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An efficient energy management and control strategy for a hybrid microgrid system

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Original Research

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Abstract:

Areas with high or unstable electricity costs implement microgrids (MGs), making them economically viable. They also provide backup power during grid outages, reducing peak demand charges and promoting grid independence. Lowering electricity costs within an MG can lead to increased economic activity and improved quality of life. MGs improve power quality and play an important role in renewable energy (RE) systems. MGs can help reduce carbon emissions by integrating renewable energy sources into the electrical grid and eliminating the need for fossil fuel electricity generation. Therefore, minimizing electricity prices in an MG is essential for ensuring affordability, sustainability, and reliability, as well as promoting the widespread adoption of MG technology. This paper uses the linear programming optimization (LPO) method as an energy management system (EMS) to manage the energy and power sharing between the MG components, which are solar photovoltaic (PV), battery energy storage system (BESS), and load. Moreover, we tested the proposed system PV/BESS under real solar irradiance and residential load profiles using MATLAB/Simulink software. We subjected the MGs to tests under different weather conditions, specifically clear and cloudy days, to evaluate the proposed system. The results show that the proposed technique provides the lowest price of electricity on clear and cloudy days when compared to the base case. The LPO-based EMS reduced the daily grid cost from 904.1$ to 580$, and it provides a cost savings of 45% when the grid usage is 3400 kWh. Finally, the suggested EMS reduces the grid's cost from 700$ to 370$ under cloudy day conditions, saving 80% of the cost.

Keywords: Microgrid; Linear programming optimization; Energy management system; Solar battery energy storage

1. Introduction

Microgrids (MGs) offer numerous benefits for energy management and control systems, including improved efficiency, enhanced reliability, integration of renewable energy sources, energy cost savings, grid resilience, reduced environmental impact, demand response programs, remote monitoring and control, scalability, energy independence, grid support, and innovation and research [1, 2]. These systems optimise energy generation, distribution, and consumption, increasing efficiency and resource utilisation. Microgrid (MG) control systems can detect and respond to power outages or disturbances faster than traditional grids, ensuring a continuous power supply [3]. They also enable the seamless integration of renewable energy sources like solar panels and wind turbines, balancing their intermittent nature. MGs can operate independently from the primary grid during emergencies, ensuring critical facilities have reliable power sources. The increased use of renewable energy sources in MGs reduces greenhouse gas emissions and dependence on fossil fuels, contributing to a more sustainable and environmentally friendly energy system [4]. Demand response programs adjust electricity consumption in response to real-time price signals or grid conditions, balancing supply and demand and leading to cost savings. Operators can remotely monitor and control MG systems, making them a valuable option for off-grid or remotoptimisee locations [5].

An MG is a localised group of electricity sources and loads that can operate independently or in conjunction with the main electrical grid. It provides reliable, efficient, and sustainable electricity to specific areas, such as communities, industrial facilities, university campuses, or military bases. The structure of an MG system includes primary power sources, secondary or backup sources, energy storage systems, power conversion and inversion, control and management systems, distribution network, loads, grid interconnection, monitoring and control centre, protection and safety systems, communication infrastructure, and cybersecurity measures. Primary power sources include solar photovoltaic (PV) panels, wind turbines (WT), diesel or natural gas generators, and combined heat and power systems [6–8]. Secondary or backup sources provide additional support during high demand or when primary sources are unavailable. Energy storage systems store excess electricity generated during low or high renewable energy production, peak demand or when renewable sources are not generating power. Also, Power electronics and inverters convert the electricity generated from DC to AC, ensuring compatibility with the MG's electrical system.

Energy management systems (EMS) in MGs aim to optimize energy generation, distribution, and consumption within a localised, decentralised system [9, 10]. These smaller, self-contained systems can operate independently or with the larger grid. Key purposes include enhancing local energy supply reliability, reducing energy costs, integrating renewable energy sources like solar panels and wind turbines, improving efficiency, and ensuring grid support and independence. In addition, effective energy management systems can also balance intermittent renewables with conventional generators for a stable power supply. Energy costs have risen steadily over the last several years, and sustainable operations have emerged as a top priority for ports seeking to reduce their environmental impact. Instead of carbon-intensive energy sources, electricity helps achieve climate change mitigation goals. Hence, many ports switch to all-electric operations [11, 12]. Ahmed Fathy et al. [13] Proposed a sparrow search algorithm (SSA) for EMS strategy, a relatively new metaheuristic technique used to oversee MG operations management efficiently. The study formulated two optimisation problems, one with a single target to minimise the total running cost or the total emission from the system and the other with dual objectives to minimize both. The second issue is multi-objective, considering the entire operating cost and the total emission. It is recommended that a revised version of SSA be used to make the most of MG's power.

S. Masoud Moghaddas-Tafreshi et al. [14] introduced a fresh modelling strategy for lowering the operating cost of an MG with various energy carriers while simultaneously optimising the management of electrical and thermal energy. The planned MG includes micro-turbines, fuel cells, power plants that burn garbage for energy, WT generator sets, boilers, anaerobic reactor-reformer systems, inverters, rectifiers, and energy storage units. The model predicts electrical and thermal demands on a micro-grid network one day in advance (24 h). Estimates of power production from WT are also based on forecasts made one day in advance.

S. Dorahaki, R. Dashti, and H. R. Shaker [15] a model for an ideal energy management program that considers BESS in particular. The optimum energy management issue is solved while accounting for the rate of return on energy efficiency investments. The energy efficiency was included in the demand model to achieve this result. In addition, the suggested demand model has been used in the smart MGs for effective energy management. Moreover, the suggested objective function has been treated as a Mixed Integer Non-Linear Programming (MINLP) problem.

Seyed Mohsen Hosseini et al. [16] proposed an EMS to minimise the energy cost of the MG, which consists of renewable energy sources RES and BESS. The goal of scheduling is to minimise the predicted energy cost while meeting device comfort, contractual limitations, and limits on the practicality of transferring energy between users and the grid in the face of uncertainty in both RES production and users' demand. The authors in [17] proposed an EMS for DC MG based on a combination of the Firefly algorithm and particle swarm optimisation (FA-PSO) to effectively minimise or alleviate fluctuations in DC voltage. An assessment is conducted to determine the capability of the suggested control approach to endure variations in solar insolation, wind speed, and load disturbance. The comparison and validation are done via hardware implementation. The findings demonstrate that the FA-PSO controller surpasses other control techniques in terms of performance.

The authors in [18] presented an enhanced EMS for the DC MG system. The system is comprised of a solar cell, a wind turbine generator, a battery energy storage (BES), a fuel cell (FC), and an electrolyser. The suggested control strategy enhanced the dynamics of the DC-link voltage and contributed to better power management between each generation/source and load. The controller of the grid-side inverter is equipped with a gain control approach. This is accomplished by the use of Takagi–Sugeno-fuzzy feedback control. A priority-based load-shedding algorithm is provided to maintain adequate power coordination between various energy sources and storage devices. This method is proposed to ensure that the DC MG operates reliably during standalone or protracted islanding modes of operation. In [19], a dynamic EMS is applied on a hybrid DC/AC MG to enhance the performance of grid-tied and island models of MG. Dynamic programming and reinforcement learning methods are proposed. Solar and wind energy sources with different load conditions are used based on uncertain and non-dispatchable processes. The suggested method provides energy dispatch control for the sources. The results show that these methods are very robust when compared with classical methods. The authors in [20] proposed a hybrid control method that has two stages: state machine (SM) control, which aims to optimise battery performance and operation mode (OM) control, which aims to optimise the performance of the SC. The findings obtained indicate that the PV power management system may successfully include the SC during rapid fluctuations in demand and PV power generation. This is accomplished by minimising the frequency of charge and discharge cycles that the battery experiences, hence substantially prolonging the lifespan of the system. Moreover, the discrepancy in power between the power obtained from the sources and the necessary equivalent is less, resulting in a decrease in power loss during the drawdown times. This enhancement in efficiency amounts to a 9.5% improvement.

In [21], a DC MG, consisting of an FC and a hybrid ESS, is managed by an EMS based on an artificial neural network (ANN)-based controller with a classical proportional-integral (PI) controller. The system is designed to handle variable load demand. The HESS utilises a BESS and a

supercapacitor (SC) to meet high energy and high-power requirements, respectively. The HESS, equipped with the suggested controller and EMS, demonstrates enhanced time responsiveness to abrupt and gradual changes in load demands. This leads to less strain on the battery and an extended lifespan. In [22], the mixed EMS-based LP and integer LP optimisation methods are applied to AC MG. The optimal control parameters of RE sources of solar PV systems and Wind turbines are investigated. The price of the electricity and the cost savings are obtained according to the 24-hour time period. The BESS-based state of charge (SOC) is estimated, and given that the size of the BES has an impact on the running cost of the MG, the EMS and BES capacity are optimised concurrently.
However, MG systems often exhibit non-linear characteristics, especially in power production, energy storage, and load demand. For example, the correlation between the amount of power produced and the amount of fuel used in generators or the level of charge in batteries might exhibit a non-linear pattern. Linear programming (LP) is based on the use of linear equations and inequalities. This implies that any non-linear features need to be approximated using linear methods. Nevertheless, despite its benefits, LP-based optimisation encounters distinct problems and limitations that serve as a driving force for more investigation and advancement. Gaining a comprehensive understanding of these matters is essential for improving the efficiency, dependability, and capacity to grow MG systems.
In this paper, a robust EMS strategy based on the linear programming optimisation (LPO) method is used to minimise the electricity price. The proposed system is verified using MATLAB software. This method aims to provide high-quality energy with cost savings by using BESS with a PV system in the grid.
The main contributions of this paper are:

i. An efficient energy management strategy for Photovoltaic (PV)/Battery energy storage (BES) system ensures a good energy quality to Microgrid.

ii. Provides optimal voltage and frequency control under clear and cloudy days based irradiances

iii. The suggested EMS provides the lowest price of electricity when compared to the other methods

2. Micro-grids structure

2.1 Proposed system configuration

MGs (MGs) are small, decentralised electrical networks that may provide power independently or in tandem with the larger utility grid. They provide electrical power to isolated communities, university campuses, or industrial complexes. MGs' capacity to increase reliability, boost efficiency, and integrate renewable energy sources has made them more attractive. Energy sources, energy storage systems, a centralised control system, inverters and converters, a distribution network, loads, islanding capabilities, and grid connectivity are all parts of the MG.
In this work, a small-scale MG consists of a PV system, battery energy storage system (BESS), and main grid. These sources are controlled using EMS and control. The bidirectional inverter DC/AC device was used to convert the DC/AC power from generation to the grid. An efficient EMS based on a liner optimisation strategy balances the MG power, as shown in Fig. 1.

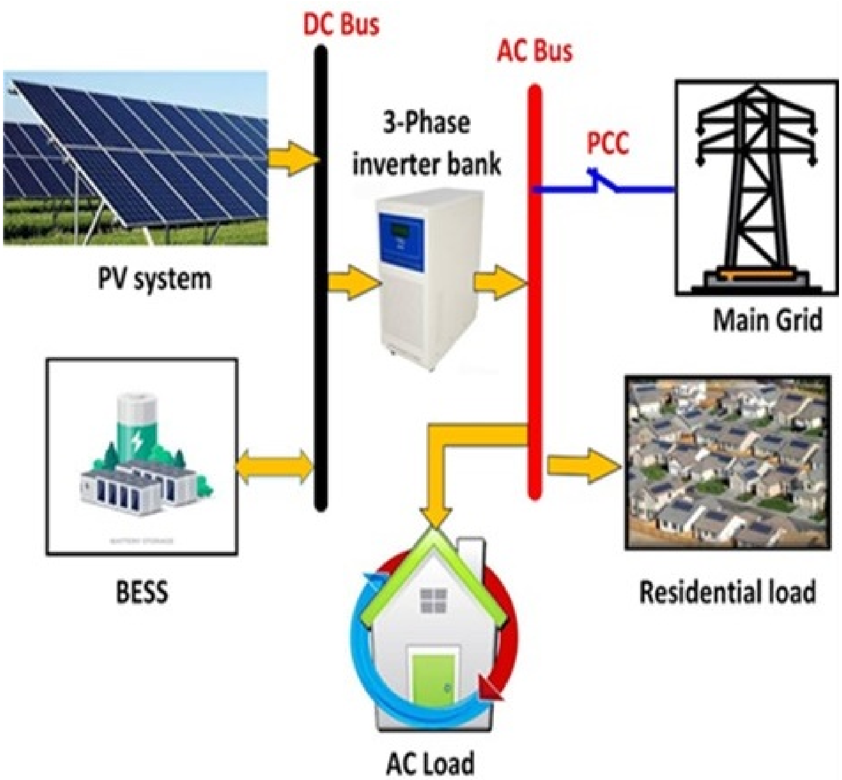

Figure 1. Configuration of the proposed MG.

2.2 Modelling of solar photovoltaic system

Solar photovoltaic (PV) systems consist of solar panels, which may harness solar energy independently or in tandem with the grid [22, 23]. PV systems have been more popular in recent years for the generation of electrical power due to the increasing need for energy, environmental concerns, low cost of operation, and absence of any fuel price. A PV array's total power output $P_{\mathrm{PV}}(t)$ may be estimated with the help of the following equation (1) [22]:

$$P_{\mathrm{PV}}(t) = R_{\mathrm{PV}} D_{\mathrm{PV}} \frac{G_T(t)}{G_{T,TST}} [1 + \alpha(T_{\mathrm{cell}}(t) - T_{\mathrm{cell}}, \mathrm{STC})] \quad (1)$$

where R_{PV} is the rated capacity; D_{PV} denotes the derating factor of the PV module; $G_T(t)$ represents the incident irradiance; $G_{T,TST}$ is the solar irradiance at standard test conditions (STC); α represents the power's coefficient; $T_{\mathrm{cell}}(t)$ represents the operating temperature of the cell; $T_{\mathrm{cell}}(t)$, STC represents the cell temperature at STC. However, data from a surface that is ideally oriented to receive solar irradiance is utilised for the study; this includes aligned clear-day and cloudy-day radiation data. The performance of solar panels is measured in,

$$\eta_{\mathrm{PV}} = \frac{P_{\mathrm{PV,max}}}{G \times A} \quad (2)$$

where $P_{\mathrm{PV,max}}$ the maximum power of the PV system, G is the irradiation, and A is the area of the panel.

2.3 Modelling of battery energy storage system

Off-peak, when power demand is low, BSS converts the energy generated by PV into a form that can be stored and delivered back into the system during peak power demand [24, 25]. In the context of this work, the function of BSS is to reduce the influence of fluctuations caused by the stochastic qualities of renewable resources, which are caused by the renewable resources themselves. Using BSS, the effect's rough edges may be polished off [24]. Maximum load demand, renewable energy production, daily energy consumption, renewable energy input, dependability of power supply, cost of the battery condition, operating temperature, and other variables all contribute to determining the BSS's capacity. Depth of discharge and availability of nearby RERs set upper limits on what may be charged into and discharged from the BSS. The optimum functioning of the BSS is contingent on meeting these limits. The BSS must function between the lowest and highest permitted states of charge (SOC). It is possible to get an estimate of the SOC of the battery by applying equation (3) [25]:

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) \int_{t-1}^{t} \frac{P_b(t)\eta_b}{V_{bus}} \quad (3)$$

where η_b is the battery's efficiency; V_{bus} is the DC bus voltage; $P_b(t)$ is the output power of the battery in kW. The $P_b(t)$ can be written as follows [25]:

$$P_(b)(t) = \frac{kQ_1(t) \cdot \exp(-k) + Q(t) \cdot k \cdot c \cdot (1 - \exp(-k\Delta t))}{1 - \exp(-k\Delta t) + c \cdot (k\Delta t - 1 + \exp(-k\Delta t))} \quad (4)$$

In this equation, the amount of energy displayed at the start of the operating interval is more than the minimum SOC denoted by $Q_1(t)$.

2.4 Energy management system

2.4.1 Energy management system strategy for microgrid

MGs rely heavily on EMS to optimise energy output and consumption, guarantee grid resilience, shift load, integrate renewable energy, decrease costs, and increase environmental benefits. Their peak load management, energy efficiency, and supply/demand balance are all optimised. EMS can predict renewable energy output and work with energy storage systems to ensure a constant electricity supply. Consumers and business owners alike may benefit from EMS systems because they maximise energy efficiency and make demand response programs possible. For these reasons, MGs cannot guarantee efficient, dependable, and cost-effective operation without EMS systems. Optima sizing MG components and using an effective EMS is crucial for keeping costs low and minimising the system's negative effects. Optimisation is generally incorporated into the EMS to provide continuous load supply and reduce the cost of energy generation, manufacturing, and distribution [26–29]. Therefore, the EMS is a strategy that examines all of the systematic methods for managing and minimising the quantity and cost of energy used to fulfil the requirements of a certain application. Quick optimisation tools are available for integrated MGs thanks to linear programming optimisation (LPO) techniques. These include data analysis, processing, simulation, control, decision-making, and optimal management models for hybrid energy production systems. Because they enable efficient and predictable use of resources, these methods help make the investment in an MG more financially viable. In this work, the LPO method was used to reduce the operational costs of electricity. The block diagram of the proposed method is shown in Fig. 2.

Furthermore, traditional grid systems are directly connected to renewable energy sources like solar and wind. As shown in Fig. 3, a significant amount of renewable energy is wasted due to the absence of energy storage technologies. When sunshine is scarce, the integrated MG may draw power from

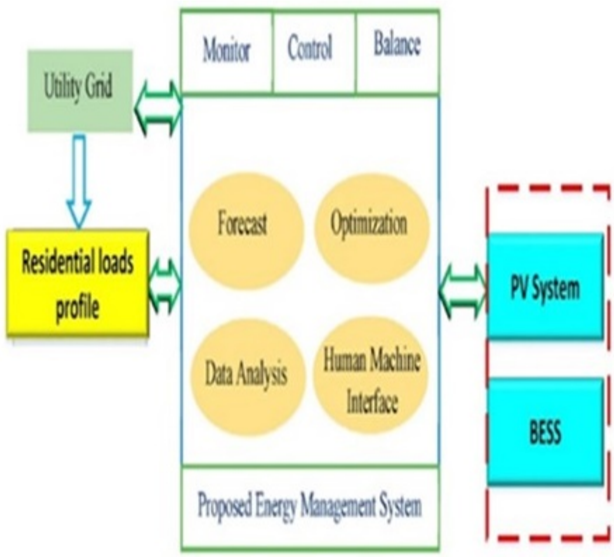

Figure 2. Proposed LPO-based EMS.

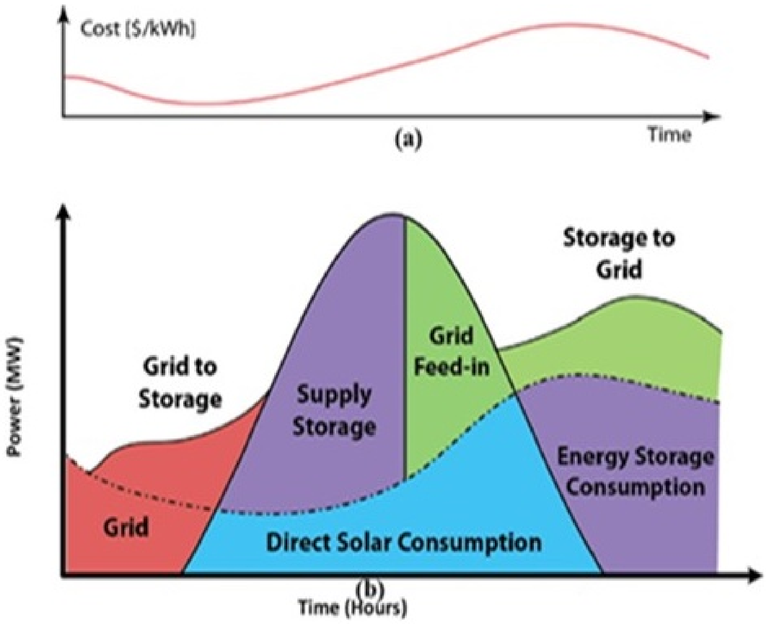

Figure 3. The effect of an energy storage system on grid electricity cost using peak demand shaft.

the main grid instead of the solar PV system as a grid feed-in system. The solar PV system is connected to the integrated grid through an energy storage (battery) device. Throughout the day, the load power profile is relatively low, which shifts or alters peak demand, but some excess solar energy is available in grid feed-in mode. As a result, some solar power is lost due to inefficiency in this traditional EMS. This EMS draws on the solar energy storage system during sun collection times.

In Fig. 3, the peak demand has altered, and the grid has switched from feeding in excess solar energy to feeding in energy from storage. This occurs during solar power generation excess since charging the battery from solar PV and the grid is necessary when the battery is not at full capacity. When the battery is ultimately charged and no solar power is available, the grid is utilised to power the battery.

2.4.2 Proposed energy management system strategy

The proposed EMS was used with two-stage coordination controllers. Based on the system net power (P_{net}) measurement and the charging/discharging rate of the battery system with energy limits, the EMS first determines the different operating modes of the solar power producers in this control logic.

The primary objective is calculated as follows:

$$\text{Minimise } f_x^T \tag{5}$$

The constraints of the system are defined as follows:

$$A \cdot x \leq b \tag{6}$$

$$A_{eq} \cdot x = b_{eq} \tag{7}$$

$$L_b \leq x \leq u_b \tag{8}$$

where the above parameters of the method are defined as:

- f is the vector of coefficients for the objective function (to be minimized).
- x is the vector of variables.
- A and b define the inequality constraints
- A_{eq} and b_{eq} define the equality constraints
- L_b and u_b are the lower and upper bounds of the decision variables.

Net power (P_{net}) is determined using equation (9). As in equation (10), the SOC restrictions determine the battery's energy limitations. While SOC is unmeasurable, it may be estimated and monitored in many ways. The rate limitations of SOC are presented in equation (11) as follows:

$$P_{net} = P_{Gen} - P_L \tag{9}$$

$$\text{SOC}_{\text{min}} < \text{SOC} \leq \text{SOC}_{\text{max}} \tag{10}$$

$$P_{BT} \leq P_{BT,\text{max}} \tag{11}$$

where P_{Gen} the generation is power, P_L is load power, and P_{BT} is battery power. Fig. 4 shows the flowchart of the proposed EMS.

The main goal of the EMS is to minimise the cost of energy by using a PV/BESS system with MG. The objective function of the proposed method is written as follows [29]:

$$C_T = \sum_{i}^{K} Cost_G(i) \times E_G(i) \tag{12}$$

Moreover, the suggested MG is operated based on the output or input power of the BESS to control the energy value and determine the balance load power. This process can be done by taking the constraints of the MG using equations (13) and (14):

$$P_{BT}(i) + P_G(i) + P_{\text{PV}}(i) = P_L(i) \tag{13}$$

$$E_{BT}(i) = E_{BT}(i-1) + P_{BT}(i) \times \Delta T \tag{14}$$

where $P_{\text{PV}}(i)$ the PV system is power; $P_G(i)$ is the grid power; $E_{BT}(i)$ is the battery energy; ΔT is the time in the hours.

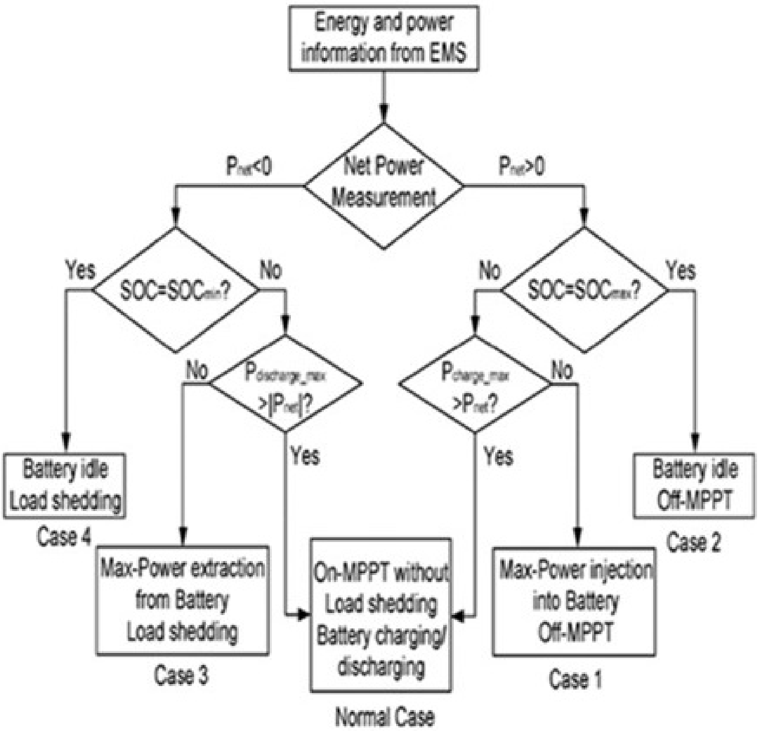

Figure 4. MG control flowchart of linear optimisation EMS.

2.4.3 Procedure for parameters selection of the proposed method under MATLAB

- Define the objective function coefficients (C_T)

The objective function in an LP problem is typically of the form:

$$\text{Minimize}C_T = \sum_{i=0}^{K} Cost_G(i) \times E_G(i)$$

The vector C_T is defined with the coefficients corresponding to each decision variable. Minimising the cost, profit, or some other metric C_T will represent those coefficients.

- Define the inequality constraints based on Eq. (6)

Inequality constraints are given in the form Eq. (6). Each row in matrix A corresponds to a constraint, and each element of b represents the upper bound for that constraint.

- Define the equality constraints Eq. (7)

Equality constraints are given in the form $A_{eq} \cdot x = b_{eq}$ each row in A_{eq} represents an equality constraint and each element of b_{eq} is the corresponding right-hand side value. Also, the bounds on the decision variables are specified by lb (lower bounds) and ub (upper bounds).

- Solving the LQ problem

After defining the objective function, constraints, and bounds, the prog function was used in MATLAB software to solve the optimisation problem as follows:

$$[x, fval] = \text{linprog}(f, A, b, A_{eq}, b_{eq}, L_b, u_b);$$

Finally, by ensuring that the dimensions of the matrices in Eqs. (6)-(8) match correctly With these steps, the EMS based LP optimization problem in MATLAB can be solved.

3. Results and discussion

A MATLAB Simulink was used to model and simulate the system to verify the suggested EMS. The PV system power is generated from two irradiance profiles: cloudily and clear days. In addition, daily solar irradiance on an ideally inclined surface is used and analysed to show the results. The residential load was used for the proposed MG. Fig. 5 shows the control scheme of the proposed EMS.

3.1 Energy management system evaluation using clear day

To test the proposed system, the evaluation of the MG is simulated under different case studies of irradiance, clear and cloudy days, as shown in Fig. 6. These figures are presented for 1440 minutes, 24 hours, or a one-day profile. The maximum irradiance of a clear day is 1013.07 W/m^2, while on a cloudy day, it is 1200 W/m^2, which is varied as shown in Fig. 6 (b).

The system's simulation results are implemented for 8600 seconds. As a result, Fig. 7 displays the EMS's input data, including the battery's residential load profile, PV power, and SOC. The load varies according to the power state, and this load has a minimum value of -100 KW and a maximum value of 280 KW. So, the value of the minimum cost is varied according to the demand load. The PV power of the precise day is shown in Fig. 7 (b).

The output power of the PV system is calculated based on solar irradiance, area of the panels, and efficacy. As presented, the maximum power of this system occurred at noon, and it produced 785 KW. Furthermore, the battery's SOC is presented based on the load and PV power, where the initial SOC is 50%, and this curve can be shown in Fig. 7 (c). Fig. 8 shows the MG performance based on the proposed

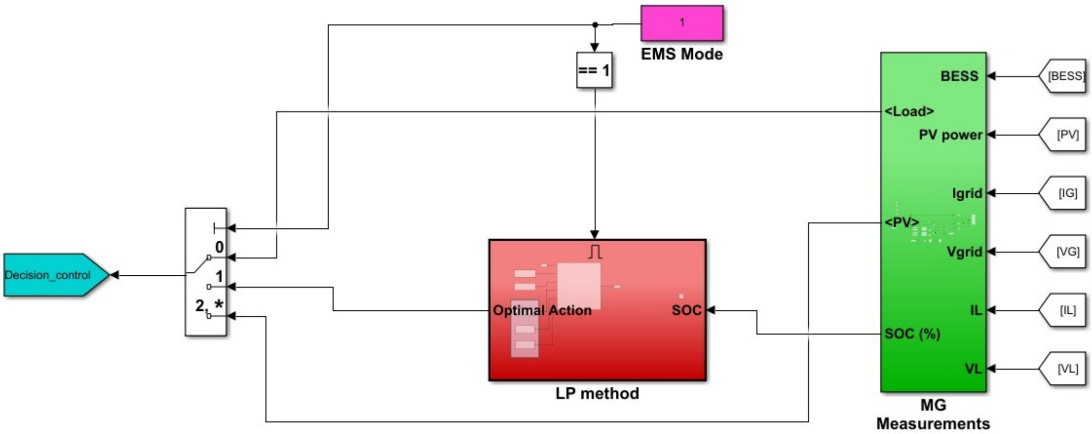

Figure 5. The control scheme of the proposed MG

EMS. This figure presents the power curves for the battery, load, grid, and PV system. Based on the battery's SOC and the solar irradiance's availability, the peak demand shaft is clear. The battery power varies with the grid power to minimise the cost of electricity.

Fig. 8 shows the price of the electricity, which is measured in cents per kWh. This figure clearly shows the price of MG, which is minimised by the suggested EMS, as shown at the beginning of the simulation, which shows a low price value. The high price of the MG occurs at the end of the day or when the PV system is off-state (zero irradiance values). Also, the load is high in this interval while the PV power is zero. Therefore, the overall power is absorbed from the battery. The maximum price of the MG, in this case, is 30 Cents per kWh. In addition, the cost per day in $ has been shown in Fig. 8 (c). The maximum cost of the energy is 580$.

Conducting stability analysis within the framework of LP optimisation for MG management is crucial to guarantee the consistent operation of the MG under various circumstances while simultaneously maximising goals such as cost, energy efficiency, or power balance. While LP is intentionally developed to provide optimum solutions based on certain assumptions, such as the linearity of the problem, many elements exist that might impact the stability of the optimisation process in actual MG systems.

Furthermore, an effective LP method is essential for MG management to guarantee reliable system operation in many scenarios while simultaneously maximising goals such as cost, energy efficiency, and power balance. A stability study evaluates the robustness of the LP model to changing circumstances and its capacity to adapt without generating inaccurate or worse-than-ideal outcomes.

The convergence of the LP optimisation process is its capacity to achieve a viable and optimum solution within an acceptable number of iterations. However, convergence issues might arise in bigger MGs with dispersed generation due to certain circumstances, such as ill-defined limits or high-complexity systems. Moreover, addressing nonlinearities in the behaviour of a system is another crucial element of the study method. The stability study assesses the extent to which the linear approximations used in linear programming accurately represent the actual behaviour of the system and if these approximations result in instability or impracticality. For these reasons, there are possible approaches

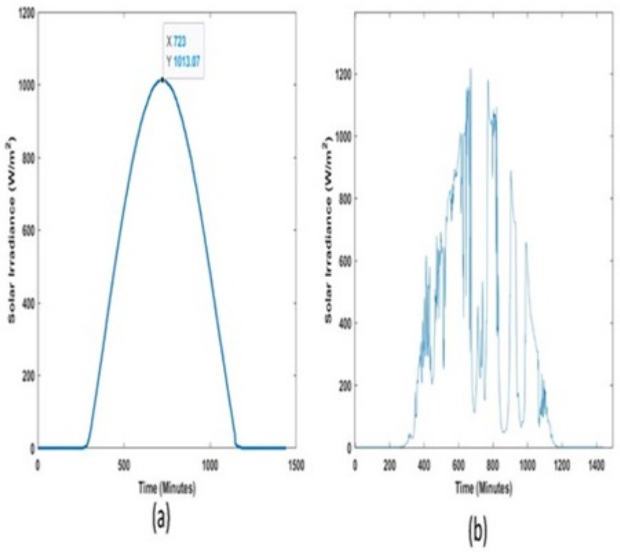

Figure 6. Solar irradiance profile: (a) Clear day; (b) Cloud day.

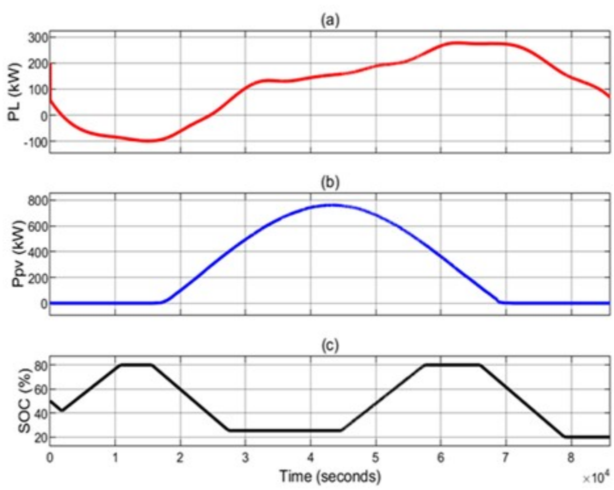

Figure 7. (a) Load power profile: (b) *PV* Power at clear day; (c) battery SOC.

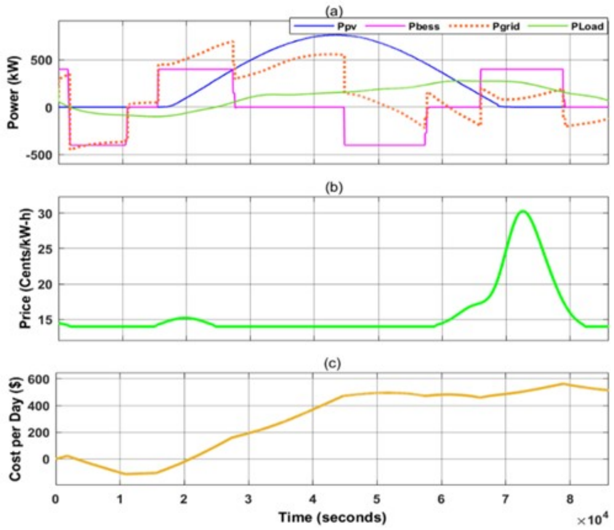

Figure 8. The results of the case are clear day irradiation: (a) power curves of MG; (b) electricity price; and (c) cost per day.

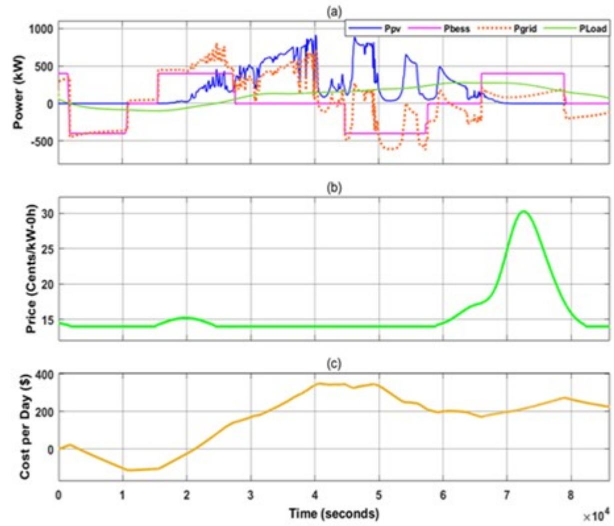

Figure 9. The results of the case clear day irradiation (a) power curves of MG (b) electricity price (c) cost per day.

to enhance stability in LP-based MG optimisation, including resilient optimisation methods, stochastic programming, piecewise linearization, mixed-integer linear programming, and real-time optimisation with feedback control.

3.2 Energy management system evaluation using cloud day

Optimised energy management, enhanced grid resilience, cost savings, precise energy forecasting and validation are benefits of simulating an MG under cloud day irradiance. Also, improved energy storage and consumption were achieved by developing the suggested EMS algorithm by simulating MG operations under different cloud situations. This aids in designing energy storage and backup-generation systems that offset abrupt reductions in solar radiation. Modelling an MG under cloud day irradiance is essential in creating and managing the system. In this section, the proposed MG is tested under cloud day of solar irradiance, as shown in Fig. 6. The obtained power in the case for MG is demonstrated in Fig. 9. To clarify the novelty of the proposed EMS, Table 1 shows the comparison and the findings obtained from the suggested MG with and without using EMS. As presented in this table, the proposed technique improves the MG by reducing the grid cost per day from 904.1$ to 580$ at a clear day case, and it provides a cost saving of 45% when the grid usage is 3400 kWh. Also, the proposed EMS provides good results in the same terms for the cloud day, reducing the cost from 700to370. According to this table, the suggested method outperforms the classical EMS method. The LP is an effective technique for reducing the expenses associated with managing an MG. It enables economic decision-making, immediate optimisation, and adaptability in resource management. The flexibility to adjust to fluctuations in demand and generation in real time ensures continuous cost efficiency. Moreover, LP has the ability to efficiently handle a combination of renewable and non-renewable energy sources by maximising the use of cost-effective renewable resources and reducing dependence on costly non-renewable sources. The system is capable of managing various limitations, such as power equilibrium, generating restrictions, and grid connectivity prerequisites, hence preventing fines and extra expenses related to non-adherence. The presented LP is a flexible and adaptable method that may be used in MGs of different sizes and levels of intricacy. Additionally, it can be included in forecasting models to anticipate and enhance the use of energy resources. This proactive strategy enables the implementation of cost-saving measures by anticipating future requirements. It optimises the efficiency of energy storage by identifying the most favourable moments to charge and discharge storage systems, mitigating expensive periods, and minimising maintenance expenses.
However, by accounting for real-world inefficiencies in energy production, storage, and consumption, the derating factor guarantees the efficient and reliable operation of the EMS system. By accounting for variables such as temperature, solar irradiance, battery SOC, and system deterioration, this approach enhances the precision of energy planning and

Table 1. Obtained results and comparison.

Irradiance type	Without EMS	Operating cost		Cost saving	Grid usage
		Classical technique [22]	Proposed technique		
Clear day	904.1$	760$	580$	45%	3400 kWh
Cloudy day	700$	630$	375$	80%	5400 kWh

optimises PV resource use, thereby enhancing the overall MG stability and performance of the MG system.

In summary, the LP-based EMS is suggested for managing microgrids due to its efficiency in solving complex energy management problems involving multiple objectives and constraints for different configurations of renewable energy sources and energy storage systems. In addition, the LP method can optimise power production and consumption from various sources to minimise operating costs, maximise efficiency, and satisfy electrical demand.

4. Conclusion

In conclusion, a linear programming optimisation (LPO) approach is employed in this work to manage energy and minimise the cost of energy or price for MG systems. The suggested system, which comprises a solar photovoltaic (PV) system, a battery energy storage system (BESS), and a main grid, is employed and evaluated using MATLAB/Simulink under various sun irradiances. First, the PV system, battery and load modelling are analysed and modelled. The residential load type is used in this work. The obtained findings suggest that the proposed technique provides the lowest cost of electricity. The data demonstrates that the suggested approach enhances the MG by decreasing the daily grid cost from 904.1$ to 580$ in a scenario with clear weather. Additionally, it achieves a cost reduction of 45% when the grid consumption reaches 3400 kWh. Finally, the suggested EMS yields favourable outcomes in the same context for the cloud day, resulting in a cost reduction from 700$ to 370$. Developing EMS in MGs for future work is (1) Utilizing AI and Machine Learning to analyse big data from grid sensors and develop AI-based predictive control systems for optimal scheduling and operation and (2) Integrating EMS with smart home technology for automatic load adjustment. (3) Using blockchain technologies to enhance transparency and efficiency in energy exchange (4) Development of interactive user interfaces for energy consumption monitoring and demand management.

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

Conflict of interests
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.

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