Al-Qadisiyah JournalFor Engineering Sciences 18 (2025) 221 – 232

Contents lists available at: http://qu.edu.iq

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: https://qjes.qu.edu.iq

Research Paper

Harnessing solar energy: Hardware implementation of solar power inverter

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ARTICLE INFO

Article history:
Received 19 August 2024
Received in revised form 10 December 2024
Accepted 03 April 2025

keyword:
Solar energy
Photovoltaic (PV) cell
Solar power inverter
Renewable energy harvesting
Push-Pull topology
H-Bridge topology

ABSTRACT

The rising demand for renewable energy sources, particularly solar power, has surged in recent years as a sustainable solution to global energy challenges. Solar power inverters show a crucial part in transforming solar-generated direct current (DC) into usable alternating current (AC), which is required for a number of applications across residential, commercial, and industrial sectors. This paper provides a concise overview ofkey aspects related to solar power inverters, highlighting their importance in the solar energy ecosystem. Specifically, this paper focuses on the design of Solar Inverter, which is needed to run AC loads and is primarily utilized for consumable purposes.Moreover, it delves into the principles and functioning of two widely-used inverter topologies: Push-Pull and H-Bridge, with a detailed focus on the Push-Pull inverter, which is employed in practical circuit. The Push-Pull topology is highlighted for its simplicity, cost-effectiveness, and efficiency in low-power applications.To validate the system, the circuit model is implemented on hardware, confirming its practicality. The developed inverter has a 100W power output, a 12V input voltage, and a 220V output with a 50Hz square wave output.

1. Introduction

The worldwide demand for electric power is steadily rising, while conventional energy resources are dwindling and their costs are increasing [1–3].As an outcome, exploring substitute energy sources has become important, with solar energy being particularly promising due to its plentiful supply and eco-friendly nature [4]. With continuous improvements in PV cell [5] efficiency, cost-effectiveness, and power conversion technologies, our aim is to create an inverter that can supply independent AC loads using solar panels. Solar panels produce DC electricity, which must be converted to AC at specific voltages and frequencies for various industrial uses or to be compatible with the power grid. This conversion is achieved using a DC-AC inverter, a crucial component of the system. The challenge, however, lies in the variability of solar panel output, which depends on factors such as sunlight intensity and ambient temperature. Despite these challenges, the aim is to develop an efficient inverter system that can effectively harness solar energy for independent AC loads, promoting resilient and sustainable energy systems in the future.The solar inverter implemented in this research is designed to support various applications across different sectors. The primary applications include providing power to small household appliances, lighting systems, and backup power solutions in residential settings. In industrial environments, the inverter can be used to power low-energy equipment or serve as part of a backup power system for critical operations. In off-grid or remote areas, where connection to the main power grid is not feasible, this inverter offers a reliable, stand-alone power solution, ensuring continuous operation of essential systems. The versatility of the inverter makes it applicable for both urban and rural energy needs, contributing to a sustainable energy infrastructure. The solar power inverter is essential for linking PV modules [6] to the electrical grid, ensuring efficient and reliable energy conversion. Amidst escalating energy demands and heightened environmental concerns, exploring alternatives to non-renewable and pollutant-laden fossil fuels is imperative. Solar energy emerges as a prominent alternative [7,8], originating directly from the sun and used somewhere, usually here on Earth, for energy stems from a thermonuclear process converting vast amounts of hydrogen to helium, generating heat and electromagnetic radiation. Although only a minute fraction of this radiation reaches Earth, it serves as an indirect source for nearly all contemporary energy forms. Even fossil fuels trace their origins to solar influence, having originated from once-living organisms dependent on the sun. Solar power has the potential to directly supply a substantial portion of the world's energy needs, with additional indirect contributions [9,10]. When it comes to energy conservation and demand-side management, the integration of PV solar cells has proven to be a significant solution [11,12]. A PV plant's efficiency is determined by three key factors: the inverter's efficiency (which normally ranges from 95 to 98%), the efficacy of the MPPT [13,14] algorithm (above 98%), and the efficiency of the PV panels (commercial panels typically range from 8 to 15%) because better components are needed, increasing the efficiency of PV panels and inverters frequently presents technological difficulties and raises costs. In contrast, improving maximum power point tracking through advanced control algorithms is a more accessible, cost-effective measure. Modern control algorithms can immediately boost PV power generation in already-existing plants, resulting in lower overall costs. Considering the relationship between voltage and irradiation, which is frequently overlooked in practice, improves both current and voltage, which raises power generation as irradiation levels grow. The tiny impact of temperature on current is frequently disregarded, even though PV panel manufacturers include temperature coefficients in their data sheets. The main goal of this research paper is to create a cost-effective PV system that can minimize space and provide electricity for stand-alone AC loads. The system's primary benefit is its capacity to produce high-quality power from renewable resources, which lessens dependency on fossil fuels and lowers related pollution emissions. Our efforts are focused on designing and creating an inverter that can handle this task efficiently. The research paper has the following format: Section II contains a review of the literature on Solar Power Inverters.

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https://doi.org/10.30772/qjes.2024.152932.1367
2411-7773

Nomenclature

Abbreviations

AC	Alternating Current
COM	Common
DC	Direct Current
FET	Field Effect Transistor
HVDC	High-Voltage Direct Current
IC	Integrated Circuit
IoT	Internet of Things
JFET	Junction Field Effect Transistor
LED	Light-Emitting Diode
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
MPPT	Maximum Power Point Tracking
NC	Normally Closed
NO	Normally Opened
PCB	Printed Circuit Board
PV	Photovoltaic
PWM	Pulse Width Modulation
RF	Radio-Frequency
SPDT	Single Pole Double Throw

Symbols

A	Ampere
Ah	Ampere-hours
Hz	Hertz
$k\Omega$	Kilo ohms
kW	Kilo watt
kWh	Kilo watt hour
mA	Milli Ampere
ns	Nanoseconds
pF	Picofarads
Q	Primary output
$\overline{Q}$	Complementary output, which is inverse of the Q output
μF	Microfarads
V	Volts
W	watt
W/ft^2	Watt per square foot
W/m^2	Watt per square meter

The design approaches are presented in Section III. Specifications for the hardware are listed in Section IV. Section V includes the circuit description of the solar battery charger and inverter. Section VI presents the hardware project in practice which includes hardware showcase and experimental results. Section VII, which concludes, discusses the findings and suggests directions for further research.

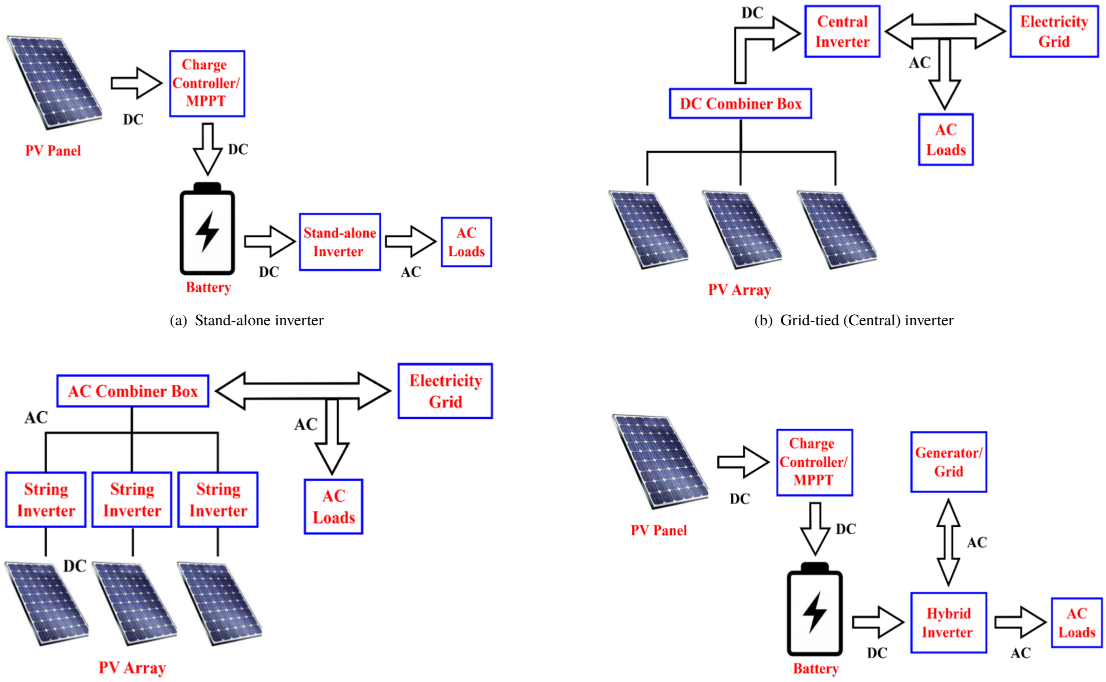
2. Literature survey

2.1 Description

Compared to fossil fuels, solar power has two major advantages [15–17]. Firstly, it is renewable, ensuring an endless supply. Secondly, its environmental impact is considerably more favorable. Acid rain and global warming are among the problems caused by the burning of fossil fuels, which releases a lot of dangerous pollutants into the atmosphere. Solar energy is completely non-polluting, in sharp contrast. Unlike the extensive land destruction required for feeding fossil fuel energy plants, solar energy plants only impact the land they occupy. The potential to integrate solar energy systems into every business and residence eliminates the need to destroy land for energy purposes. This decentralization capability sets solar energy apart from fossil fuel burning. The world scene has recently paid close attention to energy policies and global warming [**?**, 18–21]. Developed countries are making a concerted effort to reduce their emissions of greenhouse gases. For instance, the European Union aims to decrease greenhouse gas emissions by at least 55% below 1990 levels by 2030, with the goal of achieving climate neutrality by 2050. By 2040, the EU targets a 90% reduction in emissions compared to 1990 levels. Renewable energy is a critical component of this plan, with the EU striving to generate over 90% of its electricity from renewable sources like solar and wind power by the second half of the 2030s. PV power generation is environmentally friendly, with emissions limited to the production phase. Once installed, PV panels produce electricity without emitting greenhouse gases, surpassing the energy used in their manufacturing. Moreover, they can be deployed in unused spaces like roofs and deserts. PV systems have the capability to generate electricity for remote locations lacking access to an electricity network. These off-grid installations, economically viable for providing electricity in isolated areas, play a crucial role in energy provision. Nonetheless, a sizable amount of PV power generation takes place in installations that are connected to the grid, where the energy network receives generated power. In industrialized countries, this industry is flourishing. In terms of PV power generation, Germany leads the world, followed by Spain, Japan, the USA, and Italy. Silicon, the second most common element on Earth, is necessary for solar panels and contributes to a reduction in environmental disturbance throughout the panel-making process. Solar energy has little effect on the environment unless it is produced centrally and in large quantities. Compared to other energy sources, solar power still has a relatively low total environmental impact, despite the possibility of producing electricity on a massive scale. Of all the renewable resources, solar electricity is the only one that has the potential to be used as an energy source that can provide more energy than consumed [22,23]. If we were to harness just 0.1% of the 4.5×10^{17} kWh per annum Earth uses to evaporate water from the oceans, amounting to 4.5×10^{14} kWh annually, and convert it into continuous yield, we would have 2.90×10^{10} kW. This translates to supplying 2.4 kW to a population of 12.1 billion people. Essentially, this energy availability per person exceeds the current global average energy use. In production could pose unpredictable environmental consequences. If all essence, this energy availability per person is higher than the average energy use that is currently observed worldwide. However, such a scale of solar energy solar collectors was concentrated in a few extents, the local and possibly global environment might be significantly affected, leading to phenomena ranging from altered rain conditions to the potential for another Ice Age. Solar energy stands out among other energy sources due to its numerical capacity to address global energy needs. Because it's among the least toxic energy sources, it's environmentally friendly. Clearly, solar energy emerges as a promising resource for the future, offering both numerical capability and environmental benefits [24, 25].

2.2 Research contributions

The literature on inverter technologies for PV systems highlights various advancements and methodologies aimed at improving power quality and system efficiency. A key focus of recent research is the exploration of multi-level inverter topologies, which have gained attention for their ability to minimize total harmonic distortion and electromagnetic interference, thereby addressing leakage current issues [26]. For instance, the H5 inverter topology can generate a three-level output and is noted for its efficiency and reduced conduction losses in active states. However, this topology still requires significant filtering to meet grid standards. In contrast, a novel five-level inverter topology incorporates a capacitor divider and a diode to achieve five output levels, further enhancing output quality and efficiency. Advancements in inverter technology, particularly the development of multi-level inverters and sophisticated control systems, are crucial for enhancing the performance of grid-connected PV systems. The proposed five-level inverter topology and voltage control system represent a significant step forward in addressing power quality issues and improving overall system efficiency, making continued research and development in this field essential for the widespread adoption of solar PV systems and their integration into the energy grid. Multilevel invertershave been pivotal in enhancing the performance and reliability of grid-connected solar PV systems. As solar energy becomes a more prominent renewable resource, the need for efficient power conversion has led to various inverter topologies. Primary challenges in PV systems include switching frequency, THD, leakage current, and common-mode voltage, all of which affect efficiency, reliability, and system cost. Multilevel inverters, particularly the Cascaded H-Bridge topology, have shown significant promise in addressing these challenges [27]. Several types of Multilevel inverters have been explored for their suitability in PV applications, including Diode Clamped, Flying Capacitor, and Cascaded H-Bridge inverters. Each topology has its advantages and limitations. Diode Clamped inverters are commonly used in industrial applications due to their capacity to handle medium to high voltage levels, though they are typically limited to three levels due to capacitor voltage balancing issues. In contrast, the Cascaded H-Bridge topology, which requires separate DC sources, is highly suitable for PV systems, allowing each PV array to act as an independent source. The Cascaded H-Bridge multilevel inverter is particularly favoured for its modularity, scalability, and ability to operate with fewer switches while maintaining high efficiency. This topology allows for independent control of each PV array and reduces switching complexity, resulting in lower THD and improved power quality. Meanwhile, the Flying Capacitor topology offers the advantage of not requiring clamping diodes, although it presents challenges related to voltage regulation. Research has also focused on optimizing Multilevel inverters designs to reduce the number of switches while maintaining



(a) Stand-alone inverter (b) Grid-tied (Central) inverter

(c) Grid-tied (String) inverter (d) Inverters with battery baCKUP

Figure 1. Classification of solar inverters.

performance. For instance, a proposed 9-level Cascaded H-Bridge inverter with 10 switches has been shown to significantly reduce THD to 1.86%, demonstrating the potential for more efficient and reliable grid-tied PV systems [27]. Innovations in Multilevel inverters design is crucial for meeting the growing demand for clean, reliable solar power. The paper [28] explores the integration of a PV system with the grid using a three-level T-type inverter and a three-level boost converter. This research aims to enhance the power capacity of distributed generation systems while addressing the challenge of neutral-point voltage fluctuations in multilevel inverters. The study highlights the advantages of multilevel inverters, including reduced harmonic distortion and lower electromagnetic interference compared to traditional two-level inverters. To tackle the issue of neutral-point voltage imbalance, the paper proposes incorporating the control mechanism into the three-level boost converter itself. This effectively eliminates neutral-point voltage fluctuations without modifying conventional space vector pulse-width modulation algorithms or adding extra components, thereby simplifying the overall system design and implementation. Additionally, the system employs a dual-stage conversion mechanism where the three-level boost converter extracts and boosts the PV voltage while ensuring efficient and balanced DC-link voltage between two split capacitors, promoting stable and reliable operation. In conclusion, the continuous evolution of inverter technologies and their integration into PV systems is essential for realizing the full potential of solar energy. As research progresses, these innovations will play a critical role in addressing energy demands and enhancing the sustainability of global energy solutions.

2.3 Classification of solar inverters

The following diagram, Fig. 1 shows the three primary categories that solar inverters belong to:

2.3.1 Independent (Stand-alone) inverters

These inverters as shown in Fig. 1a, function in isolated systems by utilizing DC energy from batteries that are charged by PV arrays. Some feature built-in battery chargers for AC replenishment when available. They typically operate independently of the utility grid, hence aren't mandated to have anti-islanding protection measures. This stand-alone setup offers cost-effective solutions for remote areas where extending grid line is impractical, boasting superior performance ratios, yield factors, and capacity factors [29, 30].

2.3.2 Grid tie inverters

In the case of a utility supply outage, these inverters will immediately cut off to ensure safety. They synchronize with the sine wave provided by the utility [29, 30]. Nevertheless, they don't provide backup power in the event of utility interruptions. The diagram of this system is illustrated in Fig. 1b and Fig. 1c. During daylight hours when solar energy is abundant, the power produced by this system efficiently meets the energy demands of schools, offices, residential and commercial buildings, and surplus electricity can be sold back to the grid through net metering arrangements. Conversely, at night when solar power is unavailable, electricity can be drawn from the local network.To enable the transfer of excess solar power back into the grid, a grid-tie inverter system normally includes a power meter and an inverter that can measure power flow in both directions. The concept of a solar photovoltaic system linked to the utility power grid is similar to those of grid-tied, grid-interactive, and utility-interactive systems.

2.3.3 Inverters with battery backup

These inverters are also known as Hybrid inverters. These inverters extract energy from batteries, oversee battery charging via an integrated charger, and facilitate the transfer of surplus power to the utility grid [30]. Notably, they can provide AC energy to specific loads during utility outages, necessitating the incorporation of anti-islanding protection measures for safety and regulatory compliance. In certain hybrid inverters as illustrated in Fig. 1d, when the inverter senses the battery's power at bulk voltage, it can send it to the grid.

2.4 Requires input data

A solar PV system is made up of a number of components that need to be carefully selected depending on the kind of system, the location of the site, and the intended uses. The essential elements consist of:

- Solar Panel Size and Rating: These components convert sunlight into DC electricity.
- Solar Charge Controller: By controlling voltage and current from photovoltaic panels to the battery, a solar charge controller guards against overcharging and increases battery life.
- Inverter Size: The inverter changes the DC output of photovoltaic cells into pure AC current, which can be utilized to run air conditioning units or recycled back into the grid.
- Battery Bank Size: This reserves power to power appliances during periods of high demand.
- Load: It refers to electrical utilizations linked to the solar PV system, such as lights, computers, etc.
- Solar Panel Connection Type: It is the configuration in which solar panels are interconnected.

- Daily Sunlight Energy Output: It is the amount of energy generated by solar panels based on daily sunlight.
- Battery Bank Connection Type: It refers to the arrangement in which batteries are connected within the battery bank.

3. Design approaches

There are various circuit designs available for transforming low-voltage DC sources into higher power AC, with two prevalent topologies being Push-Pull and H-Bridge. The schematic representation of the general inverter operation is illustrated in Fig. 2.

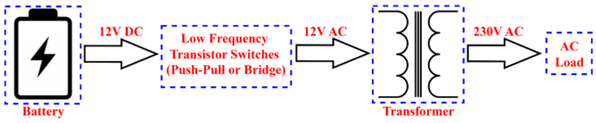


Figure 2. General operation of an Inverter.

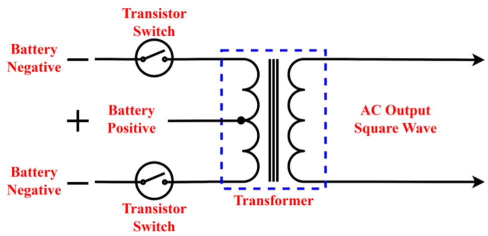


Figure 3. Push-pull topology for square wave output.

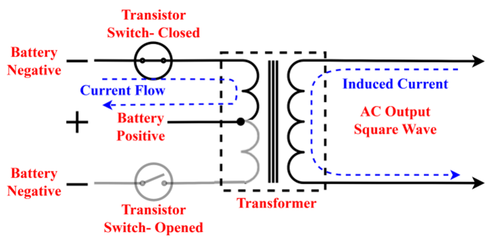


Figure 4. Push-pull topology- top switch closing state.

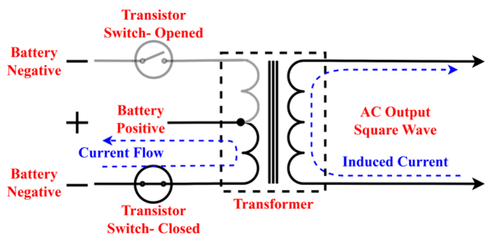


Figure 5. Push-pull topology- bottom switch closing state.

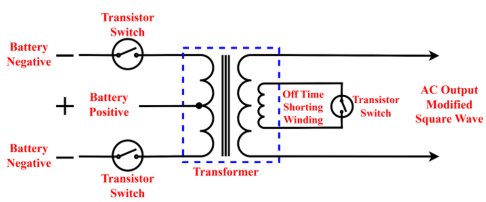


Figure 6. Push-pull topology for modified square wave output.

3.1 Push-pull topology

In Fig. 3, the fundamental idea of the Push-Pull topology [31] is displayed. Two transistor switches are used in this configuration. Current can flow from the battery's negative terminal to its positive terminal when the upper switch is closed, opening the transformer's primary winding. Because of this, the voltage experienced by the secondary side of the transformer is equal to the total of the battery voltage and the transformer's turn ratio. Figure 4 illustrates how this phenomenon has developed. At regular intervals of roughly 8 milliseconds, or half of a 50 Hz AC cycle, the switches alternate between being open and closed. The top switch opens in Fig. 5, which allows the bottom switch to close and allows electricity to flow in the opposite direction. A square waveform is produced by the constant cycling of opening and shutting switches, which in turn generates higher voltage AC power. When compared to square wave inverters, Modified Square Wave inverters significantly improve efficiency [32]. A thinned-out, separated, and taller square is the best way to describe Modified Square Wave in contrast to the square wave. The price of this inverter is more comparable with that of a square wave circuit than a sine wave unit, according to several sources [33, 34]. Figure 6 shows the Modified Square Wave inverter's circuit using the push-pull topology. Here we build a push-pull inverter that can handle three different power ratings and two different input voltages. By adding winding to the transformer, often known as an off-time short winding, the issues associated with square wave inverters and sudden reversal of current in transformers can be mitigated. An additional step is added to the switching cycle to clean the transformer, which helps with problems caused by sudden changes in the current direction. This is achieved via the off-time shorting winding described in Figure 6. Before the second switch closes, and simultaneously as one switch opens, the switch across the shorting winding is engaged. The current is so extracted from the transformer in this way. The off-time shorting feature enhances the zero crossing of the waveform, leading to improved compatibility with electronic devices. Additionally, this approach enhances efficiency and reduces the total harmonic distortion of the waveform. The ability to control voltage by adjusting pulse width and off-time period is the main benefit of a Modified Square Wave. PWM is the term used to describe the mechanism of regulating pulse width fluctuation.

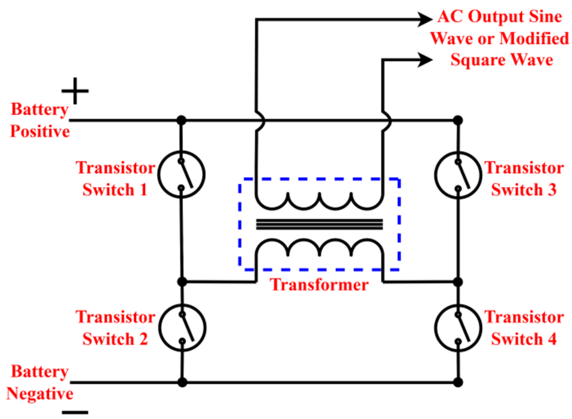


Figure 7. H-Bridge topology.

3.2 H-bridge topology

H-Bridge setup functionality and Push-Pull topology functionality are quite similar [31]. It is the traditional graphical representation of this circuit that gives rise to the term"H-Bridge".As seen in Fig. 7, an H-Bridge is made up of four sets of transistor switches that compose its four sections.The bridge's center is connected to the transformer's primary. To create the distinct wave shape segments, transistors are carefully turned on and off in a specific order. In this research, the push-pull topology was selected for the hardware implementation due to several key advantages. Firstly, its relatively simple design and the use of only two transistor switches reduce component costs and complexity. This topology is highly efficient in low-power applications like solar inverters, where the main goal is to maximize the conversion of DC power from solar panels into usable AC power. The push-pull converter also allows for the easy step-up or step-down of voltage using a transformer, making it versatile in adapting to the varying output of solar panels. Moreover, the galvanic isolation provided by the transformer enhances safety by separating the input and output sides, protecting sensitive electronics. By incorporating a modified square wave approach, the push-pull topology used in this design ensures a more efficient waveform generation, reducing harmonic distortion and making it compatible with a wider range of electronic devices. Therefore, for this project, the push-pull topology offers a balanced solution of efficiency, simplicity, and cost-effectiveness, making it an ideal choice for harnessing solar energy.

4. Hardware specifications

4.1 Solar inverter parts

The solar inverter comprises the following components:

4.1.1 Solar battery recharger

A battery charger, Fig. 8, is an essential device designed to restore energy in secondary cells or rechargeable batteries by directing an electric current through them. The charging current varies depending on the battery's technology and capacity; for instance, a 12V car battery requires a different current than a mobile phone battery. It operates as a specialized battery charger, specifically engineered for a sealed rechargeable battery of 6V 4.5Ah. Utilizing a 12V 500mA solar panel, this recharger captures sunlight and converts it into electrical energy. It then transforms the raw 12V output from the solar panel into a regulated voltage suitable for the sealed rechargeable battery. It boasts several key characteristics that enhance its functionality and efficiency [35,36]. These include custom controllable voltage regulation, which ensures the battery receives the appropriate charging voltage, and an automatic cut-off mechanism that halts charging once the battery is fully charged to avoid overcharging. Additionally, the device incorporates a filtered input from the solar panel to maintain stable voltage and current, as well as a backflow prevention feature that stops current from flowing back into the solar panel from the battery. Designed to be simple, compact, and efficient, the solar battery recharger provides a reliable and sustainable solution for maintaining the charge of sealed rechargeable batteries using solar energy.

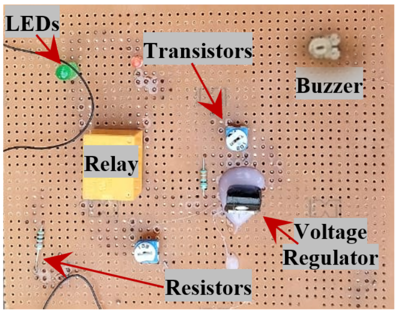


Figure 8. Solar battery recharger.

Figure 9. Solar panels, which are photovoltaic systems designed to produce and supply electricity.

4.1.2 Solar panel

Also identified as a solar module or PV panel, a solar panel is composed of linked assemblies of solar cells, or PV cells, Fig. 9. Solar panels [37,38] are essential components of larger photovoltaic systems designed to produce and supply electricity for both commercial and residential applications. Given that individual solar panels have limited power output, many installations use multiple panels to increase overall power production. A typical PV system contains an array of solar panels, an inverter, and often a battery, along with the necessary interconnecting wiring. The solar panels convert light energy, or photons, from the sun into electricity through the PV effect. The load-bearing element of a module can be either the top or back layer. The most commonly used modules feature wafer-based crystalline silicon cells or thin-film cells made from materials like cadmium telluride or silicon. The conducting wires that carry the electrical current from the panels are typically made from silver, copper, or other non-magnetic conductive transition metals. Reliable electrical connections are crucial both among the cells and throughout the entire system. To ensure durability, the cells needed to be shielded from mechanical harm and moisture. While most solar panels are inflexible, there are also semi-flexible options, usually employing thin-film cells. Electrical connections in solar panels can be configured in series to achieve the desired voltage output or in parallel to obtain the required current capacity. To prevent converse currents, particularly in cases of partial or total shading or at night, diodes are often incorporated. Recent innovations in solar panel technologyinclude concentrators that focus light onto an array of smaller cells, allowing the cost-effective usage of expensive materials like gallium arsenide [39–41]. PV panels can convert light from a range of frequencies, but they typically do not cover the entire solar spectrum. As a result, a significant portion of the incident sunlight energy is wasted. Efforts to improve efficiency include splitting light into different wavelength ranges and directing these onto cells optimized for those specific ranges. Currently, the highest achieved conversion rate of sunlight to electricity in commercial products is around 21%, slightly lower than the efficiencies of individual cells. A solar panel's energy density is defined by its peak power production per unit surface area, typically expressed in watts per square foot (W/ft^2). The most efficient mass-produced solar panels have energy density values exceeding $13W/ft^2$ ($140W/m^2$).

4.1.3 Inverter

In numerous applications, direct current (DC) is not suitable for direct use, necessitating its conversion to alternating current (AC). This essential transformation is achieved through an inverter, Fig. 10, a device designed to take DC input and convert it into AC output, delivering a voltage range appropriate for powering household appliances. In this experiment, sealed rechargeable 6V battery supplies DC, which is then fed into the inverter. The inverter converts this DC to AC with an output ranging from 140V to 220V, enabling the recharging of standard mobile chargers. In the domain of electrical devices, an inverter serves a key function in converting direct current (DC) to alternating current (AC) [42]. This transformed AC can be tailored to any required voltage and frequency using suitable transformers, switching mechanisms, and control circuits. Solid-state inverters, distinguished by their lack of moving parts, are utilized in a numerous application. These range from small switching power supplies in computers to large-scale HVDC systems used for bulk power transmission by electric utilities. Inverters are usually employed to provide AC power derived from DC sources such as solar panels or batteries, effectively performing the inverse operation of rectifiers.

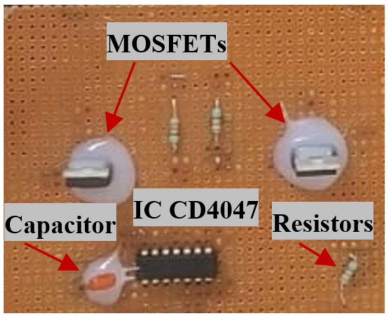


Figure 10. Inverter that used to convert the DC to AC current with an output ranging from 140V to 220V.

4.2 Component description

4.2.1 Transformer

A transformer, Fig. 11, is an electrical device composed of two wire coils connected by an iron core. It plays a crucial role in adjusting current and voltage levels as needed, either stepping up (increasing) or stepping down (decreasing) AC voltages. Faraday's law of electromagnetic induction, which involves mutual inductance between two circuits connected by a shared magnetic flux, is the foundation for a transformer's functioning. Essentially, with no direct electrical connection, no frequency change, and just a difference in voltage, a transformer uses mutual induction between its two windings to transfer electrical energy from one circuit to another. A step-up transformer produces a higher voltage because the secondary winding has more turns than the primary winding. Conversely, because the primary winding of a step-down transformer has more turns than the secondary winding, the voltage is lower. This ability to modify voltage levels is one of the primary reasons AC currents is used in homes rather than DC, as DC voltages cannot be adjusted using transformers. Thus, transformers are vital for the efficient transmission and distribution of electrical power across various applications.

Figure 11**.** Transformer that used to modify voltage levels.

4.2.2 Diode

The 1N4007 and 1N4148 diodes, Fig. 12, are both highly regarded for their distinct applications and performance characteristics. The 1N4007 diode is a widely used general-purpose silicon rectifier with a current capacity of 1.0A. It is particularly common in AC adapters for household appliances due to its versatile blocking voltage, which ranges from 50 to 1000 volts. This diode is designed in an axial-lead DO-41 plastic package, making it durable and easy to install. The 1N4148 diode is renowned for its high-speed switching capabilities and reliability. It is extensively used in applications requiring fast signal processing and switching. With a maximum current rating of 300mA and a reverse recovery time of approximately 4ns, the 1N4148 is ideal for high-speed circuits. It comes in a DO-35 glass package, providing excellent thermal and mechanical stability.

Figure 12**.** Particularly common of 1N4007 and 1N4148 diodes.

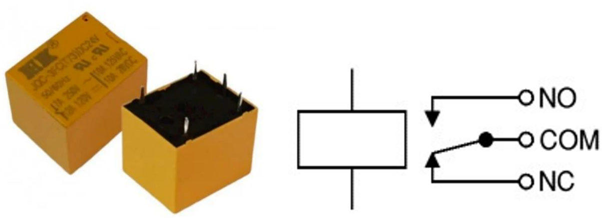


Figure 13**.** Relay device that is used as a controller by a micro-controller or sensor output.

4.2.3 Relay

The 12V 7A PCB Mount Sugar Cube Relay (SPDT) - JIH JIK, Fig. 13, is designed for the purpose of switching both AC and DC appliances, such as air conditioners, electric heaters, geysers, etc. This relay is suitable for applications requiring control by a microcontroller or sensor output [43, 44]. Operating on a 12V DC, it possesses a maximum load current capacity of 7A and functions as a SPDT relay. With 2 pins for the 12V coil and 3 pins for NO, NC, and COM, it features a total of 5 pins, ensuring reliable performance.

4.2.4 Capacitor

A capacitor, Fig. 14, is a fundamental electronic component designed to store and release electrical energy within a circuit. It consists of two conducting plates divided by a dielectric, which is an insulating substance. Positive and negative charges build up on the opposing plates when a voltage is applied across these plates, creating an electric field.This separation of charge enables the capacitor to store energy effectively. Capacitors are widely utilized in electronic circuits for a variety of functions, including smoothing out voltage fluctuations, filtering signals, and offering temporary energy storage. They come in various types, including electrolytic, ceramic, and tantalum capacitors, each with specific applications in electronics. A ceramic capacitor, part of passive electronic components, stores and releases electrical energy in circuits. Renowned for their compact size, affordability, and reliability, ceramic capacitors find extensive use in electronics. With capacitance values ranging from picofarads (pF) to microfarads (μF), these capacitors are marked with a numerical code indicating their actual capacitance value.

Figure 14**.** Capacitor component that is used to store and release electrical energy faster.

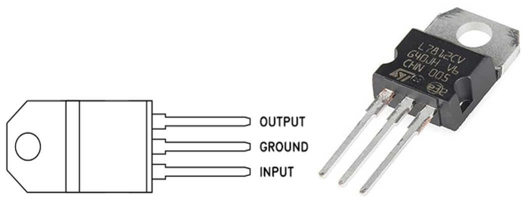


Figure 15**.** Voltage Regulator.

4.2.5 Voltage regulator IC LM7812

The 7812, Fig. 15, is a well-known integrated circuit (IC) extensively used in 12V voltage regulator circuits. This IC is essentially a self-contained voltage regulator, requiring minimal additional components. To ensure a stable voltage output, two capacitors are required to connect: one at the input and one at the output. However, these capacitors are not strictly necessary for the IC to function. For the 7812 to provide a current of up to 1A at 12V, it should be attached to a good heat sink. Its transistor-like design facilitates easy mounting on heat sinks. Additionally, 7812 IC comes with built-in overheat and short-circuit protection, making it a reliable choice for constructing power supplies.

4.2.6 Transistor

An essential semiconductor device that amplifies or switches electrical power and electronic signals is a transistor Fig. 16. It features at least three terminals for connecting to an external circuit and is made of a semiconductor material. The current passing through one set of these terminals is influenced by the voltage or current applied to another set of terminals. This characteristic allows the transistor to amplify a signal, as the power it controls (output) can be significantly greater than the power used to control it (input). While transistors are sometimes individually packaged, they are more commonly integrated into complex circuits. A transistor's main benefit is its capacity to handle a considerably greater signal at one pair of terminals with a modest signal applied to the other pair. This capability, known as gain, enables the transistor to amplify a weak input signal into a much stronger output signal, be it in terms of voltage or current. As an amplifier, it can significantly boost the strength of an input signal. Additionally, a transistor can function as an electrically controlled switch, turning current flow on or off within a circuit. The amount of current allowed to pass is determined by other elements within the circuit. This dual role as an amplifier and a switch underpins the versatility and widespread use of transistors in modern electronics.

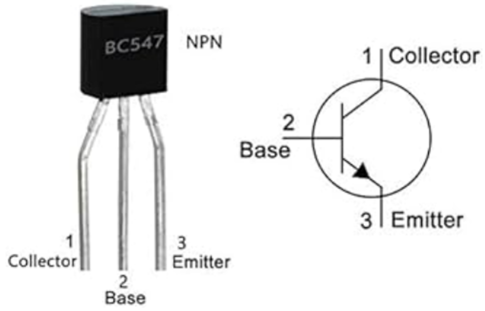


Figure 16**.** Transistor semiconductor device that amplifies or switches electrical power and electronic signals.

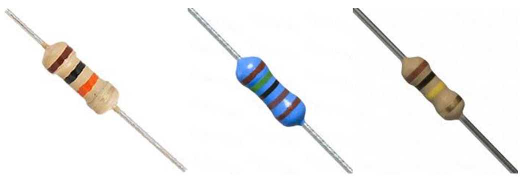


Figure 17**.** Resistors that limit the current that can pass through an electrical circuit.

Figure 18**.** Buzzer and LEDs that are commonly used in alarm systems.

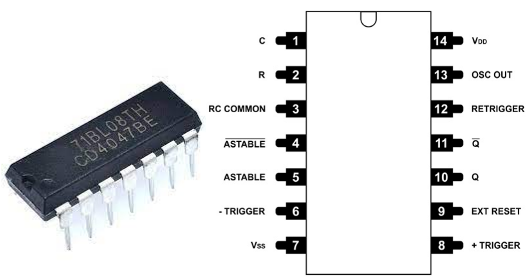


Figure 19**.** Typical integrated circuit CD4047.

4.2.7 Resistor

Resistor, Fig. 17 is an essential component that regulates or limits the current that can pass via an electrical circuit. Furthermore, resistors can provide an active device—such as a transistor—with a specified voltage. In DC circuits, Ohm's Law dictates that, under constant conditions, the current flowing through a resistor is directly proportional to the applied voltage and inversely proportional to its resistance. In AC circuits, this approach is usually valid as long as the resistor has no capacitance or inductance. Various fabrication methods exist for resistors, with the carbon-composition resistor being prevalent in electronic devices. Created by combining fine granulated carbon with clay, its resistance hinges on the carbon-to-clay ratio. Another type is the wire-wound resistor, constructed by winding Nichrome wire around an insulating form, capable of handling higher currents but introducing inductance, potentially affecting AC circuit performance.

4.2.8 Buzzer and LED

Buzzers and LEDs, Fig. 18 are essential components in electronic devices, each serving different signaling purposes. A buzzer [44], or beeper, is an audio signaling device that produces sound through mechanical, electromechanical, or piezoelectric mechanisms. These devices are commonly used in alarm systems, timers, and to provide audio feedback for user actions, such as mouse clicks or keystrokes. An LED (Light Emitting Diode) is a semiconductor light source that emits light when current flows through it. LEDs are widely utilized for indicator lights, displays, and increasingly for general illumination. Unlike traditional incandescent bulbs, LEDs are highly efficient, have a long lifespan, and are available in a variety of colors and brightness levels.

4.2.9 IC CD4047

It operates in monostable or astable modes, Fig. 19. In monostable mode, an external capacitor and resistor set the output pulse width. In astable mode, the astable input determines operation. The timing components affect the output frequency at Q and $\overline{Q}$ outputs. Although a 50% duty cycle isn't guaranteed, the oscillator output frequency is twice that of Q. Transitions from LOW to HIGH or HIGH to LOW initiate the monostable state. Retriggering happens at both the + trigger and retrigger inputs, with LOW-to-HIGH transitions. Applying a high level to the Reset input is the process of resetting.

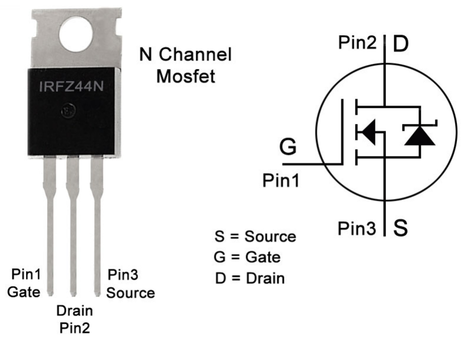


Figure 20**.** MOSFET stands for metal-oxide-semiconductor field-effect transistor.

4.2.10 MOSFET

A MOSFET, Fig. 20, is a specialized type of field-effect transistor (FET) that controls the width of a channel through which charge carriers—electrons or holes—flow. By widening the channel, the MOSFET enhances its conductivity. Charge carriers exit via the drain and enter the channel at the source. The voltage applied to a gate electrode, which is positioned between the sources and drain and separated from the channel by an incredibly thin layer of metal oxide, controls the channel width. Compared to the conventional junction FET (JFET), the MOSFET offers several advantages. One key benefit is the electrical insulation of the gate from the channel, which ensures negligible current flow between them and results in virtually infinite input impedance. This characteristic makes MOSFETs particularly valuable in power amplifier applications. Additionally, they are well-suited for high-speed switching applications. Many ICs incorporate tiny MOSFETs, making them essential components in computers and other digital devices. However, MOSFETs are highly susceptible to permanent damage from electrostatic charges due to the extremely thin oxide layer. Even a minor electrostatic buildup can irreparably harm a MOSFET. When it comes to weak-signal radio-frequency (RF) applications, MOSFETs frequently perform worse than other FET types. Despite these vulnerabilities, the unique properties of MOSFETs, such as their high input impedance and fast switching capabilities make them indispensable in a wide range of electronic applications.

5. Circuit description

Table 1 presents the specified ratings for the components used in the solar battery charger and inverter system.

5.1 Circuit diagram of solar battery charger

Figure 21 provides a detailed schematic of the solar battery charger circuit, showcasing the various components and their interconnections essential for the efficient charging of the battery using solar power. When the solar cell is exposed to light, photons (light particles) strike the silicon, liberating electrons and corresponding holes. When this happens while an electric field is present, the electrons shift to the negative side and the holes to the positive side, upsetting the balance of electrical charge. This electron flow generates a current; the electric field in the cell produces a voltage, and together they create power. The solar energy collected by the PV cells is stored in the battery through a charging circuit. Two BC547 transistors and the voltage regulator IC7812 form the core of the charging circuit. A steady 12V output is produced by feeding the DC voltage into the IC7812 voltage regulator. The voltage regulator's output is linked to a 12V rechargeable battery, allowing it to be charged while main power is available. The circuit also features a charging status indicator. An LED illuminates when the battery voltage exceeds 10.5V. If the battery voltage drops below a certain threshold, the LED turns off and a buzzer sounds, signaling that the battery is discharged and requires recharging.

Table 1. Components required.

S. No.	Component	Ratings
1	**Solar Battery Charger**	
	i) Step Down Transformer	230V/12V, 1A
	ii) Diodes	1N4007, 1N4148
	iii) Capacitors	$470\mu F$, 50V
	iv) Voltage Regulator IC 7812	IC 7812
	v) Transistor	BC547
	vi) Resistors (Each 0.25 W)	10 $k\Omega$, 1.5 $k\Omega$, 100 $k\Omega$
	vii) Buzzer	12V
2	**Inverter**	
	i) IC CD4047	CD4047
	ii) Resistors	1 kΩ, 18 kΩ, 100Ω
	iii) Capacitors	0.22µF
	iv) MOSFET	IRFZ44
	v) Step Down Transformer	230V/12V-0-12V, 5A
3	**Battery**	12V, 4.5Ah
4	**Solar Plate**	6W

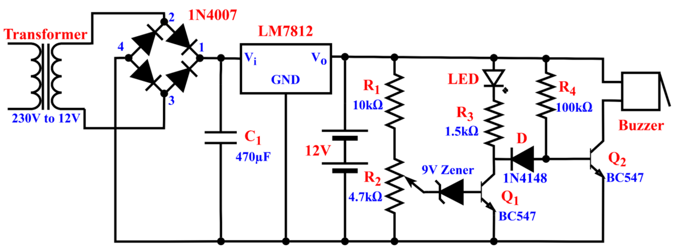


Figure 21. Circuit Diagram of Solar Battery Charger.

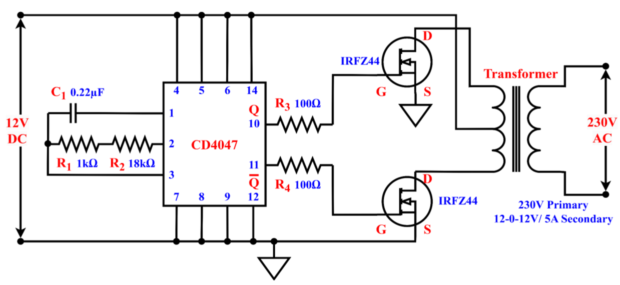


Figure 22. Circuit Diagram of Inverter.

5.2 Circuit diagram of inverter

Figure 22 illustrates a DC to an AC inverter circuit that operates using a stable multivibrator configuration. At the core of this circuit is CD4047 IC, which serves as the central component of the multivibrator. This IC is responsible for generating 50 Hz waveform. Despite its classification, the waveform is stable and consistent. The CD4047 IC features a complementary output stage, with outputs on pins 10 and 11 that are inversely related. This setup ensures a 50% duty cycle, which is essential for producing the necessary pulses for the inverter to function effectively. Because of its multiple harmonic signals and non-sinusoidal output signal, this design is known as a basic DC to AC inverter. To suppress these signals, a filter, such as a capacitor, is required. Due to its simplicity, this circuit is best suited for lighting applications. For constructing a sinusoidal DC to AC inverter, the multivibrator circuit must handle high power, necessitating the use of MOSFET IRFZ44. The IRFZ44 MOSFETs provide the high current needed to drive the step-up transformer, ensuring sufficient power at high voltage levels. The power MOSFETs in this circuit are configured in a push-pull arrangement and function as a power amplifier. These MOSFETs switch according to pulses generated by the CD4047 astable multivibrator. As a result, an AC voltage is applied to the primary winding of the transformer, which steps up the voltage to 230V.A standard step-down transformer is used in reverse for this purpose. In particular, the secondary winding in this inverter circuit is repurposed from the primary winding of the 230V to 12V-0-12V step-down transformer. The system operates using a 12V input from a 12V battery to output 220V at a frequency of 50 Hz.

5.3 Modeling of solar inverter

The solar inverter system requires careful consideration of load, backup time, battery size, and the required number of solar panels. The following detail the selection of the appropriate battery size and the solar panels required for efficient system operation.

5.3.1 Selection of Battery Size

To design an inverter system for a 40 W load with a backup time of 1 hour, the inverter rating should be 25% greater than the total load, Eq. 1.

$$40 \times \frac{25}{100} = 10W \tag{1}$$

Thus, the total inverter rating is Eq. 2.

$$40W + 10W = 50W \tag{2}$$

This means the inverter should have a capacity of at least 50W to handle the load effectively. To calculate the required battery capacity, we use Eq. 3.

$$Battery\ Capacity(Wh) = Power\ (W) BackupTime\ (h) \tag{3}$$

For a 50W load and a backup time of 1 hour, the required battery capacity is depicted in Eq. 4.

$$50W \times 1h = 50Wh \tag{4}$$

For backup, the system uses 4.5Ah, 6V batteries. The energy provided by one battery is depicted in Eq. 5.

$$6V \times 4.5Ah = 27Wh \tag{5}$$

The backup time provided by one battery for a 40W load is Eq. 6.

$$\frac{27Wh}{40W} = 0.675\ h \tag{6}$$

Since the required backup time is1 Hour, we need, Eq. 7.

$$\frac{1}{0.675} \approx 1.5\ Batteries \tag{7}$$

Therefore, we will connect two batteries (each 6V, 4.5Ah) in parallel. When connected in parallel, the voltage remains 6V, but the current capacity doubles Eq. 8.

$$4.5Ah + 4.5Ah = 9Ah \tag{8}$$

For this system, if we connect the batteries in series, the voltage would add up as shown in Eq. 9, but the current capacity would remain the same at 4.5Ah.

$$6V + 6V = 12V \tag{9}$$

In this case, since we're working with a 6V inverter, we'll connect the batteries in parallel. This results in a 9Ah, 6V battery system. The required charging current for the batteries (which should be 1/10 of the battery capacity) is Eq. 10.

$$9Ah + \frac{1}{10} = 0.9A \tag{10}$$

5.3.2 Selection of Solar Panel

To charge the batteries, the power requirement is calculated as follows, Eq. 11.

$$P = VI \tag{11}$$

For the battery charging system, the required power is, Eq. 12.

$$6V \times 0.9A = 5.4W \tag{12}$$

Thus, two 3W solar panels are required to meet the charging power needs, Eq. 13.

$$\frac{5.4W}{3W} = 2\ Solar\ panels \tag{13}$$

These solar panels will provide the necessary power for efficient charging and operation of the inverter system.

6. Hardware implementation

Table 2 presents the project's actual hardware specifications, demonstrating how the design can be practically implemented using real hardware components.

Table 2. Hardware specifications.

Description	Value	Unit
Input Voltage	012.0	V
Output Voltage	220.0	V
Battery Voltage	006.0	V
Battery Capacity	004.5	Ah
Max. Load Current Capacity	007.0	A
Frequency	050.0	Hz

6.1 Hardware showcase

The hardware demonstration for the solar inverter project is shown in Fig. 23. The variable DC output of a PV solar panel is converted to utility frequency AC by a PV inverter, sometimes referred to as a solar inverter. This converted AC can be used in an off-grid local electrical network or delivered into a commercial electrical grid. One crucial part of PV systems that facilitates the simpler integration of traditional business appliances is the solar inverter. Advanced features like MPPT and anti-islanding protection are provided by these inverters, which are specifically made for use with PV arrays. These features increase the efficiency and security of solar energy systems.

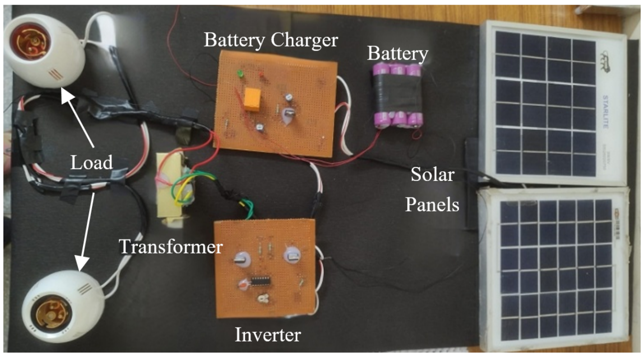


Figure 23. Hardware project demonstration.

6.2 Experimental results

The experimental setup of the solar inverter system was rigorously tested to evaluate its performance in real-world conditions.The system's performance, including the generation of the AC waveform, Fourier series approximation, and battery charging behaviour, was assessed using MATLAB. The system's calculated parameters were used to develop MATLAB code, which generated the graphs for analysis and validation under different operating conditions. The results confirmed the system's ability to convert solar-generated DC into stable AC output efficiently, meeting the design specifications. The inverter successfully maintained a steady output voltage of 220V AC with a frequency of 50 Hz. This stability was observed under various load conditions, demonstrating the system's robustness in delivering consistent power. The inverter consistently powered devices with a combined load of up to 100W without any noticeable performance degradation.

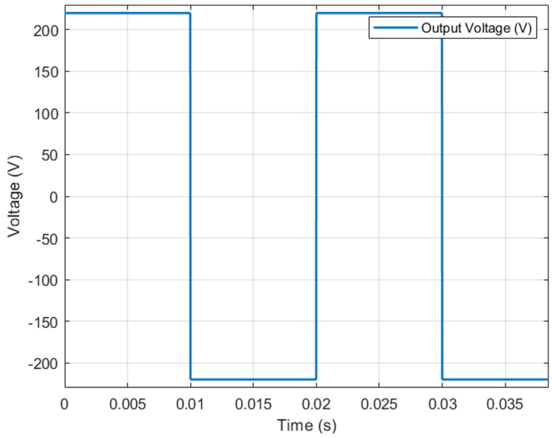


Figure 24. Output AC Waveform.

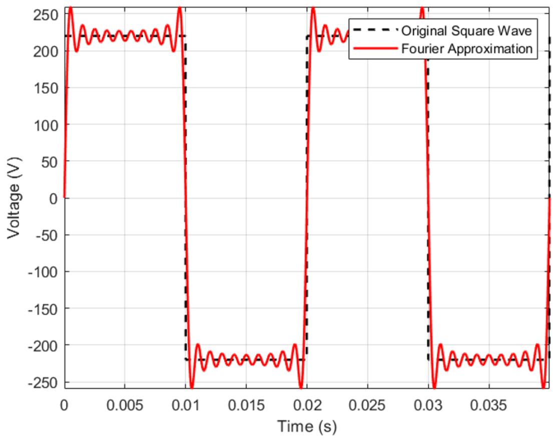


Figure 25. Fourier Series Approximation of the Square Wave.

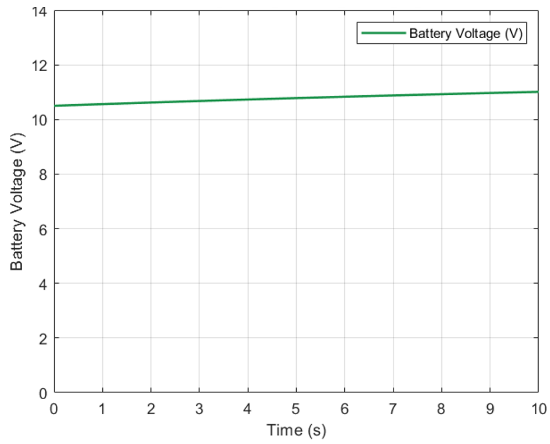


Figure 26. Battery Voltage during Charging.

The inverter's ability to handle these loads validates its design and practical applicability for standalone applications. The inverter produced a 50 Hz square wave, which is suitable for many basic AC applications. While not as clean as a pure sine wave, square wave output is adequate for targeted use cases and contributes to the system's overall efficiency. The 12V, 4.5Ah battery demonstrated adequate capacity to sustain the inverter operation for a significant duration under various loads. The charging circuit, regulated by the IC7812, efficiently maintained the battery's charge, ensuring continuous operation when solar input was available. The graph shown in Fig. 24 depicts a square wave representing the AC output waveform generated using the square function in MATLAB. The waveform was obtained by simulating the inverter circuit, and it closely resembles the 50 Hz square wave, which is typical for basic inverter designs. Figure 25 represents the Fourier series approximation of the square wave generated by the inverter. The graph compares the original square wave with its approximation using the first 10 odd harmonics, showcasing the harmonic content that contributes to the waveform shape. Figure 26 shows the charging process of a battery using a solar panel, as simulated in MATLAB/Simulink. The graph tracks the battery voltage throughout the charging cycle, from the initial state to the fully charged state, based on the calculated parameters for voltage and current. It also includes indicators for charging status and low battery alerts. The Simulink model was used to monitor the battery's charging behaviour under typical solar input conditions, with the charging current adjusted to match real-world performance. Figure 27 illustrates the Charging Status Indicator, while Fig. 28 depicts the Buzzer Status Indicator. The LED and buzzer system effectively indicated the battery's charging status. The LED lit up when the battery voltage exceeded 10.5V, and the buzzer activated when the voltage dropped below the critical threshold, prompting recharging. This feature ensured user awareness of the battery condition and prevented deep discharge scenarios. These experimental results affirm that the solar inverter system is both effective and reliable for converting solar energy into usable AC power. The experimental results affirm that the solar inverter system is both effective and reliable for converting solar energy into usable AC power. The MATLAB-generated results validate the system's design objectives and demonstrate its potential for powering standalone AC loads. Moreover, the inverter meets design goals by providing a cost-effective solution that reduces reliance on fossil fuels and contributes to environmental sustainability.

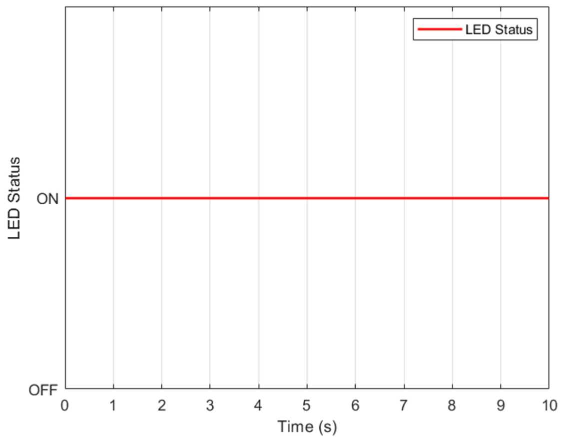


Figure 27**.** Charging Status Indicator.

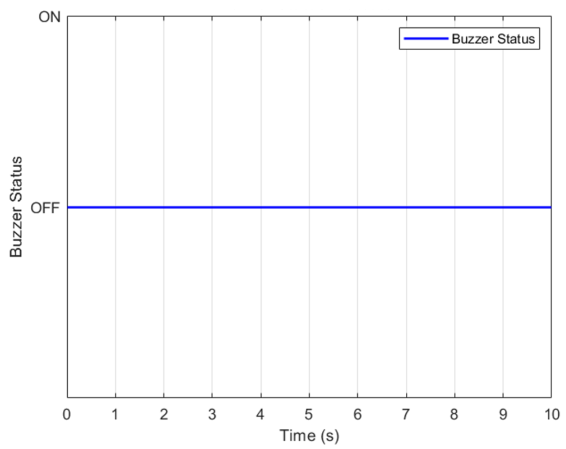


Figure 28**.** Buzzer Status Indicator.

7. Conclusion and future scope

This paper analyzes the hardware implementation of a solar power inverter that offers a promising and sustainable solution for harnessing solar energy and converting it into usable electrical power. The integral components of this experiment, comprising solar panels, charge controllers, batteries, and inverters, collaborate seamlessly to establish a dependable and eco-friendly energy system. Highlighting its versatility, the experiment accommodates both off-grid and on-grid capabilities. The inverter assumes a pivotal role by converting DC from solar panels and batteries into AC, suitable for powering diverse household or industrial appliances. The paper illustrates the efficiency and adaptability of the inverter to meet varied energy demands. Ongoing technological advancements in solar inverter systems may address these challenges. Serving as an educational tool, the solar inverter project provides insights into renewable energy technologies, power electronics, and system integration. It underscores the potential for technological innovation in the pursuit of sustainable energy solutions. The future scope of solar power inverters visualizes advancements in efficiency, grid integration, and smart technologies. Ongoing research is dedicated to maximizing solar energy conversion by enhancing inverter efficiency. The efficiency of the solar inverter system can be evaluated by comparing the AC power output delivered to the load with the total DC input power drawn from the solar panels and battery. This metric validates the inverter's capability in meeting design objectives while delivering reliable performance. Achieving high efficiency supports the inverter's role as a cost-effective and sustainable power solution, effectively reducing reliance on fossil fuels and contributing to environmental sustainability. As solar inverter technology advances, ongoing research aims to further increase efficiency and optimize energy conversion. Anticipated developments include advanced grid integration capabilities, enabling solar systems to contribute to grid stability through services like voltage regulation. Hybrid inverter systems, integrating solar with energy storage, are poised to play a crucial role in ensuring continuous power supply and bolstering energy resilience. The next generation of solar power inverters is expected to feature sophisticated monitoring and control functionalities, leveraging the Internet of Things (IoT) for real-time communication and optimized system performance. Furthermore, the integration of smart technologies and digitalization aims to enhance remote control and management. Future inverters are likely to offer improved backup power during grid outages, seamlessly transitioning between grid-connected and islanded modes. Continued efforts to reduce costs and scalability considerations will enhance the economic viability of solar power systems across various applications. Emerging technologies, such as wide-bandgap semiconductors, hold the potential to contribute to higher efficiency and reliability in solar power inverters. The integration of smart technologies and digital monitoring will also allow for improved remote control and management, making future solar inverters more responsive and adaptable to varied energy demands. As standards and regulations continue to evolve, they will shape the design and operational capabilities of solar inverters, supporting further innovation in this field.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

The authors would like to express their gratitude to the School of Electrical Engineering for providing the necessary resources and support for this study. We appreciate constructive feedback from our colleagues, which has significantly improved the quality of this manuscript.

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How to cite this article:
Nivedika Kher, Kamaldeep Boora, Krishna Yadav, and Vikram Kumar. (2025). 'Harnessing solar energy: Hardware implementation of solar power inverter', Al-Qadisiyah Journal for Engineering Sciences, 18(2), pp. 221-232. `https://doi.org/10.30772/qjes.2024.152932.1367`