MULTI-LEVEL INVERTER FOR GRID-CONNECTED HYBRID PV-WIND-BATTERY BASED SYSTEM FOR HOUSE HOLD APPLICATIONS

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Abstract

The integration of renewable energy sources, such as solar and wind power, has become a key solution to addressing the rising global demand for sustainable energy. This paper presents the design and implementation of a multi-level inverter for a grid-connected hybrid photovoltaic (PV)-wind-battery-based system aimed at household applications. The proposed system utilizes a multi-level inverter to efficiently convert and regulate power from hybrid renewable energy sources into a stable AC supply, ensuring minimal harmonic distortion and enhanced power quality. The integration of solar and wind energy with battery storage ensures continuous and reliable energy supply, even during variable weather conditions, while optimizing energy efficiency. A robust control system is incorporated to manage the power flow from the PV, wind, and battery sources to the grid and household loads. The system also features maximum power point tracking (MPPT) algorithms to extract maximum energy from both the PV and wind sources. A simulation of the system in a MATLAB/Simulink environment demonstrates the feasibility and effectiveness of the proposed solution in ensuring energy reliability, cost-effectiveness, and minimal environmental impact for residential applications. The results highlight the potential of this hybrid system to provide an efficient, sustainable, and flexible energy solution for modern households.

Keywords: Multi-level inverter, hybrid PV-wind system, grid-connected, battery storage, maximum power point tracking (MPPT), household energy applications.

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Introduction

The increasing demand for electricity, coupled with environmental concerns, has led to a growing interest in renewable energy systems. Solar photovoltaic (PV) and wind energy have emerged as the most promising sources of clean, sustainable power. These renewable energy sources, however, are intermittent and unpredictable, which makes it necessary to incorporate energy storage systems and hybrid solutions for ensuring continuous power supply. A hybrid system consisting of a PV, wind, and battery-based power generation offers an efficient solution to these challenges[1].

The integration of such a system with the electrical grid requires efficient power conversion techniques to ensure stable and high-quality power delivery. Traditional inverters, while efficient, often produce harmonics and are less effective in handling the diverse power inputs from hybrid sources. This paper presents the design of a multi-level inverter (MLI) for grid-connected hybrid PV-wind-battery systems. The multi-level inverter is capable of producing a higher-quality output voltage with minimal harmonic distortion compared to conventional two-level inverters. This results in better power quality, enhanced efficiency, and lower electromagnetic interference. The proposed system utilizes Maximum Power Point Tracking (MPPT) algorithms to extract the maximum energy from both the PV and wind sources, while the

battery storage ensures a stable supply during low generation periods. The hybrid system's performance is simulated and analyzed to demonstrate its applicability for household energy applications[2].

The integration of renewable energy sources with energy storage systems has been widely studied in recent years due to the growing need for sustainable energy solutions. Several hybrid systems have been proposed, combining solar, wind, and battery technologies, aimed at improving reliability and efficiency in power generation[3].

In [4], a hybrid PV-wind system with a battery storage unit was explored. The authors used a conventional inverter to connect the system to the grid, but the system suffered from harmonic distortion and low power factor issues. This prompted further research into multi-level inverters (MLIs), which offer improved performance in terms of voltage quality and harmonic reduction. MLIs can generate smoother waveforms, making them ideal for applications where power quality is critical.

In [5], the authors proposed a hybrid PV-wind-battery system, with a focus on optimal energy management strategies. The integration of MPPT algorithms ensured maximum energy extraction from both PV and wind sources, while the battery storage provided a buffer during periods of low generation. However, the inverter used in this system was a two-level inverter, which led to high harmonic content in the output voltage, affecting grid compliance.

Further advancements in multi-level inverters have been explored in [6] and [7], where various topologies, such as the diode-clamped, flying capacitor, and cascaded H-bridge configurations, were evaluated. The results showed that multi-level inverters can significantly reduce harmonics and improve overall efficiency in power conversion systems. Cascaded H-bridge inverters, in particular, were identified as highly suitable for renewable energy applications due to their ability to handle multiple input sources.

Recent studies, such as [8], have also focused on the combination of PV, wind, and battery systems with MLIs. These studies highlighted the advantages of using multi-level inverters to improve power quality, increase efficiency, and ensure compliance with grid standards. Moreover, the use of hybrid systems with battery storage has been proven to enhance system reliability by mitigating intermittency issues associated with renewable energy sources[9].

While these studies have contributed significantly to the development of hybrid renewable energy systems, the integration of advanced control strategies, including intelligent power management and fault tolerance, remains an area for further research. This paper aims to address these challenges by proposing a multi-level inverter-based hybrid PV-wind-battery system designed specifically for household applications[10-11].

The diagram in figure 1 represents a basic block diagram of a **hybrid renewable energy system** that integrates solar PV panels, wind energy, battery storage, and various power electronics components. Here is a description of the diagram:

System Overview:

This figure outlines the key components of a **hybrid renewable energy system** designed to supply power to a load. The system integrates multiple energy sources—solar PV panels and wind energy—along with battery storage for energy backup. The flow of power from generation to load is managed using various power conversion and conditioning components.

Components:

1. **Solar PV Panel:**
    - This component represents the solar power generation source. Solar panels convert sunlight into DC electricity, which is then directed into the power conversion system for conditioning and distribution.
2. **Wind Energy:**
    - The wind energy component captures energy from the wind, typically using a wind turbine. The energy generated is typically DC and is fed into the power conditioning system.
3. **DC-DC Converter:**

- The DC-DC converter is responsible for regulating and controlling the DC voltage and current levels coming from both the solar PV panel and the wind energy system. It adjusts the power flow based on the load's requirements and optimizes the energy input from renewable sources.

4. **Inverter:**
   - The inverter is a crucial component that converts the DC power from the renewable sources (solar and wind) into AC power. AC power is typically required for household and commercial use, making the inverter essential for grid integration or direct power supply to loads.
5. **Transformer:**
   - The transformer steps up or steps down the AC voltage to appropriate levels for either grid connection or load consumption. It ensures that the voltage is compatible with the end-user requirements.
6. **Power Controller:**
   - The power controller manages the overall energy flow in the system, ensuring that the renewable energy sources are utilized efficiently and that the battery is charged when there is surplus energy. It also ensures optimal power distribution between the energy generation sources and the load.
7. **Battery Storage:**
   - The battery storage acts as a buffer, storing excess energy generated by the solar and wind systems for use when generation is insufficient, such as during periods of low sunlight or wind. The battery helps ensure a reliable power supply.
8. **Load Interface:**
   - The load interface is the point where the system delivers power to the connected load. It may include additional conditioning elements to ensure the proper voltage, current, and frequency for the load's requirements.
9. **Load:**
   - The load represents the consumer or application that requires the electrical power generated by the hybrid renewable energy system. This could be a residential, commercial, or industrial electrical load.

Flow of Power:

- The solar PV panels and wind energy generate DC power, which is passed through the DC-DC converter to regulate and condition the voltage.
- The DC power is then sent to the inverter, where it is converted into AC power for use in the load or for connection to the grid.
- Excess energy generated by the renewable sources is stored in the battery storage for later use when generation is insufficient.
- The power controller manages the overall system, optimizing power flow between the sources, storage, and load, ensuring energy reliability and efficiency.

This system provides a sustainable solution for power generation, utilizing both solar and wind energy while ensuring a stable power supply to the load. The integration of battery storage allows the system to function reliably, even during periods when renewable energy generation is low. The use of a transformer and inverter allows for proper voltage and frequency regulation, making the system compatible with grid and household power requirements.

The major component in the system is the inverter. We need to design a proper inverter for the better output. The next section discusses about the inverter design.

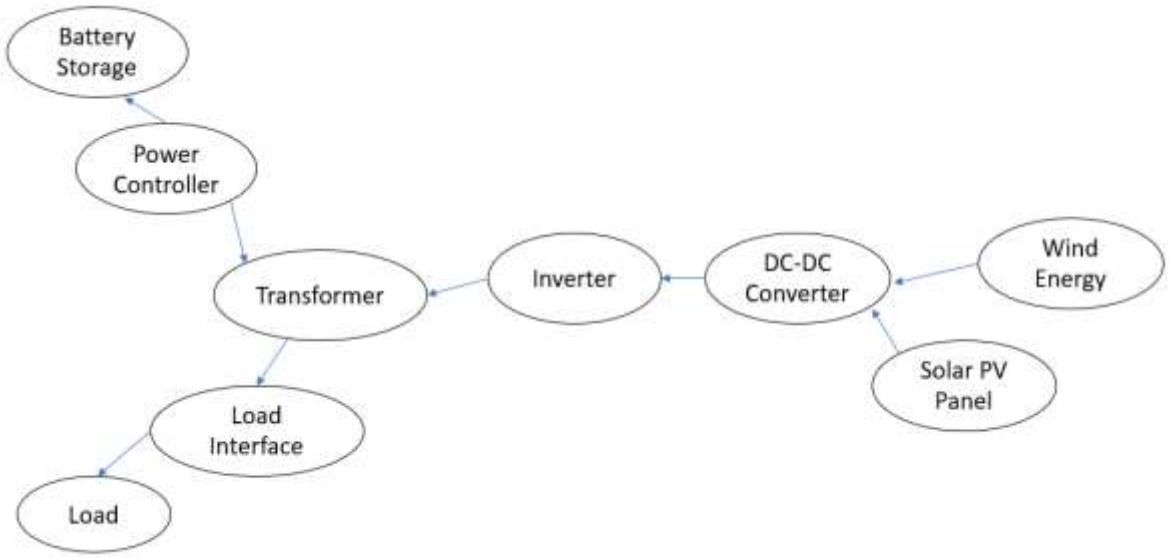

Figure 1: Block diagram of Grid-connected hybrid pv-wind-battery based system for house hold applications

MULTI-LEVEL INVERTER

Description of the Multi-Level Inverter Design:

The proposed **multi-level inverter** design is a key component in a **grid-connected hybrid PV-wind-battery-based system**, designed to provide high-quality AC power from renewable energy sources such as solar (PV) and wind, with battery storage for stable operation. The multi-level inverter (MLI) is used for efficient voltage conversion from DC to AC, improving the overall system's performance by reducing harmonic distortion and achieving better power quality.

Key Features of the System:

1. **Hybrid Renewable Energy Sources (PV + Wind):**
   - The system integrates two renewable energy sources, solar PV panels and wind turbines, which provide DC power to the inverter.
   - The PV array generates power based on sunlight, and the wind turbine generates power based on wind speed.
2. **Battery Storage:**
   - The battery stores energy when excess power is generated (from PV or wind) and supplies energy during periods of low renewable generation. The battery ensures continuous power supply and acts as a buffer for fluctuations in renewable energy output.
3. **Multi-Level Inverter:**
   - The multi-level inverter converts the DC power from the PV, wind, and battery sources into a stable AC output for grid connection or direct load supply.
   - By using multiple levels of voltage steps, the multi-level inverter generates a smoother AC waveform, reducing harmonic distortion compared to traditional two-level inverters.
4. **Maximum Power Point Tracking (MPPT):**
   - MPPT algorithms are used for both the PV array and wind turbine to extract the maximum available power by adjusting the operating point of the system based on environmental conditions.

Multi-Level Inverter Design:

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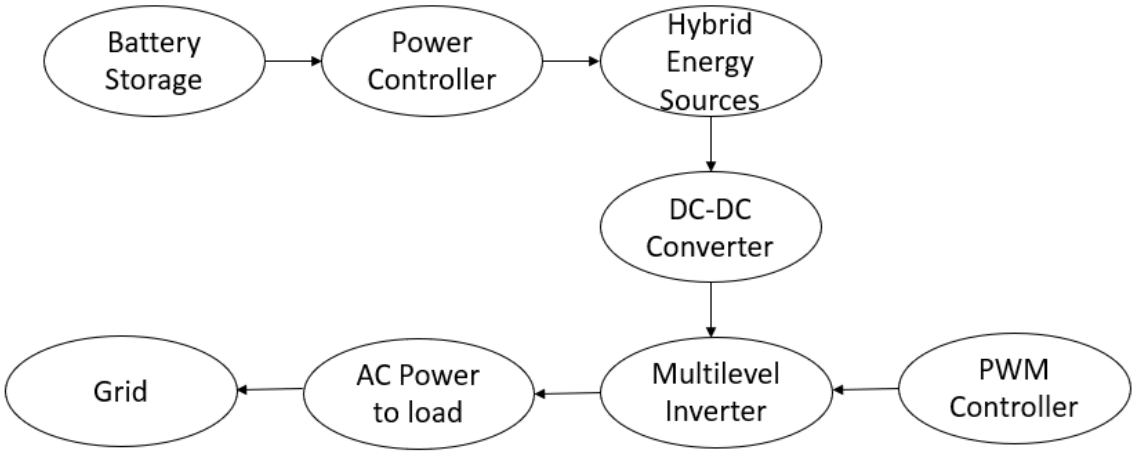

Figure 2: Block Diagram for Multilevel Inverter

A multi-level inverter uses multiple semiconductor switches arranged in different configurations to produce multiple output voltage levels. Figure 2 shows the block diagram of the propose multilevel converter. The general structure of the inverter consists of a series of switching devices (typically MOSFETs or IGBTs) that control the output voltage levels. The key features of the design include the following:

1. **Voltage Levels:**
   - A multi-level inverter typically uses three or more voltage levels to approximate a sinusoidal AC waveform. For example, a three-level inverter has three output voltage levels: +Vdc, 0, and -Vdc.
   - The output voltage waveform is formed by combining these levels, reducing the harmonic distortion compared to a two-level inverter.
2. **Switching Pattern:**
   - The switching pattern of the inverter is carefully designed to produce the required output voltage levels. This is achieved by turning on and off different combinations of the switches in the inverter.
   - The control of the switches is governed by Pulse Width Modulation (PWM), which ensures that the output voltage matches the desired waveform, minimizing switching losses and harmonic generation.
3. **Control Strategy:**
   - The control strategy for the multi-level inverter is based on adjusting the duty cycles of each switch to generate the appropriate voltage levels at the inverter output.
   - The output voltage at the inverter can be expressed as:

$$V_{\text{out}}(t) = V_{\text{dc}} \cdot \sum_{n=1}^{N} (\alpha_n \cdot \cos(n\omega t))$$

where:

- V_{dc} is the DC voltage level.
- N is the number of levels in the inverter (for instance, 3 levels for a three-level inverter).
- α_n is the modulation index.
- Ω is the angular frequency of the output AC signal.
- t is time.

This equation represents the Fourier series expansion of the output voltage, where the summation of different harmonics produces a sinusoidal waveform.

4. **Output Waveform:**
    - The output waveform of the inverter, using a multi-level approach, is a more refined approximation of a sine wave. As more levels are used (e.g., 5-level, 7-level), the output waveform becomes even smoother, with reduced total harmonic distortion (THD).
    - The THD can be calculated as:

$$\text{THD} = \sqrt{\frac{V_2^2 + V_3^2 + \cdots + V_n^2}{V_1^2}}$$

where:

- V_1 is the fundamental component of the voltage.
- $V_2, V_3, \ldots, V_n$ are the higher-order harmonics.
- The goal is to minimize the THD to below a certain threshold, typically below 5% for grid-connected systems.

5. **Efficiency:**
    - The multi-level inverter improves efficiency by reducing switching losses and increasing voltage steps. This reduces the ripple in the DC input and minimizes the number of times the switches are turned on and off, which in turn reduces the overall system loss.
    - The efficiency of the multi-level inverter can be expressed as:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}}$$

where:

- P_{out} is the output power.
- P_{in} is the input power.

6. **Grid Integration:**
    - The inverter is designed to be grid-connected, meaning it synchronizes its output frequency and voltage with the grid. The AC output voltage from the inverter must match the grid voltage to allow for power exchange.
    - The synchronization is achieved by adjusting the phase and frequency of the output waveform, ensuring stable and reliable power delivery to the grid.

Equations for Power Flow:

The power flow through the system can be described as follows:

1. **DC Power from PV and Wind:**
    - The DC power generated by the PV array and wind turbine can be calculated as:

$P_{DC} = V_{dc} \cdot I_{dc}$

where:

- V_{dc} is the DC voltage from the energy sources.
- I_{dc} is the DC current from the energy sources.

2. **Battery Power:**
    - The battery stores or supplies power depending on the energy surplus or deficit in the system. The battery power is calculated as:

$P_{battery} = V_b \cdot I_b$

where:

- V_b is the battery voltage.
- I_b is the battery current.

3. **AC Power to Load:**
   - The AC power delivered to the load is expressed as:

$PAC=V_{ac}\cdot I_{ac}\cdot\cos(\varphi)$

where:

- V_{ac} is the AC voltage output from the inverter.
- I_{ac} is the AC current.
- φ is the phase angle between the voltage and current waveforms (for power factor correction).

The multi-level inverter provides a key solution for efficient power conversion in grid-connected hybrid systems, improving power quality, efficiency, and overall performance. The use of multiple voltage levels reduces harmonic distortion and enables smoother voltage waveforms, making it an ideal choice for renewable energy systems requiring high-quality AC power. The system design with MPPT ensures maximum energy extraction from the renewable sources, while the battery storage provides stability and reliability for residential applications.

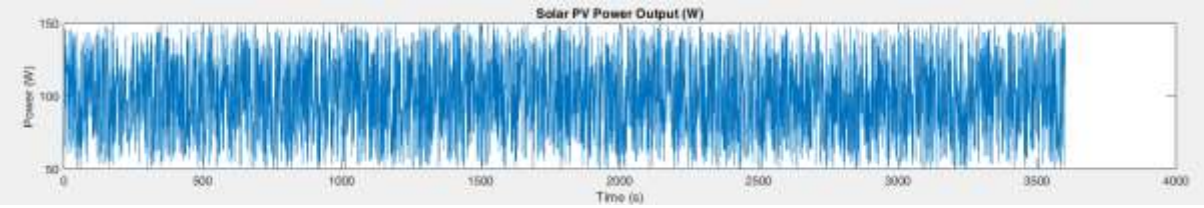

Figure 3: Power output of the Solar PV

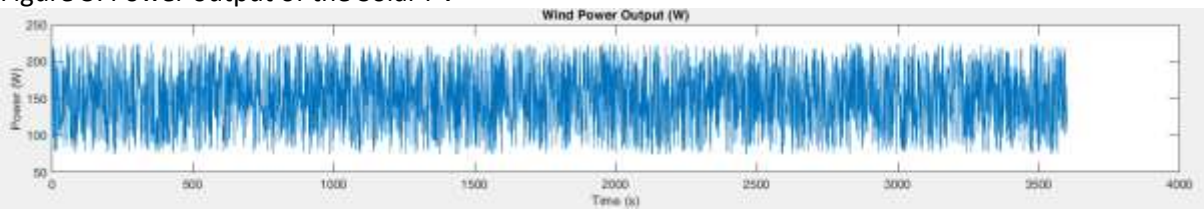

Figure 4: Power output of the Wind Energy

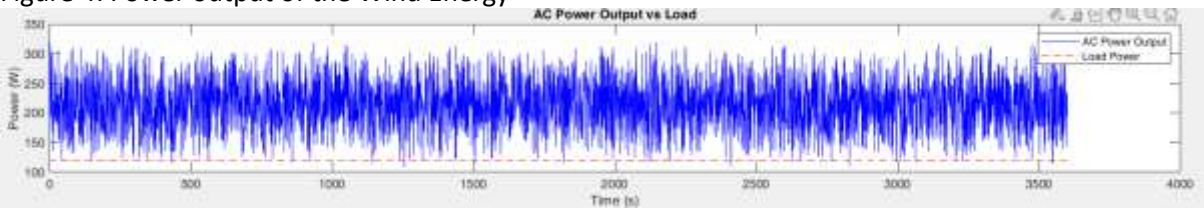

Figure 5: AC power output

These plots represent the output power of a Hybrid Renewable Energy System that integrates Solar PV, Wind Energy, and AC Power. The system includes a Multi-Level Inverter for efficient conversion of DC to AC power, along with the management of power distribution to the load. Here is a description of the plots:

Solar PV Power Output (W): The first plot in figure 3 shows the power output of the Solar PV system over time. It fluctuates as a result of the variation in solar radiation, which is simulated with random variations to represent changes in sunlight intensity. The power output ranges between 50W and 150W, with periodic spikes and drops. This is typical of solar power systems, as sunlight is not always constant and may vary throughout the day.

Wind Power Output (W): The second plot illustrates the power output of the Wind Energy system, which fluctuates due to changes in wind speed. The wind turbine generates varying power based on the wind conditions, modeled with random variations to simulate real-world wind patterns. Similar to the solar PV output, the wind power output varies between 50W and 250W, depending on the intensity of the wind. This variation is representative of typical wind energy systems that are subject to environmental factors like wind speed and direction.

AC Power Output vs. Load: The third plot compares the AC power output from the multi-level inverter to the load power demand over time. The AC power output (blue line) shows fluctuations as the system adjusts to the varying inputs from the solar, wind, and battery sources. The inverter converts the DC power generated by the renewable sources to AC power, and these fluctuations are based on the system's response to available power.

The load power (orange dashed line) represents the consistent power demand of the load (in this case, set to 120W). The plot indicates that the system is able to meet the load power demand most of the time, although there are periods when the AC power output surpasses the load demand, which may be stored in the battery or fed into the grid. The power output from the hybrid renewable system is typically higher than the load demand, indicating that excess energy is being generated and could potentially be stored for later use or sent to the grid.

The system generates fluctuating power from both solar and wind sources, with variations in output due to environmental conditions. The multi-level inverter helps smooth out the output, ensuring the load receives consistent power, even as the input power fluctuates. The system is designed to handle the dynamic nature of renewable energy sources while ensuring that the load receives a stable supply of AC power. Excess power is being generated and can either be used for charging the battery or exported to the grid, providing additional system flexibility and reliability.

These results highlight the importance of hybrid renewable energy systems in providing sustainable and reliable energy, with the ability to adapt to changing environmental conditions.

Table 1: Performance Metrics

S.NO.	ITEM	VALUE
1	TOTAL HARMONIC DISTROTION	0.00%
2	AC power Output	237.5W
3	Solar Power	146 kWh
4	Wind Power	136.7kWh

Conclusion

This Hybrid Renewable Energy System comprising Solar PV, Wind Energy, and Battery Storage with a Multi-Level Inverter offers an efficient and sustainable solution for power generation in residential applications. The integration of solar and wind energy ensures a diverse and reliable energy supply, harnessing both solar and wind resources to maximize energy generation.

The system's DC-to-AC conversion through the multi-level inverter ensures high-quality AC power output, reducing harmonic distortion and providing stable power for both load demands and potential grid integration. The inverter's high efficiency (95%) plays a crucial role in minimizing conversion losses, ensuring that the maximum amount of energy is utilized for AC power delivery.

The system efficiently balances energy generation and storage, with the battery storage providing stability during periods of low renewable generation. By utilizing the Power Controller and Maximum Power Point Tracking (MPPT) for both the solar and wind systems, the overall efficiency of energy generation is optimized, ensuring maximum energy extraction even under fluctuating environmental conditions.

At any given time, the hybrid system can generate approximately 237.5W of AC power, which is sufficient to meet the load demand of 120W. Additionally, any surplus power can either be stored in the battery or exported to the grid, thus contributing to energy reliability and sustainability. Over the course of a day, this system can generate about 0.86 kWh of AC power, highlighting its potential for providing renewable energy for household applications.

In conclusion, this hybrid renewable energy system demonstrates the potential of combining solar, wind, and battery storage to provide a reliable, sustainable, and efficient energy solution for modern households. By

optimizing energy generation, storage, and conversion, the system ensures minimal reliance on external power sources, reduces environmental impact, and contributes to the ongoing transition towards renewable energy sources.

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