

Integration of Solar Thermal Energy Conversion with a Novel Multilevel Inverter Circuit for Low-Power Applications [†]

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Abstract

The rise of carbon emissions from fossil fuel-based power generation has intensified the need for efficient and low-carbon energy systems. The global CO₂ concentration has risen from 285 ppm in the pre-industrial era to nearly 420 ppm today, and this contributes to a 1°C increase in average temperature. Therefore, in this article, a hybrid photovoltaic–thermoelectric generator (PV–TEG) system integrated with a reduced-switch multilevel inverter (MLI) is proposed. This enhances renewable energy utilization and power quality. The proposed PV–TEG model recovers waste heat from PV modules, which yields an overall efficiency improvement of approximately 2–8% compared to standalone PV systems. Further, the proposed MLI operates in symmetric (seven-level) and asymmetric (11-level) modes using eight switches. The system develops high-quality stepped output voltages with a minimum component count. Simulation work is performed, and the results show a peak output voltage of ± 220 V with Total Harmonic Distortion (THD) of 7.2% under R-load and reduced THD below 5% under RL and variable load conditions. The integrated system demonstrates improved efficiency, reliability, and suitability for sustainable power generation and rural electrification.

Keywords: Harmonic Reduction; Low-Voltage AC Applications; multilevel inverter (MLI); Solar Energy-Harvesting; thermoelectric generator (TEG)

1. Introduction

Nowadays, carbon emissions have become one of the most critical challenges threatening sustainable development across the globe, which causes environmental degradation. This has led to a rise in greenhouse gas emissions because of the overuse of non-renewable energy sources, particularly carbon dioxide (CO₂). Emissions of carbon must be lowered to ensure long-term energy security, sustainable consumption, and the preservation of natural resources and to mitigate global warming [1]. In the pre-industrial era, CO₂ concentrations increased from about 285 ppm to around 420 ppm today. This rise has contributed to a temperature increase of nearly 1 °C and accelerated environmental degradation. The electricity division serves as one of the largest sources of CO₂, which makes the transition



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to low-carbon generation and grid operation. By 2050, continued fossil fuel combustion will raise global emissions by 50%. To limit global warming to less than 2 degrees Celsius, 197 nations adopted the Paris Agreement to counter this. Recent research shows that generation expansion, network planning, and market design must explicitly integrate emission constraints, carbon pricing, and low-carbon technologies rather than treating CO₂ as an externality. For example, in China, an integrated expansion planning model reported on power systems embedding low-carbon factors into generation expansion. This enables decision-makers to evaluate tradeoffs between cost, capacity growth, and emission targets in a unified model [2].

Globally, to meet climate goals, engineering frameworks that couple physical system constraints with carbon metrics are becoming critical. As nations strive to achieve the 2030 Sustainable Development Goals (SDGs), especially carbon neutrality, reducing carbon emissions has become a global priority. Innovative policy measures and technological advancements to curb dependency on fossil fuels and promote cleaner, sustainable energy alternatives are being introduced by the government [3].

1.1. Renewable Energy

Renewable energy is an alternative sustainable approach in order to reduce dependence on fossil fuels. Using renewable energy technology takes advantage of endless sources of energy like the sun, wind, ocean waves, and biomass. Renewable energy technologies have little negative effect on the climate and the environment [4]. In the past decade, the renewable energy industry has expanded rapidly, and as shown in Table 1, there have been many successful large-scale installations of renewable energy technologies in various countries.

Table 1. Renewable energy projects of different technologies around the world.

Power Plant Name	Technology	Country	Year	Installed Capacity (MW)
Bhadla Solar Park	Photovoltaics	India	2018	2245
Huanghe Hydropower Hainan Solar Park	Photovoltaics	China	2020	2200
Ouarzazate Solar Power Station	Parabolic Trough and Solar Power Tower (CSP)	Morocco	2016	580
Mohammed bin Rashid Al Maktoum Solar Park (Phase IV)	Photovoltaic + CSP Hybrid	UAE	2024	5000
Tengger Desert Solar Park	Photovoltaic Solar Power	China	2019	1547
Baihetan Hydropower Station	Hydroelectric Power	China	2021	16,000
Dogger Bank Wind Farm (Phase A–B)	Offshore Wind Power	United Kingdom	2022	2400
Noor Abu Dhabi Solar Plant	Photovoltaic Solar Power	United Emirates	2023	1177

Although there is much growth potential for renewable energy technologies, there are still many challenges associated with their implementation. Solar power can be reduced by nearly 70% during days with clouds, and wind turbines may not produce energy in still air, resulting in fluctuations in available electric power. To address those issues, energy storage technology has been developed to store and balance the supply of renewable energy with the demand for it, and hybrid renewable systems that combine multiple energy types can provide higher efficiency and reliability. Furthermore, smart grids and artificial intelligence-enabled intelligent energy management systems help improve operational flexibility, increase performance, and facilitate the transition to a sustainable, low-carbon global energy future [5].

1.2. Rural Electrification

Rural electrification plays the role of reducing poverty and achieving sustainable rural development. The objective of rural electrification has been hindered by various obstacles, such as infrastructure constraints, costly construction, and maintenance of the power lines. Also, the high cost of installation and maintenance with low revenue returns limits the availability of access to reliable energy sources, trained labor, and equipment [6]. Although several programs are designed to bring electricity to all citizens, the demand continues to grow.

Table 2 illustrates the progress made toward rural electrification in several states. However, to address these challenges, renewable and decentralized sources like solar home systems (SHS) are being promoted. Electrification enhances education, healthcare, and livelihoods, particularly benefiting women and children. Despite notable progress, challenges such as affordability, reliability, and policy implementation persist, making rural electrification a complex issue. The largest obstacle to achieving universal access to energy, as defined in the UN Sustainable Development Goal 7, is to focus on providing energy to rural regions (areas outside major cities), while continuing to improve the reliability and affordability of that energy. Achieving universal access includes providing quality electric service and building sustainable and inclusive energy consumption practices to create the opportunity for long-term socio-economic transformation [7].

Table 2. Rural electrification and primary source of power in several states.

State/Region	Rural Households Electrified	Average Daily Supply (h)	Primary Source of Power	Renewable/Off-Grid Penetration (%)
Uttar Pradesh	96%	17 h/day	Grid + Solar Mini-grids	14%
Bihar	94%	16 h/day	Grid + Solar Home Systems	22%
Rajasthan	99%	20 h/day	Grid + Solar	25%
Madhya Pradesh	98%	19 h/day	Grid + Biomass	12%
Odisha	92%	15 h/day	Grid + SHS	18%
West Bengal	97%	18 h/day	Grid	9%
Jharkhand	91%	14 h/day	Grid + Solar Hybrid	21%
Tamil Nadu	100%	23 h/day	Grid	8%
Assam & NE States	89%	13 h/day	Grid + Solar	19%
All India Average	96%	18 h/day	Grid+ Renewables	17%

2. TEG Assisted MLI for Rural Electrification

TEG: In this contemporary world, we are facing a lot of challenges, and there is an urgent call for the use of alternative sources to reduce our dependency on non-renewable resources. In our day-to-day life, electricity plays a very major role; it helps us to improve our social and economic growth. But if we look at our day-to-day demands, it is very challenging to meet all our needs, and the supply of electricity is in demand. Keeping in mind environmental sustainability and energy security, we are in need of a new alternative for our needs, which is new, cleaner, and the best alternative for our ecology [8]. One such solution for our problem is thermoelectric generator temperature gradient devices that convert residual thermal energy into a current supply through the Seebeck effect.

A basic diagram is shown in Figure 1. T_c and T_h indicate the temperatures at the end of the two materials; the difference in temperatures generates the voltage. When it is integrated into a system such as a combustion engine exhaust or an industrial heat

source, a TEG recovers the waste heat and transforms it into a usable power supply. It also improves the overall efficiency by increasing the generation of electricity from the same fuel input while cutting air pollution through using a lesser amount of fossil fuels. As we have mentioned earlier, a higher temperature difference gives us a large output voltage and power. On one hand, thermoelectric machines are weak; however, better parts and smart internal designs are slowly growing their potential. This paves the way for the world to move away from oil and coal [9].

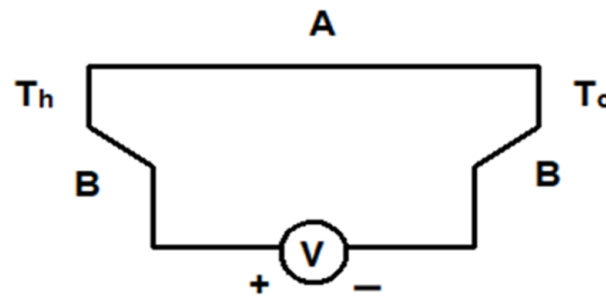


Figure 1. Basic model of TEG.

MLI: In a growing world, the use of solar panels to generate electricity in grid-connected applications has created a strong demand for reliable and efficient power conversion. Inverters play an important role in addressing the power quality issues such as harmonics, voltage imbalance, and frequency deviations [10]. Shunt Active Power Filters (SAPFs) with multilevel inverter topologies are widely used to enhance current waveform quality and the stability of the system. Multilevel Converters (MLCs) offer modularity, scalability, and enriched suitability of the medium and for high-voltage applications to improve the power backup; the system is integrated with a battery storage system [11]. MLIs are advanced converter topologies developed to improve power quality and reduce harmonic distortion of the medium and for high-voltage applications. Among them, the diode-clamped, or neutral-point-clamped (NPC), inverter uses clamping diodes to fix the voltage levels at the DC bus midpoint, providing improved harmonic performance and reduced voltage stress on switching devices, although it suffers from neutral-point voltage imbalance and higher component count at greater levels [12]. Clamping diodes are replaced by a Flying Capacitor Multilevel Inverter (FCMLI) with capacitors that fly between voltage levels, offering backup in switching states, and it provides better voltage, but its design becomes more complex as capacitor count and balancing requirements increase [13].

The cascaded H-bridge (CHB) inverter consists of multiple H-bridge cells that are connected in series. It is provided by an isolated DC source, producing high-quality stepped waveforms with modular and scalable design advantages suitable for high-power applications; however, it requires multiple isolated supplies, which leads to an increase in the cost of the system and control complexity. Overall, these topologies, NPC, FC, and CHB, represent the three primary structures of multilevel inverters, each balancing its efficiency, control complexity, and hardware requirements to achieve optimal performance in modern power electronic systems [14]. As compared to NPC MLIs, T-type multilevel inverters offer a lower switch count and reduced conduction. Because it uses a T branch in each switch arm (commonly two switches plus a bidirectional device), it can achieve midpoint voltage control and smoother output voltage with fewer devices. A modular switched capacitor T-type structure eliminates the H-bridge and significantly reduces device count while achieving higher voltage gain [15]. The topology is particularly suitable for RES and medium-voltage applications, with advantages of improved efficiency and lower THD.

However, while the T-type shows great promise, it still faces challenges in terms of balancing DC-link voltages, ensuring reliability of the bidirectional switch, and extending efficiently to high voltage/high level systems [16]. The sub-module-based multilevel inverter concept introduces a modular cell (“sub-module” or Sub-M) that can be cascaded or stacked to form higher-level ML converters with reduced switch count, fewer isolated DC sources, and improved modularity. In one topology, these Sub-Ms consist of combinations of unidirectional/bidirectional switches and DC voltage sources arranged so that the number of IGBTs, drivers and DC sources is minimized compared to conventional topologies.

The design methodology provides mathematical analyses for switching and conduction losses, device count, and voltage stress across components, showing improved performance trade-offs. These Sub-M architectures are especially relevant in applications like the Modular Multilevel Converter (MMC) for high-voltage/high-power systems, where modularity, fault tolerance, and scalability become critical [17]. The PUC inverter topology uses a compact “U-cell” structure, each U-cell combining two power switches and a clamping (or floating) capacitor, enabling multilevel voltage output with a single DC source plus auxiliary capacitor rather than multiple isolated sources. By leveraging redundant switching states and the floating capacitor in the U-cell, the PUC topology reduces the number of switching devices and DC sources compared to traditional multilevel inverters (such as NPC or CHB) [18].

Another work demonstrates a single-DC-source, three-phase modified PUC inverter (nine-level) with active floating-capacitor balancing and fewer active and passive devices, showing viability for standalone or grid-connected applications. The PUC topology is particularly suitable for renewable energy applications, where it can offer lower component count, lower switching losses, and reduced harmonic distortion (THD) than many conventional multilevel topologies [19]. In an asymmetric multilevel inverter topology, the DC input sources have unequal magnitudes (e.g., $V_1 \neq V_2 \neq V_3$), enabling a larger number of output voltage levels for the same number of switches and modules compared to symmetric designs. Because more discrete voltage steps are available, the output waveform approximates a sine more closely, leading to lower total harmonic distortion (THD) and reduced filtering effort [20].

One design study demonstrated that the nine-level asymmetric configuration achieved a THD of 14.54% under sinusoidal PWM, compared to 26.92% for a five-level symmetric topology using the same switching structure. The trade-offs involve careful DC-link voltage selection, balancing of unequal sources, and often more complex modulation or balancing control to manage unequal voltages and ensure safe operation. Asymmetric topology is particularly useful in applications requiring high output voltage quality and high level counts (e.g., renewable interface, medium voltage drives) while saving on semiconductor count and cost [20].

From the above discussions, in this article, the following contributions are shown:

1. The article demonstrates an integrated PV–TEG system that effectively recovers waste heat from conventional PV modules, achieving an overall efficiency improvement of 2–8%, which reduces PV operating temperature and enhances system reliability.
2. An MLI circuit that employs eight switches is proposed, capable of operating in both symmetric (seven-level) and asymmetric (11-level) modes. This reduces component count, cost and switching losses compared to the conventional MLIs referred to here.
3. Simulation results demonstrate enhanced harmonic performance with voltage THD reduced from 7.2% (R-load) to below 5% under RL and variable RL loads. This highlights the inverter’s robustness and suitability for practical renewable energy systems.
4. Finally, the independent DC–DC conditioning of PV and TEG outputs prior to MLI integration enables stable voltage regulation despite the low and variable nature of

TEG voltage. This ensures reliable hybrid operation for grid-connected and standalone renewable applications.

3. Design and Modelling of TEG and MLI

3.1. Design of TEG Model

Standard photovoltaic (PV) modules typically convert only 15–20% of incidental solar irradiance into electricity, with the remaining energy dissipated as heat that raises cell temperature and decreases efficiency. In order to overcome this, hybrid photovoltaic–thermoelectric generator (PV-TEG) systems integrate a TEG module, as shown in Figure 2, which is attached to the rear surface of the PV panel to recover this waste heat. In this study, a solar panel with a 10 W polycrystalline PV module is utilized, featuring a total surface area of 0.1 m² (285 mm × 350 mm) and a 36-cell configuration. In this configuration, the PV module absorbs visible and UV radiation to produce primary DC power, while the residual heat is transferred to the hot side of the TEG. The system utilizes an optimized tilt angle and a heat absorber to facilitate thermal collection [21]. By maintaining a cold-side temperature via the heat sink, a significant temperature gradient is established, triggering the Seebeck effect to produce supplementary DC voltage. This dual-action approach not only generates additional power but also provides active cooling, which lowers the PV operating temperature and improves overall reliability. Consequently, the total hybrid efficiency, defined as the ratio of combined PV and TEG power to incident solar energy, can achieve a net improvement of 2–8% over standalone PV systems [22]

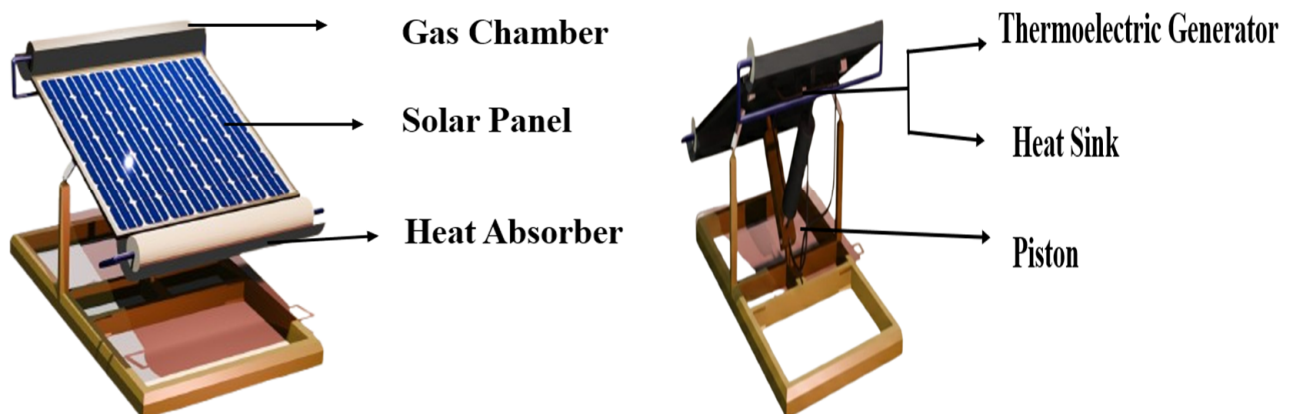


Figure 2. Model of PV with TEG-integrated MLI.

3.2. Design of MLI Model

The proposed inverter topology shown in Figure 3 uses eight switches (S1–S8) and multiple DC sources to produce the stepped output voltage levels with reduced component count. The same circuit can work in symmetric and asymmetric modes. This makes it flexible and suitable for renewable energy and lower-power applications. In the symmetric operation, all DC voltage sources have the same value. This configuration features equal voltage steps on the output waveform, which facilitates the modulation strategy and provides balanced voltage stress across the switching devices. The proposed inverter, which is shown in Figure 3, uses three DC sources and eight switches (S1–S8) to generate seven levels of output voltage (+3, +2, +1, 0, −1, −2, −3).

During the positive half-cycle period, the load is connected to DC sources through a selected switch combination to generate an increasing voltage level. The switching combinations required to obtain each output level are summarized in Table 3, and during the negative half-cycle period, the polarity is reversed by commutating the appropriate

switches while maintaining the same magnitude of voltage levels. This method gives evenly spaced voltage levels and helps reduce harmonic distortion [23].

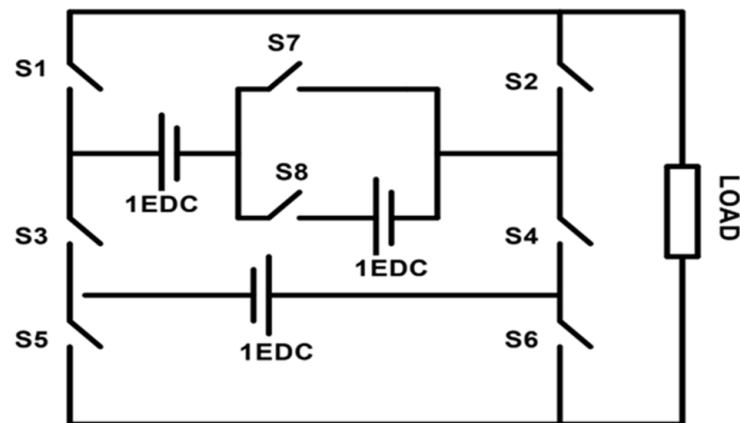


Figure 3. Symmetric MLI circuit.

Table 3. Switching table of symmetrical MLI.

Output Level	S1	S2	S3	S4	S5	S6	S7	S8
+3	1	0	0	1	0	0	0	1
+2	1	0	0	1	0	1	0	0
+1	0	1	0	1	1	0	0	0
0	0	0	1	0	1	0	0	0
−1	0	1	1	0	0	0	0	1
−2	0	1	1	0	1	0	0	0
−3	0	1	1	0	0	0	1	0

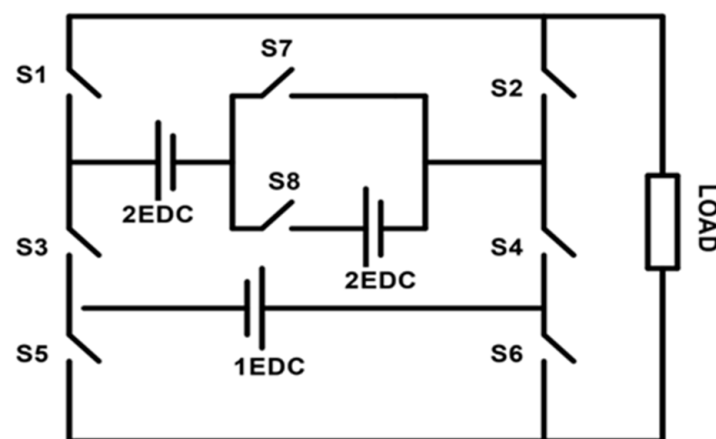
In the asymmetric operation, all DC voltage sources have different values as shown in Figure 4. This approach allows the inverter to produce more voltage levels using the same number of switches, which improves the output waveform and reduces harmonic distortion. The proposed inverter uses DC sources of 1EDC and 2EDC to generate an eleven-level output voltage (+5 to −5). By properly controlling switches S1–S8, more intermediate voltage levels are obtained, giving better harmonic performance than the symmetric model. The corresponding switching states for each voltage level are provided in Table 4. MLIs exhibit superior harmonic performance and higher voltage resolution when compared to symmetric topologies with the same number of power switches [24]. Compared to the symmetric configuration, the asymmetric mode produces more voltage levels without adding extra switches or components. Symmetric MLIs are easier to control, while asymmetric MLI gives better output quality with lower harmonic distortion. The proposed inverter can operate in both modes, allowing the best choice based on the application, available DC sources, and required output quality.

Table 4. Switching table of asymmetrical MLI.

Output Level	S1	S2	S3	S4	S5	S6	S7	S8
+5	1	0	0	1	1	0	0	1
+4	1	0	0	1	0	1	0	1

Table 4. *Cont.*

Output Level	S1	S2	S3	S4	S5	S6	S7	S8
+3	1	0	0	1	1	0	1	0
+2	1	0	0	1	0	1	1	0
+1	0	1	0	1	1	0	0	0
0	1	1	1	1	1	1	0	0
−1	1	0	1	0	0	1	0	0
−2	0	1	1	0	1	0	1	0
−3	0	1	1	0	0	1	1	0
−4	0	1	1	0	1	0	0	1
−5	0	1	1	0	0	1	0	1

**Figure 4.** Asymmetric MLI circuit.

3.3. Design of TEG Integrated with Proposed MLI

The integration of a photovoltaic (PV) and thermoelectric generator (TEG) with a multilevel inverter (MLI) significantly enhances the overall performance and energy utilization level of the renewable energy system.

In the proposed model, the PV panel serves as the primary electrical energy source, while the waste heat from the PV module is effectively treated by TEG, thereby increasing the total power extraction from the same solar input. As illustrated in the block diagram in Figure 5, the DC output of the PV panel is processed further through a DC–DC converter, and a battery storage unit is used to ensure voltage regulation and energy continuity, whereas the DC output obtained from the TEG is independently conditioned using a dedicated DC–DC converter due to its low and variable voltage characteristics.

The conditioned DC outputs from both PV and TEG subsystems are then supplied to the multilevel inverter, which converts the combined DC power into a high-quality AC output for the load. By using MLI in this hybrid architecture, it offers reduced total harmonic distortion, lower switching stress, and improved power quality compared to conventional two-level inverters. Consequently, the proposed PV-TEG-MLI configuration improves overall system efficiency, enhances reliability under varying environmental conditions, and enables effective utilization of both solar radiation and thermal energy.

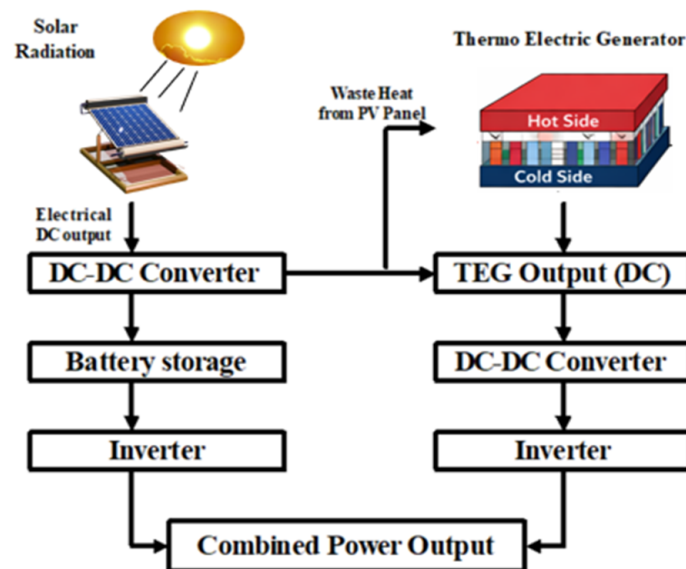


Figure 5. Hybrid TEG with MLI based on PV.

4. Simulation of Proposed TEG and MLI (Integration)

The MATLAB Simulink model, which is shown in Figure 6, illustrates a thermoelectric generator (TEG) system that has been developed to convert a temperature difference into electrical energy based on the Seebeck effect. In this simulation, the powergui block is used to ensure proper and accurate electrical behavior of the executed simulation. The thermoelectric generator receives four input parameters, and their ratings are the hot-side temperature ($T_h = 692$ K), which represents the applied heat source; the cold-side temperature ($T_c = 238$ K), which represents the modeling of effective cooling conditions; the Seebeck coefficient ($S_b = 0.025$ V/K), which defines the voltage generated per unit temperature difference of the thermoelectric material; and the module number ($M_n = 4$), indicating multiple TEG modules.

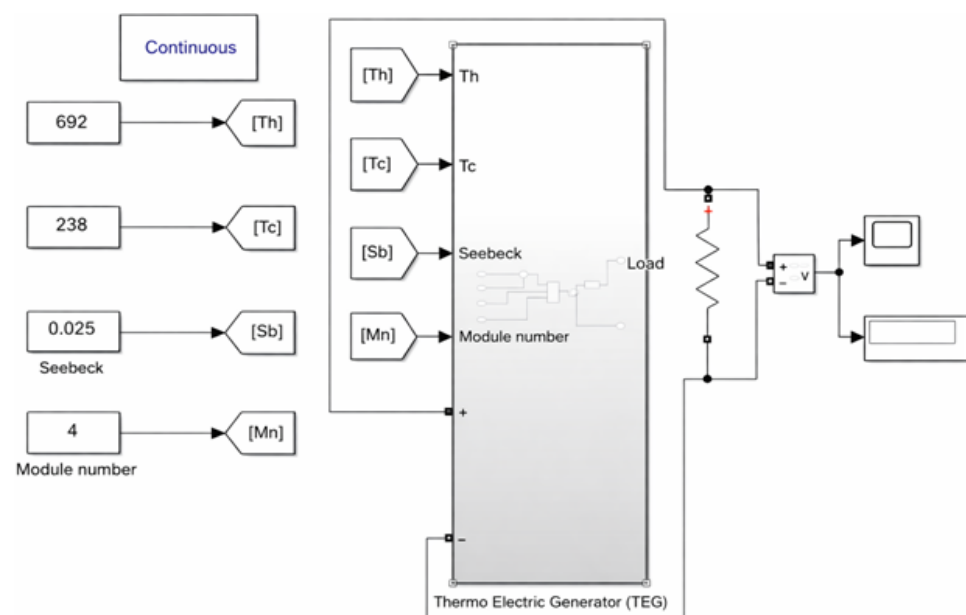


Figure 6. Simulation of the TEG.

The modules are connected in series to enhance the output voltage. The inputs help to determine the thermally induced electromotive force generated within the TEG block,

and further, the electrical output terminal of the thermoelectric generator is connected with an external resistive load, across which the generated voltage is measured using a voltage measurement block. The output voltage is observed through a scope, which indicates that the thermoelectric generator delivers a stable and steady output under the applied temperature difference.

The buck converter waveform shows that there is an effective step-down operation with a fast transient response and good voltage regulation. The boost converter output waveform demonstrates an efficient voltage step-up operation with minimal ripple and steady-state stability. This simulation framework effectively demonstrates low-power energy-harvesting capability from thermal gradients and serves as a foundation for integrating TEG systems with power electronic converters and multilevel inverters.

To evaluate the performance of the proposed inverter under different loading conditions, namely R-load, RL-load, variable R-load, and variable RL-load, is carried out using MATLAB Simulink version 2024. We can clearly understand the electrical behavior and harmonic performance of the system through the output voltage and current waveforms obtained from the simulation provided. As shown in Figure 7, the output voltage under R-load exhibits a stepped quasi-sinusoidal waveform that has a peak value of approximately ± 220 V and an RMS value of 155 V, which indicates proper switching and balanced operation of the inverter, and its corresponding output current waveform shows a peak value of about ± 2.5 A and remains in phase with the voltage, which confirms that the load is of a purely resistive nature.

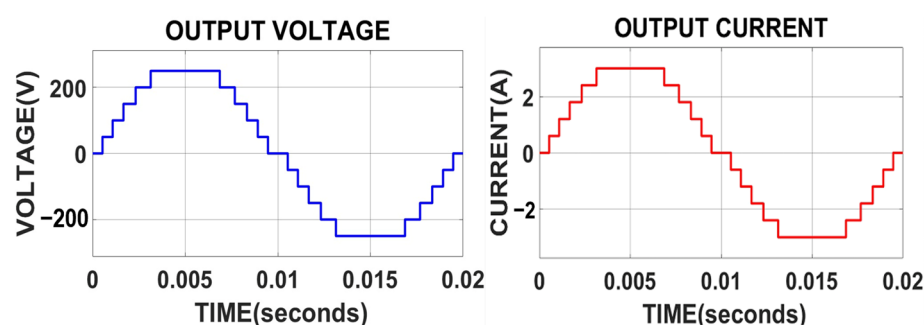


Figure 7. Output current and output voltage for R load.

However, the absence of a reactive component makes harmonic components higher, which results in voltage and current total harmonic distortion values of approximately 7.2%. The Figure 8 shows the load waveform of the inverter fed to variable R load and it is can be inferred that the load current varies with the change in load values.

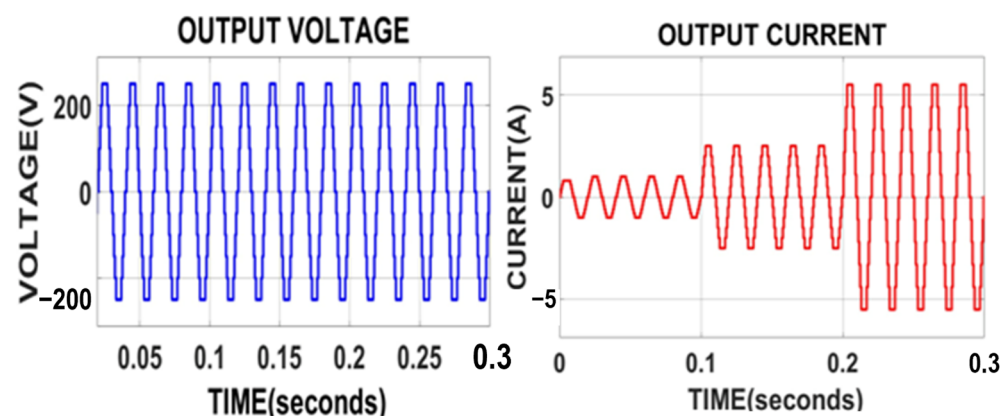


Figure 8. Output current and output voltage for variable R load.

The output voltage of the RL load maintains a stable stepped waveform, which indicates proper multilevel switching, proper and stable voltage regulation, and reduced harmonic distortion due to the filtering effect of the inductive load. The stepped waveform has a peak magnitude of ± 220 V and an RMS value of nearly 150 V. The peak value of output current 2.1 A, which has some lag due to the inductive component of the load. As inductance acts as a natural filter, it helps to smooth the waveform, and it also reduces the harmonic distortion, which lowers the voltage total harmonic distortion to 5.3% and the current total harmonic distortion to 4.1%. From Figure 9, we can understand the performance of the variable RL—the load voltage output remains constant at ± 220 V even though a load impedance change occurs, which shows the robustness of the inverter system, and the output current amplitude varies between ± 1.6 A and ± 2.4 A according to the load variation while maintaining a near-sinusoidal shape. It has an increase in inductive reactance, so the current ripple is reduced and the phase change becomes more pronounced, which helps to make the reduction progressive, reducing the current total harmonic distortion from 4.5% to 3.6%, and the voltage THD remains below 5% for all operating conditions.

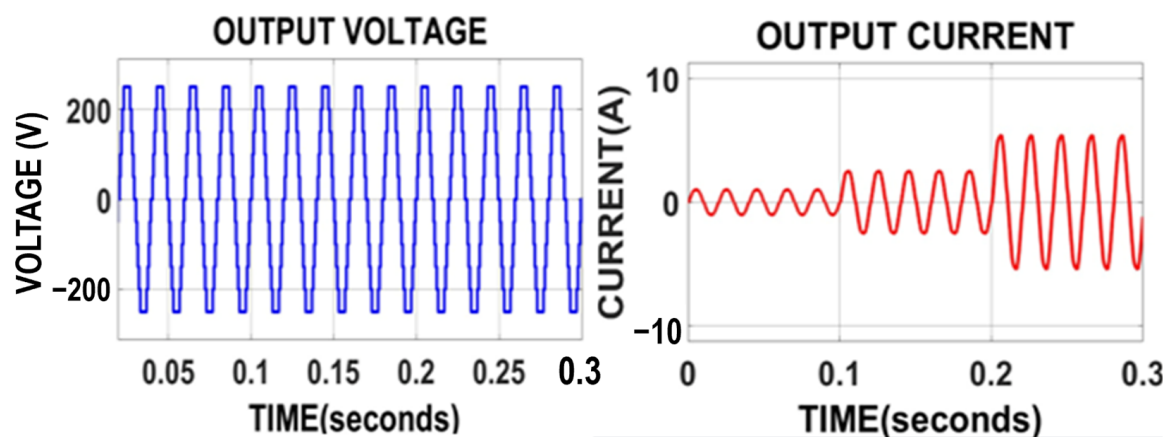


Figure 9. Output current and output voltage for RL load.

From all the results, we can confirm that the proposed multilevel inverter delivers stable voltage output, improves current quality, and helps in reducing the harmonic distortion under inductive and variable loading, which makes it more suitable for the practical use of power electronics and also for renewable energy applications.

5. Conclusions

This paper presents a hybrid renewable energy conversion system using a solar PV source integrated with TEG and a new topology of multilevel inverter for low-power applications. The approach effectively utilizes solar irradiance and waste thermal energy, enlarging the net utilization of energy compared to conventional systems that only consider photovoltaic transduction. A TEG model was developed and simulated in this work, showing that it can provide stable DC voltages under temperature gradients, hence validating its suitability as a supplemental source of energy. Also, the symmetric and asymmetric MLI topologies that were designed were effectively implemented and analyzed, which proves improvements within output voltage quality, reducing harmonic distortion and lowering switching stress. The MATLAB/Simulink simulation results hereafter prove that the integration of PV, TEG, and MLI increases overall efficiency, provides better quality of power, and has a reduced component count over conventional inverter configurations. In this regard, research trends are carried out to show that hybrid PV-TEG systems combined with

advanced multilevel inverters need to be considered as a promising solution for compact, efficient, and sustainable power conversion of low-power and distributed energy applications. Possible future work may include experimental validation, higher-order modulation strategies, and intelligent control techniques to achieve superior system performance.

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