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Review of Hybrid Source Single Phase Inverter

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Abstract-This article presents a comprehensive review of various inverter configuration, power electronic converter topologies and controlling and optimization techniques utilized in single phase inverter fed with multi-input (wind and Solar PV Array) to power the varying load. Furthermore, this paper discusses classical as well as recent advancements in maximum power tracking of solar output including Neural Network, fuzzy logic and ANN with integration of IOT connectivity and real time enabled monitoring and communication in Smart Inverter.

Keywords- Hybrid Renewable Energy Source (HRES), MPPT, Power converter, SPWM, Stand-alone PV system

I. Introduction

Renewable energy is playing a critical role in the global shift towards sustainable power solutions. With increasing concerns over fossil fuel depletion, climate change, and energy security, solar and wind energy are emerging as dominant sources due to their abundance and environmental benefits. n current scenario, India ranked fourth in both wind and solar power capacity, and in total renewable energy capacity. The country's renewable energy capacity has been growing quickly, with an annual growth rate of 15.4% from 2016 to 2023. By the end of FY23, India had 125.15 GW of renewable energy capacity. It is the fastest-growing market for renewable electricity, and by 2026, the country is projected to significantly increase its capacity—potentially doubling the current levels.

With more deployment of solar panels and wind turbines to derive the renewable energy from nature. These sources suffers some drawback that are primarily due to intermittent nature of these source which effect extraction of output power after installing costly infrastructure. Other drawbacks are losses occurring in power electronic devices in conversion of mechanical or Photovoltaic energy into useful electricity.

Discussed HRES systems combine the strengths of both renewable sources, overcoming their individual limitations and enhancing overall efficiency, reliability, and sustainability. Since solar PV systems generate maximum power during the day, while wind energy production is often stronger at night or during cloudy conditions, a hybrid system ensures a more consistent and continuous power supply.

This reduces the dependency on energy storage and minimizes power fluctuations, making it ideal for both off-grid and grid-connected applications. Additionally, hybrid systems improve the overall capacity factor, ensuring better utilization of available renewable resources. The major points discussed in this paper are summarized as follows:

- Inverter Configuration
- Single Phase Inverter Topologies
- Modulating and Controlling Techniques
- MPPT and various algorithms for PV system
- Smart Inverter

Inverter Configuration

The efficiency and performance of an inverter depend on its configuration, which defines its topology, control strategy, and operational characteristics. PV inverter usually has two stages for shaping the PV array output power before feeding it into the AC load. The first stage is in charge of increasing PV array voltage and monitoring the MPPT; the second stage inverters convert usable DC power to AC power. The major classification of the inverters is discussed in this section.

Stand-alone Photovoltaic System

A stand-alone PV (photovoltaic) system is an independent solar power system that operates without being connected to the electricity grid. It generates electricity using solar panels and stores excess energy in batteries for use when sunlight is unavailable.

In standalone applications, a multi-input fused buck and buck-boost converter is employed in paper [10] at the DC-end to integrate photovoltaic (PV) and wind energy sources for supplying power to a 1 kW load. This configuration replaces the need for individual

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converters for each source, optimizing power conversion. Additionally, a full-bridge inverter is incorporated to convert the DC voltage to an alternating current (AC) output, while an LC filter is used to mitigate harmonic distortions in the injected current. Despite the combination of both sources at the DC-end, the system retains the capability for Maximum Power Point Tracking (MPPT) through the implementation of an optimized algorithm.

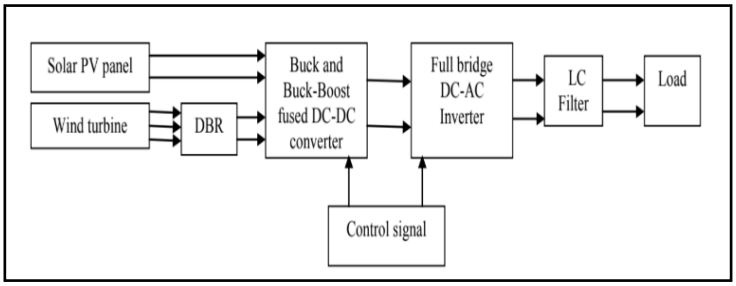

Figure 2.1 Block Diagram of multi-input inverter

Grid Tied PV Inverter

A grid-tied PV inverter is a type of solar inverter designed to convert the **DC** power generated by a photovoltaic (PV) solar panel system into **AC** power that can be fed directly into the **electric utility grid**.

This inverter ensures that the electricity produced by the solar system is synchronized with the grid's voltage and frequency. If the grid fails (such as during a power outage), the inverter will shut down to prevent any power from being fed back into the grid (a feature known as **anti-islanding protection**).

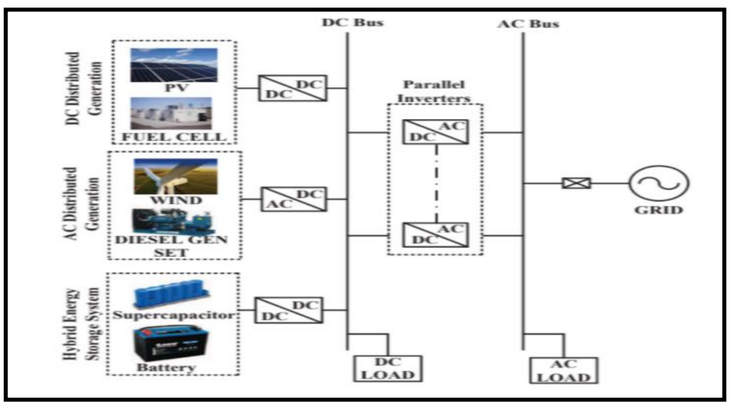

Figure 2.2 Grid-Tied HRES

This implemented grid tied SPWM inverter integrated with MPPT, in this paper Phase-Locked Loop (PLL) is used to generate an output signal whose phase and frequency are synchronized with the phase and frequency of an input signal. The phase and frequency of the input signal are synchronized by comparing the phase of the input signal with that of the output signal from a voltage-controlled oscillator (VCO) using a phase detector. The grid synchronization method significantly influenced the system's performance, ensuring stable and reliable operation under varying conditions, demonstrating its practical application potential.

II. Inverter Topology

Inverter topology refers to the configuration and structure of the power electronic circuits used to convert DC (direct current) power from sources like solar panels or batteries into AC (alternating current) power for grid integration or standalone use. There are two main categories of inverter topologies: single-stage and multi-stage. Single-stage topologies aim to directly convert DC to AC with minimal stages. On the other hand, multi-stage topologies involve an additional DC-DC conversion stage before the DC to AC conversion. The selection of an inverter topology depends on the specific application, such as grid-connected PV systems, hybrid energy systems, or off-grid installations.

H-Bridge Inverter

The single-phase inverter under study [11] is integrated with an H-bridge inverter, an LC filter, and an inductive load. This inverter is made up of four MOSFET switches, which are controlled to generate a switched signal that produces an alternating voltage at the output. The passive LC filter, consisting of an inductor (L) and a capacitor (C), functions as a low-pass filter, smoothing the output. Additionally, the inductive load at the output filter represents the energy consumer that utilizes the continuous power converted by the inverter.

In [15] single stage current source inverter proposed as shown in with doubled tuned resonant filter in series with the DC-link inductor.

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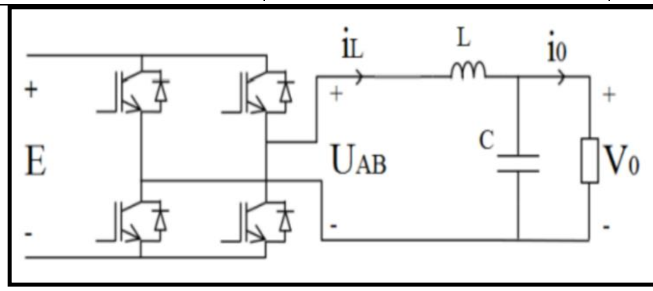

Figure 3.1 H- Bridge circuit with LC filter

This filter is used to eliminate the 2nd and 4th order harmonics on the DC side. Others preferred H-bridge topology in Arduino based development of inverter to generate pure sine waveform of output thereby reducing Total Harmonic Distortion and reducing switching losses.

III. Modulating and Controlling Techniques

PWM

The PWM circuit used in this paper is based on the Arduino Uno microcontroller (AT-mega). The output frequency is 50 Hz with a reduced ripple factor, and the carrier frequency is 1500 Hz. As a result, each complete cycle of the sinusoidal output contains 30 impulses [13].

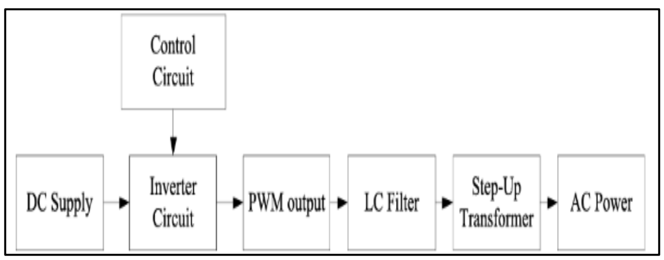

Figure 4.1 Block Diagram of PWM inverter

SPWM

Sinusoidal Pulse Width Modulation (SPWM) is a technique used to generate a sine wave output from DC input. Pulse Width Modulation (PWM) involves adjusting the width of pulses to regulate the inverter's output voltage. Sinusoidal Pulse Width Modulation (SPWM) is a modulation technique employed to convert a DC input into an AC output that resembles a sine wave. It is a form of Pulse Width Modulation (PWM). In SPWM, the pulse widths are determined by sampling the amplitude of a reference sine wave at the midpoint of each pulse, resulting in a pulse train that mimics a sinusoidal waveform.

In [13] EGS002 SPWM Driver Board is used, which is PWM inverter driver that requires a filter to produce pure sine wave voltage. The AC voltage of high quality with precise and steady characteristics is produced.

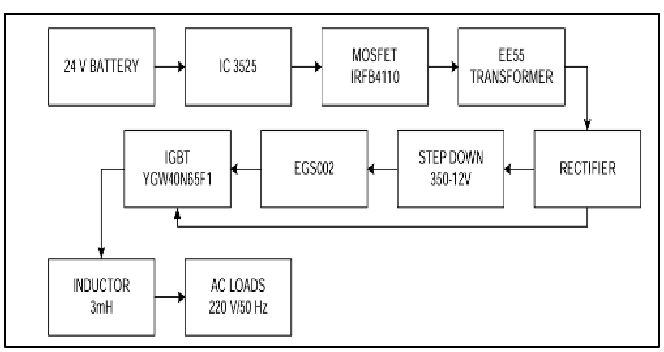

Figure 4.2.1 Block Diagram of Sine wave generation using EGS002.

A sine lookup table is used as a virtual sine reference wave, which is then compared with the triangular wave to generate the corresponding PWM signals. For single-phase sine wave generation, two PWM pulses are required. These pulses have reference sinusoids that are phase- shifted by 180° while maintaining the same frequency.

In [14] PIC18F4431 microcontroller is used which features a power PWM module capable of generating a PWM counter. The counter is configured in up-down counting mode, producing an isosceles triangular waveform. A sine lookup table is used as a

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virtual sine reference wave, which is then compared with the triangular wave to generate the corresponding PWM signals. For single-phase sine wave generation, two PWM pulses are required. These pulses have reference sinusoids that are phase-shifted by 180° while maintaining the same frequency.

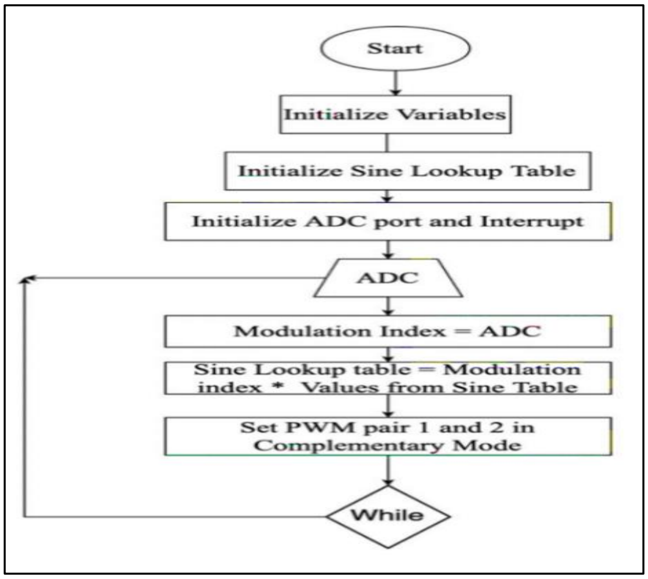

Fig 4.2.2 Program Flow of SPWM

In [3] unipolar SPWM inverter designed through Arduino Uno by the use of sin lookup table resulting in THD of 2.95% and gave result that THD with filter is lower than THD without filter.

IV. Maximum Power Point Tracking

MPPT techniques are used to optimize energy extraction from solar panels under varying environmental conditions. Various MPPT algorithms used in photovoltaic systems include P&O, Inc. Cond., FOCV, MPC, and ANN. In [6] presented Fuzzy Logic Control Algorithm according to it the input variables, solar irradiance and temperature, are fuzzified into terms like "low," "medium," and "high." The output variable, the duty cycle of the DC-DC converter, is adjusted to maintain the optimal operating point. This algorithm is reliable in highly variable environmental conditions but complex in implementation.

In [12] implemented two algorithms P&O and I&C. In the case of the Perturb and Observe algorithm, the system is perturbed by increasing or decreasing the duty cycle at each MPPT cycle, while observing the array's terminal voltage and current to detect the maximum point of the PV curve. Results show improved efficiency of solar panel output in presence of MPPT.

Comparative Table of Various MPPT Algorithms

Table 5.1: Comparison of MPPT Algorithm

Sr. No	MPPT Algorithm	Working Principle	Efficiency	Complexity	Response Time	Suitability / Remarks
1	Incremental Conductance (IC)	Compares incremental conductance (dI/dV) to instantaneous conductance (I/V)	High (~98-99%)	Moderate	Fast	Good for rapidly changing irradiance; grid-tied systems (Ref: Mishra & Tiwari, 2021)
2	Perturb and Observe (P&O)	Perturbs voltage and observes power change	Moderate (~95-97%)	Low	Moderate	Simple and widely used; oscillates around MPP (Ref: Beriber & Abdeleziz, 2019)
3	Constant Voltage (CV)	Maintains PV voltage at a fixed fraction of Voc	Low (~85-90%)	Very Low	Fast	Inefficient under varying environmental conditions; for fixed loads
4	Fuzzy Logic Control (FLC)	Uses fuzzy rules and membership functions to determine MPP	High (~98%)	High	Fast	Adaptive and robust; requires expert tuning (Ref: Beriber & Abdeleziz, 2019)

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5	Neural Network Based (ANN)	Uses trained neural networks to predict MPP	Very High (>99%)	Very High	Very Fast	Complex, but adaptive to non-linear characteristics (Ref: Vitthal Wankhede, 2022)

Smart Inverter

Through his work in paper [9] discussed the implementation of a smart inverter i.e., a solar charged inverter that uses Wi-Fi technology to engage in a two-way communication with the user The MSP430F5529 microcontroller with 12 ADC pins, allowing for the connection of up to 12 loads. It is interfaced with the ESP8266 Wi-Fi module, which can be programmed in both Access Point mode and Server mode.

Launchpad from Texas Instruments is a low-power In Access Point mode, it connects to a local Wi-Fi network to access the internet and interact with other internet-connected modules. Through this work, an IoT-based Smart Inverter was successfully implemented by retrofitting an existing inverter, adding new functionalities such as bidirectional communication with the user. In [4] proposed system IOT is enabled through USART module of microcontroller and Py-Serial language of python.

V. Conclusion

In conclusion, this review paper highlights the development in Inverter technologies through the integration of advanced technologies such as MPPT algorithms, microcontrollers, and IoT systems in enhancing the performance and functionality of photovoltaic systems. The use of algorithms like Perturb and Observe (P&O), Incremental Conductance (I&C), and Fuzzy Logic Control (FLC) has proven effective in optimizing energy output under varying environmental conditions. Additionally, the incorporation of low- power microcontrollers like the MSP430F5529 and Wi-Fi modules such as ESP8266 has enabled the development of smart inverters, offering features like bidirectional communication and remote monitoring. These innovations demonstrate the potential for improving efficiency, reliability, and user interaction of solar power systems, paving the way for smarter, more adaptable energy solutions, simultaneously improving system design to be effectively used in rural and desolate regions.

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