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Real-Time Renewable Energy Optimization in Smart Grids: FPGA and Reinforcement Learning Synergy

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Abstract

Sustainable energy distribution in smart grid environments depends on the effective use of renewable resources. By using reinforcement learning approaches, this research improves on current FPGA-based algorithms to enable optimal decision-making. The main goals are to precisely allocate power to ensure energy conservation and cost-effectiveness, automatically transition to alternate sources when unfavourable conditions arise, and continuously monitor the states of renewable resources. This study provides an extensive framework that includes hardware implementation, algorithmic decision-making, and circuit monitoring. Furthermore, the suggestion is to incorporate algorithms for reinforcement learning to improve decision-making. Through interaction with the surroundings, the reinforcement learning agents pick up the best practices for dynamically adjusting the distribution of power depending on real-time data inputs. This paper demonstrates, through research and testing, how the proposed method enhances system performance, reliability, and productivity.

Keywords: Algorithm, Field Programmable Gate Array (FPGA), Monitoring, Power management, Smart grid, Renewable resources.

INTRODUCTION

An electrical grid is an interconnected electrical power system that delivers electricity from producer to consumer and can be operated by one or more control centers. In this context, machine learning, particularly reinforcement learning (RL), has emerged as a promising approach to enhance the efficiency and reliability of resource allocation in smart grids. Reinforcement learning techniques enable the system to learn optimal strategies through trial and error, adapting dynamically to real-time conditions (Gholami, M., et al. 2020), (Y. Li. Et al., 2023), by leveraging RL, this research seeks to address the complexities associated with renewable resource integration, aiming to improve operational efficiency and grid resilience (Venkatesh, R., et al., 2021). The integration of renewable resources such as solar and wind power into smart grid systems presents unique challenges due to their dependence on fluctuating environmental conditions. Traditional approaches rely on predefined algorithms for resource management, which may lack adaptability and optimization capabilities. This research addresses these limitations by introducing reinforcement learning techniques to dynamically optimize resource allocation in response to changing conditions. By leveraging the advantages of machine learning, the aim is to enhance the efficiency and reliability of renewable resource management in smart grids. The adaptability of RL-based models is especially beneficial in scenarios where environmental variables and energy demand fluctuate unpredictably (NREL et al., 2022). Comprised power plants, transmission lines, substations, distribution lines, and consumers. Unfortunately, today's grid system is suffering from four major problems including losses, cause of pollution, high cost, and limited storage capacity (Keshav, Srinivasan, et al., 2011). To solve these problems and improve its reliability, and efficiency and include the feature of automation, the smart grid is the application to supervises the whole process at a centralized location. A smart grid is an outcome of a combination of electrical network and digital communication technology. FPGA technology is one of the most used real-time simulation devices. It is used in many industrial applications (R.C. Cofer, Benjamin F. et al., 2016) The FPGA achieves a fast response time by making the control executable in real time. Modeling and simulation of a control system for a hybrid system are presented. This system consists of PV, WT, and ESS. FPGA is used to control this system. The results prove that the use of FPGA reduces the execution time by conducting parallel processing. Smart energy management system (SEMS) has become an effective energy-saving tool (M.H. Elkholy, Hamid Metwally et al., 2022). By integrating SEMS with RL-based optimization models, this research aims to bridge the gap between theoretical advancements and practical applications in renewable resource management within smart grids (Alimohammad, M., & Bolic, M., et al., 2021).

As the world grows, electricity consumers' expectations cannot be fulfilled by the existing electrical grid system. Additionally, the smart grid can also be profitable for utility companies in terms of fraud detection, wireless communication, energy saving, and much more. Table 1 compares the smart grid with the existing grid (Farhangi, Hassan et al., 2010). Recognized initiatives for the smart grid by the Federal Energy Regulatory Commission (FERC) are reliability, green energy, quick response, and large storage capacity (Moslehi, Khosrow, and Ranjit Kumar. Et al., 2010). A smart grid can also be known as a Self-healing grid as it uses smart devices and real-time communication that constantly monitor the system and can react within a fraction of a second in case of any emergency. Electric Power Research Institute (EPRI) initiated many programs to achieve tremendous gains in reliability, digitalization, flexibility, capacity, and intelligence of smart grid. But still, customer needs and environmental and infrastructure challenges have to cover for future grid and industries believe that that future is not so far. (Moslehi, Khosrow, and Ranjit Kumar. Et al., 2005), (Li, Fangxing, et al., 2010), and (Fang, Xi, et al 2012)). Technical challenges that arise in the integration of renewable energy in the existing grid include variability and balancing supply and demand. Also, economic challenges include grid upgrades and uncertainty in cash flow. But currently, their integration is a necessity for a pollution-free and green environment.

Smart grids can deal with these problems efficiently by using smart inverters, demand response, real-time system management, and other advanced power controls (B. Speer, M. Miller, Gungor, et al., 2015). Power Management System (PMS), in this context, can also be known as Power Distribution Control System (PDCS) can supervise and stabilize the generation, distribution, and supply of an electrical network. The use of PMS can prevent blackouts and reduce energy costs as well as operational costs. This system can be used in industries, places where there is a poor or no grid supply, or to manage the hybrid system. In recent years, the advancement and simplicity of the SCADA system also integrated it into PMS, through this we can access various information or control tasks with just a few clicks. The paper's structure is as follows: Section II explores the impact of smart grids on distribution systems, providing insights into their transformative effects. Section III presents the proposed methodology, including an in-depth discussion of the overall system diagram. Section IV details the implementation process, highlighting the experimental setup used for validation. Finally, section V summarizes the results, emphasizing the hardware's capability to ensure system performance, reliability, and productivity.

Table 1.
Comparison of Existing grid with Smart grid

Existing Grid	Smart Grid
One-way communication	Two-way communication
Electromechanical system	Digital system
Less number of sensors	A large number of sensors
Manual	Automatic
Limited control	Wide control

Impact of smart grid on distribution system

The Due to the lack of communication capabilities in the existing grid, renewable sources cannot integrate with its distribution system. It seems to be a promising technology in smart grids with efficiency, reliability, and automation (Vehbi C., et al., 2011). The smart grid is conceived of as an electric grid Generation and transmission have been evolving and improving as they have been under the control of utility companies, but distribution has been lagging on some of these improvements. The proposed idea is to develop a prototype that can improve all of the three major blocks and bring smartness to the grid system by involving information and communication systems. Functionally, a smart grid should be able to provide new abilities such as self-healing, high reliability, energy management, and real-time pricing. From a design perspective, a smart grid will likely incorporate new technologies such as advanced metering, automation, communication, distributed generation, and distributed storage (Nadeem, G., Majeed, M. K., et al., 2020), (Brown, Richard E. et al., 2008), (Khaliq, A., ahmed Memon, J., et al., 2024), (Hill, Cody A., et al., 2012). According to the fact that almost 90% of power losses and disturbances occur at the distribution part, the concept of a smart grid was first introduced to overcome this problem. So, it should be noted how much the development of recent years affects the distribution system. In a few decades, today's distribution system will be modified completely.

There will be a system with Advanced Metering Infrastructure (AMI), automation, two-way communication, and a system that can heal and protect itself. Presently, it is much more favorable to design a smart grid from scratch rather than modifying the existing grid. The electricity sector is confronted by critical challenges viz. growing energy demand, high aggregated technical and commercial (AT&C) losses, and quality of power supply. These challenges led to the development of smart grid technology which brings efficiency and sustainability in meeting the growing electricity demand with reliability and best quality (Nadeem, G., Khalid, M., et al., 2024). As stated earlier, the output of renewable resources depends on the weather. The cloudy condition can reduce to output of PV cells from maximum to none. For the successful integration of solar power in the distribution system, the issue of voltage fluctuation has to be solved. Battery Energy Storage System (BESS) is the efficient solution to this problem (Abdul Azeem, Idris Ismail Majeed, M. K., et al., 2025). A private permissioned chain is typically considered a fully protected authorized blockchain. (Usman, M., et al., 2024). Wind station also experiences a variation in voltage due to many reasons including operating conditions, load demand, or wind speed. This variation can highly affect the normal performance of the system. Relatively few turbines cannot cause enough variation and can be easily absorbed without any storage system. However, in large systems, batteries are located at the base of a wind turbine to absorb the variations and help the turbine to work efficiently. Recent research underscores the advantages of integrating battery storage with wind systems. Hybrid setups smooth out variable power output, enhance grid reliability, and enable energy shifting to peak demand times. Lithium-ion batteries due to their efficiency and falling costs, dominate current applications but long-duration storage technologies are being explored for extended support to grid systems. Additionally, hybrid systems contribute resilience, allowing localized microgrid disruptions (Memon, J. A., Yasin, S., et al., 2024). Concept drift presents a significant challenge for accurate load forecasting in smart grids. Existing frameworks have explored various approaches, each with its strengths and weaknesses.

METHODOLOGY

We aim to make a decision-making system for distribution purposes also referred to as an intelligent system. An FPGA-based algorithm can manage and control renewable resources. The main objectives of our system are: The algorithm continuously monitors the state of renewable resources. As the throughput of renewable resources is affected due to unfavourable climatic conditions, the system automatically switches to alternative resources to fulfill the load requirement The algorithm supplies the exact amount of power that is required at the load side, to make the system cost-efficient and saves energy. The block diagram of our system is shown in Figure 1. The throughput of renewable sources is monitored through monitoring circuits and transmits the output to FPGA.

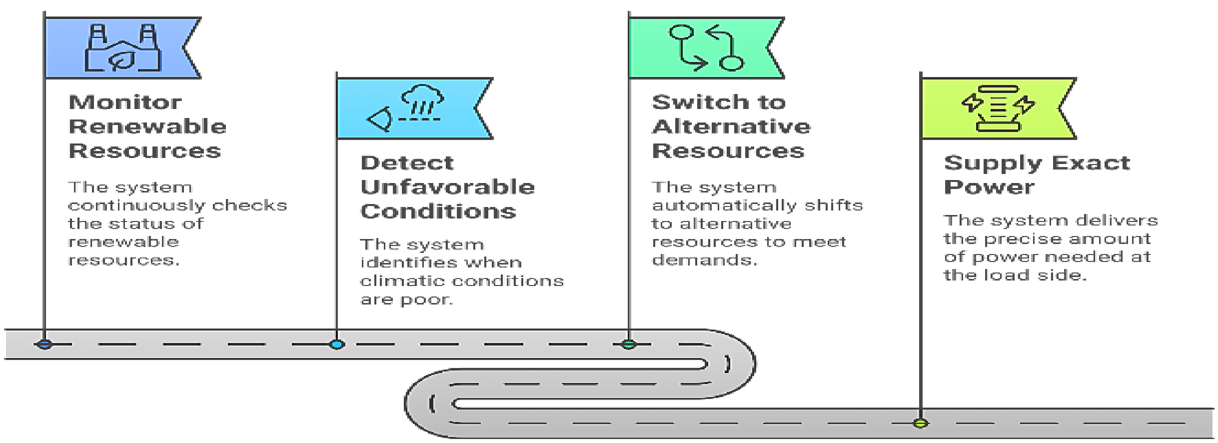

Figure 1.
Block Diagram

The amount of power consumption at the load side is monitored through a wattmeter and transmitted the data to the FPGA in digital form then FPGA makes decisions based on this data and operates the switching circuit. Through the switching circuit, alternative thermal generators connect or disconnect from the load as per the requirement of load or weather conditions. To compensate for the energy gap, we have to monitor the renewable resources and on behalf of that, operate the alternative sources. As the BESS is installed in both types of green energy, the focus is on the state of the battery. The charging percentage of the battery depends on different factors including voltage. Voltage is proportional to charging percentage as shown in Figure 2. It is clear that a minimal amount of decrease in voltage exponentially decreases in charging. So, our monitoring circuits monitor the state of the battery concerning its charging percentage and transmit the data to FPGA with the help of an Analog to Digital converter. The purpose of the algorithm is to dynamically control six output signals based on a hierarchical evaluation of complex input conditions. The algorithm's structure decision-making ensures that various input combinations are handled systematically, leading to consistent and reliable output generation. The key output of the algorithm includes its ability to handle intricate combinations while maintaining a clear and logical decision flow. By breaking the input into hierarchical levels of evaluation, the system can implement sophisticated logic without excessive complexity.

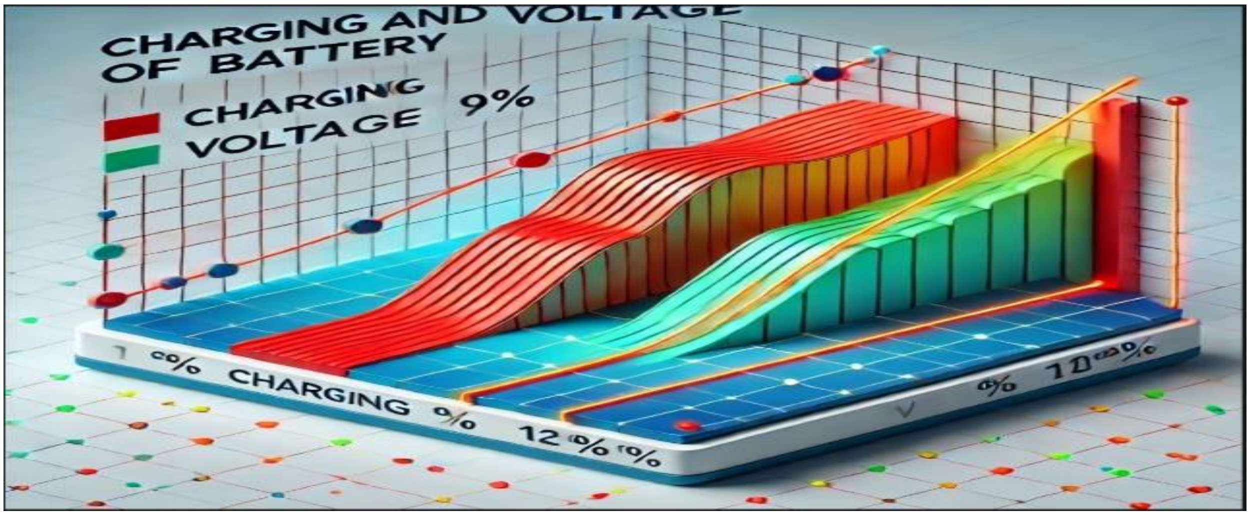

Figure 2.
Charging and Voltage Relation

This ensures smooth operation in scenarios requiring real-time decision-making and adaptability. For optimization suggestions focus on improving clarity, maintainability, and resource efficiency. Simplifying repetitive logic by defining default states, reducing deep nesting through modular structures, and grouping related conditions into manageable segments can make the algorithm more efficient. Additionally, parameterizing commonly used patterns or constants enhances flexibility, while simulation and testing help ensure robust performance under all input scenarios. The benefits of this optimization include better readability, allowing future developers or engineers to understand and modify the algorithm with ease. Streamlining the logic reduces hardware resource usage, making it more suitable for FPGA implementation or similar platforms. Furthermore, the improvements enhance scalability, making the algorithm adaptable for larger or more complex systems while maintaining reliability and performance.

This creates a robust framework for responsive control in real-world applications.24-bit data is received as an input in the General-Purpose Input Output (GPIO) port of FPGA. 8-bit data from the solar monitoring circuit, 8-bit data from the wind monitoring circuit, and 8-bit data from the wattmeter as feedback. Six alternative sources were assigned, three for solar and three for wind, to compensate for the energy gap. Six pins of the GPIO port function as outputs to operate the switching circuit. Table 2 presents the availability of alternative sources corresponding to the charging percentage. The algorithm gives priority to the input from the wattmeter which gives information about how much power is consumed at the load side. If the consumption at the load side is less than or equal to the defined level, there is no need to turn on the alternative source. When the consumption increases, renewable resources monitoring circuit input comes into concern. Based on this data, the algorithm commands a switching mechanism.

Table 2.
Performance of Alternative Sources

Battery Charging %	Available Alternative Sources
10 - 30%	All
40 – 60%	Two
70 – 85%	One
85 – 100%	None

IMPLEMENTATION

We made a complete DC model of this system. The maximum power generation in this model is 100W. Table 3 shows the power source concerning its generating capability and the number of alternative sources in our model.

Table 3.
Power Chart

Power source	Max. Power Output	Alternative sources
Solar	10W	Three
Wind	10W	Three
Thermal	80W	None

Figure 3 shows the hardware model of our system. For continuous sources of power, we use a power supply. Our complete system works on 4V. 20A is supplied by the power supply, 2.5A from the battery charged by PV cells, and 2.5A from the battery of the wind station. For the wattmeter, we interface the current sensor ACS712 with Arduino UNO. Sensor transmit the analog value of consuming current and in the programming section of Arduino, amperes are converted into watts in digital form. Then the final 8-bit value is delivered to FPGA. Figure 4 shows the dependencies of load in 24 hours on Solar and thermal units (in our case, alternative batteries). It indicates that in peak hours, solar provides maximum throughput. So it is possible to shift the dependencies totally on solar during day time. Figure 4 is our experimental consideration but it is feasible for the entire solar power-based scenario. A thermal energy source operates continuously, providing a stable and reliable power supply, making it an essential part of any energy generation system.

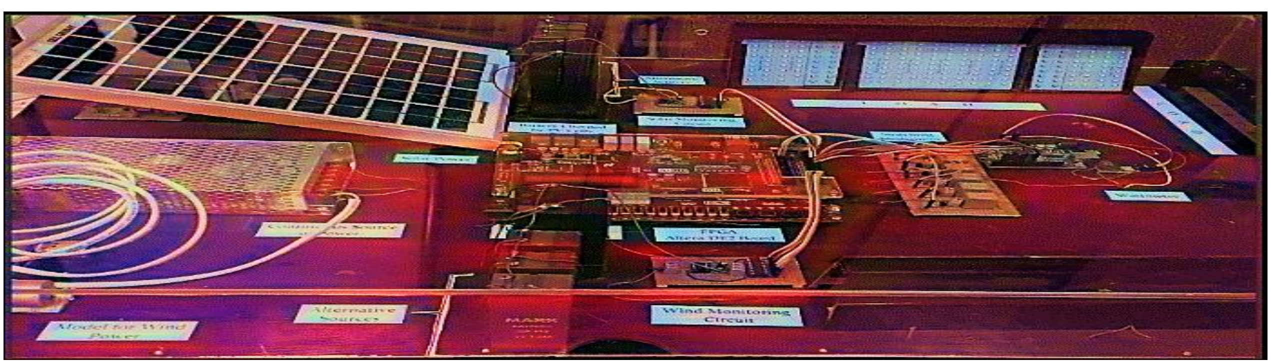

Figure 3.
Hardware Model

However, renewable energy resources, such as solar and wind, are highly dependent on weather conditions and environmental factors. This dependency can lead to fluctuation in energy production during unfavourable conditions such as cloudy days, low wind speeds, or at night. To address this challenge and ensure a consistent supply of energy, alternative energy sources are integrated into the system. These sources act as a backup, stepping in to compensate for any energy gaps that occur when renewable sources are unable to meet the demand. The switching between renewable and alternative sources is managed automatically by an FPGA, which is programmed to monitor energy demand and the availability of renewable energy in real-time. Based on this data, it seamlessly switches between energy sources, ensuring uninterrupted power supply without manual intervention. This smart switching mechanism enhances the efficiency and reliability of the system, making it capable of adapting to varying conditions dynamically. In an analog setup analog pin is designated to receive data, such as voltage from the sensor, this will be converted to digital form by the microcontroller. A constant defines the millivolts per ampere sensitivity of the sensor, and a predefined offset value is used to calibrate the sensor's zero-current output. Several variables are initialized to store raw input values, computed voltages, current, and power as well as their rounded integer equivalents.

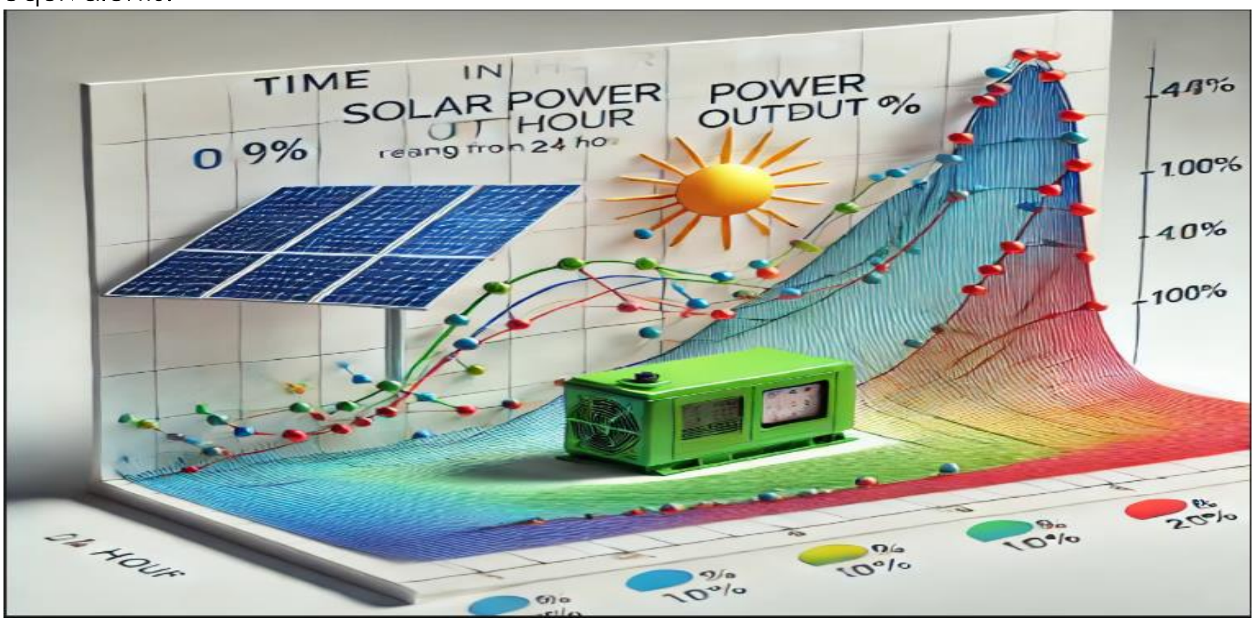

Figure 4.
Solar and Thermal Usage

Digital pins are assigned for computing the calculated power in binary format. The program starts serial communication, allowing data to be transmitted to a connected computer. It also sets specific pins as outputs, which will later be used to represent the power value in binary. The analogy input value is read and stored as a raw digital value, the raw input is converted into voltage using a formula that factors in the resolution of the analog-to-digital converter and a scaling value. The current is calculated by subtracting the sensor's offset voltage from the measured voltage and dividing the result by the sensitivity constant. Power is calculated by a constant factor [22, 23]. The motives of LEDs and the virtual terminal connecting here are similar to ADC, just to observe the behavior separately. Rather the output pins are directly connected to FPGA's GPIO pins. The 8-bit digital output shown in Figure 5, is the binary value concerning the current sensing by the ACS712 multiplied by constant voltage. For instance, if the power consumption is 10W, it shows 0000 1010, if the power consumption is 84W, it shows 0101 0100, and so on.

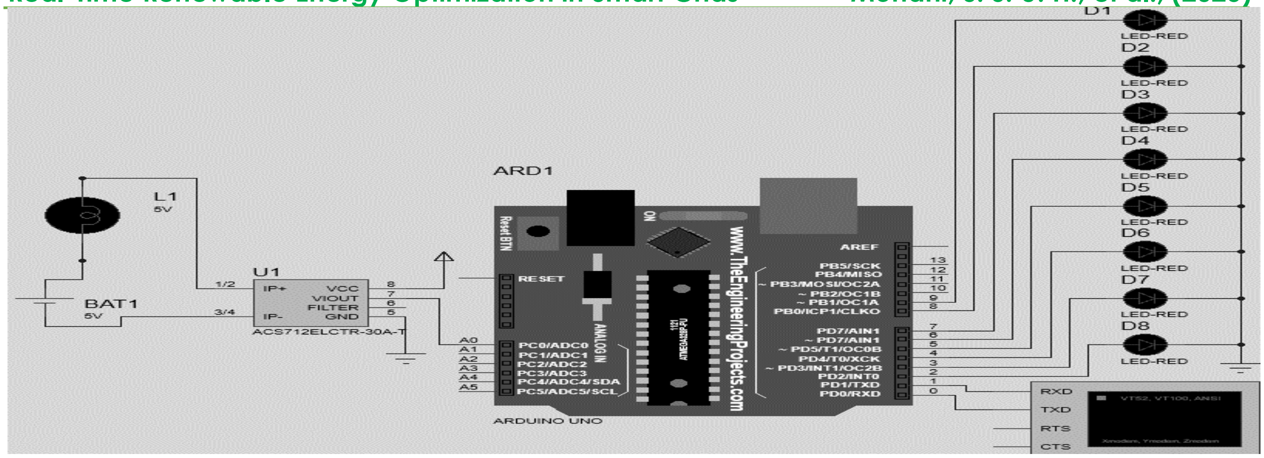

Figure 5.
Wattmeter circuit

RESULTS

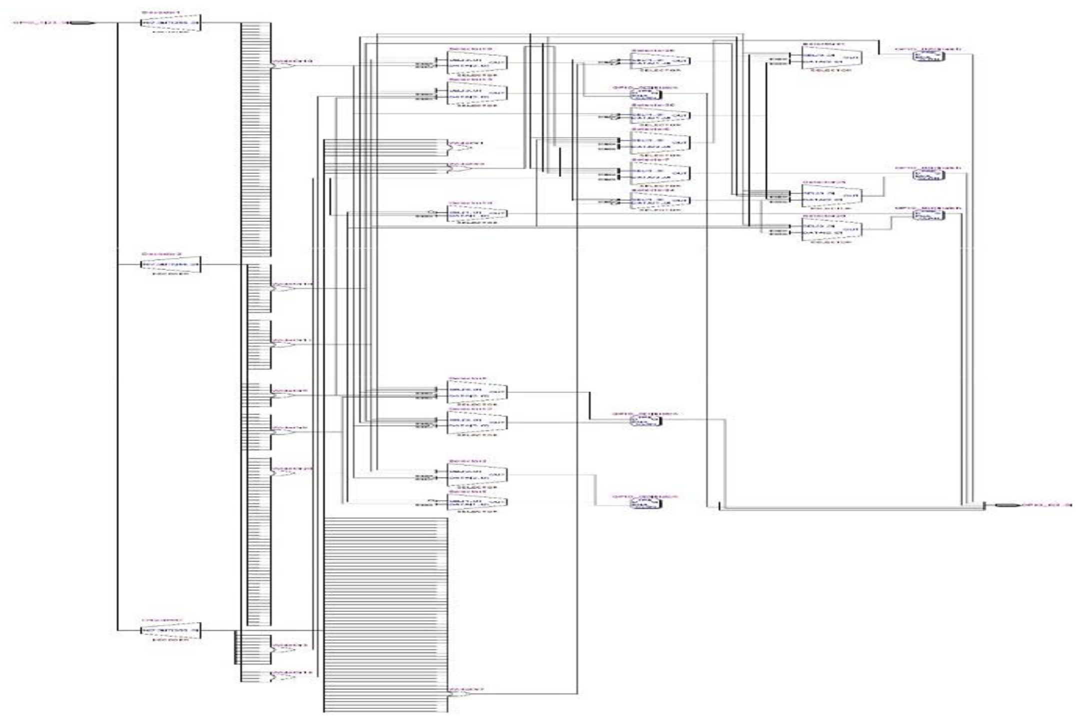

Figure 7.
ModelSim output of our system

The Register Transfer Level (RTL) diagram, used in the Hardware Description Language (HDL) of our system is shown in Figure 6. It represents the high-level description of our system. The coding used in the Arduino gives the value from an analog input pin, processes it to calculate current (in amps), and power (in watts), and then outputs both calculated and raw data over the serial connection. Additionally, it uses digital pins to represent the wattage in binary form via LEDs or other connected devices. The system is built with modular logic, ensuring scalability and clarity in its structure. Decision-making logic is efficiently implemented to minimize delays and maximize processing speed, reflecting its suitability for FPGA. The following diagram shows the flow input to processing and finally to output, emphasizing the hardware's capability to handle complex computations and control logic. ModelSim output of our system is shown in Figure 7. We manually insert the input values (which in the practical scenario will receive from monitoring circuits and wattmeter), based on which algorithm decides which alternative source should connect. The performance of each alternative source is shown individually.

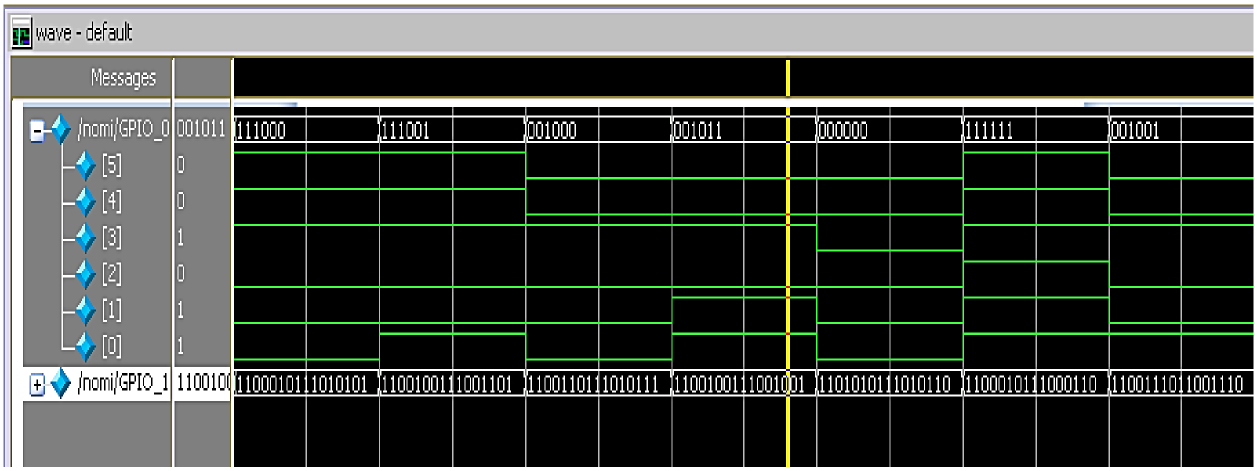

Figure 7.
Modelsim Output

Figure 8 shows the Post mapping diagram of our model which was created by a software that we used, Quartus II.

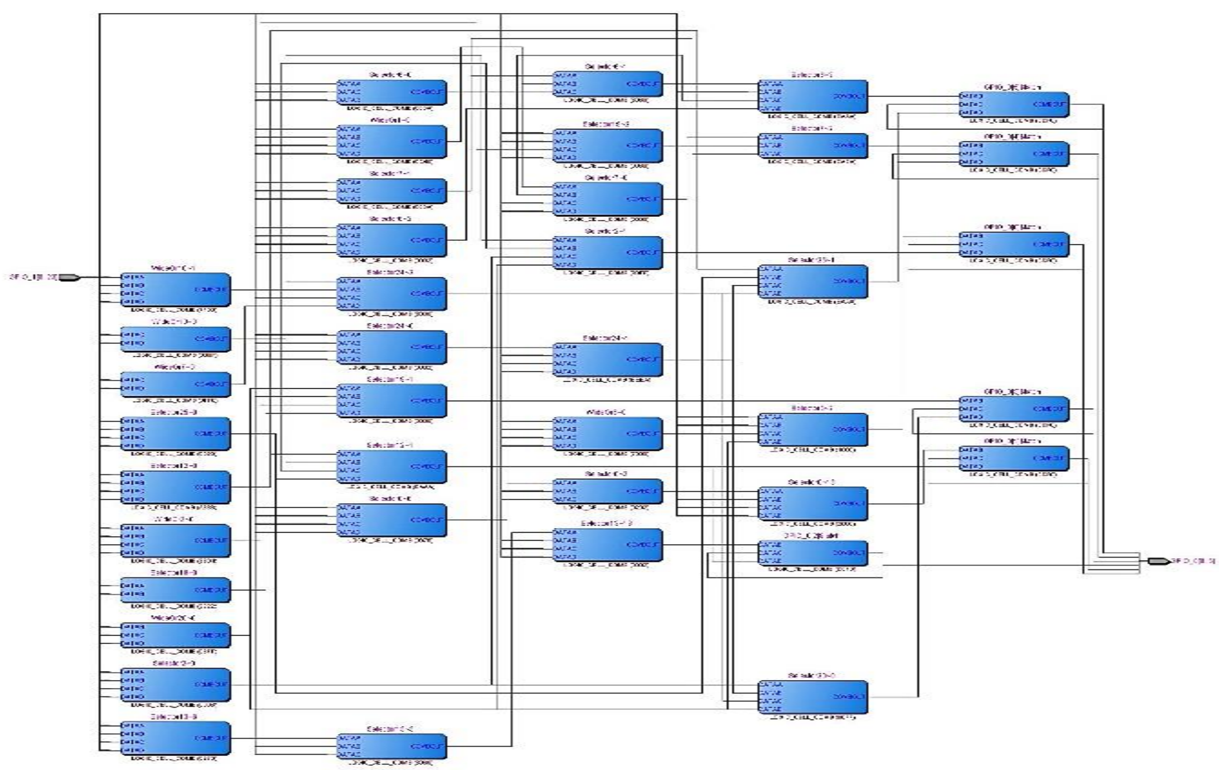

Figure 8.
Post mapping Diagram

CONCLUSION

The smart grid is largely depending on state of the art technologies. For example, information related to each unit or smart devices. However, development in technology must go along with green and pollution free environment. As the population increasing rapidly, usage of fossil fuels increased dramatically. It is necessary to divert all of our dependencies towards renewable resources. But due to their dependence on weather conditions, renewable resources cannot deliver continuously. To integrate them into the distribution unit, we have to achieve much more first. This algorithm will help to manage and control the power utilization of a hybrid system in a smart grid environment. It can manage the renewable resources throughput by arranging an equal amount of power source to compensate for the generation. Also, to make the system cost-efficient and decrease the losses, it is capable of supplying just enough power that is consumed at the load side at that time.

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Consent to Participate: Yes

Consent for publication and Ethical approval: Because this study does not include human or animal data, ethical approval is not required for publication. All authors have given their consent.

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