



Design and Development of Micro Off-grid Inverter for Solar Photovoltaic System using Proteus Simulation

Sonu Kumar^{1,2}, C Sethuraman^{1,3*} and Chandru G⁴

¹Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201 002, Uttar Pradesh, India

²CSIR-Structural Engineering Research Centre (SERC), Chennai 600 113, Tamil Nadu, India

³CSIR-Central Scientific Instruments Organisation (CSIO), CSIR Madras Complex, Chennai 600 113, Tamil Nadu, India

⁴SRM Easwari Engineering College, Ramapuram, Chennai 600 089, Tamil Nadu, India

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Solar photovoltaic panel generates DC power. It needs to be converted to AC power since most electrical appliances used in our day to day life runs on AC power supply. The conversion of DC to AC power happens using an inverter comprising of multiple electronic components, which generates harmonics in the AC power systems. The present investigation is focused to design a micro off-grid solar inverter with a minimal number of components using Proteus design suite simulation to generate quality power at an optimum cost. The designed solar inverter circuit mainly consists of resistors, capacitors, voltage regulators, CD 4047 IC, OP07 IC, R-C Circuit, MOSFETs and step-up transformer. The output of CD 4047 IC was given to the R-C three stage circuits for conversion from square to sinusoidal wave through amplifiers OP07 to boost the waveform voltage from 3.5 V to 7.0 V. The amplified sinusoidal waveform signal was applied to the gate of MOSFET combinations. Each set consists of two MOSFETs connected in parallel to produce voltage with 180° out of phase waveforms at MOSFET drain terminal and then supplied to center tapped step-up-transformer to produce constant 230 V AC output voltage at 50 Hz. The voltage regulation was achieved with the help of a DC-DC Boost Converter which makes the system capable of giving reliable power at 230 V even for varying solar irradiation from 145 W/m² and above. Frequency regulation was achieved by varying the values of R and C across pins 1, 2 and 3 of CD 4047 IC. The maximum efficiency of the developed micro off-grid solar inverter's hardware circuit was found to be 93.49% based on experimental measurements and 95.72% based on the simulation studies.

Keywords: Astable multi-vibrator, Micro off-grid inverter, MOSFET, Proteus simulation, Solar energy

Introduction

Solar energy is abundantly available in India which can be considered as a best source of clean energy for fulfilling the ever-increasing energy demand. The weather condition of India is about 300 days of bright sunny sky which allows for extensive solar power generation.¹ Over the previous decade, the solar sector has flourished and this trend is expected to continue in the forthcoming years.² Over the last ten years, global annual solar photovoltaic (PV) installed power generation capacity has increased at a rate of 57% on average.^{3,4} The amount of solar energy received in a single day is more than ten times the total annual energy consumption of everyone on earth.⁵ With the demand for energy becoming intensively increasing, the photovoltaic industry has developed rapidly.⁶ The biggest difficulty in delivering uninterrupted power to

the load is the deployment of renewable energy supplies.^{7,8} In a solar photovoltaic system, the sun is the source of energy and the intensity of solar irradiance will vary with respect to time and so the voltage produced by the panel also changes. There is a requirement for designing the solar inverter mainly to meet the loads in such a way that it produces highly constant output voltage even under the varying intensity of irradiation.

India receives over 5000 trillion kWh of solar energy each year, greatly exceeding its total annual consumption of about 1200 TWh.⁹ The daily global solar radiation in most parts of India is approximately 5 kWh/m²/day, with sunshine varying between 2300 and 3200 hours per year.¹⁰ India because of its location between the tropic of cancer and the equator has solar power potential of around 7,50,000 MW. India has set a target of achieving 450 GW renewable energy based power plants capacity by the year 2030. As of 28 February 2022, India had a total installed

*Author for Correspondence
E-mail: sethuenegy@csircmc.res.in

power plant capacity of 395.60 GW, with renewable power plants accounting for 106.37 GW (26.88%), including 50.77 GW from solar PV-based plants.¹¹ Considering the government's support for clean energy technology and the tremendous increase in the solar PV system based energy users in the country, there is a requirement for developing suitable solar inverters which can support in fulfilling the energy requirements of every household in the country.

An inverter is a power electronic device¹² that converts DC power to AC power. Generally, normal inverters take input power from a battery connected to the voltage regulator to supply a constant DC voltage as input voltage to the inverter. A block diagram of the solar photovoltaic system is given in Fig. 1, in which it can be seen that the inverter takes input from the battery and gives output to the load. Since the constant input voltage is maintained there won't be any effect on the inverter's output voltage. Unless and until the voltage of the DC battery starts deteriorating and input voltage falls below the threshold level, there won't be any effect on output AC voltage.

Inverter acts as a bridge between a solar panel and the load since most of the load runs on AC power and it is very much important that all the components in the circuit are properly designed in such a way that it should not create any problems in terms of impedance, voltage and current level mismatch which may cause inverter failure or fire accidents. Many loads or processes not only require continuous power supply but also quality power which can't be expected from grid power obtained from the electricity board. During power cut, DC power produced by the solar PV system and stored in a battery can act as a source of power to run the AC appliances. For this, the inverter is a highly necessary device to convert the DC power stored in the battery to AC power. Considering the SPV system as an alternate source to run the appliances, the AC power produced by the inverter must be of good quality sinusoidal waveform with required voltage levels. Because the regulated square wave is harmful to appliances, pure sine wave inverters are employed to produce a pure sine wave at the load's output.^{13,14}

The solar inverter should have all the qualities mentioned above to supply reliable and quality power

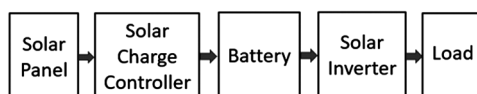


Fig. 1 — Block diagram of solar photovoltaic system

for running critical and sophisticated AC appliances. There are two main challenges in designing an inverter, one is getting higher efficiency with quality power and another is making low-cost inverter¹⁵ than the present commercial inverters available in the market at the cost of 6–12 ₹/VA.¹⁶ In order to overcome these challenges, one has to use the simulation tools effectively. Mainly Proteus and Multisim software are used for simulating inverter circuits. The present investigation is carried out in Proteus software because of its simplicity and reliable simulation results. By using proteus simulation tool, an attempt was made in this present investigation to design and develop a cost-effective energy efficient micro off-grid inverter for the solar PV system.

Literature Survey on Solar Inverters

The development of inverters started in the late 19th century. Back in the year 1956, solar systems had only 6% efficiency and solar inverters were not in practice. Residential solar inverters were first introduced in the year 2000 once scientists at Sandia laboratories in New Mexico developed the modern inverter. With advances in solar panel technology and more efficient solar inverters, the average solar PV system now has an efficiency of 14 to 18% and costs as little as \$3/W.¹⁷ Currently a variety of solar inverters are available in the market, however they have their own limitations and challenges. Classifications of solar inverters are discussed in the below sections.

Classification of Inverters

The inverters are mainly classified into three categories 1) battery backup inverters¹⁸, 2) grid-tied inverters and 3) stand-alone inverters. Battery backup inverters consume energy from the battery and the charge of the battery is managed by the onboard charge controller and it¹⁹ exports excess energy to the utility grid.²⁰ These inverters produce AC power and supply it to the utility loads during power outages. Grid-tied inverters have the same phase as the utility-supply sinusoidal wave. Grid-tied inverters will automatically shut down for safety reasons when there is no utility supply. It doesn't provide backup power during utility outages.²¹ Solar grid-tied inverters are classified into three types based on the highest amount of power fed into the grid. Micro, string and central inverters are the three types of inverters.^{22–26} Stand-alone inverting devices are also called off-grid inverters which take DC input from a battery charged

from solar panels and supply AC power to the local loads. Further, the off-grid inverters are classified based on output characteristics, input characteristics, switching devices and the voltage level of output which are described in the below sections.

Off-Grid Inverters Inter-Classification

Based on Output Waveform Characteristics

There are two waveforms produced by inverters viz square wave and sinusoidal wave. Square waveform inverter is one type of inverter which produces a square wave as an output voltage waveform. These circuits are generally less complex since square wave generation is simple and can be generated with even one integrated circuit or with some basic circuits. Square wave inverters can serve non-critical loads. Modified sinusoidal wave inverter is another type of inverter that produces a modified sine waveform as an output waveform. These inverters are also not preferred for supplying power to sensitive equipment. Generally, PWM techniques are used for producing modified sine waves.

Pure sinusoidal wave inverter is an inverter whose output voltage waveform is purely sinusoidal. This type of inverter can be used to supply power to any type of load including critical loads and highly sophisticated equipment and these inverters are of a higher cost compared to other inverters.

Based on Input Voltage

Micro solar inverter can be operated supplying input voltage either at 12 V or 24 V. Since the inverter takes input power from the battery, it is very much dependent on battery voltage. Supply of 12 V DC can be converted to a 230 V AC voltage. In this type of inverter, the circuit is designed in such a way that 12 V is sufficient for the circuit to operate and the inversion process to take place as well as boost the voltage to 230 V. This type of inverter is generally of lesser cost.

In 24 V battery system, the solar inverter takes 24 V DC as input voltage and gives 230 AC as output. In this system, the voltage may be regulated down to 18 V or 12 V to operate the ICs and other components present in the inverter circuit. Generally 24 V solar inverters are more preferred than the 12 V, as they are relatively more efficient.

Based on Switches

Inverters operation is based on the functional properties of ON/OFF switching devices. Metal oxide semiconductor field-effect transistor (MOSFET),

Insulated gate bipolar transistors (IGBT), Bipolar junction transistors (BJT), Gate turn-off thyristors (GTO) are normally used as switching devices in the inverters.

MOSFETs are solid-state² electronic devices that can function as a switch, amplifier or buffer depending on their operating region (linear, saturation and cut-off). When a MOSFET operates in the saturation and cut-off region, it is completely OFF or ON i.e. switch operation. These characteristics of MOSFET make it suitable to be used in different inverter circuits.

Insulated Gate Bipolar Transistors (IGBTs) are mainly used in inverters where the demand for switching is not fulfilled by MOSFETs. The integrated device configuration's gate drive signal is given to the power MOSFET structure, allowing for small, low-cost gate drive circuits that enable high input impedance in voltage-controlled operations.²⁷

Bipolar Junction Transistors (BJTs) were the first power electronic component to be used for power switching devices and applications. It comes in two versions NPN and PNP, with only NPN being frequently utilized in drive inverters, primarily for applications up to a few KW.²⁸ To switch ON the device, a low-value current must be made to flow from base to emitter and this is caused by the input voltage. When the current flowing from base to emitter is zero, the device is switched off.²⁵

Gate Turn-off thyristors (GTOs) are turned ON by a gate pulse current as same as that of a thyristor. A normal thyristor couldn't be turned off by gate action, but a negative gate-cathode current can turn GTOs off.²⁸ The GTO is employed in high-power inverters because it has far higher voltage and current ratings (up to 3 kV and 2 kA) than BJT, MOSFET and IGBT.²⁹

Based on Output Level

Off-grid inverters can have either two-level or multi-level output. Regular two-level inverters are inverters whose output waveform is of two-level, one is high and another one is low. Two-level inverters require only a few switches for the inversion process, whereas multi-level inverter needs many switches depending upon the level of output to be produced.

Multi-level inverters are designed to give high output power from the medium voltage source. Sources like super capacitors, solar panels and batteries are medium voltage sources.³⁰ As the name states, the multi-level inverter requires an important switching arrangement for producing multi-level output.³⁰

Based on the literature survey, we observed that various types of inverters are reported in the literature as well as available in the market, however, they have their own limitations and challenges due to power electronics circuits, varying solar input and changing load patterns. Hence, there is a need to develop a micro off-grid inverter for solar photovoltaic systems with optimum cost to produce constant AC voltage output even under varying solar irradiances and also to obtain stable performance even under maximum load conditions.

Material and Methods

Parts of Micro Off-Grid Solar Inverter

IC7812 Voltage Regulator

This integrated circuit produces 12 V constant DC voltage. The minimum input voltage for which the output of 12 V is produced is 14.5 V. If the input to this voltage regulator falls below 14.5 V, then there will be a decrease in the output voltage level. In the present investigation, 24 V battery system was used, which is sufficient to provide greater than 14.5 V to the voltage regulator unless the battery gets deep discharged.

IC CD4047 Astable Multi-vibrator

The pin diagram for IC CD 4047 is shown in Fig. 2. This integrated circuit can be considered as the heart of the inverter since it is responsible for the production of a square wave of suitable frequency. The CD4047's 1, 2, and 3 pins are used to connect R and C. The frequency of the square wave, which is output from pins 10 and 11, is controlled by this R and C. The formula for calculating frequency is given in Eq. (1)

$$Frequency (f) = \frac{1}{4.44 \times R \times C} \quad \dots (1)$$

By adjusting the values of R and C, a suitable frequency can be achieved. The output of IC7812 is

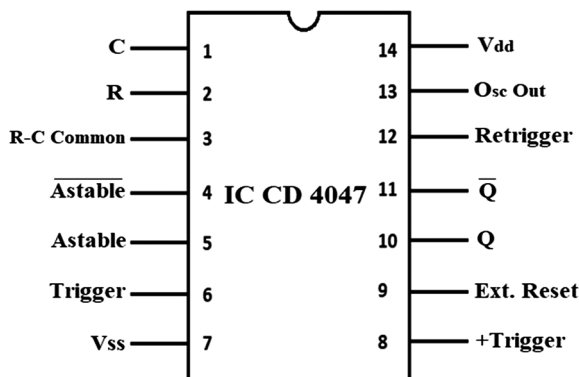


Fig. 2 — IC CD 4047 pinout diagram

served as input to this integrated circuit. The output available at CD4047, 10 and 11th pins is square waves with 180° phase differences.

OP07 Operational Amplifier

In this circuit the operational amplifier is employed to amplify the output from IC CD4047. The formula for calculating the gain of the operational amplifier is given by Eq. (2).

$$Gain = 1 + \frac{R_2}{R_1} \quad \dots (2)$$

In the current study, the operational amplifier with R₂ and R₁ of 1 kΩ was chosen based on simulation results. As a result, the gain of the op-amp used in this investigation is 2.

RC Three Stage Wave Conversion Circuit

To produce a sinusoidal wave as an output, each RC conversion circuit consists of three resistors and capacitors of proper values. The amplified square wave is converted into a sinusoidal wave by two sets of three-stage RC conversion circuits, which supply the proper wave to the gate of MOSFETs.

MOSFET Combinations

MOSFETs are used in power electronics circuits for switching applications. But due to continuous operation or high current, MOSFET may get heated and become unstable to perform switching operations. To avoid this, multiple MOSFETs can be connected in parallel along with the heat sink. In this present study, the IRFZ44N N-channel MOSFET with high drain current and low resistance value 17.5 mΩ was used with two parallel combinations of two-two MOSFETs as obtained from the simulation studies.

Step-Up Transformer

Input center-tapped step-up transformer is used in this circuit as described in the simulation studies. The center tap is connected to a 24 V DC supply and it is linked to the drain of the MOSFET. The specified transformer has a 500 VA rating.

Pictorial View of Major Components

The pictorial view of major components used in the proposed solar inverter is given in Fig. 3. It contains IC 7812 voltage regulator, IC CD4047 astable multi-vibrator, OP07 operational amplifier, IRFZ44N MOSFET and 24 V - 0 - 24 V step-up transformer.

Proteus Design Suite Software Simulation

The present investigation is carried out in Proteus design suite simulation software because of its simplicity and reliable simulation results. The Proteus

design suite is a simulation software tool used for simulating various electronic designs like PCB, schematics. The first version of this Proteus Design Suite was developed by John Jameson in 1988. In recent years, this suite is integrated with many features namely SPICE simulation, microcontroller simulation, shape-based auto-routing, 3D board visualization, MCAD import and export and high-speed design. Schematic capture is used for

simulation of the user's design as well as PCB layout design. It is one of the best software available for design engineers and engineering works departments to manufacture printed circuit boards and it has also been used by researchers and engineering students to design and analyse circuits and develop products.

The entire circuit of the micro solar inverter was designed in the Proteus Design Suite, as shown in Fig. 4. The input DC supply was given from a 24 V battery system. The DC 24 V was then passed through an IC7812 voltage regulator which is used to serve input voltage to the CD4047 as table multi-vibrator. This regulator was used to get a constant 12 V for providing power to CD 4047.

This 12 V DC voltage was applied to the CD4047's pins 4, 5, 6 and 14. The IC CD4047's pins 7, 8, 9, and 12 were all grounded. The output pins are the 10th and 11th pins which create square waves that are 180° out of phase. The OP07 operational amplifier amplifies these square waves even further.

Before amplification, the square wave's voltage was 3.5 V and after amplification it became 7 V. A three-stage RC conversion circuit was used to transform the amplified square wave to a sinusoidal wave. A sinusoidal wave was obtained at the end of

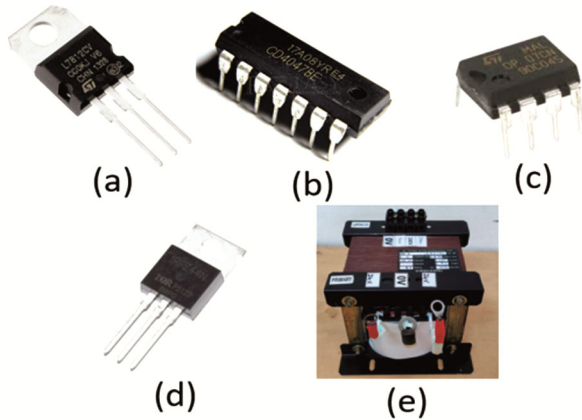


Fig. 3 — Parts of micro off-grid solar inverter: (a) IC 7812, (b) IC CD4047, (c) IC OP07, (d) IRFZ44N MOSFET and (e) Centre tapped step-up transformer

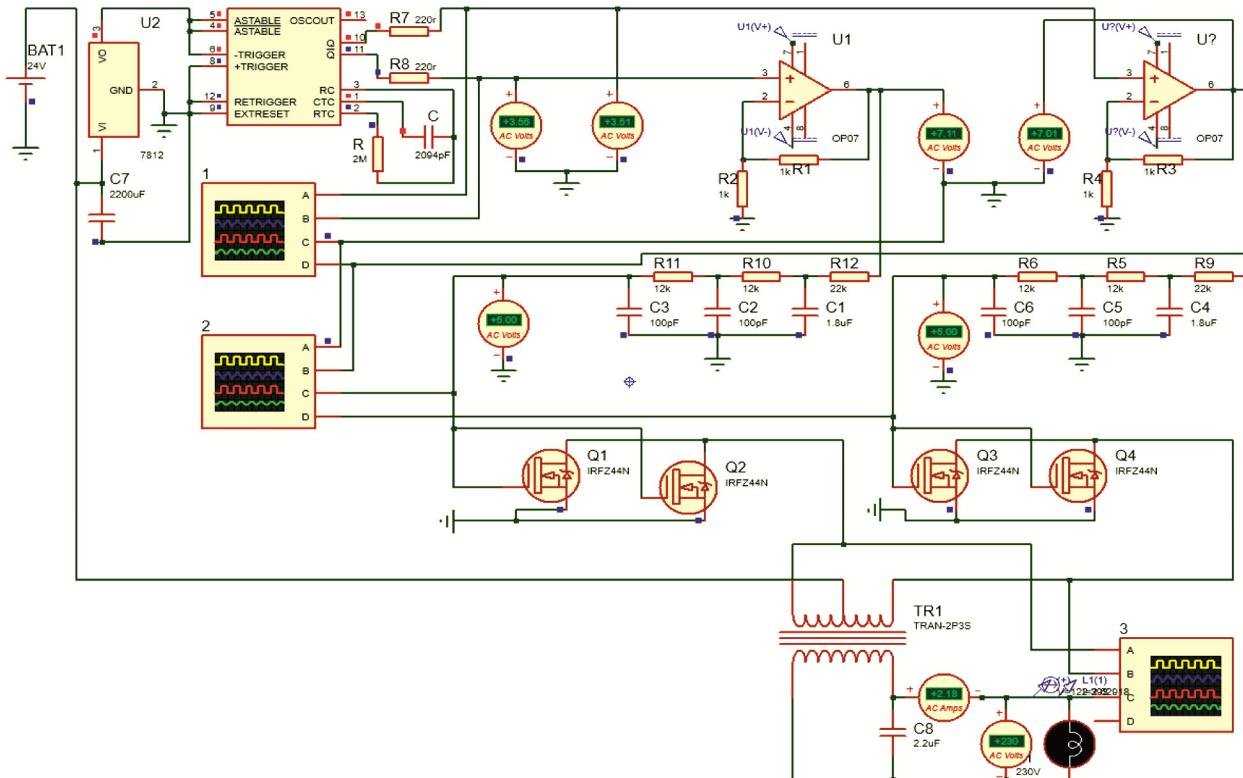


Fig. 4 — Design of micro off-grid solar inverter in proteus softwar

the three-stage RC circuit. This sinusoidal wave was also applied to the IRFZ44N MOSFET configurations' gate terminal (combination 1: Q1, Q2 and combination 2: Q3, Q4). The MOSFET's drain terminal was connected to the 24 V - 0 - 24 V step-up transformer's two terminals. 24 V battery was linked to the transformer's center tapped terminal. A single-phase load, an electrical bulb (230 V, 50 Hz) varying power from 9.20 W to 152.25 W was connected to verify the simulation work done by us and also to test the quality of output voltage sinusoidal waveform of the designed solar micro off-grid inverter. It was observed that the bulb was glowing at 230 V, 50 Hz and obtained pure sinusoidal current and voltage waveforms.

Hardware Development

The hardware circuit was developed for the micro off-grid solar inverter based on the simulations carried out in proteus software. The developed solar inverter hardware circuit is shown in Fig. 5. It can be seen that the inverter has a large size heat sink to avoid temperature rise due to heat loss at MOSFET terminals.

Inverter supplying power to loads (bulbs) is shown in below Fig. 6.

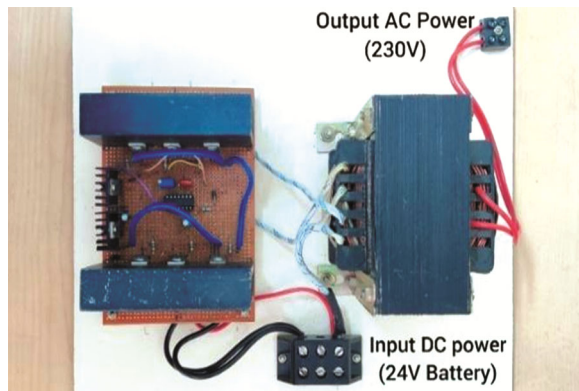


Fig. 5 — Developed hardware for micro off-grid solar inverter



Fig. 6 — Inverter supplying power to the load

Voltage Regulation

The voltage regulation was done using DC-DC boost converter module as shown in Fig. 7, which boosts voltage from 10 – 32 V input to 24 V output.

This module consists of one fixed inductor, two fixed capacitors and one potentiometer. The potentiometer employed in the circuit was varied in order to vary the output voltage of the DC-DC boost converter. STP80NF70 MOSFET was used since drain voltage and drain current rating is high which is 68 V and 98 A respectively. STPS2045C power Schottky diode integrated circuit was used which consists of two diodes connected in parallel and each can handle 10 A. UC3843 Current-mode PWM controllers were used for controlled regulation of current along with a 1 Ω power resistor. Heat sinks were provided for dissipating the heat away from MOSFETs when high current passes through them.

The DC-DC boost converter module was used after the battery in the solar inverter set-up to boost the battery voltage and provide 24 V at the solar input terminal as shown in Fig. 8. It gives always 24 V DC as input to the solar inverter, even if the battery voltage decreases because of discharging or due to

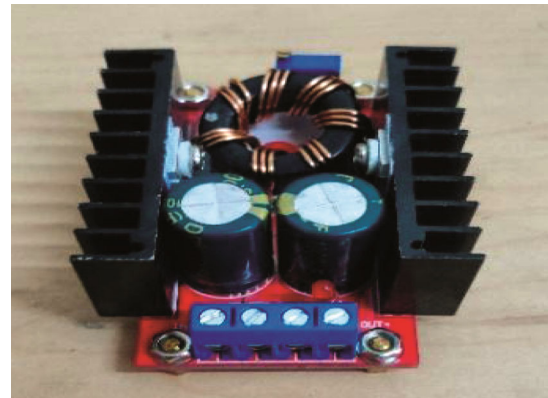


Fig. 7 — DC-DC Boost converter module

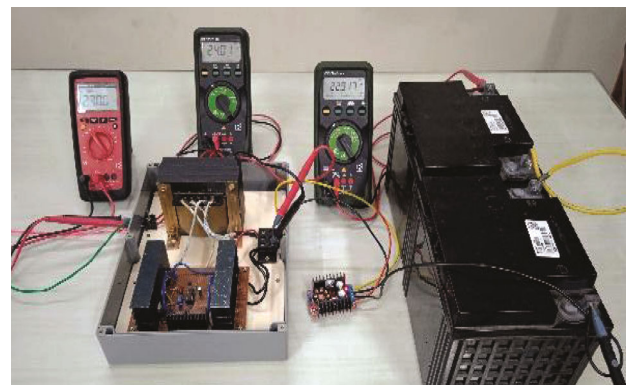


Fig. 8 — Voltage regulation of solar inverter

very low solar irradiance. Moreover, during high solar irradiance buck converter which is used before the battery and after the solar panel takes care in maintaining a fixed 24 V as battery charging voltage.

The voltage at the battery terminal which is 22.9 V is boosted to 24 V at the solar inverter’s input terminal in order to produce precise 230 V under no load condition as depicted in Fig. 8. Whenever the battery voltage falls below 24 V, the boost converter module will take care of voltage regulation and at the same time the buck converter which has been used before the battery through which the battery charge takes care of maintaining 24 V at the battery terminals. In Fig. 9 it can be seen that the inverter output voltage is almost constant at 230 V, under a wide range of solar irradiances from 145 W/m² to 735 W/m².

At solar radiation higher than 145 W/m² since the charging voltage is controlled by a boost converter, the excess current generated due to higher solar radiation can bypass IC CD4047 and three-stage RC circuit, it can (i.e. higher current) can go to the central point of transformers and from its other two terminals to MOSFET. The amplitude magnified quality pure sinusoidal voltage waveform goes to connected single-phase AC load.

Current Regulation

The inverter output current waveform should be sinusoidal. In this developed micro off-grid inverter for the SPV system, the current waveform follows the voltage waveform which is sinusoidal. The inverter output AC current waveform is shown in Fig. 10. Each cycle takes 20 ms, hence its frequency is 50 Hz.

Results and Discussion

The results obtained and the waveforms generated from the proteus software simulations are discussed below. CD4047 output and amplifier output square waveform is shown in Fig. 11.

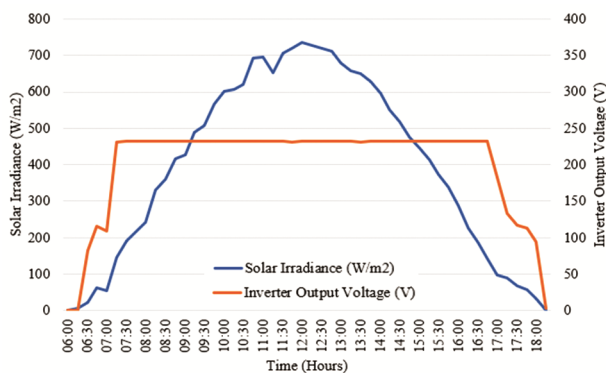


Fig. 9 — Inverter Output under different solar irradiance

The waveform of an RC three-stage conversion circuit is shown in Fig. 12. It is evident that a perfect sinusoidal waveform was obtained only at the end of the third stage which is more suitable for switching the IRFZ44N MOSFET combinations. This sinusoidal

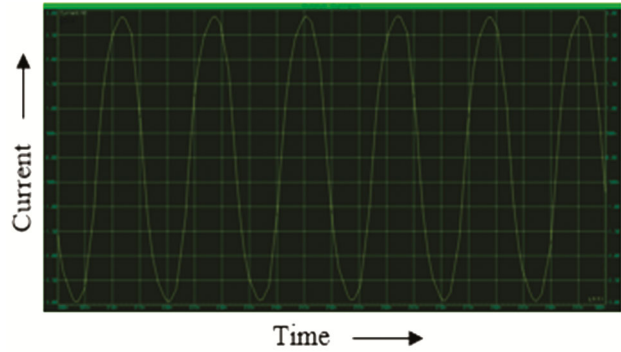


Fig. 10 — Regulated sinusoidal output current waveform

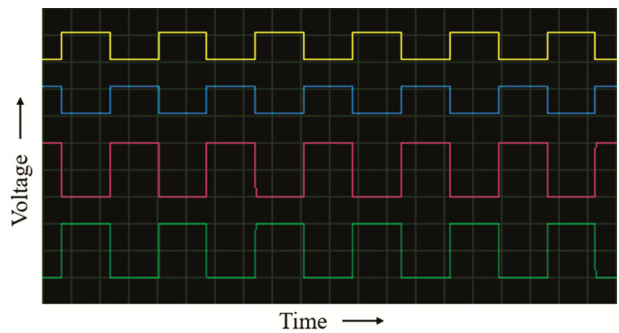


Fig. 11 — CD4047 Output and amplifier output square waveform (Yellow: Output from 10th pin of CD4047, Blue: Output from 11th pin of CD4047, Pink: Amplified output of 11th pin & Green: Amplified output of 10th pin)

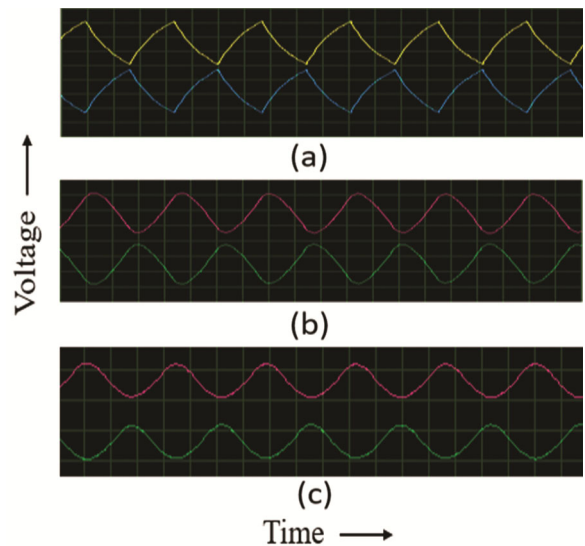


Fig. 12 — (a) RC first stage output waveform, (b) RC second stage output waveform and (c) RC third stage output waveform

wave can be fed into the gate of a MOSFET to operate it and generate sinusoidal drain voltage.

The waveform of the drain voltage of MOSFET combinations are shown in Fig. 13. These two MOSFET combinations drain voltage has been made 180° out of phase, so that to drive the center-tapped transformer.

The output from the 24 V - 0 - 24 V step-up transformer is 230 V AC, as shown in Fig. 12. This

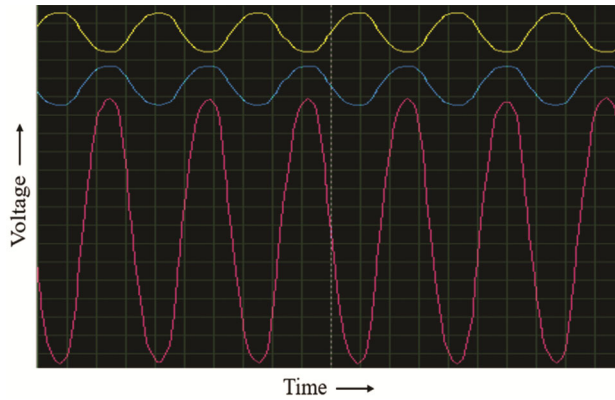


Fig. 13 — MOSFET output waveform and transformer secondary voltage (Yellow: Drain of MOSFET, Blue: Drain of another MOSFET & Pink: Output of transformer)

output wave form obtained from the transformer was supplied to the AC load bulb.

Performance Testing of Developed Inverter

The performance of the developed solar off-grid micro inverter hardware circuit was studied with twelve different AC loads varying from 9.20 W to 152.25 W. The results of voltage, current and power values as well as efficiency calculation for the designed solar inverter based on proteus simulation are given in Table 1. The measured values of voltage, current, power and efficiency are given in Table 2. From Table 1, it can be stated that for the designed solar inverter the average efficiency is 85.17% (excluding no load condition), and maximum efficiency is 95.72% based on the simulation studies. From Table 2, it can be stated that for the developed solar inverter circuit the average efficiency is 82.79% (excluding no load condition), and maximum efficiency is 93.49% based on the experimental results.

Frequency Regulation

The inverter output can be varied by changing the resistor and capacitor values, which are connected with pins 1, 2 and 3 of CD 4047 IC. The expression

Table 1 — Voltage, current and power measurement for the developed inverter connected with load based on simulation studies

Load	Input side			Output side			Efficiency (%)
	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)	
Load 1	23.67	0.41	9.71	232.00	0.00	0	0
Load 2	23.34	0.83	19.37	230.00	0.04	9.20	47.79
Load 3	23.13	1.50	34.69	228.00	0.11	25.08	72.29
Load 4	22.84	2.16	49.33	227.00	0.19	43.13	87.42
Load 5	22.57	2.52	56.88	225.00	0.22	49.50	87.03
Load 6	22.55	2.85	64.27	223.00	0.26	57.98	90.22
Load 7	22.26	3.52	78.36	220.00	0.32	70.40	89.85
Load 8	21.85	3.83	83.68	218.00	0.36	78.48	93.78
Load 9	21.70	4.43	96.13	214.00	0.43	92.02	95.72
Load 10	21.21	6.53	138.50	209.00	0.61	127.49	92.05
Load 11	20.86	7.31	152.49	206.00	0.67	138.02	90.51
Load 12	20.40	8.27	168.71	203.00	0.75	152.25	90.24

Table 2 — Voltage, current and power measurement for the developed inverter connected with load based on experimental results

S. No	Solar irradiance (W/m ²)	Boosted voltage (V)	Input DC			Output AC			Efficiency (%)
			Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)	
1.	405	24.02	23.67	0.47	11.13	232.1	0	0	0
2.	404	23.76	23.34	1.05	24.51	227.6	0.043	9.81	40.03
3.	407	23.75	23.13	1.63	37.70	225.3	0.110	25.68	68.12
4.	410	23.74	22.84	2.23	50.93	223.3	0.197	44.06	86.50
5.	400	23.71	22.57	2.70	60.94	220.2	0.237	52.14	85.56
6.	401	23.73	22.55	2.89	65.17	221.0	0.260	58.12	89.19
7.	395	23.70	22.26	3.34	74.35	218.0	0.303	66.08	88.87
8.	399	23.70	21.85	3.97	86.74	215.8	0.372	80.28	92.54
9.	402	23.71	21.70	4.66	101.12	213.4	0.443	94.54	93.49
10.	394	23.70	21.21	6.63	140.62	206.6	0.607	125.32	89.12
11.	397	23.70	20.86	7.35	153.32	204.4	0.667	136.36	88.93
12.	398	23.70	20.40	8.18	166.87	202.1	0.729	147.37	88.31

Table 3 — Inverter output frequency variations study

S. No	Resistance value (M Ω)	Capacitance value (pF)	Theoretical output frequency (Hz)	Measured frequency (Hz)	Frequency variation (%)
1.	3.300	2000	34.13	32.35	5.215
2.	2.620	2094	41.05	38.70	5.724
3.	2.620	2047	41.99	39.44	6.072
4.	2.680	2000	42.02	39.73	5.449
5.	2.159	2094	49.82	46.50	6.663
6.	2.091	2094	51.44	48.10	6.493
7.	2.000	2094	53.78	50.03	6.972
8.	3.459	1047	62.19	58.70	5.611
9.	2.680	1000	84.04	79.16	5.806
10.	2.000	1000	104.32	97.93	6.125

Table 4 — Cost analysis for the developed solar inverter 500 VA

S. No.	Details of Items	Quantity	Cost in INR
1	IC CD4047 Astable multi-vibrator	1	30
2	7812 Voltage regulator	1	20
3	Resistors (220 Ω , 1 k Ω , 12 k Ω , 2 M Ω)	—	20
4	Capacitors (1000 pF, 47 pF, 1 uF)	—	30
5	OP07 Operational amplifier	2	50
6	IRFZ44N MOSFET	4	120
7	24 V - 0 - 24 V Transformer	1	1800
			Total = 2070

for obtaining the frequency theoretically is given in equation (1). The theoretical frequency obtained with different R and C, measured frequency and frequency variation in percentage is given in Table 3. It is observed that the average variation in frequency between theoretical and measured is 6.013%.

Cost of Inverter

The cost breakdown for different components of the proposed micro off-grid solar inverter is given in Table 4. The cost spent for making this solar off-grid micro inverter is INR 2070 for 500 VA. It is cheaper than the cost of inverters available in the market. It has been observed that the cost of commercial solar inverters varies from INR 3355 to INR 7600 which is higher than the proposed solar inverter cost.^{31–34} Hence, it can be said that the proposed micro off-grid solar inverter is cost-effective.

Conclusions

A micro off-grid solar inverter was designed in Proteus Design Suite Simulation. A hardware circuit was developed for the same to evaluate the simulated design using IC CD4047, OP07 amplifier, three-stage R-C wave conversion circuit, MOSFETs and center tapped step-up transformer. The square waveform produced by IC CD4047 was amplified from 3.5 V to 7 V and converted to sinusoidal waveform by R-C three-stage wave conversion circuit. Sinusoidal

waveform thus obtained from R-C circuit at 7 V was applied to the gate terminals of the MOSFET combinations to produce an amplified sinusoidal waveform of 24 V at MOSFET drain terminals. Then the amplified sinusoidal waveform was supplied to center tapped step-up transformer to obtain a quality power output at 230 V AC at 50 Hz. The voltage regulation was achieved with the help of a DC-DC boost converter which makes the system capable of giving inverter output voltage almost constant as 230 V under a wide range of solar irradiances from 145 W/m² to 735 W/m². Output frequencies were also varied by changing the values of R and C across pins 1, 2 and 3 of CD 4047 IC. The maximum efficiency of the developed micro off-grid solar inverter hardware circuit was 95.72% based on simulation studies and 93.49% based on the experimental measurements. The cost of the proposed solar inverter is INR 2070 which is found to be lower than the commercially available products.

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