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A hybrid one step voltage-adjustable transformerless inverter for a one-phase grid incorporation of wind and solar power

Bonigala Ramesh, Madhubabu Thiruveedula, Rahul Inumula, C. Poojitha Reddy, Mohammad Abdul Khadar, K. Sri Sai Hareesh
Department of Electrical and Electronics Engineering, Teegala Krishna Reddy Engineering College, Hyderabad, India

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ABSTRACT

This paper presents a hybrid one-step voltage-adjustable transformerless inverter designed to efficiently integrate both solar photovoltaic (PV) and wind energy sources into a single-phase grid. The primary objective is to enhance power conversion efficiency while minimizing system complexity and cost. The proposed architecture combines a buck-boost DC-DC converter with a full-bridge inverter in a compact and modular design, enabling voltage regulation across a wide input range typical of hybrid renewable systems. By grounding the PV negative terminal, the system effectively eliminates leakage currents and ensures compliance with IEEE harmonic standards. The inverter operates with reduced switching losses and supports multiple operational modes tailored for variable solar and wind conditions. Simulation of a 300 W prototype demonstrates reliable performance, achieving a total harmonic distortion (THD) below 1%, validating its compatibility with grid requirements. Key contributions include the development of a unified topology for hybrid energy sources, in-depth analysis of energy storage components, and implementation of efficient modulation strategies. This work addresses significant challenges in renewable energy integration and provides a scalable solution for next-generation grid-connected hybrid power systems.

Corresponding Author:

Bonigala Ramesh
Department of Electrical and Electronics Engineering, Teegala Krishna Reddy Engineering College
Medbowli, Meerpet, Saroornagar, Hyderabad–500097, Telangana, India
Email: r.bonigala@gmail.com

1. INTRODUCTION

Solar and wind power act as primary renewable energy sources, supplying variable DC power to the single-stage buck-boost transformerless inverter. The inverter regulates and converts this power to grid-compatible AC. However, conventional transformerless inverters (TLIs), commonly used in these systems, face significant challenges, particularly with leakage currents when integrated into single-phase networks [1], [2]. Leakage currents pose a safety risk and can lead to energy losses, particularly when the systems are connected to the grid, where grounding is essential. Therefore, efficient and safe operation of these inverters is critical for the long-term success of PV energy integration into the grid. Several inverter topologies have been proposed to mitigate these issues. One such topology is the Pentagram design, which enforces a common neutral-ground connection to eliminate leakage currents [2]-[5]. While this approach addresses the leakage current issue, it often results in higher energy losses and necessitates additional components such as boost converters to handle low-voltage conditions. These extra stages increase system complexity and reduce the overall efficiency, especially in situations involving fluctuating irradiance or shading, which are common in real-world PV applications [6]-[9]. Additionally, many existing solutions struggle to provide the flexibility required under dynamic environmental conditions.

In response to these limitations, a variety of transformerless inverter topologies have been explored, including buck-derived and buck-boost configurations. While buck-derived inverters work well under high irradiance conditions, they encounter performance issues when the input voltage is low, or when shading affects the system's efficiency [10], [11]. For instance, a single stage grid linked inverter with maximum power point tracking (MPPT) was presented by Salem and Sedraoui [12] who showed excellent efficiency under steady irradiance conditions. However, such systems still struggle under low-voltage and shading conditions, limiting their flexibility. On the other hand, incorporating a buck-boost functionality allows the inverter to operate efficiently across a wider range of input voltages, thus improving system reliability and flexibility [13]. This paper proposes an unique transformerless buck boost inverter design, which addresses the limitations of traditional designs by offering high efficiency and reduced complexity. The system integrates a solitary input inductance and five power regulators to achieve a symmetrical output across both halves of the AC cycle, ensuring continuous power delivery with minimal losses [14]-[17].

The proposed design also provides several key advantages. By directly grounding the PV negative terminal with the neutral grid, leakage currents are effectively eliminated, thereby enhancing safety and reducing operational risks. Additionally, the system reduces DC current injection and minimizes switching and conduction losses, which are typically problematic in conventional inverters. These features make the proposed inverter design a viable solution for integrating hybrid renewable energy systems, such as solar and wind, into the grid, contributing to sustainable and efficient power generation.

2. SUGGESTED TOPOLOGY FOR BUCK-BOOST TRANSFORMERLESS INVERTER (BBTI)

2.1. Functional characteristics of the proposed BBTI

The proposed design combines a voltage-adjustable direct current to direct current converter and a full-bridge inverter to provide a compact and efficient solution for hybrid energy systems. The topology features five controllable switches (S1-S5), a power diode, an input inductor, and an auxiliary capacitor. High-frequency switches (S1, S3, and S4) are utilized for rapid energy transitions, while line-frequency switches (S2 and S5) ensure proper grid synchronization [18]. A distinguishing feature of this design is the direct grounding of the PV negative terminal, effectively eliminating leakage currents and meeting IEEE harmonic standards [19], [20]. The system operates seamlessly in four modes, ensuring efficient energy storage and delivery. The grid is connected through both negative and positive cycles. Figure 1 illustrates the proposed topology for a buck-boost transformerless inverter (BBTI).

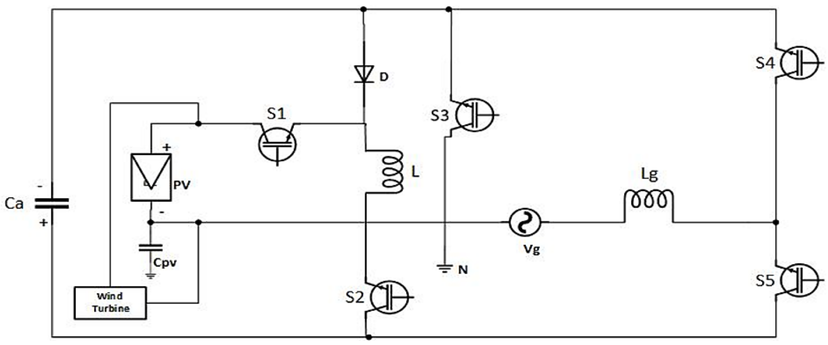


Figure 1. The recommended configuration for a BBTI

2.2. Operational modes of the transformerless inverter

The four different modes of the BBTI's continuous conduction mode (CCM) functioning are designated Mode (a) through Mode (d), which represent the grid's positive and negative half-cycles. In particular, Modes (a) and (b) stand for the positive half-cycle, and Modes (c) and (d) for the negative half-cycle, as illustrated in Figures 2(a)–2(d). Each mode is defined by a unique configuration of switching states, enabling controlled energy transfer and efficient grid interaction. The operational behavior of the BBTI under these four modes is described below.

- Mode A: energy collection and output supply (positive cycle)

  During this mode, as seen in Figure 2(a), S1, S3, and S5 are turned ON to deliver power to the grid. The inductor L stores power from the renewable source (such as PV) through S1, while the capacitor C_a

supplies power to maintain output continuity. The current flow path to the grid is established via switches S3 and S5. This switching arrangement ensures efficient energy transfer and minimizes power loss during the positive half cycle.

– Mode B: inductor energy transfer (positive cycle)
 In this mode, as illustrated in Figure 2(b), only S5 is turned ON, while all other switches remain OFF. The capacitor C_a receives the stored power from the inductor L via diode D and switch S2's antiparallel diode. Simultaneously, the inductor L_g allows current to freewheel via S5 and the antiparallel diode of S2. The complete conduction path for this freewheeling phase is marked with in Figure 2(b), ensuring efficient energy redirection and reduced switching losses.
– Mode C: reverse cycle power delivery (negative cycle)
 This mode, shown in Figure 2(c), corresponds to the negative half-cycle power delivery. In this phase, switches S4, S1, and S2 are turned ON. The inductor L takes power from the renewable source via S1, while the capacitor C_a gives power to the grid through S2 and S4. All current-conducting paths are highlighted in Figure 2(c), ensuring efficient energy transfer and maintaining system stability, as detailed in [21].
– Mode D: controlled energy dissipation (negative cycle)
 This mode, shown in Figure 2(d), corresponds to the negative half-cycle freewheeling operation. In this phase, only S_2 remains ON while all other power switches are turned OFF. The capacitor C_a receives the stored power from the inductor L via diode D and switch S_5's antiparallel diode. Concurrently, the grid inductor L_g current freewheels through switch S_2 and S_5's antiparallel diode. As indicated in Figure 2(d), all active conduction paths are highlighted with thick lines, ensuring minimal switching losses and extended component life [22].

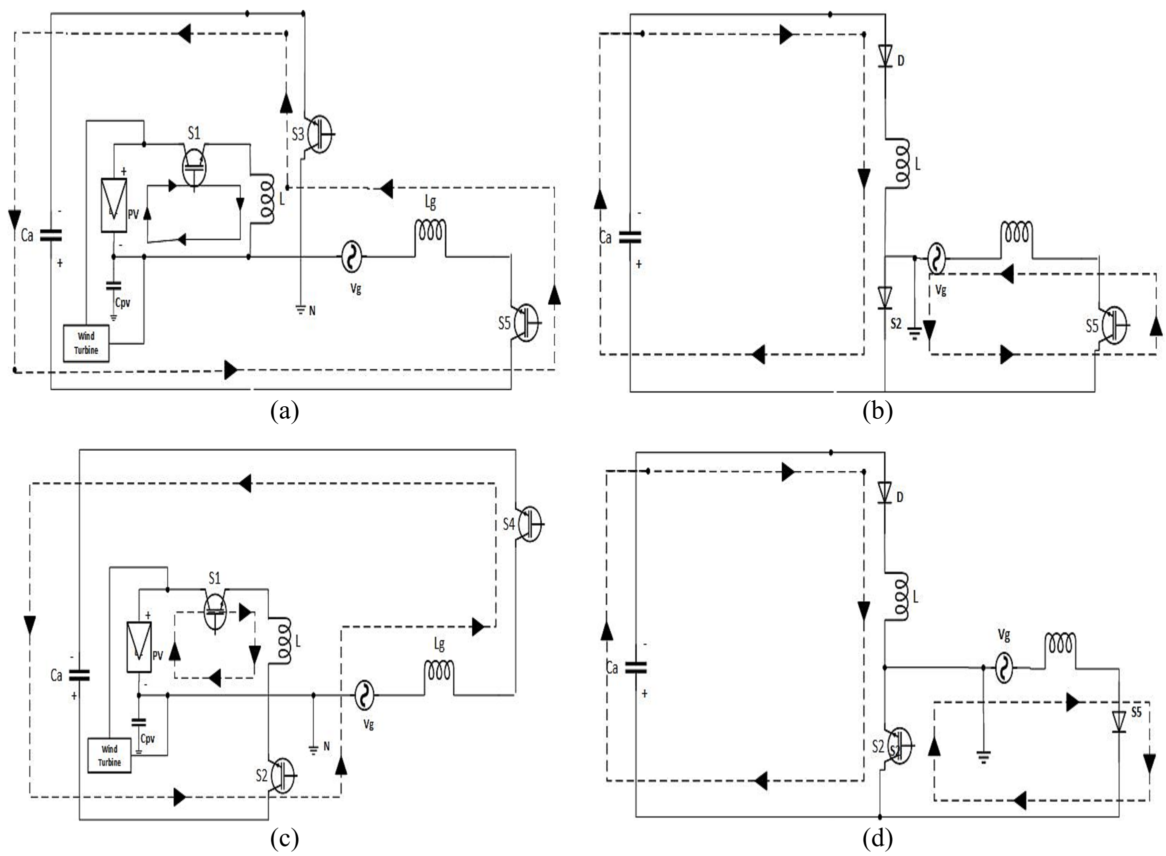


Figure 2. The operational modes: (a) powering mode (positive half cycle), (b) freewheeling mode (positive half cycle), (c) powering mode (negative half cycle), and (d) freewheeling mode (negative half cycle)

2.3. Steady-state examination of the suggested BBTI

The stable-state evaluation of the recommended BBTI relies on the subsequent assumptions: i) The DC capacitor is adequately sized to ensure a stable voltage is maintained across its terminals; ii) All semiconductor devices operate without any losses; and (iii) Parasitic elements are negligible. The following expression is obtained by using the principle of voltage maintaining over an inductor L. The auxiliary capacitor's voltage (CA) can be found using (1).

$$\int_0^{m_i T_s} V_{PV} dt + \int_{m_i T_s}^{T_s} (-V_{ca}) dt = 0 \quad (1)$$

$$V_{Ca} = (\frac{m_i}{1-m_i}) V_{PV} \quad (2)$$

The following is an expression for the highest AC output voltage. The predicted BBTI gain can be attained by changing (2) in (3).

$$V_{AC} = m_i \times V_{Ca} \quad (3)$$

$$G = \frac{V_{AC}}{V_{PV}} = (\frac{m_{i^2}}{1-m_i}) \quad (4)$$

Where V_{pv} is the voltage from the photovoltaic (PV) panel, V_{ca} is the voltage across the auxiliary capacitor, V_{ac} is the peak AC output voltage, G is the voltage gain V_{ac}/V_{pv}, M_i is the modulation index (duty ratio in the switching cycle), and T_s is switching time period.

2.4. Design of BBTI topology energy retention components

2.4.1. Inductor (L) for energy retention

The design of the input energy retention inductor (L) for the proposed BBTI is analogous to that of a typical buck-boost direct current to direct current converter. The inductance value is selected to ensure that the BBTI operates in continuous conduction mode (CCM). To achieve CCM operation, the critical inductance (Lc) must be less than the inductance. The following formula is used to calculate critical inductance.

$$L_C = \frac{(m_i V_{Pv})^2}{2 P_0 f_s} \quad (5)$$

Where M_i is the modulation index, V_{pv} is PV voltage input, P_o is AC energy output, and f_s is switching frequency.

2.4.2. Auxiliary capacitor architecture (C_A)

The auxiliary capacitor (C_A) is designed to manage energy storage and stabilize voltage levels in the system. A voltage ripple of 5% is typically considered sufficient for stable operation. The auxiliary capacitor value is calculated using (6).

$$C_A \geq \frac{P_O}{\Delta V_{Ca} \times V_{Ca} \times F_s} \quad (6)$$

Where C_a is the auxiliary capacitor (output-side capacitor) value, P_o is the output power delivered to the load, ΔV_{ca} is allowed ripple or voltage deviation across the auxiliary capacitor, F_s is switching frequency, and V_{ca} is the voltage across the auxiliary capacitor. Where P represents the output power, V is the potential along the supplementary capacitor, with ΔV serving as the permissible ripple voltage. These parameters help maintain stable voltage levels while accommodating power fluctuations.

3. METHODS OF MODULATION AND SUPERVISION FOR THE BBTI ARCHITECTURE DESIGN

3.1. Control and modulation strategy for the BBTI topology

Figure 3 shows the modulation technique for the suggested Transformerless Inverter with BBTI. It employs a triangle-shaped reference waveform to produce the five controllable switches' switching signals. (S1 to S5). This strategy ensures efficient operation while maintaining synchronization with the grid, allowing seamless power transfer from renewable energy sources to the grid [23].

The modulation process involves the following steps:

- The input waveform (Vin), its absolute value (|Vin|), and its inverse (−Vin) are compared against a high-frequency triangular reference waveform.
- Switches S_2 and S_5 operate at the grid's line frequency of 50 Hz, ensuring synchronization with the AC voltage cycle.

- Switch S_3 pulses are derived by comparing |Vin| with the triangular reference waveform.
- Similarly, the pulses for S_1 and S_4 are generated by comparing Vin and −Vin, respectively, with the reference waveform.

This modulation approach enables precise control over energy transfer, minimizing switching losses and ensuring stable operation. The current modulation technique maintains seamless power flow to the grid, optimizing energy usage from renewable sources such as solar and wind [24], [25].

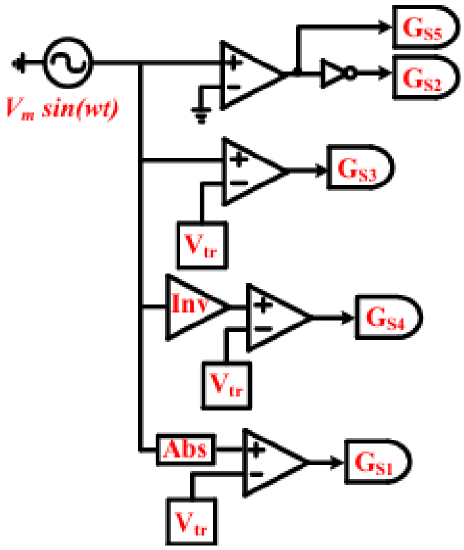


Figure 3. The BBTI topology's modulation approach

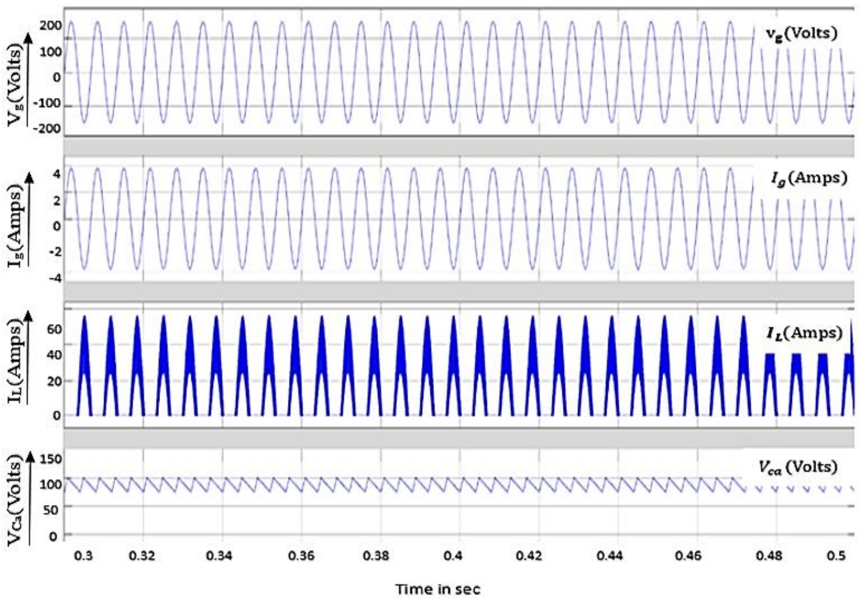
4. SIMULATION RESULTS AND DISCUSSION

The hybrid solar-wind grid-connected buck-boost transformerless inverter (BBTI) system was modelled and simulated in Simulink/MATLAB with 300 W energy ranging. Table 1 lists the specifics of the system that was utilized for the simulations. The combined input voltage sources, including both solar PV and wind energy, deliver a total voltage. The suggested BBTI configuration effectively transfers the highest power accessible from the hybrid energy sources to the grid, achieving a total harmonic distortion (THD) of less than 1% in the output voltage, thereby adhering to IEEE grid standards.

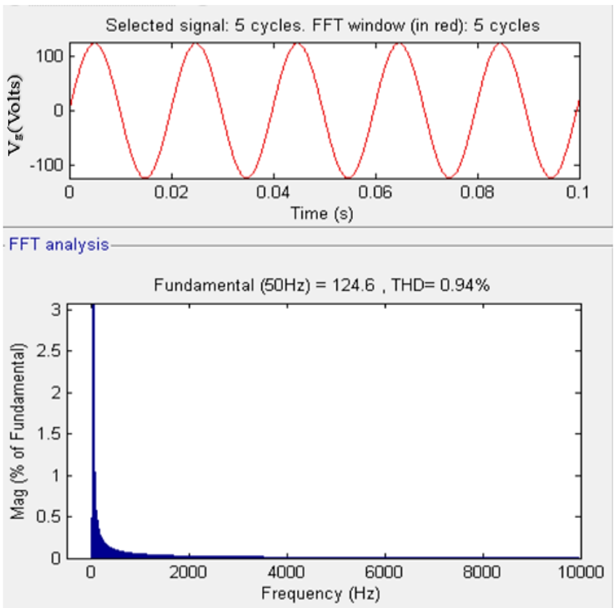
Table 1. System specifications for simulation research

System parameters	Ratings
Nominal power	300 W
Operating frequency	10 kHZ
Input voltage level	75 V
Inductor at input (L)	115 μh
Capacitor for auxiliary circuit (Ca)	50 μh
Inductor at output (Lg)	1 μh
Capacitor for filtering (Cf)	10 μh

Key waveforms, such as the grid current (Ig), grid voltage (Vg), voltage across the auxiliary capacitor (VCA), and input current through the inductor (IL), are shown in Figure 4(a). These waveforms validate the smooth energy transfer from the renewable sources to the grid under steady-state conditions. The proposed buck-boost transformer less inverter outperforms conventional inverters by achieving higher efficiency, particularly under low-voltage and fluctuating irradiance conditions, eliminating leakage currents through direct grounding, and reducing switching losses. Unlike traditional pentagram and buck-derived inverters, Figure 4(b) shows THD of proposed method, it maintains stable output voltage with lower THD, ensuring better grid compliance and power quality. Simulation results confirm improved efficiency, reduced leakage current, and enhanced reliability, making it a superior choice for PV grid integration.



(a)



(b)

Figure 4. Waveforms of the proposed inverter: (a) grid voltage (V_g), grid current (I_g), current through inductor (I_L), auxiliary capacitor voltage (V_{ca}) and (b) total harmonic distortion of grid voltage

5. CONCLUSION

The developed inverter system successfully integrates hybrid solar-wind energy into single-phase grids, addressing key challenges such as leakage currents and switching inefficiencies. The proposed buck-boost transformerless inverter (BBTI) ensures stable operation, achieves low harmonic distortion, and demonstrates adaptability under varying environmental conditions. Simulation results confirm the system's reliability, with a THD of less than 1%, indicating high compatibility with IEEE grid standards. Additionally, the design minimizes switching losses and ensures seamless power transfer to the grid. These features make the system an excellent candidate for hybrid renewable energy integration, supporting sustainability and efficiency.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Bonigala Ramesh	✓	✓	✓		✓	✓	✓			✓		✓	✓	✓
Madhubabu Thiruveedula	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓
Rahul Inumula	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
C. Poojitha Reddy	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Mohammad Abdul Khadar	✓	✓			✓		✓		✓	✓		✓	✓	✓
K. Sri Sai Hareesh	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

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

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BIOGRAPHIES OF AUTHORS

Bonigala Ramesh is received M.Tech. in electrical power engineering in 2011. He is working presently as an assistant professor at Teegala Krishna Reddy Engineering College, Hyderabad, India. His areas of interest include power systems, power electronics, and power quality. He can be contacted at email: r.bonigala@gmail.com.

Madhubabu Thiruveedula is received B.Tech. from JNTU Hyderabad, Hyderabad, India, in 2010 and M.Tech. from NIT Calicut in 2012, respectively, and pursuing a Ph.D. at Annamalai University, India. He is presently working as an assistant professor and HOD at Teegala Krishna Reddy Engineering College, Hyderabad, Telangana, India. He has presented technical papers in various national and international journals and conferences. He can be contacted at email: madhumk448@gmail.com.

Rahul Inumula is received the diploma from Jyothismathi Institute of Technology Science (JMTK), Karimnagar in 2022 presently a UG student in electrical and electronics engineering at Teegala Krishna Reddy Engineering College, Hyderabad, India. He completed an internship in diploma in TLO Ramagundam, Malyallapalli Substation Peddapalli district. He has an interest in power systems and machines. He can be contacted at email: inumularahul@gmail.com.

C. Poojitha Reddy completed her intermediate studies from Vignan Junior College, Shadnagar in 2021 and is presently a UG student in electrical and electronics engineering at Teegala Krishna Reddy Engineering College, Hyderabad, India. She has an interest in power systems and machines. She can be contacted at email: poojithareddy640@gmail.com.

Mohammad Abdul Khadar is received the diploma TRR College of Technology in 2021 and is presently a UG student in Electrical and Electronics Engineering in Teegala Krishna Reddy Engineering College, Hyderabad, India. He completed an internship in diploma in Radiant Appliances and Electronics Pvt Ltd, Ravirala Village, RR District, Hyderabad, Maheshwaram. He has an interest in machines. He can be contacted at email: abdulkhadar6779@gmail.com.

K. Sri Sai Hareesh is received the diploma from Govt Polytechnic College Husnabad, Siddipet district in 2022 and is presently a UG student in electrical and electronics engineering at Teegala Krishna Reddy Engineering College, Hyderabad, India. He completed an internship at RKJ Technology Pvt Ltd, Koti, Hyderabad. He has an interest in power systems. He can be contacted at email: hareeshkoyyada@gmail.com.