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An Intelligent Approach for MPPT Extraction in Hybrid Renewable Energy Sources

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ABSTRACT- A multi-source power system that integrates sustainable energy sources for power generation. MPPT, or Maximum Power Point Tracking, is a method employed to optimise the power generation of sources, such as solar panels or wind turbines. Since the efficiency of these sources can vary due to environmental conditions (like sunlight intensity or wind speed), MPPT algorithms optimize the electrical operational parameters of the modules to guarantee they are functioning at their highest efficiency. In the context of MPPT, fuzzy logic is used to handle the uncertainties and nonlinearities in the behaviour of these sources. It allows for a more adaptive and resilient control strategy, which can be particularly effective in fluctuating environmental conditions. When fuzzy logic is applied to MPPT in a hybrid power system, the goal is to intelligently manage and optimize the power output from various sources. This process involves continuously monitoring environmental factors and the performance of each power source. This integration of fuzzy logic into MPPT for hybrid power systems represents an advanced step in renewable energy management, making it possible to get the most out of these resources even under varying and unpredictable conditions.

Keywords: Fuzzy Logic Controller, Maximum Power Point Tracking, Solar, Wind

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1. INTRODUCTION

Power systems are the lifeblood of modern society, providing the electricity necessary for a wide range of applications and services. Their reliability, efficiency, and resilience are essential for economic prosperity, social well-being, and technological advancement. Power systems play a crucial role in integrating sustainable energy sources like solar and wind into the grid. They manage the variability of these sources and ensure a stable and balanced power supply [1].

PV systems are instrumental in advancing renewable energy goals, reducing environmental impact, and fostering a more sustainable and resilient energy future. Their versatility, environmental benefits, and technological advancements make them a cornerstone of the global transition to cleaner energy sources [2].

Photovoltaic (PV) systems efficiently transform sunlight into energy without releasing any greenhouse gasses or other harmful pollutants. They contribute to the generation of clean and sustainable energy, reducing reliance on fossil fuels and mitigating environmental impacts. PV systems contribute to energy independence by harnessing the abundant and freely available energy from the sun. This reduces dependence on finite and sometimes geopolitically sensitive fossil fuel resources. Many regions and countries have established Renewable Portfolio Standards, mandating a certain percentage of electricity generation to come from renewable sources. PV systems play a significant role in meeting these targets and supporting the transition to a more sustainable energy mix [3].

PV systems are vital for providing electricity in remote or off-grid areas where traditional power infrastructure is impractical or expensive to install. Off-grid solar installations contribute to rural electrification and improved living conditions. PV systems are scalable and can be easily added to or modified based on energy needs. This scalability makes them adaptable to various applications, from small residential rooftop installations to large utility-scale solar parks. The growth of the solar industry, driven by the deployment of PV systems, has led to job creation in manufacturing, installation, maintenance, and research and development. The renewable energy sector contributes to economic development and innovation [4].

PV systems can provide ancillary services to the grid, such as frequency regulation and voltage support. Advanced inverters and smart grid technologies enable PV systems to contribute to

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grid stability and reliability. PV systems, especially those equipped with energy storage solutions, can provide a reliable source of electricity during grid outages or disasters. This enhances resilience and aids in disaster recovery efforts [5].

Wind energy is highly crucial in renewable energy systems because to its multiple benefits, which include contributing to a more sustainable and diverse energy supply. Wind energy plays a crucial role in the transition to a more sustainable and resilient energy system. Its environmental benefits, economic contributions, and technological advancements make wind power a key component of the global renewable energy landscape [6].

Wind energy is a clean and renewable resource that doesn't produce greenhouse gas emissions during electricity generation. Harnessing the power of the wind reduces dependence on fossil fuels, mitigates climate change, and supports sustainable energy practices. Wind power generation displaces the need for electricity produced by fossil fuels, helping to reduce carbon dioxide and other air pollutants. This contributes to efforts to combat climate change and improve air quality [7].

Wind is an abundant and widely available resource. Many regions around the world have significant wind resources, making wind energy a viable option for electricity generation in various geographical locations. Wind power enhances energy autonomy by broadening the energy range and diminishing dependency on imported fossil fuels. This enhances energy security and helps countries become less vulnerable to geopolitical fluctuations in energy markets [8].

Wind power projects can range from small-scale, distributed installations to large utility-scale wind farms. This scalability allows for flexibility in designing systems that match local energy needs and conditions. Unlike conventional power plants, wind turbines do not require large amounts of water for cooling. Wind energy contributes to water conservation and is particularly valuable in regions facing water scarcity. Wind power can contribute to grid stability through advanced control systems and smart grid technologies. While the variability of wind can present challenges, proper integration and grid management techniques can enhance reliability [9].

Wind farms can be located on agricultural or otherwise underutilized land, allowing for dual land use and minimizing the impact on ecosystems. This efficient use of land is especially important in densely populated areas. Wind energy can be integrated with other renewable sources and energy storage technologies to create hybrid systems that provide a continuous and reliable power supply, addressing intermittency concerns associated with wind power [10].

Maximum Power Point Tracking (MPPT) is crucial in both energy systems for optimizing energy capture and improving overall system efficiency. MPPT extraction is crucial for both solar and wind energy systems as it maximizes energy harvesting, increases system efficiency, adapts to varying, particularly in solar photovoltaic (PV) and wind turbine systems, to maximize the energy extraction under various conditions The Maximum Power Point Tracking (MPPT) in these energy systems lies in its ability to significantly enhance the efficiency of these renewable energy sources [11].

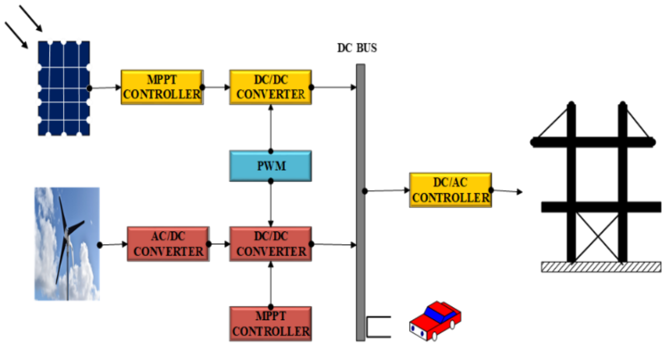

Figure 1. Block diagram of MPPT Extraction in Hybrid Power system

2. PROPOSED METHOD

2.1 Solar Energy Systems

Optimizing Power Output: Solar panels have a specific point at which they produce maximum power, which varies with temperature and irradiance levels. MPPT ensures the solar system operates close to this maximum power point at all times, extracting the most energy possible from the panels [12].

- Adapting to Environmental Changes: Solar energy generation is highly dependent on weather conditions. MPPT dynamically adjusts to changes in sunlight intensity and temperature, ensuring optimal performance throughout the day and across different seasons.
- Increased Efficiency: By constantly tracking and operating at the maximum power point, MPPT can significantly improve the efficiency of solar power systems, often by 20-30% compared to systems without MPPT.
- Compatibility with Various Panel Configurations: MPPT allows for flexibility in designing solar panel arrays. It can optimize power output even when panels are partially shaded or when using panels with different characteristics in the same system.

MPPT controllers adjust the electrical load connected to the solar panels. By modifying the voltage and current, they ensure that the panels operate near their maximum power point. In the solar energy systems MPPT is a critical technology for maximizing the efficiency of solar panels, adapting to varying environmental conditions, and ensuring that solar installations, regardless of their size, deliver the best possible performance [13].

2.2 Working Principle of MPPT In Solar Energy System

Figure 2 depicts, the working principle of Maximum Power Point Tracking in solar energy revolves around optimizing the power output from photovoltaic (PV) panels by continuously finding and maintaining operation at the maximum power point (MPP). Solar panels have a characteristic voltage-current (V-I) curve, which changes based on factors like sunlight intensity

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and temperature. There's a specific point on this curve, known as the Maximum Power Point, where the product of current (I) and voltage (V) is at its peak, meaning the panel produces its maximum power [14].

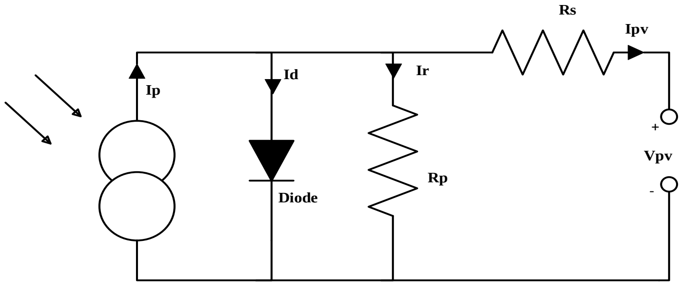

Figure 2. Equivalent circuit of PV Cell

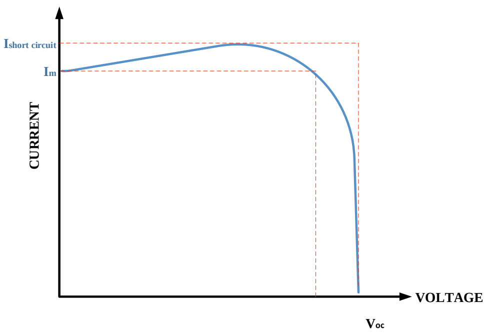

Figure 3. I-V Characteristics of Solar Energy System

The MPP is not static; it shifts with changing environmental conditions. For instance, on a cloudy day or as the temperature changes, the MPP also changes[15].

From the *figure 2*

$$Ip = Id + Ir + Ipv \quad (1)$$

$$v = Ip - (Id + Ir) \quad (2)$$

$$Vpv = Vr + Vs \quad (3)$$

$$Vpv = IrRr + IpvRs \quad (4)$$

$$Ppv = Vpv * Ipv \quad (5)$$

2.3 Temperature effect on PV System[16]

The temperature has a significant impact on the performance of a photovoltaic (PV) system in several ways.

2.3.1 Module Temperature

- **High Temperatures**: Elevated temperatures can negatively impact the efficiency of solar panels. As the temperature of the solar cells increases, the efficiency of converting sunlight into electricity decreases. Most solar panels operate less efficiently at higher temperatures.
- **Cooling Methods**: Some PV systems incorporate cooling methods, such as ventilation or water cooling, to mitigate the temperature effect and improve overall system efficiency.

2.3.2 Output Voltage

The voltage output of a PV module is also affected by temperature. Generally, an increase in temperature leads to a decrease in the voltage output. This effect is particularly relevant for off-grid PV systems where voltage regulation is crucial for proper battery charging.

2.3.3 Inverter Efficiency

Inverters, which convert the DC electricity generated by solar panels into usable AC electricity, may experience changes in efficiency with temperature variations. Some inverters are designed to operate optimally within specific temperature ranges, and their efficiency may decrease if they operate outside these ranges.

2.3.4 Energy Production

Overall energy production of a PV system is influenced by temperature. While higher temperatures may reduce the efficiency of individual solar cells, the increased solar irradiance on hot days can partially offset the reduction in efficiency, leading to a complex interplay of factors influencing overall energy production.

2.3.5 Temperature Coefficients

Manufacturers often provide temperature coefficients for their solar panels. These coefficients describe how the performance parameters of the PV modules (such as power output or voltage) change with temperature. It's essential to consider these coefficients when assessing the expected performance of a PV system under different temperature conditions.

2.3.6 Thermal Management

Proper thermal management strategies, such as providing adequate spacing between modules for air circulation or using heat sinks, can help dissipate excess heat and maintain optimal operating temperatures for improved efficiency.

While high temperatures can have a negative impact on the efficiency of individual solar cells, other factors such as increased solar irradiance may partially counteract these effects. Proper system design, including consideration of temperature coefficients and implementation of thermal management strategies, is crucial for optimizing the performance of a PV system across a range of temperature conditions.

2.4 Wind Energy Systems[17]

- **Variable Wind Speeds**: Wind speeds are unpredictable and can vary greatly. MPPT helps in adjusting the operating points of wind turbines to align with changing wind speeds, ensuring maximum energy extraction.
- **Enhancing Turbine Efficiency:** Similar to solar panels, wind turbines have an optimum operating point where they generate maximum power. MPPT identifies and maintains operation at this point.
- **Reducing Mechanical Stress**: By optimizing the power extraction, MPPT can also help in reducing the mechanical stress on wind turbines, potentially increasing their lifespan and reducing maintenance costs.
- **Grid Integration:** For wind systems connected to the power grid, MPPT ensures more consistent and efficient power delivery, which is crucial for grid stability and reliability.

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The following equation must be determined for electricity generation from a wind turbine.

$$P = \frac{1}{2} * \partial * Cp * \beta * \vartheta^3 * Sa \quad (6)$$

Here, ∂ = Air density, Sa is swept area of wind blades, Cp depends on Tip Speed Ratio and blade pitch is β

2.5 General Benefits of MPPT[18]

- **Cost-Effectiveness**: While MPPT systems add to the initial cost of renewable energy systems, the increase in energy yield can lead to a quicker return on investment and greater long-term savings.
- **Scalability:** MPPT systems can be scaled for both small and large installations, making them suitable for a wide range of applications.
- **Reduced Energy Wastage**: By maximizing energy extraction, MPPT contributes to the overall goal of reducing reliance on fossil fuels and minimizing energy wastage.

2.6 Integration of Solar and Wind Energy System

The integration of solar and wind energy sources offers a more reliable, resilient, and balanced renewable energy supply. This approach addresses the inherent variability and intermittency associated with individual sources and contributes to the overall sustainability and effectiveness of the energy system[19].

Solar and wind energy resources often complement each other. Solar power production is typically higher during the day, while wind power can be more consistent throughout the day and night. Integrating both sources helps to balance energy generation, ensuring a more continuous and reliable power supply. Solar and wind power generation can exhibit variability and intermittency due to changes in weather conditions. By combining these sources, the impact of fluctuations in one source can be mitigated by the more stable output of the other. This integration helps smooth out overall energy production and enhances grid stability[20].

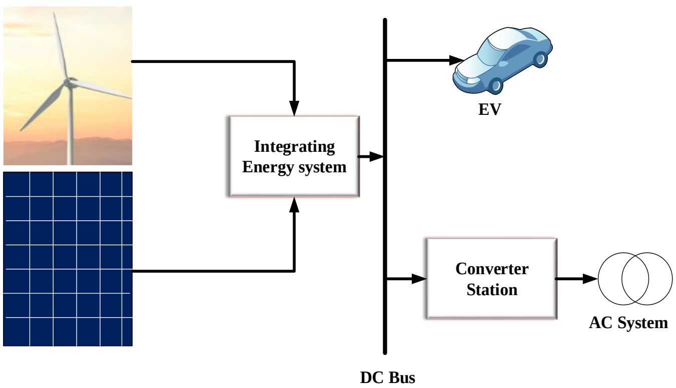

Figure 4. Block diagram solar and wind energy collaboration

Integrating solar and wind energy provides a more consistent and reliable energy supply. When one source experiences lower generation due to weather conditions, the other may compensate, ensuring a more continuous availability of renewable energy. The combination of solar and wind resources can result in a higher capacity factor for the integrated renewable energy system. By utilizing both sources, the system can achieve more consistent power output, increasing the overall efficiency and effectiveness of the renewable energy installation[21].

Solar and wind resources vary geographically. Integrating both sources allows for harnessing energy from diverse locations, reducing the impact of localized weather patterns on overall energy production. This geographic diversification enhances the resilience and reliability of the integrated system. The variability of one renewable source can be compensated by the more predictable output of the other. This can reduce the reliance on large-scale energy storage systems, as the combined solar and wind generation profile helps smooth out fluctuations and enhances grid stability[22].

Integrating solar and wind technologies provides a diversified portfolio of renewable energy sources. This diversification can enhance the overall resilience of the energy system, reducing the vulnerability to specific technological or environmental challenges that may affect one source but not the other. Solar and wind installations often require different types of land use. Integrating both sources allows for more efficient use of available land, as areas suitable for solar panels may differ from those suitable for wind turbines. This enhances the overall land use efficiency of the renewable energy system. Solar and wind energy resources often align with different patterns of energy demand. Solar power is more prevalent during daylight hours, while wind power can be more consistent throughout the day and night. Integrating both sources helps match energy production with varying demand patterns[23].

2.7 Hybrid System with Fuzzy Topology

Integrating fuzzy logic controllers with solar and wind energy systems requires a thorough understanding of the specific system dynamics and the design of effective fuzzy control strategies. It's essential to consider the unique characteristics of each system and tailor the fuzzy logic approach accordingly. Using fuzzy logic controllers (FLCs) in conjunction with solar and wind energy systems can help optimize the performance and efficiency of these renewable energy sources. Fuzzy logic is a mathematical framework that deals with uncertainty and imprecision, making it suitable for systems that involve variables with vague boundaries[24].

Fuzzy logic controllers can be employed to optimize solar panel orientation for maximum energy absorption. The inputs might include factors such as solar irradiance, cloud cover, and time of day. Membership functions can be defined for these inputs, and rules can be created to determine the appropriate tilt and azimuth angles for the solar panels[25].

Fuzzy logic can be used to manage the charging and discharging of batteries in a solar energy system. Inputs may include battery voltage, solar energy availability, and load demand. The fuzzy controller can adjust the charging rates based on these inputs, ensuring efficient energy storage and utilization[26].

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Fuzzy logic controllers can optimize the pitch angle and rotational speed of wind turbine blades. Inputs may include wind speed, turbulence, and generator load. By defining appropriate membership functions and rules, the fuzzy controller can adjust the turbine parameters to maximize energy extraction while ensuring the safety of the system. Fuzzy logic can be applied to control the interaction between the wind energy system and the electrical grid. Inputs may include grid voltage, frequency, and power demand. The fuzzy controller can adjust the power output from the wind turbine to match the grid requirements, contributing to grid stability[27].

3. RESULTS AND DISCUSSION

In hybrid solar-wind systems, fuzzy logic controllers can be employed to dynamically allocate resources between the solar and wind components based on real-time conditions. Inputs may include solar irradiance, wind speed, energy storage levels, and load demand. The fuzzy controller can determine the optimal mix of solar and wind energy to meet the load requirements. *Table I* represents parameters required in the topology, have been considered 8*8 Fuzzy Controller Rule and *Table III* represents Model Parameters of proposed technique.

Table I. Parameters required in Hybrid System

S. No.	Parameter
1	Sun Power SPR-415E-WHT-D Solar Panel
2	7-Module string
3	88 Parallel Strings
4	45°C Temperature
5	1000 Irradiance
6	38m blade radius
7	15m/s wind speed
8	3 blades
9	4 m/s cut-in speed
10	3 rad/s rated speed

Table II. Represents comprehensive analysis of various parameters with different techniques at 1000w/m^2 irradiation and 15m/s wind speed.

Table II. Comprehensive Analysis of Various Topologies

Method	Voltage (volts)	Current(amps)	Power(watts)
HC-PID	160.3	481	7.712*10^4
PID	142.7	428	6107*10^4
IC	125	374	4.686*10^4
Proposed Topology	177.87	533.76	9.52*10^4

Table III. (Parameters required for Proposed Model

S. No.	Parameter	Value
1	Light-generated current IL (A)	6.09
2	Diode saturation current I0 (A)	$7.17{*}e^{-13}$
3	Diode ideality factor	0.873
4	Shunt resistance Rsh (ohms)	419
5	Series resistance Rs (ohms)	0.54
6	Temperature coefficient of Voc (%/deg.C)	-0.23
7	Temperature coefficient of Isc (%/deg.C)	0.031

In proposed topology Maximum Power (401.8W), Open circuit voltage Voc (85.3V), short circuit current Isc (6.09A) and 3 blade wind turbine with 3rad/sec of speed have been considered. *Figures 5 and 6* depicts the solar energy system characteristics of current – voltage, power- voltage with different temperature values.

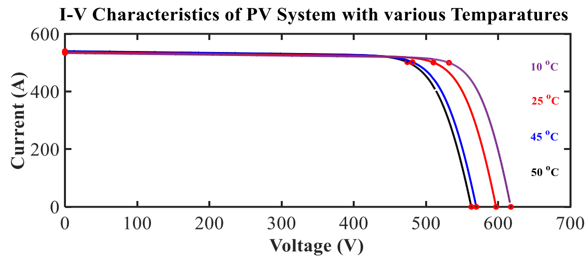

Figure 5. current –voltage characteristics at different Temperatures

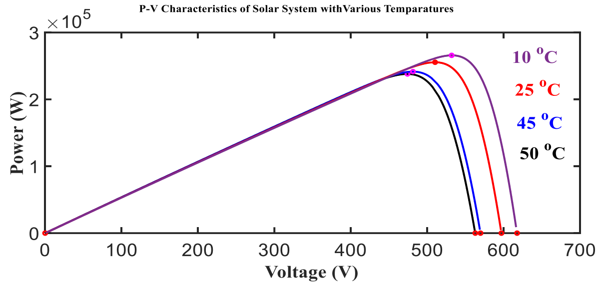

Figure 6. Power –voltage characteristics at different Temperatures

Figures 7 depicts maximum power in solar energy system, when FLC is adopted for MPP extraction. Here the maximum power of hybrid system acquired at 0.8 seconds.

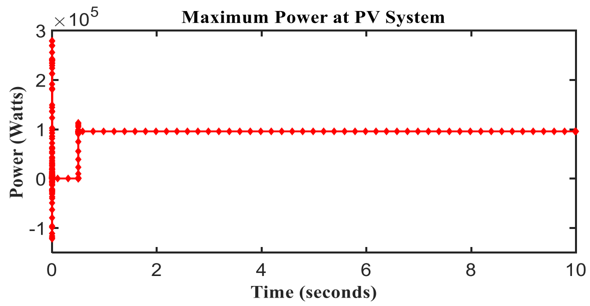

Figure 7. Maximum Power at solar energy system

Figures 8 depicts maximum voltage in solar energy system, when FLC is adopted for MPP extraction. Here the maximum voltage of hybrid system acquired at 0.8 seconds

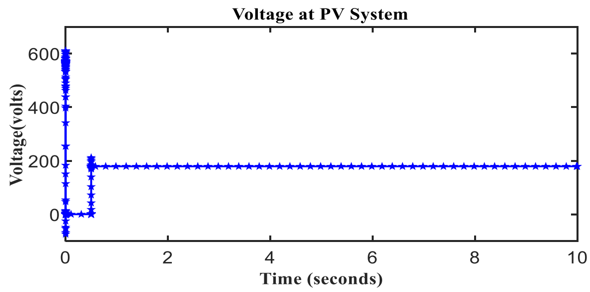

Figure 8. Maximum Voltage at solar energy system

Figures 9 depicts maximum current in solar energy system, when FLC is adopted for MPP extraction. Here the maximum current of hybrid system acquired at 0.8 seconds

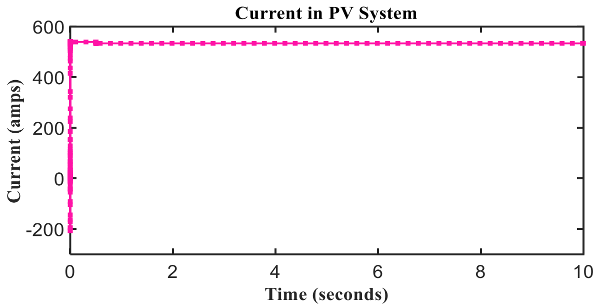

Figure 9. Maximum Current in solar energy system

Figures 10 depicts load power in hybrid energy system, when FLC is adopted for MPP extraction. Here the maximum power of hybrid system acquired between 0.7-0.8 seconds.

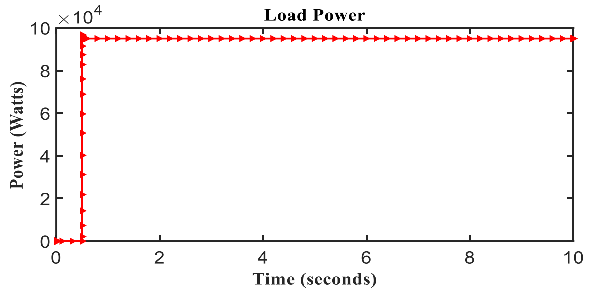

Figure 10. Load Power at Hybrid energy system

Figures 11 depicts load current in hybrid energy system, when FLC is adopted for MPP extraction. Here the maximum current of hybrid system acquired between 0.7-0.8 seconds.

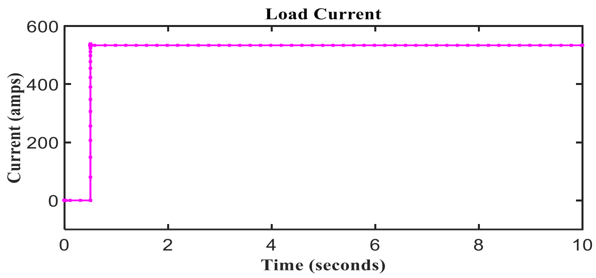

Figure 11. Load current in Hybrid energy system

Figures 12 depicts load voltage in hybrid energy system, when FLC is adopted for MPP extraction. Here the maximum voltage of hybrid system acquired between 0.7-0.8 seconds

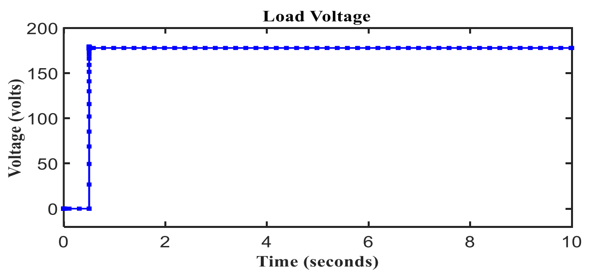

Figure 12. Load voltage at Hybrid energy system

4. CONCLUSION

The implementation of Fuzzy Logic Control (FLC) for Maximum Power Point Tracking (MPPT) in solar and wind energy systems offers several advantages. This approach leverages the inherent flexibility of fuzzy logic to handle the inherent uncertainties and nonlinearities associated with renewable energy systems. The integration of fuzzy logic-based MPPT in solar and wind energy systems represents a promising approach to enhance energy harvesting efficiency, improve system stability, and facilitate the integration of renewable energy into the broader energy landscape. This technology showcases its potential to contribute significantly to sustainable and reliable energy solutions.

5. FUTURE SCOPE

The future research scope of fuzzy control-based Maximum Power Point Tracking (MPPT) extraction in solar and wind energy encompasses several exciting avenues, considering the evolving landscape of renewable energy technologies and the need for more advanced and efficient control strategies. Some potential areas for future research include:

- Investigate and develop advanced fuzzy logic controllers for optimizing hybrid solar-wind energy systems. This involves improving the coordination between solar and wind components in a hybrid setup, dynamically adjusting their contributions based on real-time conditions.
- Research the application of fuzzy logic-based MPPT for fault detection and tolerance in solar and wind energy systems. Develop controllers that can identify and mitigate faults in components such as solar panels or wind turbines, ensuring system reliability and minimizing downtime.

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