systems into The Grid and Control of Power Quality with Fuzzy Logic

Yüksel OĞUZ[1], Sediqullah HABİBİ[2], Muhammed Mustafa KELEK[3*]

[1,2,3]Afyon Kocatepe Üniversitesi, Teknoloji Fakültesi, Elektrik Elektronik Mühendisliği Bölümü, Afyonkarahisar

[1]https://orcid.org/0000-0002-5233-151X
[2]https://orcid.org/0000-0002-3675-6593
[3]https://orcid.org/0000-0002-9915-4776
*Corresponding author: mmustafakelek@aku.edu.tr

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ABSTRACT

This study modeled and analyzed a grid-connected hybrid system composed of solar and wind power generation systems in Matlab/Simulink. In addition, the quality of power generated by the hybrid power generation system was improved using Fuzzy Logic (FL) and Proportional-Integral (PI) controllers. Measurements of the frequency, voltage, power, and harmonics of the system and the grid were evaluated. In addition, the voltage and frequency fluctuation times before synchronization between the hybrid generation system and the grid were analyzed. The voltage rises on the grid while the system is idling have been checked. After synchronization, the voltage, power, frequency, and phase angle values measured at the load and the grid in the hybrid system were observed individually. According to the measured values obtained from the simulation study, the performance of the hybrid power generation system was analyzed.

Rüzgâr ve Güneş Hibrit Güç Üretim Sisteminin Şebekeye Entegre Edilmesi ve Güç Kalitesinin Bulanık Mantık ile Kontrolü

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ÖZ

Bu çalışmada, güneş ve rüzgâr enerjisi üretim sisteminden oluşan şebeke bağlantılı bir hibrit sistem Matlab/Simulink'te modellenmiş ve analiz edilmiştir. Hibrit enerji üretim sistemi tarafından üretilen gücün kalitesi Bulanık Mantık (FL) ve Oransal-İntegral (PI) kontrolörler kullanılarak iyileştirilmiştir. Sistemin ve şebekenin frekans, gerilim, güç ve harmonik ölçümleri değerlendirilmiştir. Ayrıca hibrit üretim sistemi ile şebeke arasındaki senkronizasyon öncesi gerilim ve frekans dalgalanma süreleri analiz edilmiştir. Sistem rölantide çalışırken şebekede meydana gelen gerilim yükselmeleri kontrol edilmiştir. Senkronizasyon sonrasında hibrit sistemde yükte ve şebekede ölçülen gerilim, güç, frekans ve faz açısı değerleri ayrı ayrı gözlemlenmiştir. Simülasyon çalışması sonucunda elde edilen değerlere göre hibrit güç üretim sisteminin performansı analiz edilmiştir.

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1. Introduction

Most of the energy used today has been obtained from conventional energy sources. However, these energy sources are rapidly depleting today. Due to the rapid depletion of energy resources and the damage these resources cause to nature during processing, the tendency towards renewable energy resources is increasing (Erdal, 2011). One of the advantages of energy sources that can be obtained from different areas of use is that they do not have any negative impact on nature. One advantage of energy sources from different regions is that they have no negative effect on nature. Many examples of renewable resources include hydroelectricity, geothermal, solar, wind, plant residues, biomass, tidal, and wave (Erdal, 2011). Solar and wind energy, among the renewable energy sources, has become more common in electricity generation. The primary reason for their common use is that these forms of energy do not require any clean fuel and have no negative impact on the surrounding environment. To obtain uninterrupted energy, hybrid systems have been developed in which energy sources are used together. Thus, it is possible to increase the efficiency of the hybrid power generation system and to meet the energy required for the system from the other source in case one of the sources is not available or scarce. Hybrid systems can be composed of two or more source components. Examples include solar & wind, solar & wind & diesel, solar & wind & hydrogen, and solar & wind & fuel cell.

Regionally, 2020 was a record year for onshore installations in Latin America, Asia-Pacific, and North America. 74 GW of new wind power was installed in these three regions. 8.2 GW of wind power was installed in the Middle East and Africa. For Türkiye, it has been accepted that in areas 50 meters above ground level and with wind speeds above 7.5 m/s, it would be appropriate to build a wind farm of 5 MW per kilometer. Türkiye's wind energy potential is estimated to be 48 GW. This potential equal 1.30% of Türkiye's total land area (T. C. Enerji ve Tabii Kaynaklar Bakanlığı, 2024). According to the report published by IRENA (International Renewable Energy Agency) in 2024, the installed capacity of renewable and wind energy in Türkiye and the world is shown in Table 1 (IRENA, 2024).

Table 1. Installed capacity of renewable energy and wind energy in Türkiye and the world according to IRENA 2024

Installed capacity of renewable energy sources (MW)			**Wind energy installed capacity (MW)**		
Year	World	Türkiye	Year	World	Türkiye
2013	1566487	25551	2013	300027	2760
2014	1699064	27940	2014	349466	3630
2015	1852777	31516	2015	416347	4503
2016	2018264	34446	2016	467028	5751
2017	2186038	38746	2017	514423	6516
2018	2359398	42230	2018	564513	7005
2019	2543378	44389	2019	620841	7591
2020	2813159	49195	2020	731656	10607
2021	3077238	53175	2021	824171	10607
2022	3371793	55946	2022	898824	11396
2023	3869705	58462	2023	1017199	11697

In hybrid systems, controlling and increasing efficiency is very important. For this reason, the necessary modeling, optimization, analysis, and design studies are carried out before installing the system, and the system is evaluated in terms of risk and cost analysis (Ulutaş, 2015). Some studies related to hybrid systems can be found in the literature.

Dursun analyzed the performance of a hybrid system (wind, solar, fuel cell) in his study. In the designed system, the electrical energy generated by the wind turbine and the PV panel is stored in the battery. Three different control algorithms were used to determine the ideal algorithm for the battery. His study aimed to increase the lifetime of the fuel cell, which was used as a backup storage element in the system, by using it less. Simulation studies of the system were carried out, and the results were evaluated (Dursun, 2013).

In his study, Ersoy created a hybrid system by integrating wind and solar power plants into an interconnected grid. The production cost reduction rates of the wind and solar plants added to the system are analyzed. The production costs of the system were calculated using five different algorithms: PSO (Particle Swarm Optimization), DGA (Differential Development Algorithm), AKO (Bee Colony Optimization), GA (Genetic Algorithm), and BTA (Simulated Annealing Algorithm). It was found that the DGA, AKO, and BTA algorithms produced similar results. PSO and GA algorithms showed more stable performance (Ersoy, 2015).

Oğuz simulated a battery-supported hybrid power system consisting of solar and wind using a Matlab/Simulink program. In the system, the energy flow was controlled by BM-based control. It was found that the generated energy was directly supplied to the batteries, and the overcharge-discharge situations in the batteries consumed the battery life very quickly. To not shorten the battery life, it was stated that the generated power should first be sent to the consumer, and the remaining surplus power should be stored in batteries depending on the occupancy rates (Oğuz, 2012).

In Başaran's study, the energy generated by the wind-solar hybrid system was first used to charge the batteries and then to supply the load or the grid. In the study, the batteries are charged from the grid if the required amount of energy cannot be obtained from the hybrid system. A BM controller controls DC/DC and DC/AC voltage converters to achieve the highest efficiency in the system. Compared to conventional operation, 7-10% more energy was transferred to the load or grid when controlled with BM (Başaran, 2013).

A hybrid fuel cell, wind, and solar system were modeled in Matlab/Simulink by Kumar and Garg. The modeled hybrid system was also studied with other storage systems besides fuel cells. The study found that the hybrid system worked more efficiently using the fuel cell instead of the battery and battery group (Kumar and Garg, 2019).

Oğuz used Matlab/Simulink to model the power generation system required to meet the electricity demand of a rural settlement in his Ph.D. thesis. The system was controlled using PID and ANFIS. In addition, a filter circuit was applied to the system in this study to minimize the voltage harmonics generated during power conversion. As a result, it was found that the desired quality and efficiency of the energy were obtained with the use of ANFIS in the hybrid system (Oğuz, 2007).

Shashi and Rekha proposed a solar-wind hybrid system in their study. In the study, the effect of environmental conditions was observed by simulating the arrays of the photovoltaic cell. Then the nonlinear I-V (current-voltage) and P-V (power-voltage) characteristic curves are analyzed. Similarly, the wind energy system and diesel generator were also simulated, and their characteristic curves were obtained. Compared to the others, the output waveforms of the diesel generator contained less harmonics than the battery output. As a result, a hybrid system consisting of off-grid wind-solar and diesel generators was proposed for off-grid and island areas (Shashi and Rekha, 2015).

In his thesis, Kaya designed an off-grid hybrid system. It consisted of a 300W wind turbine and three 80W solar panels. The system also used a 12V, 130Ah gel battery. The aim was to store excess power in the battery and ensure system continuity by activating when the power generation system was insufficient. The Arduino-based BM controller used in the study was compared to conventional systems. It was observed that the energy generated by the Arduino-based system powered the load without recharging the battery, thus preserving the economic life of the batteries. It was observed that the battery used in the system contributed 4% to the battery life by preventing 140 charge-discharge cycles for nine months with the BM control system. As a result, the BM-based system was better than the classical system in terms of performance (Kaya, 2019).

This study modeled and analyzed a grid-connected wind-solar hybrid power generation system in the Matlab/Simulink environment. The electrical energy obtained from the hybrid power generation system through power converters was equalized to the grid voltage and frequency and transmitted to the grid or loads. The quality of the power obtained from the hybrid power generation system was analyzed using BM and PI controller methods to improve the quality. Frequency, voltage, power, and harmonic measurements of the modeled hybrid power generation system have been carried out. These measurements were used to evaluate the power quality improvements of the hybrid power generation system.

2. Materials and Method

2.1 Hybrid Energy Production Systems

Non-renewable energy sources have short life spans and many drawbacks in energy generation systems. For this reason, renewable energy sources (such as wind, water, solar, and geothermal) are often preferred in power generation systems. Hybrid systems have been developed to use renewable energy sources together. This increases the efficiency of the system. In addition, if one of the sources is unavailable or of low availability, the energy required for the system is provided by the other source, thus ensuring continuity. Hybrid systems are created by combining two or preferably more resource components. Examples include solar-wind, solar-wind-diesel, solar-wind-hydrogen, and solar fuel cell-wind (Ulutaş, 2015). Figure 1 shows a block diagram of a hybrid system.

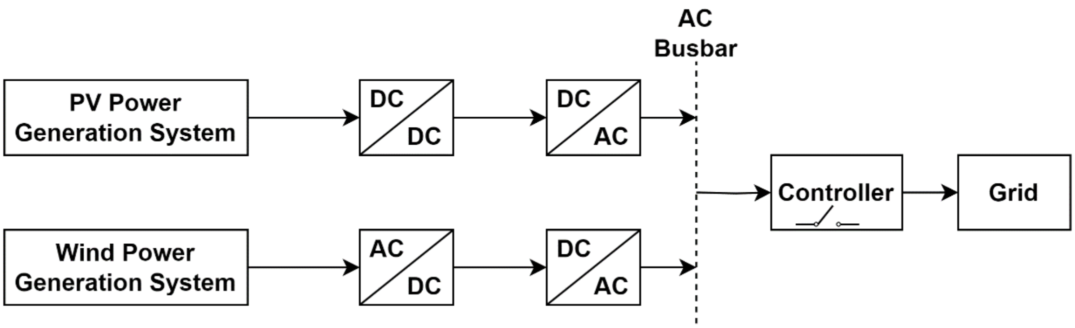


Figure 1. Block diagram of a hybrid system

The energy produced by a grid-connected hybrid generation system is used as needed, and the remaining energy produced can be transferred to the grid. In addition, if the energy produced by the system is insufficient, energy can be added to the system from the grid. Because the system is grid-connected, there is no need for auxiliary storage devices such as batteries.

2.2 Simulation Model of Hybrid Power Generation System

The hybrid power generation system study used a wind turbine and solar panels. Adjustments were made to the parameter values required for the wind turbine in the system, and a simulation was carried out. The simulation block diagram is shown in Figure 2.

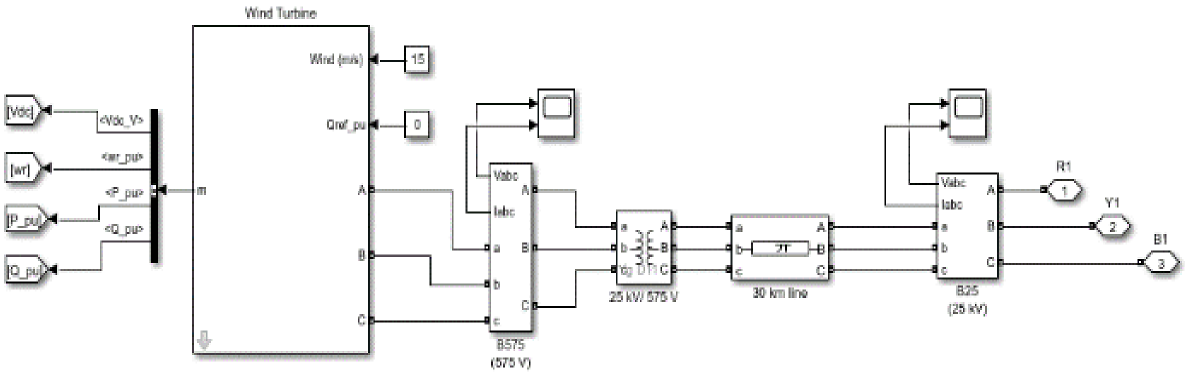


Figure 2. Simulation block diagram of grid-connected wind power generation system

Five 315W Sunpower-T5-SPR-315E (monocrystalline cell) PV panels were used in the solar power generation (PV) system realized in the Matlab/Simulink environment. Detailed specifications of the PV panels used in the solar power generation system are given in Table 2.

The current-voltage graph of the PV panels in the solar power generation system at three different temperatures (0°C, 25°C, and 50°C) is shown in Figure 3. As can be seen from the graph, the power increases as the voltage rises up to the maximum power point at different temperature values. However, as the temperature increases, there is almost no change in the current values, while the voltage values decrease.

Table 2. Characteristic values of the PV panel

Parameters	Value
Maximum power	315.072 **W**
Number of cells in the panel	96 **pcs.**
Open circuit voltage (Voc)	64.6 **V**
Open circuit voltage temperature coefficient (%/deg.C)	-0.27269 **(%/deg.C)**
Current at maximum power point (I_{MP})	5.76 **A**
Short circuit current (I_{sc})	6.14 **A**
Short circuit current temperature coefficient (%/deg.C)	0.0761743 **(%/deg.C)**
Light-induced current (I_L)	6.1471 **A**
Diode saturation current (I_0)	$6.5048e^{-12}$ **A**
Diode ideality factor	0.9507
Shunt Resistance (R_{SH})	430.058 **Ω**
Series Resistance (R_S)	0.43042 **Ω**

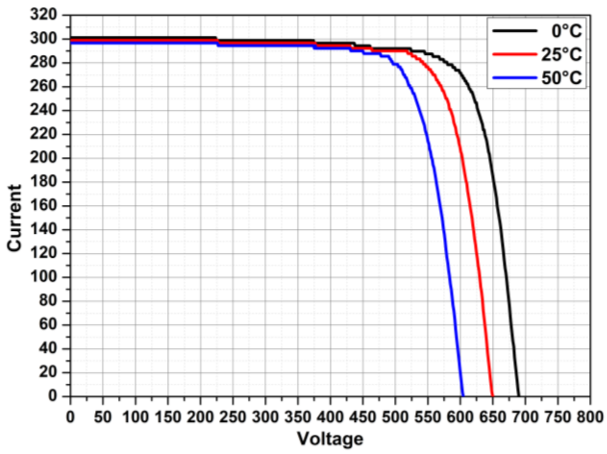


Figure 3. Current-voltage graph of the PV panel at 1000 W/m^2 and three different temperature values.

2.3 Fuzzy Logic Controller to Improve Power Quality

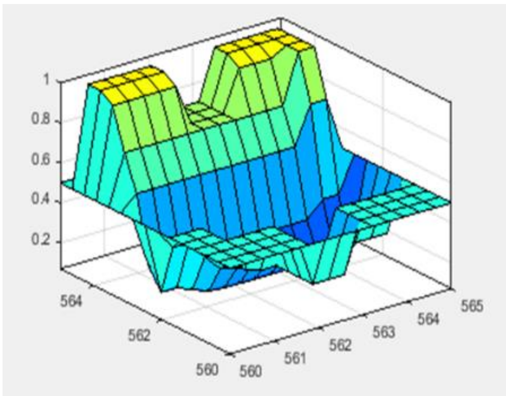
A power generation system can be controlled using classical methods such as PI, PD, PID, BM, and various artificial intelligence methods. With the introduction of artificial intelligence and its applications in our lives, many conveniences have been created for people. Nowadays, it is a fact that electric power is one of the most essential things. Therefore, power generation systems that meet this need are of great importance. Instead of classical controls in power generation systems, using methods controlled by the UN or artificial intelligence instead of classical controls ensures more stable and efficient system operation (Katırcıoğlu et al., 2018). For this reason, BM control has been successfully used in studies of power generation systems (Ismail et al., 2010).

In this study, the electrical values of the grid-connected hybrid power generation system were compared with the electrical values (voltage and frequency) of the grid. The voltage and frequency control of the hybrid power generation system and the grid were compared using the BM controller. This ensured that the generated electrical energy could be used more efficiently and with better quality. The BM controller analyzed the fault and its variation in voltage and frequency. The fault signal generated by the BM controller was transmitted to the switch block when the voltage or frequency was equal, and the contact closed fully without any external intervention. The breaker contact is automatically closed, and the hybrid power generation system is connected parallel to the grid. The Sugeno method is used in the BM controller design. The BM controller had two inputs and one output. The first input was the grid, and the second input was the output of the hybrid generator. The BM controller's output was the circuit breaker's switching signal, which acts as a parallel connection. The BM controller was designed to ensure that the voltage and frequency values of the hybrid power generation system are equal to the grid voltage and frequency values before parallel connection to the grid.

The rule table required for the control of the designed system is given in Figure 4 (a), and its three-dimensional representation is presented in Figure 4 (b). The membership functions shown in the rule table are NB (Negative Large), NS (Negative Small), ZE (Zero), PS (Positive Small), and PB (Positive Large).

Hibrit \ Grid	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

(a)



(b)

Figure 4. FLC rule table (a) and 3-D representation (b)

The model created in the Matlab/Simulink environment to control the grid-connected hybrid system developed with BM using wind and solar energy is shown in Figure 5. Voltage control is required at the system grid connection. The time-varying voltage should be in the form of a sinusoidal signal. As it deviates from the sinusoidal waveform, undesirable waveforms occur and create harmonics. Harmonics occur at exact multiples of the fundamental frequency of the primary waveform. Harmonics play an active role in regulating or consuming power in electrical power generation systems. Controlling the BM controller minimizes voltage fluctuations or harmonics that occur as the load is added or removed from the system. Once synchronization is achieved, the RC-type load connected between the hybrid system and the grid is connected to the grid with breaker control.

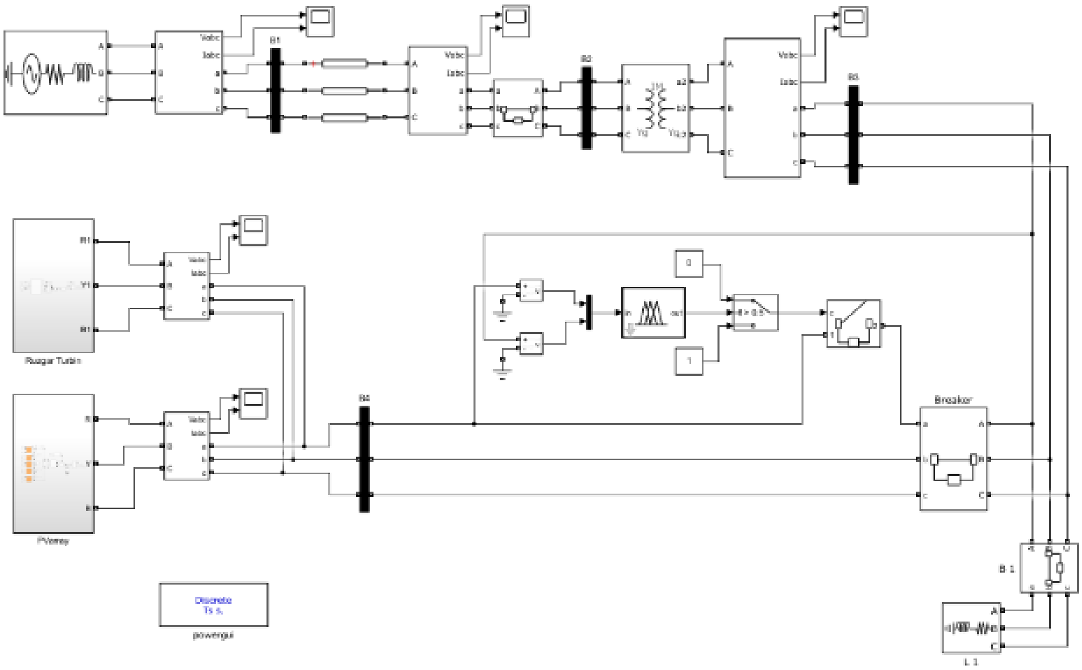
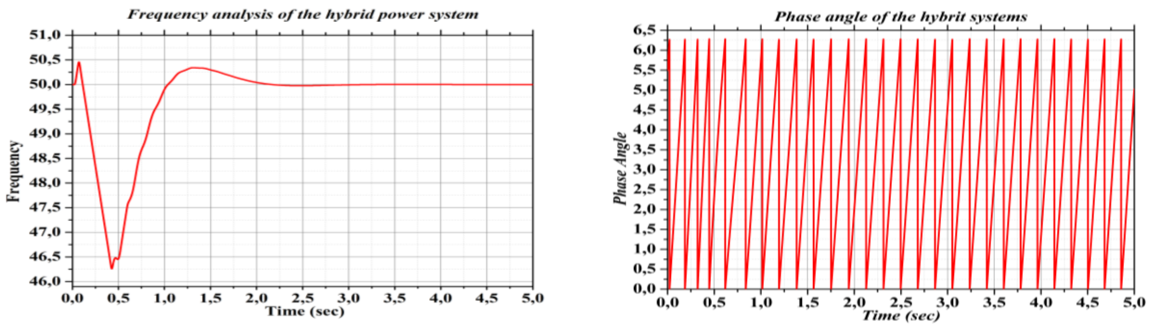


Figure 5. On-grid Hybrid power generation system controlled by BM

3. Findings and Discussion

The frequency, voltage, and power values of the hybrid power generation system and the grid were analyzed in the Matlab/Simulink environment. The system's voltage level control was realized using the BM controller. The frequency analysis of the hybrid wind and solar power system is shown in Figure 6 (a), and the phase angle analysis is shown in Figure 6 (b).



(a) *(b)*

Figure 6. Frequency analysis (a) and phase angle analysis (b) of the hybrid power system in the simulation environment

In the event of a fault that occurs while the wind turbine is connected to the grid, the system is kept in balance by analyzing the active and reactive power outputs. In the event of a fault, the active power generated would decrease depending on the magnitude of the voltage drop. To generate reactive power, the excitation current was increased inductively to increase the voltage drop. At the end of the faults, the active and reactive power generation returned to their initial state within the desired time. In this way, the wind turbine remained in operation, and the balance of the system was maintained without any loss of production. Figure 7 shows the voltage graph of the 3-phase hybrid power generation.

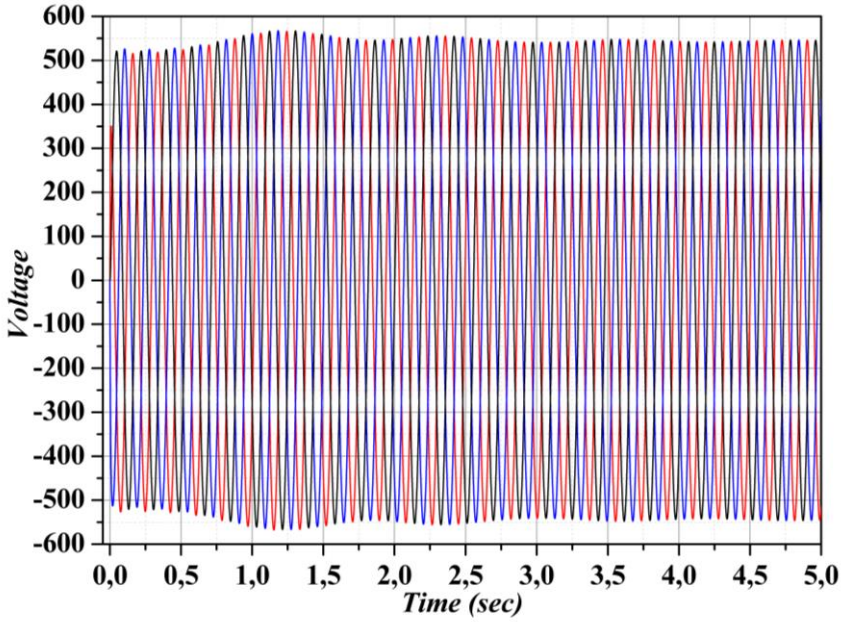
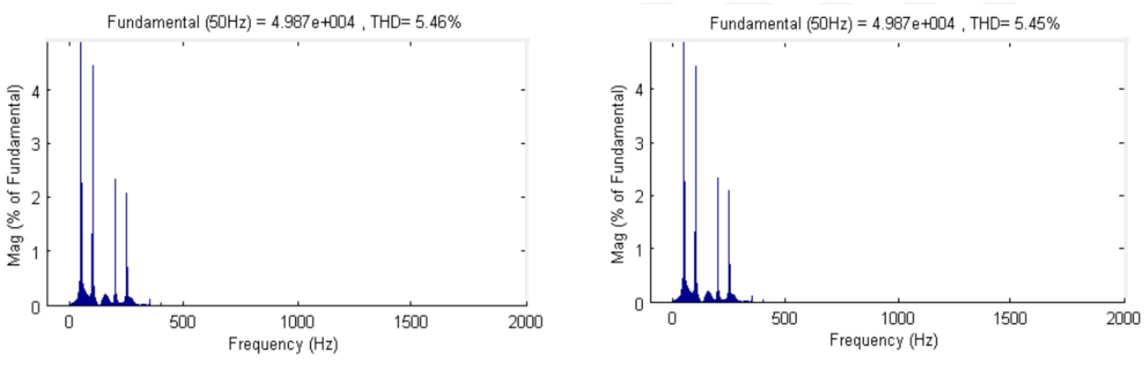


Figure 7. Three-phase voltage measurement of hybrid power generation system in Matlab/Simulink environment

The harmonic ratio occurring in the voltage wave at the beginning of the 30 km pi-type hybrid power line in the designed system was calculated as 5.46%. The harmonic measurement made at the end of the same line was calculated as 5.45%. The harmonic analysis at the beginning of the line is shown in Figure 8 (a), and the harmonic analysis at the end is shown in Figure 8 (b).



(a) ***(b)***

Figure 8. Harmonic analysis of the voltage wave at the beginning (a) and end (b) of the line

The result of the low voltage harmonic analysis performed on the hybrid power generation system designed is given in Figure 9.

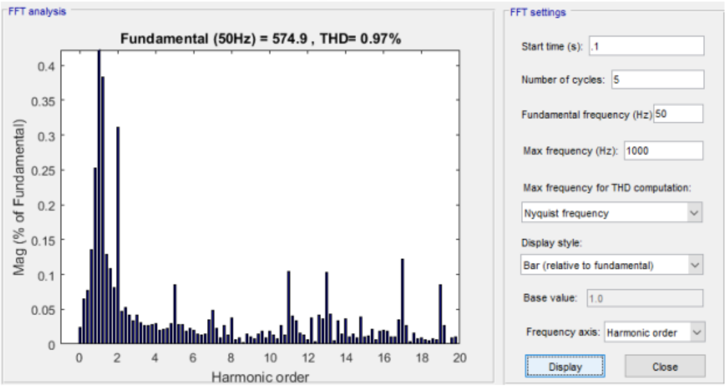


Figure 9. Matlab/Simulink harmonic analysis of low-voltage

The measurement of the BM of the wind and solar power generation system connected to the hybrid grid is given in Figure 10.

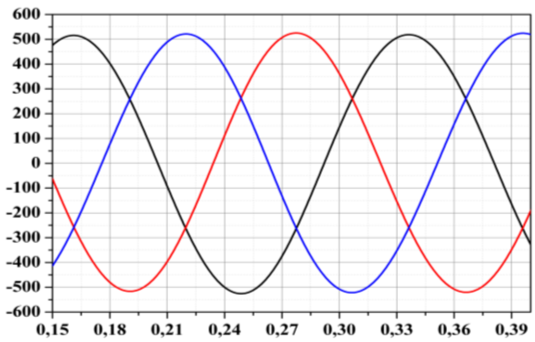


Figure 10. Time-dependent graph of the fuzzy logic-controlled voltage of the hybrid power generation system connected to the grid

4. Results

In this study, a hybrid power generation system was designed by combining wind and solar power generation systems, and the control of the parallel connection to the grid with the BM controller was realized in the simulation environment. In the designed hybrid power generation system, the wind and solar power generation system's voltages were combined in a single bus bar and compared with the reference grid voltage in the BM controller. If the two voltages were equal (when the error was zero), the contact in the switch block connected to the BM controller was automatically lowered, and the breaker contact was closed. If the voltages were not equal, the contact was opened, and the system was de-energized. In this way, the BM controller automatically controlled the system, and the errors that could occur were minimized. In the study, it was observed that the BM controlled system reacted faster than conventional control systems.

Statement of Conflict of Interest

The authors have declared no conflict of interest.

Author's Contributions

The contribution of the authors is equal.

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