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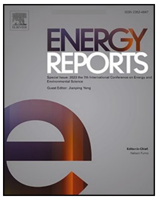

Research paper

Load management design and techno-economic analysis for an islanded hybrid Pv-Teg microgrid

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ABSTRACT

Integration of various renewable energy sources (RES) is one of the critical factors behind microgrid (MG) capacity development and MG expansion. Distributed energy resources with and without RES, electrical loads, controllers, and storage units constitute the essential components of MGs. On the other hand, with the addition of different power generation sources, load prediction on the user side of the MG becomes an important issue. Demand response solutions and changing end-user behavior are the other sources of uncertainty in the performance of MGs. Therefore, matching supply and demand is a very important issue that must be done immediately at every moment of the operation. A load management system (LMS) in a community MG is essential to ensure the system's adaptability. Fuzzy logic (FL) controllers and energy management systems will ensure optimum use of energy resources and efficient operation of MG and reduce energy waste. In this study, an 85 kW photovoltaic (PV) and thermoelectric generator (TEG) hybrid MG system (PVTEG-MG), which can operate as an island grid in all regions of the World with hot water resources, has been designed for the first time and its techno-economic analysis has been made. The state of charge (SOC) for the proposed PVTEG-MG remained stable at 40% charge state by adding charge management. The average value of the Levelized Cost of Energy (LCOE) is $0.456/kWh for PV, $0.456/kWh for TEG, and 0.399/kWh over the total energy produced, 219,000 kWh for the PV and 493,650 kWh for the TEG. Overall, this PVTEG-MG system is a promising solution for hot water regions that can be used as an island grid to reduce electricity costs, increase efficiency and reliability, and provide a more sustainable energy source.

1. Introduction

Conventional electricity grids are being replaced worldwide by MGs; an innovative electricity grid powered by renewable energy (Uddin et al., 2023). This transformation is driven by the potential of MGs to reduce energy costs, and greenhouse gas emissions, and facilitate the integration of substantial quantities of RES into power networks (Hai and Zhou, 2023). MGs, considered low-voltage power supply networks suitable for feeding small settlements, are a method for increasing the dependability, security, cooperation, and efficiency of the regular power grid network (Khare and Chaturvedi, 2023). MGs are expected to be more reliable and cheaper than conventional centralized grids. The main objectives of MGs are to increase the use of RES, add storage, increase the efficiency of energy supply, strengthen the system's resilience, and allow for simple adjustments (Gharehveran et al., 2023). To achieve these goals, conventional distributed energy sources such as diesel generators and microturbines, non-traditional distributed energy sources such as RES, energy storage devices such as batteries, and critical or non-critical loads as primary components can be found in an integrated management structure (Ali et al., 2023).

Integration of many renewable energy types, such as wind and solar energy, tidal (Faridnia et al., 2019), biogas (Nawab et al., 2022), biomass (Araoye et al., 2023), wave energy (Barajas-Ritchie et al., 2023), and hydrogen (Alzahrani et al., 2022) into MGs continues. Nearly zero-emission energy use in MG (Liu et al., 2022), modeling and optimization of distributed energy sources in MG (Twaisan and Barışçı,

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Abbreviations: AC, Alternative Current; BMS, Battery Management System; DC, Direct Current; FL, Fuzzy Logic; LCOE, Levelized Cost of Energy; LMS, Load Management System; OMC, Operating and Maintenance Cost; MG, Microgrid; PV, Photovoltaic; RES, Renewable Energy Sources; TEG, Thermoelectric Generator; PVTEG-MG, Photovoltaic and Thermoelectric Generator Hybrid Microgrid System.

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2022), energy sharing based on cloud computing (Su and Shi, 2023) are among the topics that continue to be researched. Among RES, PV energy stands out mainly due to its ease of installation and installation and maintenance costs. The total installed capacity of solar photovoltaic at the end of 2017 was 402.5 GW or around 2.1% of the World's electricity generation (Brunisholz, 2017). According to the International Renewable Energy Agency, it is expected to reach 4500 GW by 2050. PV energy significantly contributes to countries' national development (Apeh et al., 2022). In addition, PV energy can be easily used with other RES and can create various hybrid structures such as PV-wind-fuel cell (Samy et al., 2021), pumped hydroelectric storage-integrated hybrid PV/wind (Nassar et al., 2021), implementation of hybrid solar/wind/biomass considering meteorological conditions (Hossen et al., 2022). However, the sun does not constantly shine, and on many occasions, there is no wind. Therefore, PV and wind energy are unstable and unavailable 24 hours a day. In addition, the water resources required for hydroelectric energy may not be sufficient. In this case, hot water resources in many parts of the World have emerged as a great and new renewable energy potential.

TEGs are very up-to-date renewable energy generators based on the Seebeck effect and work on converting the temperature difference at the ends to electrical voltage (Jaziri et al., 2020). TEGs use hot sources of nature such as hot water from hot springs and ground or by-products of the industrial or consumption processes such as waste heat recovery, industrial waste heat, flue gas waste heat, and vehicle exhaust waste heat to generate free electricity (Tohidi et al., 2022). However, permanent hot springs are located primarily in small residential areas away from the central settlements.

In on-grid mode, MG can easily regulate system parameters such as current, voltage, frequency, and battery status by getting support from the main grid in case of any source or load change. On the other hand, today, many people still live in settlements far from the main grid, both on the mainland and on the islands. For these reasons, even though an MG can operate in both modes, the island design of the PV-TEG system is a more difficult but more realistic option for electrifying remote rural areas (Akinyele et al., 2018). An innovative approach to optimizing an islanded MG has been proposed, but no solution or method has been provided to optimize the cost of MG (Ignat-Balaci et al., 2021). This issue must be addressed to make MGs a viable and cost-effective solution for energy producers and consumers.

A working MG must be constructed, though, requiring sophisticated control (Olivares et al., 2014). It takes intelligence to create individual controllers, converters, and battery chargers. On the other hand, a well-planned MG that is not well-run will not provide a sizable amount of electricity, even if it is well-designed. Because of this, intelligent design alone is inadequate. An intelligent MG energy management system will also be required. MGs can be managed intelligently for several reasons, such as cost savings, load reduction, and matching the profiles of electricity generation and consumption (Nanfang Yang et al., 2013). For instance, a smart MG management system might enhance the management of RES by increasing the number of loads or storage components during times of peak supply and reducing the number of dispatchable loads during times of low supply (El-Bidairi et al., 2018). It might transport electricity from the main grid to compensate for insufficient RES. Due to the high start-up and maintenance costs of RES like photovoltaic (PV) and TEG, the MG must be run efficiently. Such an MG requires a sophisticated management system. Both supply management and demand management can be used to run an MG. Energy production is regulated by supply management within the bounds of the system. Demand management, however, describes any method for lowering energy usage.

The potential of using a FL controller and algorithm for energy flow management to manage the consumption of households in other cities or countries was studied (Zec and Mikulovic, 2022); however, further research is needed to understand how these techniques can be applied in different contexts and to evaluate their effectiveness. RES without stability, like PV and wind, pose problems with LMS and operation. Power distribution state of local generation sources through a Point of Common Coupling (Boqtob et al., 2019), frequency deviations resulting from reduced system inertia (Alharbi and Bhattacharya, 2018), structured MG operation integrated with energy storage systems (Faisal et al., 2018) controlling and management of demand side optimally (Sedhom et al., 2021), an efficient protection system organized by protective relaying (Rezaei and Uddin, 2021), and extensive controlling of the overall MG system in AC, DC, and Hybrid AC–DC MGs (Sahoo et al., 2018), using the power flow in both directions, are the indispensable factors that affect how well a system operates. Beside these factors techno-economic analysis is another crucial criterion for long-term daily remote and local measurements (Mardani et al., 2024), for decarbonization in the flexibility of renewable grid-connected energy systems (Hoseinzadeh et al., 2023).

PV and TEG studies began in 1998 with a grid-connected system that addressed the installation of the system in an apartment in Spain (Lloret et al., 1998). In the following years, some studies focused on efficiency of hybrid PV/thermal system (Zakharchenko et al., 2004), the maximum power extraction (Belkaid et al., 2018), and energy, exergy, energy-economic and environmental analysis (Fini et al., 2022). Artificial neural network (Ammar et al., 2013), parameter determination (Cotfas et al., 2022), and Salp swarm optimization (Yang et al., 2023) were also studied as different aspects related to the TEG system. Advances in solar thermoelectric and photovoltaic-thermoelectric hybrid systems for power generation were also reviewed from different aspects (Tyagi et al., 2023). In none of these studies, comprehensive energy management and techno-economic analysis, including load classification, battery management, and techno-economic analysis, was found for the hot water sourced PVTEG-MG.

This paper presents a new hybrid RES with PV and TEG that uses hot water from hot springs to generate free electricity. A PVTEG-MG, controlled by the islanded management with a BMS, is presented in the new islanded MG. Additionally, the proposed PVTEG-MG can function for 24 hours without dropping out critical loads when the proposed RES is combined with an LMS controller that can continuously read the power supply from TEG and PV sources. So, the appropriate action can be taken continuously to get the MG into a stable mode. The PVTEG-MG distributes the loads while focusing on the effective use of already available energy. This strategy also considers consumer convenience and cost reduction through prioritization.

2. The proposed PVTEG-MG system

In this section, A PVTEG-MG system is presented. RESs, including PV and TEG, are connected to a DC-DC boost converter and a controlled off-grid inverter converts the power from DC to AC before going to smart meters or loads. The methodology of the proposed system is shown in Fig. 1. FL controllers are used to construct intelligent energy

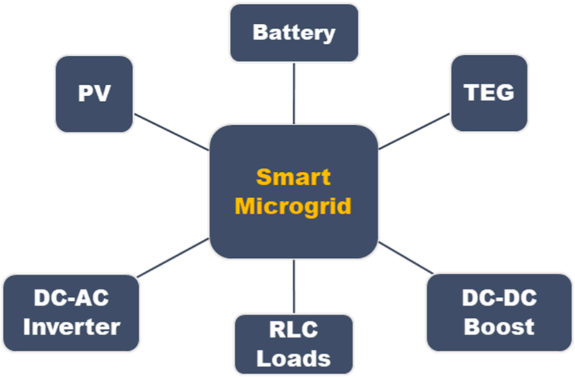

Fig. 1. Methodology of proposed PVTEG-MG.

management systems; in this study, the scheduling of load activities based on the state of power generation is examined. Understanding the MG component is simple, but understanding how the overall system works is more complex as there are multiple energy sources in the MG's system. In the traditional interconnected power system, as the distance between the source and user in electrical energy transmission and distribution increases, the number of electrical installation equipment used increases, efficiency decreases due to electrical transmission losses, and malfunctions occur along the transmission distance. For these reasons, a PVTEG-MG system is expected to reduce end-user electricity costs, increase energy use efficiency, and provide a more reliable energy source. Using RES, such as PV and TEG, also provides a way to reduce emissions and increase sustainability. FL controllers and energy management systems will ensure optimal utilization of the energy sources, reduce energy waste, and provide efficient operation of the MG. Additionally, the smart meters will provide the necessary information to the controller to adjust the power output from the sources accordingly. Overall, this MG system is a promising solution that can reduce electricity costs, increase efficiency and reliability, and provide a more sustainable energy source. The clear contribution of the proposed model for LMS in MGs lies in its ability to address the challenges posed by the integration of RESs, optimize energy use, enhance system reliability and efficiency, reduce costs, and support the broader goals of sustainability and environmental protection. This makes it an important and timely proposal for advancing the capabilities and benefits of MGs in a future oriented towards renewable energy.

The proposed PVTEG-MG, designed in MATLAB/Simulink® as shown in Fig. 2, is a distributed energy system consisting of multiple small-scale power sources and end-use loads. The MG is designed to operate in both islanded and grid-connected modes. The components of the MG include a PV array, a TEG, a BMS, and loads. The PVTEG-MG also includes a DC-DC power converter, an inverter, and a control system that manages the power flow within the system. The PVTEG-MG is designed to switch loads between weather modes in islanded mode operation based on energy source availability and load demand. The control system manages the power flow and ensures efficient and reliable operation. The entire PVTEG-MG system design in the Simulink® environment is shown in Fig. 2.

2.1. TEG section

TEGs or Seebeck generators are complex devices that use the Seebeck phenomenon to directly transform heat flux or temperature differential into electricity (Fernández-Yáñez et al., 2021). Heat engines and TEGs have similar functions; however, the former is smaller and lacks mechanical components. The TEG module is a circuit composed of semiconductor materials that can produce energy directly from heat. A direct electric current passes across the circuit if there is a temperature differential between the two ends of the materials. The relationship between the current's size and the temperature differential is generally linear. A typical TEG's construction is shown in Fig. 3a (Kumar et al. 2019). Additionally, the TEG equivalent circuit used in electrical calculations is shown in Fig. 3b.

Producers of TEG items include specifications with their products. The data sheets describe the maximum output, current, and voltage if impedance matching is feasible. Manufacturers also provide the Seebeck coefficient, one of the most important criteria, by achieving hot and cold surface temperatures of TEGs. Calculating the power from a TEG is easy when modeled using a temperature difference and the Seebeck coefficient. To generate the necessary power, modules must be linked in series and parallel in terms of module design (Liu et al., 2014) and maximum power point and load power tracking (Wu et al., 2018a). Heat transfer causes the change of electrons from n-type to p-type materials. Consequently, a voltage is produced by Eq. (1) (Liu et al., 2014) as follows:

$$\text{Open circuit voltage} = \alpha \times \Delta T \tag{1}$$

where α is the Seebeck effect, and ΔT presented to the different temperatures. The ideal Seebeck value varies between 100 and 300, depending on the substance. Short circuit can be calculated by Eq. (2):

$$\text{Short circuit current}_{\text{TEG}} = \frac{\text{Open circuit voltage}}{(R_{\text{int}} + R_L)} \tag{2}$$

Where the internal resistance, $R_{int,}$ and load resistance, R_L. One of the most widely used MPPT approaches is based on open-circuit voltage and is arguably the most suitable for the linear electrical properties of TEGs. This approach requires the voltage at the load to be half of the open circuit voltage (Montecucco and Knox, 2014a). So, the TEG power can be calculated at the maximum power point when $R_{int} = R_L$ by using Eq.

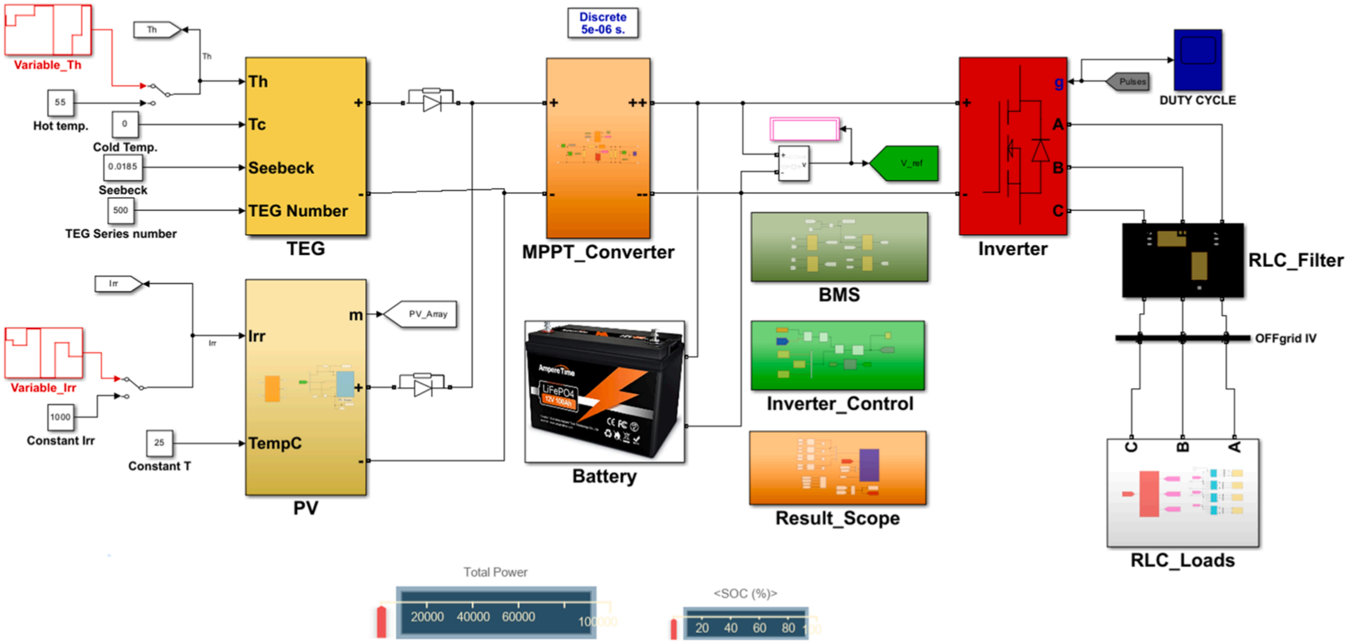

Fig. 2. Block diagram and connections of the proposed PVTEG-MG.

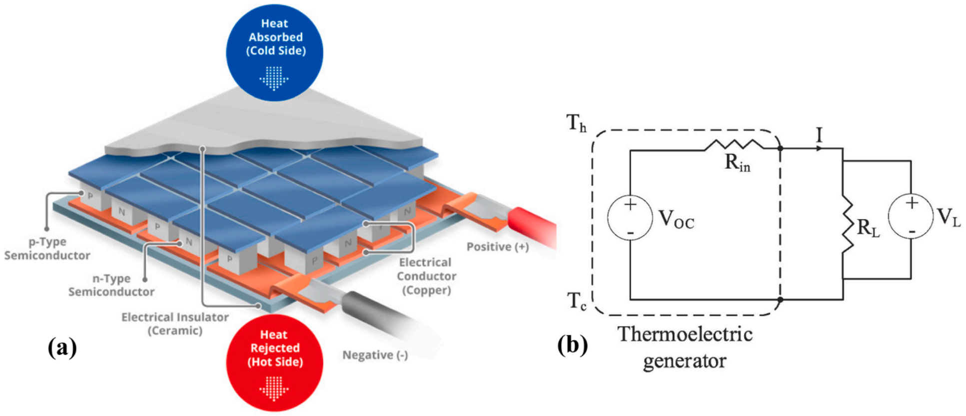

Fig. 3. TEG (a) module structure (Kumar et al. 2019), (b) equivalent circuit.

(3) (Montecucco and Knox, 2014a):

$$P = (\text{open circuit voltage TEG})^2 \times \frac{R_L}{(R_{\text{int}} + R_L)^2} \tag{3}$$

The parameters of the TEG are shown in Table 1 (Li et al., 2019).

TEG consists of three parallel units with 500 modules connected in series. Therefore, there are 1500 TEGs in total for this investigation. Fig. 4 shows the proposed TEG design in Simulink®.

2.2. PV section

A PV is an electrochemical component that uses the PV effect to transform light energy into electricity directly. PV modules, made up of PV cells coated in an environmentally friendly laminate, are the essential components of PV systems. These modules can also be connected in series or parallel to provide higher voltages, currents, and power. A string comprises a series of interconnected PV modules or arrays. One or even more pre-wired and set-up-ready PV modules comprise a PV module.

PV cells include multilayer, thin-film, crystalline, Gratzel, and dye-sensitized. Several variants are presented by (Wu et al., 2018a). By contrasting PV with diodes, it is possible to comprehend their performance. In cells exposed to light energy, electron-hole pairs are created. An electric field separates electrons and holes at the diode junction, and they are then driven into an external circuit by the junction's potential. This energy loss causes some current to flow back through the shunt and series resistance of the semiconductor (L. B., 2000). The equivalent circuit of a PV cell can be seen in Fig. 5.

Three components may represent PV cells: a parallel diode, a shunt resistor, and a constant current. The series resistance connects all three of these parts. The current via the diodes I_D and the shunt leakage current I_{sh} is deducted from the value of the sunlight-generated current I_{ph}, assuming it is the same as the output current as in Eq. (4).

$$I = I_{ph} - I_D - I_{sh} \tag{4}$$

The resistance in series and the semiconductors' properties impact the current flow's internal resistance. The shunt's resistance level determines how much current flows into the ground. If the temperature in the analogous circuit is higher than the currents flowing through the diode and the ground shunt, the power of the PV cell can be significantly reduced. When the cell's open circuit voltage is reached, this current flows toward an external load and is defined with Eq. (5).

Table 1
TEG Parameters in the PVTEG-MG (Li et al., 2019).

Parameters	Proposed Value
TEG Max power	45 kW
Max hot temperature	55 °C
Cold temperature	0 °C
Seebeck	0.0185 (μV/K)
TEG number	500 /3

$$\text{open circuit voltage pv} = V + IR_s \tag{5}$$

V is the cell output voltage. Eq. (6) is used to calculate the current of a diode, according to (Mukund, 1999):

$$I_D = I_d\left[\frac{qV_{oc}}{A_{cf}K_BT} - 1\right] \tag{6}$$

Where I_D is the diode current, I_d is the diode maximum current, q is the electron charge value 1.6×10^{-19} (C), A_{cf} is the constant curve fit, and K_B is the constant of Boltzmann 1.38×10^{-23} (Joule/° KT). Also, the output current is represented by Eq. 9 (Chiang et al., 2003):

$$I_{ph} = \frac{G}{100}\left[I_{SCR} + K_I(T - 25)\right] \tag{7}$$

$$I_{os} = I_{or}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_{GO}}{BK_B}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \tag{8}$$

$$I = I_{ph} - I_{os}\left\{\exp\left[\frac{qV_{oc}}{A_{cf}K_BT}\right] - 1\right\} - \frac{V_{oc}}{R_{sh}} \tag{9}$$

Table 2 shows the ET Solar New Energy ET-P672320WW PV parameters for one panel (ANON, 2024). All PV system consists of 20 parallel and 16 series connected modules per string.

2.3. DC-DC Boost converter

Converters can easily switch between two distinct voltages. Fig. 6 shows a boost converter in action. The converter's coil is crucial for maximum power points, which are discovered using a programmable coil current. The boost converter voltage grows as the switching frequency is increased from kHz to MHz. The optimal switching frequency ranges from 20 kHz to 2 MHz. The duty cycle controls the voltage. The L coil's magnetic field contains energy released when the switch is flipped on. The $C2$ capacitor supplies the current to the load, while the D diode does not transmit any current. After the S switch is turned off, the voltage of coil L is added to the source voltage, and coil L's current drop is subjected to the back electromotive force. The $C2$ capacitor is charged when current flows through the RL load, D diode, and L coil (Mamur and Çoban, 2019). Boost converter control is accomplished by maximum power point tracking. With maximum power tracking, the output of a PV generator and a TEG is maximized under various environmental conditions, especially those involving solar radiation and temperature.

The boost converter is a DC-to-DC converter that can be used to

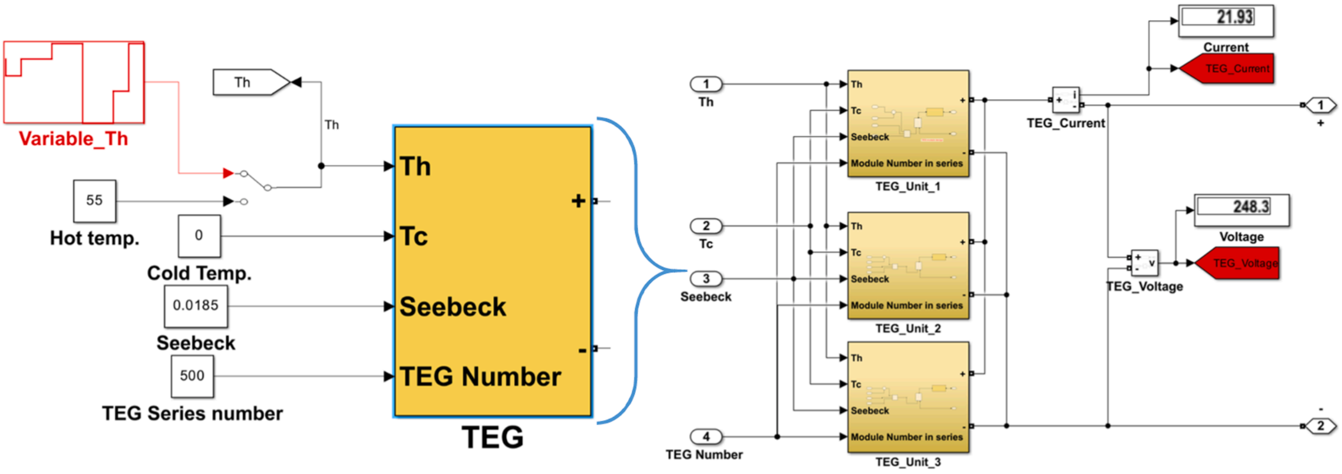

Fig. 4. TEG design in Simulink®.

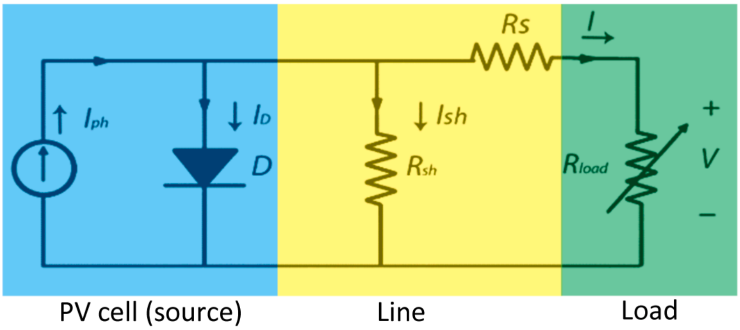

Fig. 5. PV equivalent circuit.

Table 2
PV Panel Parameters in the PVTEG-MG (ANON, 2024).

Parameters	Proposed Value
Maximum power	230 W
Cell per module	60
Open circuit voltage	36.5 V
Short circuit current	8.3 A
Voltage at the maximum power point	29.4 V
Current at the maximum power point	7.82 A

increase the voltage of the PVTEG-MG system. It converts a low input voltage to a higher output voltage by storing energy in an inductor and releasing it. The boost converter can be used to increase the voltage of a PVTEG-MG so that the distributed energy resources connected to the PVTEG-MG can operate adequately. The boost converter can also regulate the voltage of the PVTEG-MG, providing a stable voltage to the distributed energy resources connected to it. The input voltage of the boost converter is typically determined by the voltage of the MG, which is typically a DC voltage. The converter's output voltage is typically determined by the desired operating voltage of the devices connected to the PVTEG-MG. When the PVTEG-MG is connected to a TEG and PV panel, as in our proposed study, the converter's output voltage may be set to the desired voltage for the distributed energy resources to operate correctly. The input and output voltage of the boost converter for the PVTEG-MG system is shown in Fig. 7.

2.4. DC-AC islanded inverter

Islanded inverters cannot synchronize with the grid because they are

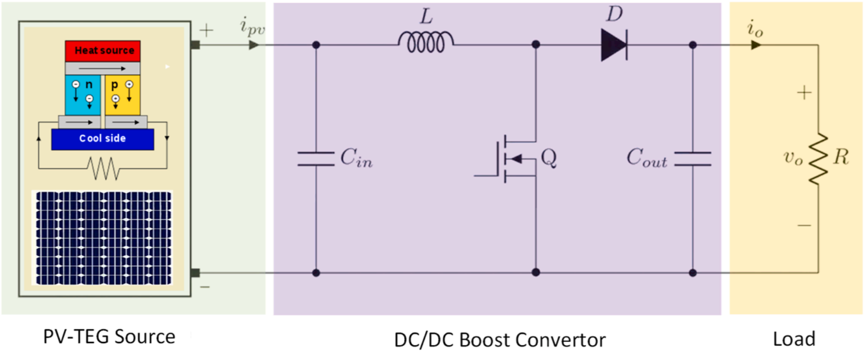

Fig. 6. Boost converter circuit.

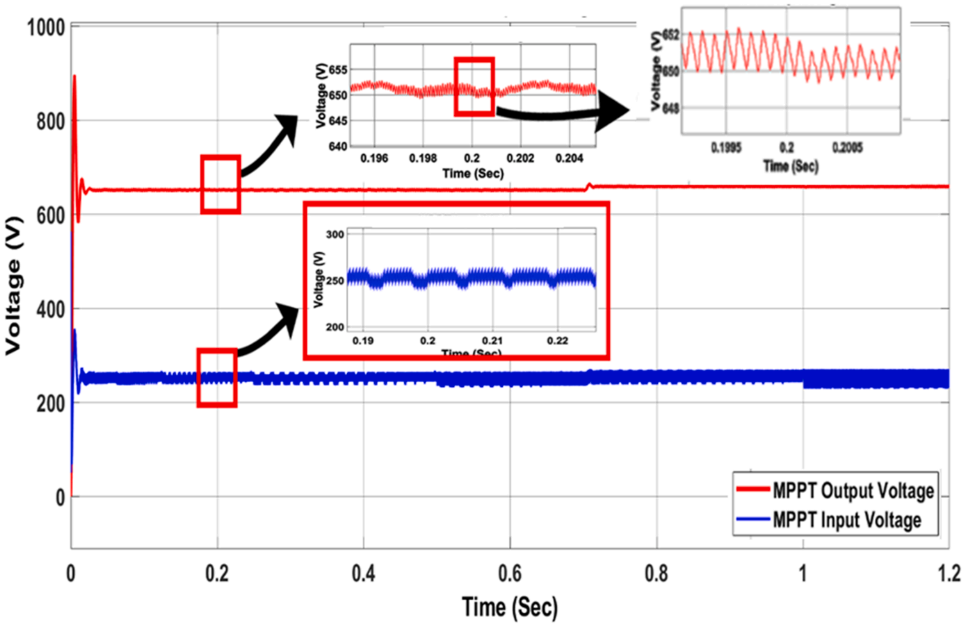

Fig. 7. Boost converter input and output voltage.

built to operate independently. Off-grid inverters must instantly convert DC to AC to power devices. They must react quickly and at a level equal to or greater than the inverters' rated capabilities. It converts the boost converter's DC power to AC power. The intended loads are powered by a clean three-phase signal voltage that is provided. Fig. 8 shows an off-grid inverter control unit in a PVTEG-MG. This control unit controls the power flow in the proposed islanded MG. The control unit also ensures that the PVTEG-MG is operating safely and efficiently. Fig. 9 shows the generated duty cycle from this control.

3. Control of the proposed PV-TEG hybrid energy system in islanded MG

In the control of the PVTEG-MG system, firstly, the priority and quantities of the loads, then the application of FL according to these priorities, and the creation of the BMS, which is more critical in islanded MGs, are explained. In PVTEG-MG, local criteria such as ambient and water temperature affect the number of solar panels and TEG modules used, demand levels of load types, ensuring the balance of energy production and demand, and optimizing the SOC curve according to the priority of the demand load.

3.1. Description of a LMS

The four types of loads presented in this paper are critical to the successful operation of an MG. The RLC critical load is the most crucial of the proposed loads, as it can work for 24 hours without any power drop due to external factors. RLC secondary load, RLC non-critical load 1, and RLC non-critical load 2 are all controlled by an FL controller, which is programmed to adjust the power output according to the amount of power produced. The LMS algorithm is used to optimize the BMS and increase its stability and flexibility. By balancing the power generation and demand, the LMS helps ensure that the total load of the PVTEG-MG is equal to the RES. Thus, controlling the loads and the RES' capacity is necessary for LMS in MG applications. The load subsystem is shown in Fig. 11.

3.2. FL controller

The FL algorithm presented in Fig. 12 provides a convenient way to schedule loads based on the amount of generated power. The input to the algorithm is the total power generated by PV and TEGs. The output functions are the secondary loads, non-critical load 1, and non-critical load 2. Using the FL, the PVTEG-MG system can accurately and effectively optimize the power consumption of the loads, allowing loads to be

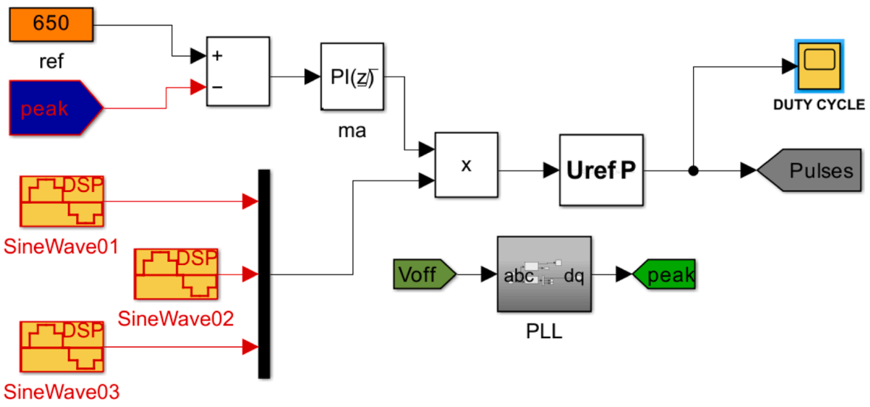

Fig. 8. Off-grid inverter control unit.

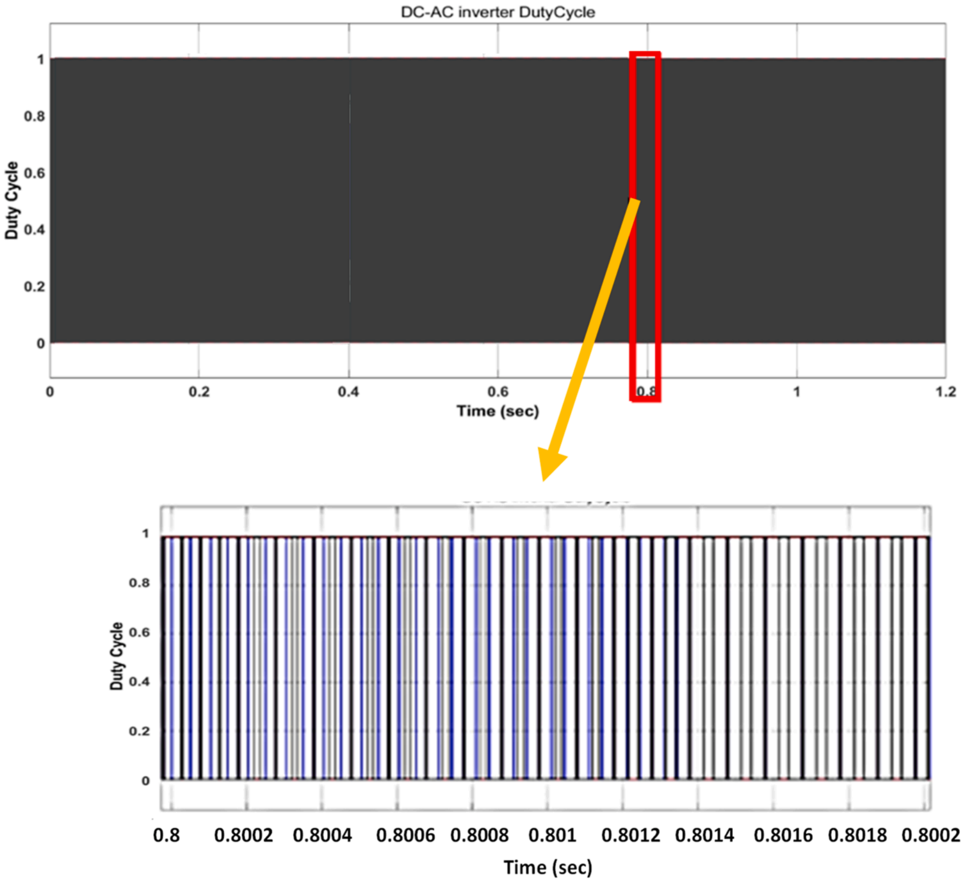

Fig. 9. Off-grid inverter control unit. The generated output three-phase voltage from the proposed PVTEG-MG is shown in Fig. 10.

scheduled according to the amount of generated power. This ensures that the loads are used efficiently and the energy generated is used to its fullest potential. Furthermore, using FL can improve the accuracy of power optimization, as the algorithms can be trained on real-world data and adjusted to changing environmental conditions. This, in turn, results in improved power management and energy efficiency.

3.3. *The BMS*

Using a BMS in islanded MGs is becoming increasingly popular due to the need for reliable and secure electricity supply in remote or isolated locations. BMS can benefit MGs, including improved power quality, increased system reliability and flexibility, and reduced energy costs. BMS can store RES-generated electricity, such as PV and TEG, allowing users to use this energy when demand is highest. This helps reduce energy costs as electricity generated from RES is typically cheaper than energy from other sources. In addition, BMS can provide backup power in case of a power outage, ensuring that users always have access to electricity. BMS can also provide frequency regulation services, helping maintain the MG's stability. The primary disadvantage of BMS is the significant maintenance and expensive relocation cost associated with them. In addition, batteries have limited energy storage capacity, meaning they can only provide a finite amount of energy. Despite the cost, BMSs are becoming an increasingly popular choice for islanded MGs due to their ability to provide a reliable and secure electricity supply. With the increasing energy cost from traditional sources, BMS offers an attractive alternative for MG users. BMS is a crucial component of any islanded MG. It is responsible for monitoring, controlling, and protecting the batteries, ensuring it can deliver its intended services reliably and safely. A BMS can manage the charge and discharge of batteries, monitor their temperature, balance their cells, and manage other safety features.

In addition, a BMS can be used to optimize the performance of the BMS and maximize its life cycle. A properly functioning BMS can also extend the lifetime of the BMS, as it can help to ensure that the batteries are not overcharged or discharged too deeply. This can help prevent the batteries' early failure due to damage caused by overcharging or deep discharging. In addition, BMSs can be used to monitor the health of the BMS and alert operators to potential problems before they become serious. This can help to reduce the amount of costly downtime due to BMS failures. Finally, BMSs can be used to optimize the operation of the MG, helping to ensure that the system is operating as efficiently as possible and that the batteries are being used to their fullest potential. Fig. 13 shows the BMS blocks in a Simulink® environment for charge and discharge control.

4. Techno-economic analysis

The techno-economic analysis is a methodology used to evaluate the economic feasibility of a technology or project. It is also a very usable tool for the penetration of renewables (Hoseinzadeh et al., 2022), and hybrid energy flexibility systems (Hoseinzadeh and Garcia, 2022). In daily energy production, techno-economic analysis involves assessing the costs and benefits of installing and operating an energy generation system. This analysis typically includes considerations such as the initial cost, annual operation and maintenance cost, total cost over the lifetime, total energy generated over the lifetime, and the levelized cost of energy (LCOE) for the solar (Ud-Din Khan et al., 2022) and thermoelectric powered electrical systems (Anderson and Brandon, 2019). Daily energy production refers to the amount of energy the system generates daily. It can be calculated using Eq. (10).

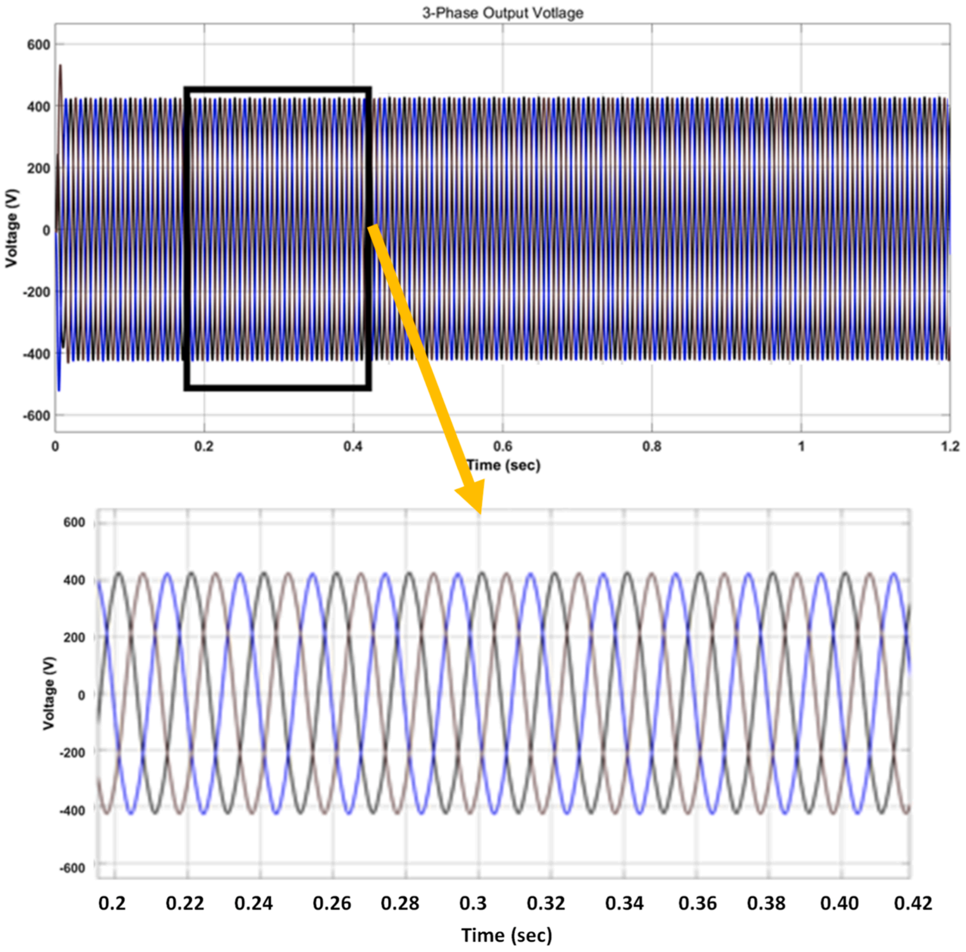

Fig. 10. The three-phase output voltage of the proposed MG.

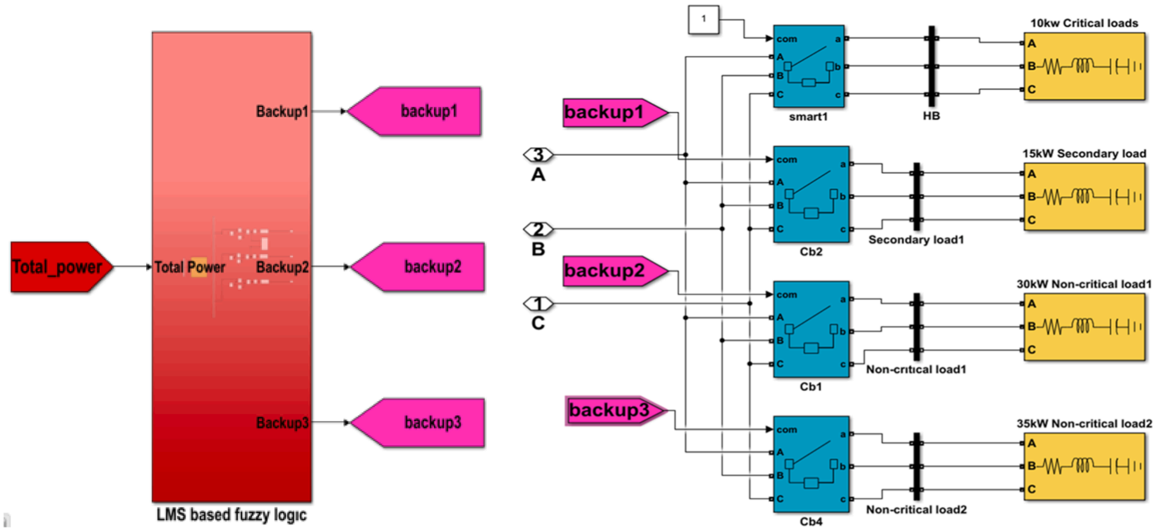

Fig. 11. Load subsystem in Simulink® environment.

$$E = P \times H \tag{10}$$

Where E is the daily energy production, P is the system's power output, and H is the number of hours of operation per day. The initial cost represents the upfront investment required to install and commission the energy generation system. It includes equipment, installation, permits, and engineering costs. The Eq. (11) represents for the initial cost.

$$IC = C + I \tag{11}$$

Where IC is the initial cost, C is the system's capital cost, and I is any additional installation or commissioning costs. Annual operation and maintenance costs refer to the expenses incurred to operate and

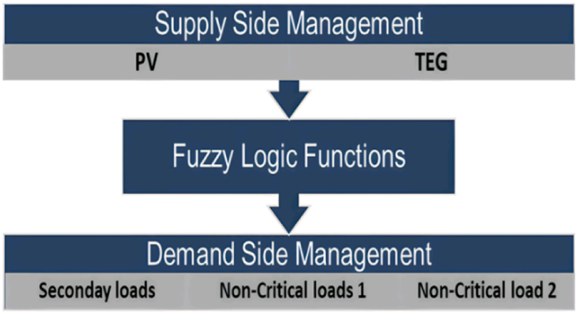

Fig. 12. Structure of FL in the proposed islanded MG.

maintain the energy generation system over a year. It includes expenses for regular maintenance, repairs, monitoring, and administrative overheads. Annual operating and maintenance costs can be expressed by Eq. (12).

$$OMC = M \times Y \tag{12}$$

OMC is the annual operating and maintenance cost, *M* is the annual maintenance cost, and *Y* is the number of years of operation. The total cost over the lifetime represents the sum of the initial cost and the cumulative annual operation and maintenance costs for the entire lifespan of the power generation system. It can be calculated using the following Eq. (13).

$$TC = IC + (OMC \times L) \tag{13}$$

TC is the total cost over the lifetime, *IC* is the initial cost, *OMC* is the annual operation and maintenance cost, and *L* is the system's lifetime in years. The total energy generated over the lifetime refers to the cumulative energy production of the system over its operational lifespan. It can be calculated using Eq. (14).

$$TE = E \times L \tag{14}$$

Where *TE* is the total energy generated over the lifetime, *E* is the daily energy production, and *L* is the system's lifetime in years. The levelized energy cost represents the average cost of generating one unit of energy over the system's lifetime. It is calculated by dividing the total cost over the lifetime by the total energy generated. *LCOE* is given by the Eq. (15).

$$LCOE = TC/TE \tag{15}$$

5. Results and discussions

The LMS are based on the analysis of MG operation according to the state of demand and the availability of generation sources. These strategies can be implemented using a control system that allows the MG to adjust loads based on the available energy supply. A load limit is adopted for each load type to ensure the system's security. This limit depends on the system's total load and RES generation capacity. In addition, load shedding reduces demand when the generation sources cannot meet the demand.

Furthermore, the load can be shifted to different times of the day so that RES can be used more efficiently. Finally, demand response techniques are used to reduce the system's peak load and ensure its stability. Implementing these strategies allows the system to manage the load more effectively and efficiently. In Figs. 14–16, the horizontal axis is simulation time as seconds and each second corresponds an hour for real time calculations. Fig. 14 shows the generated power from TEG and PV throughout the day under different weather conditions. From Fig. 14, it can be seen that TEG hot temperature varies between 30 °C and 55 °C. For TEG, 40 °C is taken as the basis for power production and it is assumed that TEG mainly operated at 45 °C. The irradiation value for PV power generation varies between 100 W/m^2 and 1000 W/m^2. PV output is quite low below 200 W/m^2. On average, the PV output can be taken as 30 W for 800 W/m^2. The maximum power of TEG is 45 kW at 55°C, and the maximum PV is 40 kW at 1000 W/m^2, so the total power for this system is 85 kW.

5.1. LMS without FL

Fig. 15 illustrates the relationship between the proposed load and the total power generated by the battery's state of charge (SOC). In this scenario, all loads are operating without the LMS. The battery is in charging mode when the generated power is between 60 kW and 85 kW. However, when the power is insufficient, the system will go into

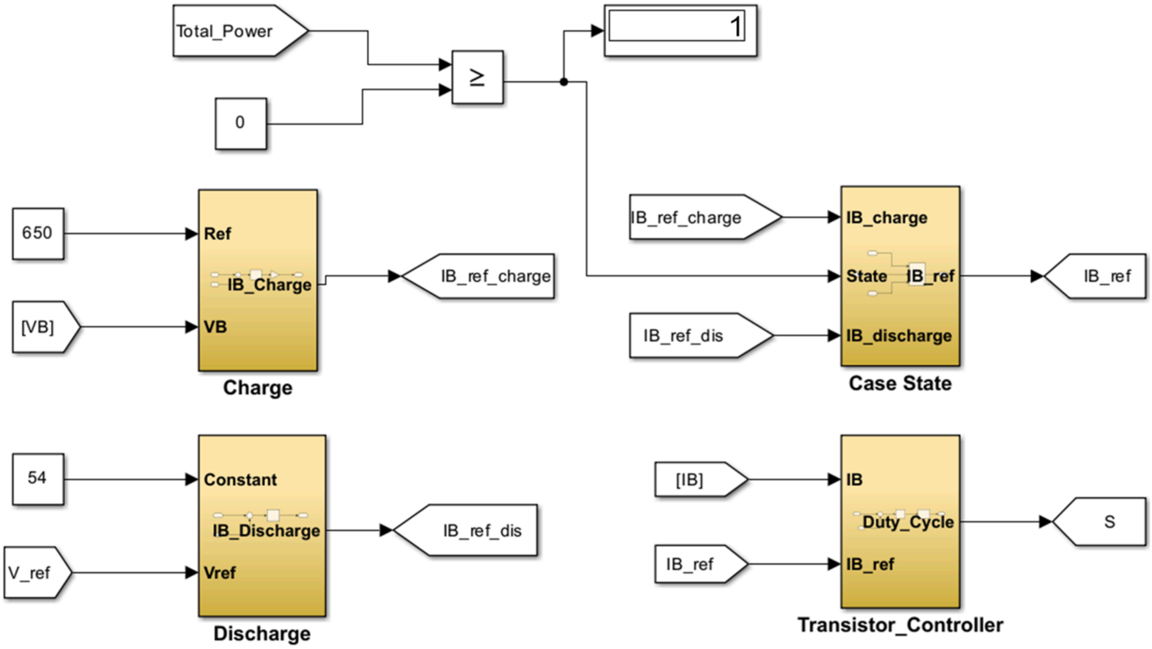

Fig. 13. BMS blocks in Simulink® environment for charge and discharge control.

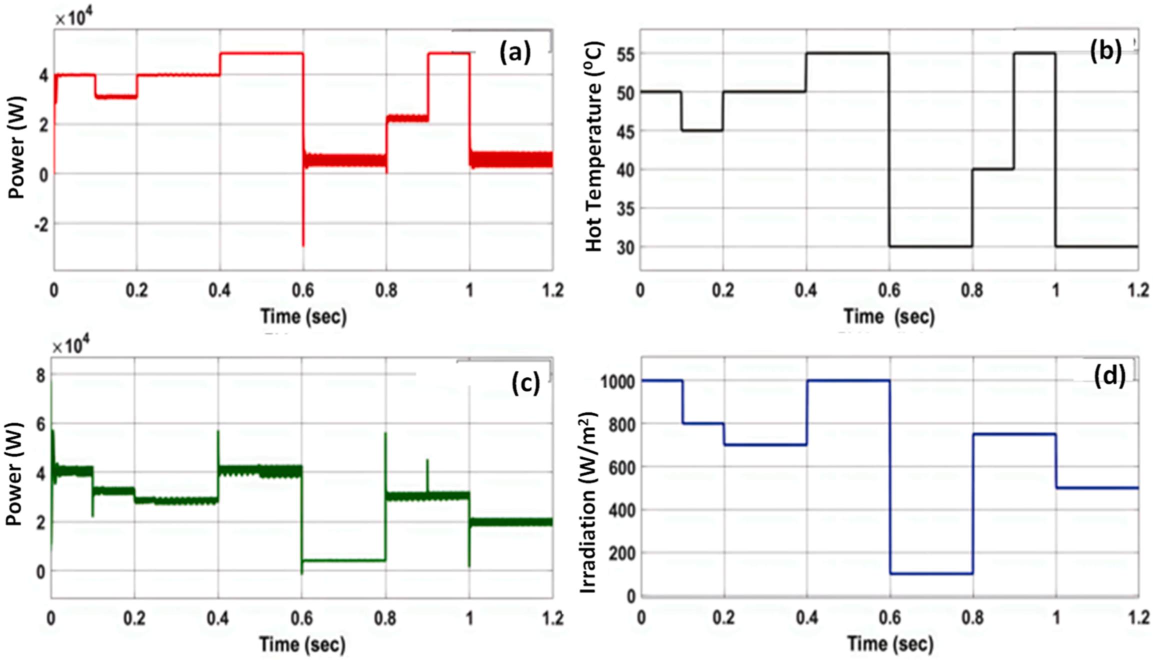

Fig. 14. TEG power and PV under different weather conditions (a) TEG power, (b) TEG hot temperature, (c) PV power, (d) PV irradiation.

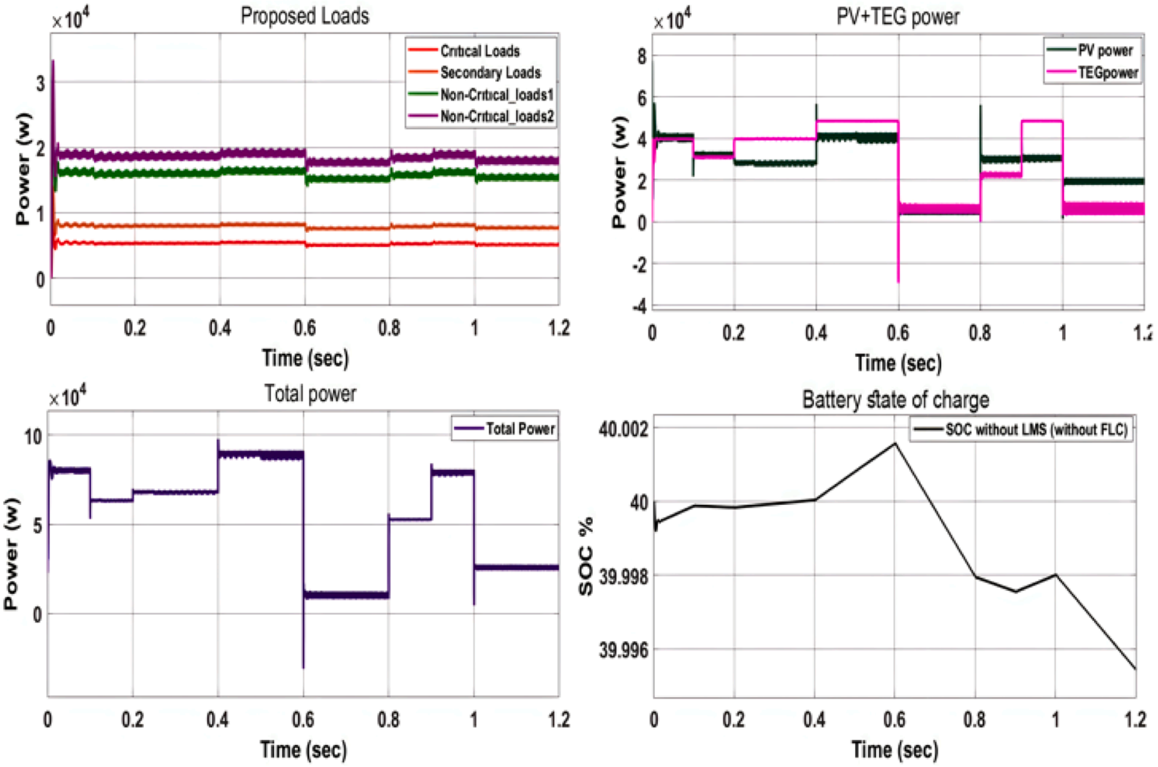

Fig. 15. Simulation results without LMS.

discharge mode, reducing all demand loads. In Fig. 15, since there is no LMS, especially after 0.6 s, non-critical loads 1 and 2 continued to be fed and therefore the battery remained in discharge mode. As a result, the battery may become fully discharged, and the MG will sometimes be out of service. In addition, this could cause an imbalance between the power generated and the power consumed, leading to inefficient energy distribution. Therefore, an LMS should be implemented to maximize energy efficiency and optimize battery use.

5.2. *LMS with FL*

The proposed LMS based on FL can provide efficient and reliable control of secondary and non-critical loads 1 and 2. It can adjust the load according to the amount of power generated and the battery SOC in different weather conditions. The system can provide optimal operation of the PVTEG-MG by keeping all the loads in service when the generated power is in excellent mode and only the most critical loads when the

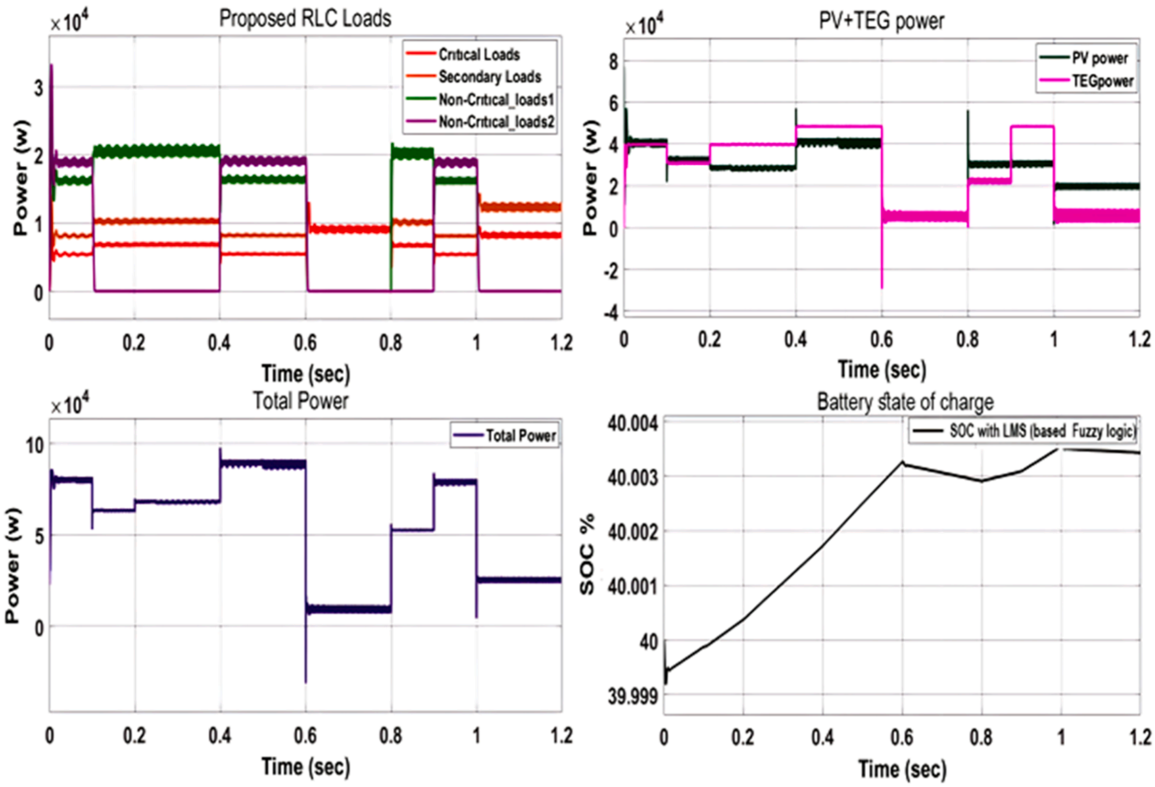

Fig. 16. Simulation results with LMS.

generated power is between 0 and 20 kW. When the power is between 21 kW and 40 kW, the secondary load has critical loads in service. Additionally, when the power is between 40 and 75 kW, the first non-critical load will be in service alongside secondary and critical loads. When the generated power is in excellent mode, between 75 and 95 kW, the entire load will be in service. This ensures that the PVTEG-MG can serve its purpose and provide reliable energy even in low-power generation scenarios. Furthermore, the improved SOC of the battery increases the efficiency and flexibility of the PVTEG-MG without sacrificing power. Fig. 16 shows the results of the LMS with an FL controller. In Fig. 16, it can be seen that when the LMS disabled non-critical loads, no energy is consumed by the battery for these loads, the primary loads are fed and the battery maintained its charge stability.

According to different weather condition, Table 3 describes the load operation according to the LMS with FL control in a proposed scenario.

Fig. 17 shows the SOC before and after LMS-based FL. The graph shows that the SOC of the battery is higher when using an LMS than without an LMS. This indicates that the LMS can manage the charge and discharge of the battery more efficiently, resulting in a higher SOC. This is because the LMS can regulate the current drawn from the battery, preventing it from being over-discharged.

5.3. *Techno-economic analyses for the proposed PVTEG-MG*

The techno-economic analyses for the PVTEG-MG have specific details about factors such as the local solar irradiance or temperature gradient, the cost of components, installation and operation, maintenance, efficiency and expected lifetime of the system, and financing conditions. In this paper, the techno-economic analyses have been done for 85 kW (40 kW PV and 45 kW TEG) according to daily energy production, initial cost, annual operation and maintenance cost, and cost per unit energy over the lifetime (levelized cost of energy, LCOE). In the Iraqi conditions where the study is conducted, the local average solar radiation is optimally around 5.5 kWh/m^2/day (Global solar atlas, 2024). However, in this study, due to the possibility of local sandstorms or the high number of cloudy days and shading, this value of 4 kWh/m^2/day is accepted as the lower limit and calculations are made according to this value. Thus, the power values of the proposed model have been made more realistic and reliable. The efficiency of the PV system is 15%, and the TEG system is 5%. The PV system costs $2/W, and the TEG system is $3/W installed. Both systems have an expected lifetime of 25 years. Operation and maintenance costs are 1% of the initial cost per year. Techno-economic analysis results is given in Table 4.

Therefore, under these assumptions, the TEG system, although

Table 3
Load operation according to the LMS with FL control.

Time (s)	Amount of power (kW)	Critical loads	Secondary loads	Non-critical loads 1	Non-critical loads 2	SOC
0	80	✔	✔	✔	✔	Charge
0.1	60	✔	✔	✔	×	Charge
0.2	70	✔	✔	✔	×	Charge
0.4	95	✔	✔	✔	✔	Charge
0.6	15	✔	✔	×	×	Discharge
0.8	50	✔	×	✔	×	Charge
1	80	✔	✔	✔	✔	Charge
1.2	30	✔	✔	×	×	Discharge

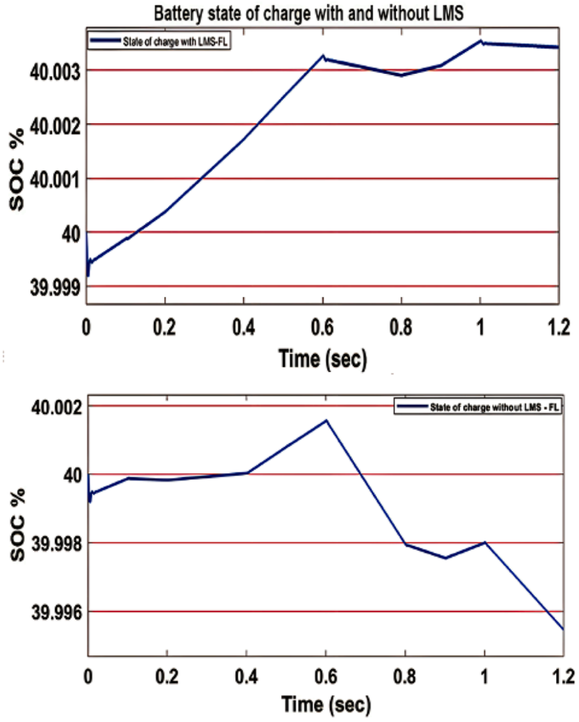

Fig. 17. Battery SOC with and without LMS.

Table 4
Techno-economic analysis results of the proposed PVTEG-MG.

Parameters	PV	TEG
Daily energy production	24 kWh/day	54 kWh/day
Initial cost	$80,000	$135,000
Annual operation and maintenance cost	$800/year	$1350/year
Total cost over the lifetime	$100,000	$168,750
Total energy generated over the lifetime	219,000 kWh	493,650 kWh
Levelized Cost of Energy, LCOE	$0.456/kWh	$0.342/kWh

initially more expensive due to higher energy production, will be more cost-effective over its lifetime.

In Table 5, current studies in the literature are given in comparison with the study we presented. In this context, the subject of Technoeconomic Analysis has not been examined in any of the studies. Additionally, there are very few studies on BMS and LMS processes. Moreover, when the studies were examined, at most 3 of the 5 parameters mentioned were discussed.

Table 5
Summary of various characteristics relating to PVTEG-MG researched in recent literature.

Ref.	Characteristic				
	BMS	LMS	AIM	MPPT	TEA
(Mirza et al., 2022)	×	×	✔	✔	×
(Kwan and Wu, 2017)	×	×	×	✔	×
(Bond and Park, 2015)	×	×	×	✔	×
(Ramadhani et al., 2020)	×	×	×	×	×
(Montecucco and Knox, 2014b)	×	×	×	✔	×
(Laird and Lu, 2012)	×	×	×	✔	×
(Bhatta et al., 2023)	✔	×	✔	×	×
(Fauzan et al., 2021)	×	×	×	✔	×
(Zhang et al., 2020)	×	×	✔	✔	×
(Wu et al., 2018b)	✔	×	✔	✔	×
(Zafar et al., 2022)	×	×	✔	✔	×
(Teke et al., 2023)	×	✔	✔	✔	×
Proposed	✔	✔	✔	✔	✔

BMS: battery management system, LMS: load management system, AIM: artificial intelligence method, MPPT: maximum power point tracking, TEA: techno-economic analysis.

6. Conclusion

Integrating more renewable energy into the traditional grid is a new trend for power system work due to its positive environmental impact. Energy yielded from the hot springs, found in many parts of the World, and have great potential, are far from the settlements. In this respect, there is a considerable opportunity for islanded MG expansion using TEG technology. These resources can only be exploited by using an efficient control system with islanded MG structures containing storage, load control, and BMS components. In this study, A PVTEG-MG system with all its components is presented and investigated for the first time, the system is analyzed with and without LMS, and battery states are observed. Thus, an energy solution has been proposed with hot water and solar radiation for many rural areas. The performance of two scenarios, with and without FL, is evaluated under critical, secondary, and uncritical loads. The FL approach is used to develop the LMS because it reduces processing time, learns faster, and produces fewer errors. The proposed PVTEG-MG is also characterized by the charged storage system, enabling the system to operate 24 hours without shedding any critical loads. An algorithm is designed to continuously estimate the generation power from TEG and PV sources and make the right decisions to maintain the stability of the MG. The results showed that using FL improved the BMS and the flexibility between the proposed RLC loads, thereby increasing the efficiency of the MG and providing stability to the loads with low losses in generated power.

The techno-economic analysis of the developed system is also made, and the average value of the LCOE is obtained as 0.399/kWh over the total energy produced, which is 219,000 kWh for the PV and 493,650 kWh for the TEG. It is concluded that this PV and TEG hybrid MG system is a promising solution that can be used as an island grid for hot water regions to reduce electricity costs, increase efficiency and reliability, and provide a more sustainable energy source. For future studies, considering the load classification and BMS system in this study, first the energy diversity and then the storage types can be expanded and further analyzes can be carried out for larger-scale power systems in various locations.

Author Agreement Statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs

CRediT authorship contribution statement

Firas Hasan Muhi MUHI: Software, Investigation. **Mehmet Güçyetmez:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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