The FPGA-Based Design of an Optimal Fuzzy Logic Controller for Hybrid Renewable Energy Systems

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ABSTRACT

The fast-growing energy requirements and the decreasing availability of conventional fossil fuels require new sustainable alternatives for energy production. Among sustainable resources, solar and wind are the most mature and widely used technologies, and integrating both results in a higher availability of energy during the day. However, previous studies indicate that the existing controllers in hybrid solar and wind systems are less efficient and take longer to achieve steady state conditions. In contrast to existing models, the proposed solar and wind system integrates FLC and MPPT and results in higher efficiency and relatively fewer response times to achieve steady state conditions. The proposed method includes the implementation of an integrated MPPT-FLC-based FPGA to obtain the maximum power from hybrid systems. The proposed system demonstrates better stability performance and faster convergence speed than conventional control. MATLAB/Simulink was employed for modelling purposes, along with an Xilinx system for hardware implementation. The experimental results show a superior MPPT efficiency and better response time (5%). The proposed system is aimed at utility companies in Pakistan for meeting the increasing load demands in a sustainable manner.

Keywords-wind power energy; solar power energy; maximum power point tracker; FLC; PMSG; FPGA; XSG

I. INTRODUCTION

The world is facing energy issues due to the increasing demand for electrical load. The limited supply of fossil fuels, the growing demands for energy from industrialization, and population growth are the three main causes of the energy crisis. Fossil fuels are the main cause of greenhouse gas emissions that endanger climate change and its effects, such as altered weather patterns, rising sea levels, and disruptions to agriculture [1-2]. The need for renewable energy becomes crucial because of growing energy demands and deteriorating pollution from fossil fuels. The International Energy Agency (IEA) projects a 25% increase in global energy demand until 2040, which calls for sustainable energy resources.

Pakistan experiences severe energy crises due to a rising population, which jeopardizes its financial stability and damages its environmental resources. The country's dependence on importing petrol and oil puts further strain on its foreign exchange reserves and contributes to environmental damage. Although the promotion of renewable energy has made progress, its actual contribution is minimal. Solar and wind energy possess considerable development potential for Pakistan, as the geographical location is rich in irradiance during the day and wind during the night. The combination of solar and wind power in a single hybrid system secures stable electricity generation while reducing the regular interruptions experienced by single energy sources. The current national grid power shortage can be efficiently addressed by integrating solar and wind energy sources. Figure 1 shows the increasing capacity (in GW) of renewable energy in Pakistan in the last 20 years [3].

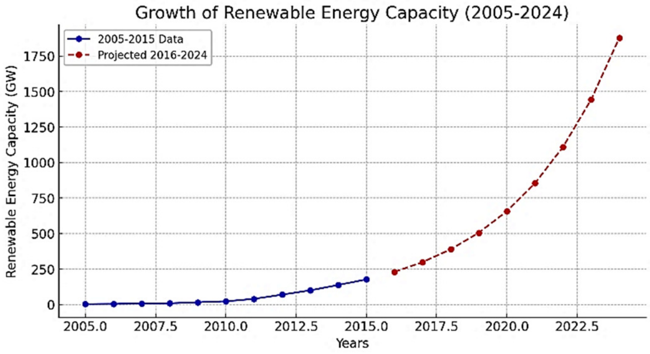

Fig. 1. Total renewable energy generation in Pakistan.

II. LITERATURE REVIEW AND PROPOSED CONTRIBUTION

Multiple research studies have investigated hybrid renewable energy systems for improving stability or response time. The integration of intelligent controllers, which include FLCs, brings important benefits to Maximum Power Point Tracking (MPPT) applications. Traditional MPPT with fuzzy logic control operates in microcontrollers, leading to delayed computation together with reduced MPPT precision. The conventional micro-controllers suffer from poor response time and efficiency. Recently, FPGA implementations offer a variety of benefits, which include parallel data processing capabilities, rapid execution, and adaptable functionality in real-time operations [4-7]. FPGA-based fuzzy control can be an improved solution for hybrid energy system control. Previous studies exhibited slow responses along with complicated hardware procedures. Lately, using FPGAs to design hybrid energy controllers has gained attention, while finding the best intelligent controllers is still a key research aim.

It is difficult to promptly manage hybrid energy sources, which influences the reliability and efficiency of control systems [8]. FPGAs have been proposed to control hybrid power plants by setting the best operating points using curve fitting. However, optimal control in hybrid energy systems requires that certain physical limits be set in the management system [9-10]. Hybrid systems operate more effectively when FPGA control and ANNs are optimized using MFO approaches. Different FPGA MPPT methods have been employed in PV systems. In [11], the performance of the proposed fuzzy logic-based controller was tested and evaluated, showing the effectiveness of FPGAs in controlling PV systems. FPGA-based controllers can offer highly sophisticated and improved control systems for hybrid energy applications. Many studies have investigated hybrid solar and wind energy systems to improve efficiency and response time using a variety of controllers. The existing literature highlights the use of traditional microcontroller-based systems for hardware implementation, which are found to have poor response times and compromised efficiency [12]. As a result, the latest literature implements hardware implementation on FPGA-based devices. Although FPGA-based systems are extremely efficient, the literature has either focused on a single source of energy or used less robust controllers to increase stability, response time, and efficiency, which must be addressed. In view of the identified gaps, this study seamlessly integrates solar- and wind-based FLC and MPPT into an FPGA to increase response time and efficiency.

MATLAB/Simulink and FPGA technology were used to evaluate the proposed model, allowing the solutions to be verified in practice. Building the data collection and model parts, the model properly represents the PV and wind energy systems, making it easier to study them. An MPPT comparison with traditional control methods showed that the proposed FPGA is sufficiently capable. The optimization and verification process confirmed that the proposed model and control concepts are effective in making the process more stable and efficient. In general, this technique offers a promising approach for putting together effective and trustworthy hybrid energy systems that meet the research goals of using sustainable and renewable resources.

III. PROPOSED HYBRID (SOLAR-WIND) SYSTEM MODELING EQUATIONS

This study used a hybrid approach. The two renewable energy sources incorporated into the design of the power system, solar and wind, are connected to conventional energy sources. This approach is the most effective hybrid blend of the most popular forms of renewable energy systems for most applications.

A. Modelling the Solar System

Solar cells are divided into two types: bulk and thin films. These cells are made from a variety of materials and have varying levels of effectiveness. Monocrystalline silicon was chosen due to its cost-effectiveness and generating efficiency. The characteristic IV curve for P-V modules is given in (1) [13], and Table I presents the specifications of the system developed in MATLAB Simulink.

$$I = n_p I_{pv} - n_p I_0 \left(\frac{T_c}{T_{ref}}\right)^3 e^{\frac{qE_g}{ak}\left(\left(\frac{1}{T_{ref}}\right)-\left(\frac{1}{T_c}\right)\right)} \left[e^{\left(\frac{q(VI+IR_S)}{akt_C n_S}\right)-1}\right] - \frac{V+IR_S}{R_p} \tag{1}$$

TABLE I. DETAILS OF THE PV GENERATOR

Rated Power	60 W
Current at the maximum point	3.25 A
Voltage at the maximum point	16.8 V
Short circuit current	3.56 A
Short circuit voltage	21.6 V
Number of cells in parallel	1
Number of cells in series	36

B. Proposed Wind System

Following aerodynamic calculations, the mechanical power output can be determined using:

$$P = \frac{1}{2}\,\pi\rho C\rho(\lambda)\beta R^2 V^3 \tag{2}$$

where ρ is the air-density, $C\rho(\lambda)$ is the power-coefficient, λ is the tip speed ratio, β is the pitch-angle, R is the turbine-radius, and V is the wind-speed. The power coefficient is given by:

$$C\rho(\lambda) = -0.2121\lambda\, + 0.0856\lambda\, + 0.2539\lambda \tag{3}$$

As wind speed changes, the system produces its maximum power at the speed (measured in rad/s):

$$\lambda = \frac{\Omega \mathrm{R}}{V} \tag{4}$$

with Ω being the turbine's rotational speed [14-15].

C. Permanent Magnet Synchronous Generator (PMSG)

The following assumptions were made for an easier characterization of the PMSG model:

- As the stator is formed as a star and has air as neutral, the homopolar current components disappear.
- Magnetic fluxes are predictable and can be thought of as linear to changes in phase current, provided we ignore saturation effects.
- The air gap electromotive force is expected to vary smoothly like a wave, with no attention given to irregularities from spatial harmonics.
- This approach does not include temperature changes that affect resistance.
- The effects of both EMF hysteresis currents are not considered.

A generator is modeled using the voltage equations shown in the rotor (d, q) reference system in [16]:

$$V_d = R_s i_d + L_d \frac{di_d}{d_t} - p\Omega L_d i_q$$

$$V_q = R_s i_q + L_d \frac{di_d}{d_t} + p\Omega L_d i_q + p\Omega \emptyset_f \tag{5}$$

The electrical torque applied to a PMSG's rotor is given by:

$$T_e = p i_q ((L_d - L_q) i_d + \emptyset_f \tag{6}$$

where p shows how many pole pairs are in the synchronous machine. The mechanical form is given by:

$$J \frac{d\Omega}{dt} + f\Omega = T_e - T_r \tag{7}$$

Here, J is used to represent the total rotor inertia, f describes electrical resistance, and T_r refers to the torque from the electromagnet.

D. MPPT Fuzzy Logic Controller

Many PV and wind energy systems include an MPPT controller as an essential part of their design. The proposed system is designed to select appropriate points of operation for the PV generator and wind turbine to manage both new demands and a changing climate. In the solar subsystem, MPPT makes sure that the system draws and moves all the maximum power it can. The objective is to find the point at which the PV cell and load both have the same impedance. Implementing MPPT in PWM, the controller helps the power converter bring the DC load bus to the optimal energy level [16]. Figures 3 and 4 illustrate the layout of the fuzzy controller for the solar part, and Figures 6 and 7 illustrate the arrangement for the wind part.

A fuzzy logic controller works by following three steps: weighing in, setting rules, and answering. In the next stage, numerical P_{pv} and V_{pv} are expressed as linguistic terms using membership values. In addition, another block focuses on computing the error (E) and how it changes at any given point (dE), as specified in (8) for time k:

$$dE(k) = E(k) - E(k-1) \tag{8}$$

For each combination of $E(k)$ and $dE(k)$, the linguistic variables selected from Table II for factor d are calculated accordingly.

TABLE II. INFERENCE RULES FOR A FUZZY LOGIC CONTROLLER

E	**dE**				
	NB	**NS**	**ZE**	**PB**	**PS**
NB	PB	PB	PB	PB	PB
NS	PB	PS	PS	PS	ZE
ZE	PS	PS	ZE	NS	NS
PB	NS	NS	NS	NS	NS
PS	NB	NS	NS	NS	ZE

This table uses linguistic-controller variables that cover PB (Positive Big), PS (Positive Small), ZE (Zero), NS (Negative Small), and NB (Negative Big). A controller that follows a Mamdani-type fuzzy inference system supports min–max logical operators for its operation. By applying the set rules to every combination of stimulus and difference, the fuzzy toolbox forms an output response. The MPPT control of the wind subsystem is achieved by error inputs using the kinetic energy $P(k)$ measured by the wind turbine reactor and wind speed measurement of $\Omega(k)$.

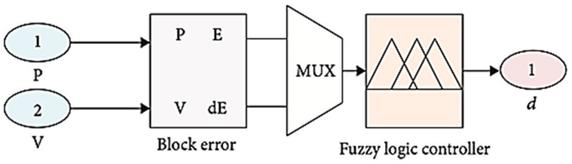

Fig. 2. Proposed SIMULINK model for solar subsystem fuzzy logic control.

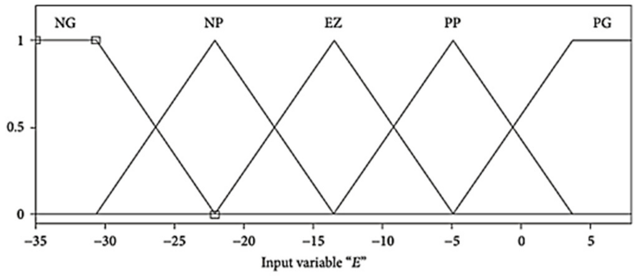

Fig. 3. Solar input member function of E.

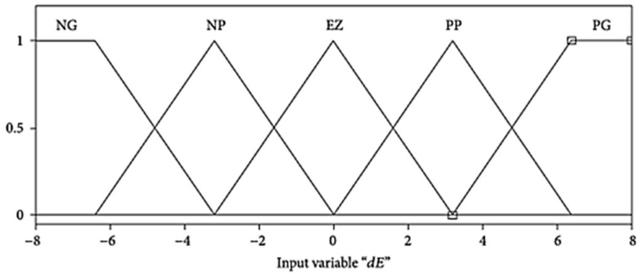

Fig. 4. Solar input member function of dE.

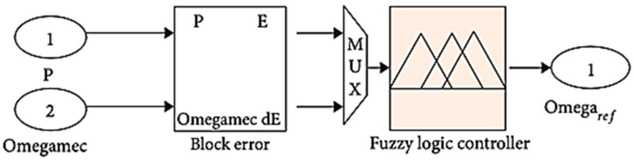

Fig. 5. Structure Of Simulink model for FLC of the wind subsystem.

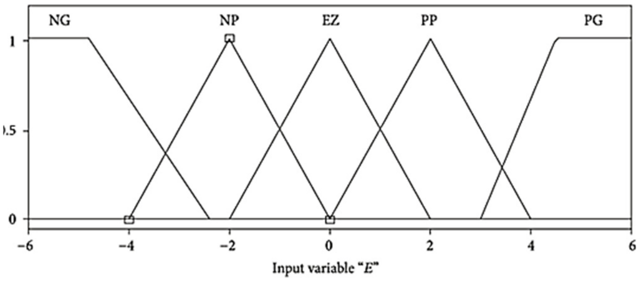

Fig. 6. Wind input member function of E.

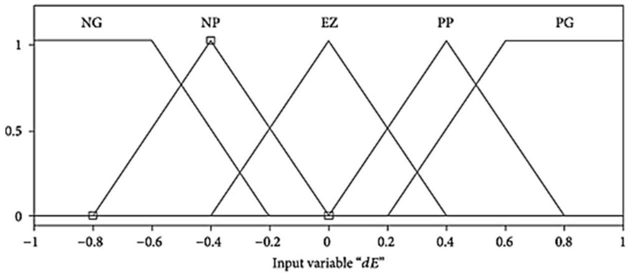

Fig. 7. Wind input member function wind input dE.

E. Field Programmable Gate Array (FPGA)

System development for FPGAs requires two separate steps, which include modeling in MATLAB/Simulink followed by HDL code creation. Xilinx System Generator (XSG) acts as the enabling tool for FPGA design at a high level through its Simulink-based graphical interface. XSG provides a collection of specialized logic cores that help users create efficient models to automatically produce hardware syntheses and simulations. The system creates netlist files through Xilinx ISE, which generates bit-streams for JTAG interface transmission to FPGA devices. The requirement for adaptive multiple operations makes FPGAs more suitable than DSP implementations for controlling hybrid energy systems. Word-length optimization methods reduce hardware usage by maintaining computational precision through their application. The simulation process repeatedly shortened word length until it achieved the most precise and resource-effective solution. The XSG Gateway blocks enable complete data transfer between double-precision Simulink models and fixed-point FPGA operations.

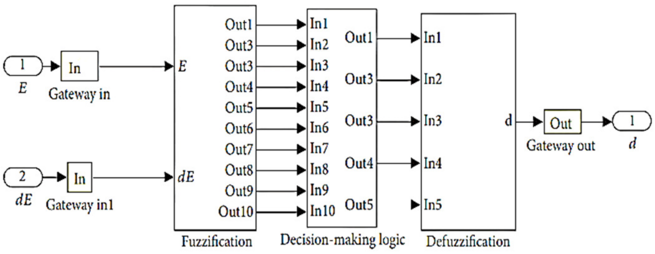

Fig. 8. XSG-based solar fuzzy logic controller design.

IV. EXPERIMENTAL HYBRID MODEL DESIGN

For simulation in XSG, the system used library blocks made by Xilinx. The fuzzy logic controller was used to develop the global wind-solar system in Figure 9. The main simulation can only be completed successfully when the system generator blocks and both solar and wind controllers are included. Thanks to the Xilinx library, the MATLAB/Simulink component was removed from the design, and suitable XSGs were inserted with gateway inputs and outputs. Since there is no fuzzy toolbox in the XSG library, it was built manually. The system has min-max inference, four linguistic variables (PB, PS, ZE, NS, and NB), and defuzzification. The output was converted from analog into numeric using the gravity center method, with the Xilinx library MUX. Since both E and

dE are significant, the fuzzy controller is added to the wind and solar power system control design. Then, it is important to implement the system generator blocks. Netlist files are generated with the Xilinx ISE. Once created, the design is transferred into JTAG as a bitstream file for physical transfer.

Cycle accuracy and bit-correctness are both achieved in simulation. Single bits are processed accurately, and the transactional parts happen precisely as planned. All operations are performed by the model within precisely the same number of execution cycles. Figure 9 shows how the system operates, from the initial design to generating and testing the hardware. Both architectures, MATLAB simulation and Xilinx implementation, showed similar results.

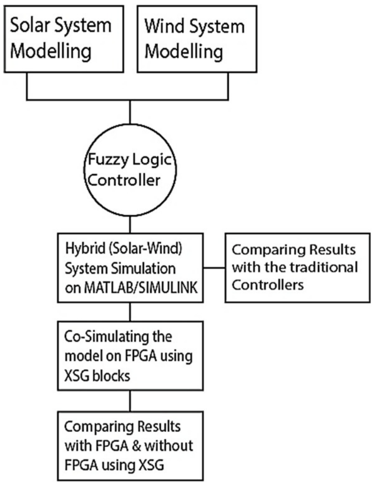

Fig. 9. Block diagram of the proposed system.

V. RESULTS AND DISCUSSION

The proposed FPGA for hybrid energy systems is based on MPPT and fuzzy logic. An FPGA is important for its ability to function in parallel, for programmable hardware, offering faster responses and greater input/output. d indicates the percentage of time the transistor is on throughout the switching cycles. The DC-DC stage increases the voltage of d to match the panel's Maximum Power Point (MPP), and the graph runs from $t = 0$ to 120 ms after the beginning. In this duty cycle, d falls to 0.38, which is the best way to meet the agreed-upon delivery time for these conditions of irradiance and temperature. From then onwards, d is almost flat, showing that the controller has indeed locked on, is at the MPP operating point, and there are zero perturbations anymore. This shows that the system achieved the MPP in the range of approximately 10 ms after start-up, which is very fast for a power controller.

At d = 0.38, the duty cycle is rock-steady, i.e., no hunting or oscillation, hence the panel is delivering its max power without ripple. Figure 10 demonstrates a drop in percentages from 55% to 38%, implying that the converter has scaled down its ON-time in conformity with the voltage/current optimum curve of the panel, hence making better energy yield generation.

Figures 10 and 11 show the cycle performance of the solar fuzzy logic controller and the Ω_{ref} output of the wind fuzzy logic controller, respectively. A duty cycle stabilization of 0.41 was achieved with a wind speed stabilization of 15 m/s. This figure compares how power and time change in two different cases, one controlled with MPPT and the other without, using MATLAB/Simulink (PHyb) and XSG models. Although peak power occurs at the same time in both systems, XSG achieves power stability more quickly.

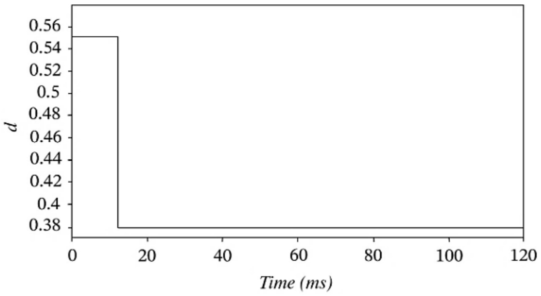

Fig. 10. Fuzzy logic controller output of solar subsystem.

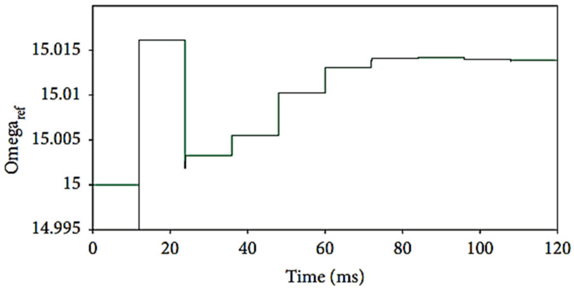

Fig. 11. Wind subsystem FLC output.

The results in Figure 12 show that training an XSG-based model helps the model to become stable faster. At the point where the carrier signals link up with the modulator, the switching time is as shown in Figure 13. If the modulator is greater than the carrier, the output is 1. When the modulator is below the carrier, the signal is 0. A combination of input and output signals sets the state (0 or 1) at each junction. It is clear from the 30 cycles that the converter moves from soft start to MPP operation.

After MPP has settled, steady pulses are observed, reflecting a locked-in duty that obtains the most power out of the panel. An output of 1 is returned if the modulator exceeds the carrier, and 0 is returned if the carrier is greater. Consequently, the output switches from 0 to 1 and back at every moment where both input signals meet (Figure 14). In Figure 14, the green line indicates a fast computer signal that leads switching, shaped as a sawtooth. For each sample, the simulation lasts one ms (~1 kHz). The output amplitude at a frequency of 50 Hz (20 ms period) shows an approximately ±220 V peak sinewave. Varying the duty ratio each ms at the same rate as the sine allows the inverter to output a wave with low distortion and good regulation of its waveform.

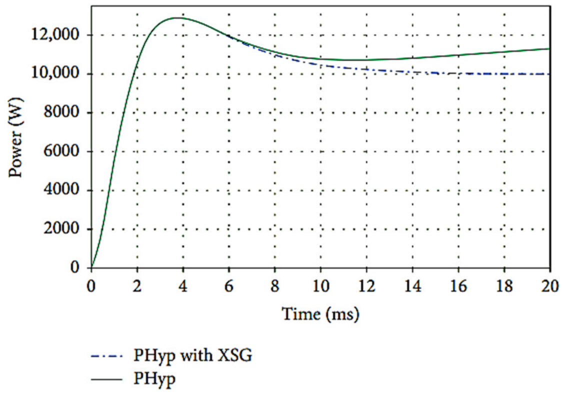

Fig. 12. Comparative study using a wind-solar regional system under fixed atmospheric conditions with XSG and MATLAB/SIMULINK.

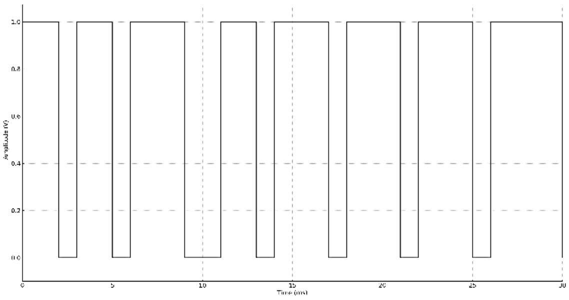

Fig. 13. Switching signal of the inverter.

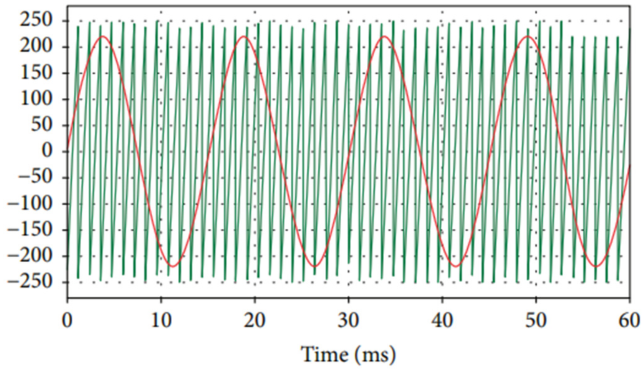

Fig. 14. Inverter outlet voltage from one phase.

Each phase of the inverter's output voltage is set 2π/3 degrees apart. The fixed 50 Hz signals of Session 1 are replaced in Session 2 with signals that include frequencies of 5 Hz, as demonstrated in Figure 15. Forcing the DC bus to ±60, ±40, ±20, and 0 V during certain time periods allows the inverter to produce a nearly sinusoidal 50 Hz voltage with few harmonics and reasonable simplicity. Thus, the control system shows a steady nature, as represented in Figure 15. To evaluate these results, the XSG and the MATLAB simulation were compared under constant atmospheric conditions, as shown in Table III. Figure 17 presents the schematic diagram of the proposed hybrid system. Table IV shows a comparison with other approaches.

TABLE III. WIND AND SOLAR DATA

Atmospheric condition	**Values**
Wind speed	10 m/s
Sunlight	1000 W/m^2
Temperature	300 K

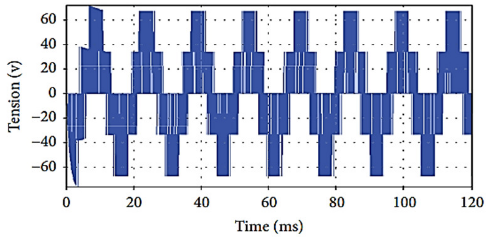

Fig. 15. Changes in signal levels before transmission.

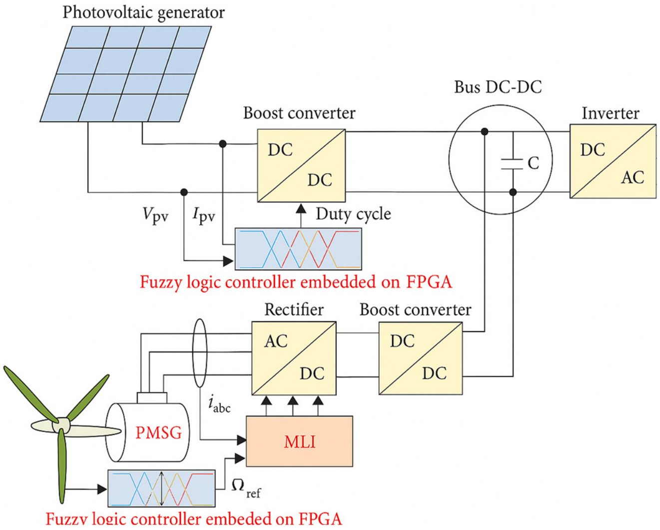

Fig. 16. Wind-solar system designed model using XSG block.

TABLE IV. COMPARISON WITH OTHER STUDIES

Ref.	**Models**	**Tracking efficiency in MPPT (%)**	**Response time (s)**
Proposed model	Fuzzy logic	99.7	0.38
[8]	Fuzzy logic	99.61	0.40
[17]	Fuzzy logic P&O	99.22 96.98	0.80 2.95
[18]	Wind subsystems controlled using ANFIS and solar with fuzzy logic.	99.34	0.80

VI. CONCLUSION

This study presented an experimental setup for a hybrid system using MATLAB/SIMULINK and XSG. With the ability to perform parallel operations, XSG has made the system more stable. After designing the system, it was optimized on a Virtex 6-XC6VLX315T FPGA circuit with Xilinx ISE. The system was implemented in an FPGA controller for situations where the input from solar and wind is variable or not always present. The proposed system achieved MPP at 0.38 ms and was found to stabilize quickly, tracking power with an efficiency of 99.7%. The proposed system reacted 5% faster than existing models. In addition to the timing efficiency and accurate tracking of the entire design on the XSG architecture, this study compared the experimental results for tracking time, efficiency, and effectiveness against similar methods. In the future, algorithms such as deep learning or reinforcement learning can be used for FPGA-based control strategies to provide even better solutions in integrating hybrid energy models with grid stations.

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