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A new communication platform for smart EMS using a mixed-integer-linear-programming

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Abstract
Integration of renewable energies into the microgrid (MG) operation can potentially lead to some significant benefits, e.g., less transmission expansion planning cost, direct power supply to the AC loads based on its type, lower costs, higher power quality services and enhanced technology. However, the optimal energy management of the system would be more challenging and complicated. To this end, this paper proposes an effective energy management method for optimal management of the microgrid using advanced mixed-integer linear programming. In this paper, a new demand-side management (DSM) engine is proposed using mixed-integer linear programming for IoT-enabled grid. The microgrid is simulated using MATLAB, and a two-level communication setup facilitates communication to the cloud server. Local and global communication is facilitated using TCP/IP and MQTT protocols, respectively. Lastly, simulation model is built with distributed generators (such as photovoltaic or wind turbines) and hybrid microgrid, which is applicable in various scenarios, like residential buildings and small commercial outlets.

Keywords Mixed-integer-linear-programming · IoT · ThingSpeak · Demand side management · Microgrid

1 Introduction

Nowadays, people are more involved in ground-breaking technological research in pertinent areas, especially smart cities, smart homes, the internet of things (IoT), and others. These technological advancements are quite demandable in present times—from the original constituents of a city, smart homes, and factories in the fourth industrial revolution smart cities, which are developed by combining IoT with artificial intelligence (AI). The rapid development in building construction and urbanization increases power demand, and these changes require an efficient energy management program (EEMP), especially for developing countries [1].

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In general, DSM can be divided in two main categories: Energy Efficiency (EE) and Demand Response (DR). The main purpose of EE is to reduce energy net consumption while accomplishing the same tasks, while DR refers to load profile adjustments, as, for example, load shifting and load shedding, which are driven by market incentives [2]. In [3] the authors proposed robust control strategy for parallel operated inverters in green energy applications, however, the optimal cost-effective energy management system operation based on mixed-integer-linear-programming is not investigated. In [4] the authors suggested new and more practical research models in four scenarios to assess peak demand. The proposed system is based on the assumpton of a finite number of devices in area under study, which is expressed by a quasi-random process for the arrivals or power requests. In [5], the authors proposed a distributed algorithm that focuses on planning the problem of smart devices for sparing load change in demand management. The sparse strategy for load shifting reduces customers' discomfort. In [6], the authors proposed to develop the residential microgrid (RMG) cloud-based Multi-agent Framework (MAS) for smart grid culture. The presented MAS is composed of intelligent home (SHAs) agents and a micro grid designed to alleviate peak load and reduce energy costs of intelligent households. In [7] the authors introduced a robust smart EMS for smart homes based on Internet of Energy, however, the optimal cost-effective energy management system operation based on mixed-integer-linear-programming is not investigated.

In [8] the author implemented an islanded microgrid framework peer-to-peer construction. The multi- layered and multi-agent procedures and designs that achieve this P2P construction are several goals. The agent with communcation and computation capabilities can simultaneously run these multi-layer control-related processes. In [9] the authors investigated successful DSM techniques to minimize the peak-to-average energy consumption (PAR) ratio from the grid. They analyze the trend of energy consumption, power costs, the weather, and a variety of attributes to determine the best method for load control to level the load curve. It provides a genetic algorithm for energy storage units and energy management game-based methods. In [10] the authors introduced a SCADA controlled smart home using raspberry Pi3, however, the optimal cost-effective energy management system operation based on mixed-integer-linear-programming is not investigated. In [11] the authors implemented a hybrid cloud and fog framework that uses both fog nodes and cloud servers. They used their framework on a Wi-Fi IoT board via the Constricted Application Protocol (CoAP) and ThingSpeak cloud service in open-source formats.

In [12] the authors introduced EMS of on-grid/off-grid using adaptive neuro-fuzzy inference system, however, the data storage and processing using the ThingSpeak platform are not considered. The authors presented in [13] the architecture framing, design and implementaton of an IoT and an electronic Cloud computer, which offers a consumer recharge profile for remote access by utilities and users. Consumers' load profiles allow companies to control and disseminate incentives and encourage consumers to change their use of energy. A multi-agent system for active network control of delivery networks was developed and implemented by reference in [14] using demand response. The goal of this project is to provide a dynamic platform as an effective and useful tool to support the transacton between DSO (Distribution Network Operators) and distribution network operators.

In [15] the authors introduced hierarchical EMS based on optimization for multi-microgrid, however, the data storage using IoT is not introduced. In [16] the authors implemented a new agent-based framework to combine industry and residential flexibility capacity. This approach proposes the coordination of response plans for industrial and residential demand aggregators by a central demand response provider (DRP) (IDRA, RDRA). In [17] authors presented a multi-objective problem, whose resolution is based on an evolutionary algorithm and a methodology of task management. The multi-objective issue involves a response to demand at real time prices (RTP). Two goals were taken into account: energy costs daily and customer frustration, which both reduce.

In [18] the authors introduced a SEMS as a service over a cloud computing platform for nanogrid appliances, however, the optimal cost-effective DSMS operation based on mixed-integer-linear-programming is not investigated. In [19] the authors suggested a method of adaptive power management for insulated mode and grid mode. A hybrid system including electricity distribution, photovoltaics, and battery are used as energy sources in the consumer's residential area to meet demand in this paper. The proposed system allows for the organized operation of energy delivery services to provide the required active power and service whenever necessary. In [20], the authors have launched a Smart Homes Energy Management Framework (EMS). This device communicates with a specific IP address IoT module leading to a large network of wireless appliances on every home computer. In [21] the authors introduced a new internet of things enabled trust distributed demand side management system, however, optimization based on mixed-integer-linear-programming is not investigated.

In [22] a Binary Backtracking Search Algorithm (BBSA) to handle energy consumption is suggested for a real time optimal time schedule controller for HEMS. In order to minimize overall demand and arrange household appliances operating at particular times of the day, BBSA offers optimum schedules for domestic equipment. In [23] the authors proposed an optimal load shedding scheme using grasshopper optimization algorithm for islanded power system with distributed energy resources. In [24], an approach called home energy management as a service, based on a Q-Learning algorithms, is proposed by the authors. In [25] the authors introduced a novel real-time electricity scheduling for home energy management system using the Internet of Energy, however, optimization based on mixed-integer-linear-programming is not investigated. In [26], the authors introduce as a fog computing network service a new power management system. The implementation of the fog computing platform supports flexibilities, interoperability, accessibility, data protection and real-time energy management needs. In [27] the authors introduced a self-learning domestic administration framework. The communication and interactions between agents were implemented on the IoT concepts on a Multi-Agent System platform. In [28] the authors introduced a new robust EMS and control strategy for a hybrid microgrid system based on green energy, however, data storage and processing using IoT is not considered. In [29] the authors introduced a collaborative advanced machine learning techniques in optimal energy management.

In [30] the authors introduced a consensual negotiation-based decision-making for connected appliances in smart home management systems.

Researchers aforementioned have recently proposed several forms of energy management methods in smart grid. However, there are limitations to the existing approaches as follows;

- In many systems like [3, 12], and [19], a cloud-based platform for energy management system in smart grid not investigated.
- In many systems like [22], and [24], the authors did not use a optimization technique (e.g., mixed-integer-linear-programming) to minimize the cost.
- In many of the above studies, the focus of the authors is on the approach to solving energy management problems, however, the transfer of a massive amount of data on the existing communication infrastructure is challenging.

Thus, in this paper, based on the drawback above, a new communication platform for smart EMS using a mixed-integer-linear-programming. The chief contribution as follows:

1. The designing mixed-integer-linear-programming based on IoT for EMS purpose.
2. The simultaneous daily cost of electricity and peak to average ratio reduction and user comfort increase.
3. Designing a new management using ThingSpeak for real-time construction of the HEMS based on MATLAB.

2 Problem formulation

Figure 1 shows the considered MG system, which consists of wind turbine (WT), photovoltaic (PV) units as well as energy storage (ES) device and local loads. The central energy-management system as a central controller collects information of power consumption and generation as well as ES states and sends commands to the dispatch able units.

IoT is an extensive system of knowledge objects connected to the internet, which can identify and communicate data on the internet to objects. This work uses IoT to provide a web server for WiFi clients. The proposed microgrid framework is shown in Fig. 1.

Stochastic optimal power management of MMG system is solved for 24-h day-ahead. The outputs include the total produced and consumed power of each MG in the MMG, the produced power of each dispatchable unit, the rate, and hours of charging/dis-charging of batteries, the power sharing among the MGs and the hourly power shared between the MMG and the main electricity grid. Moreover, since in the operation of MMG it is aimed to use the maximum produced and achievable power of renewable-based units (WT and PV) CEMS should accurately forecast the available power of WT and PV units. Additionally, since there exist local loads in each MG and due to the power sharing between

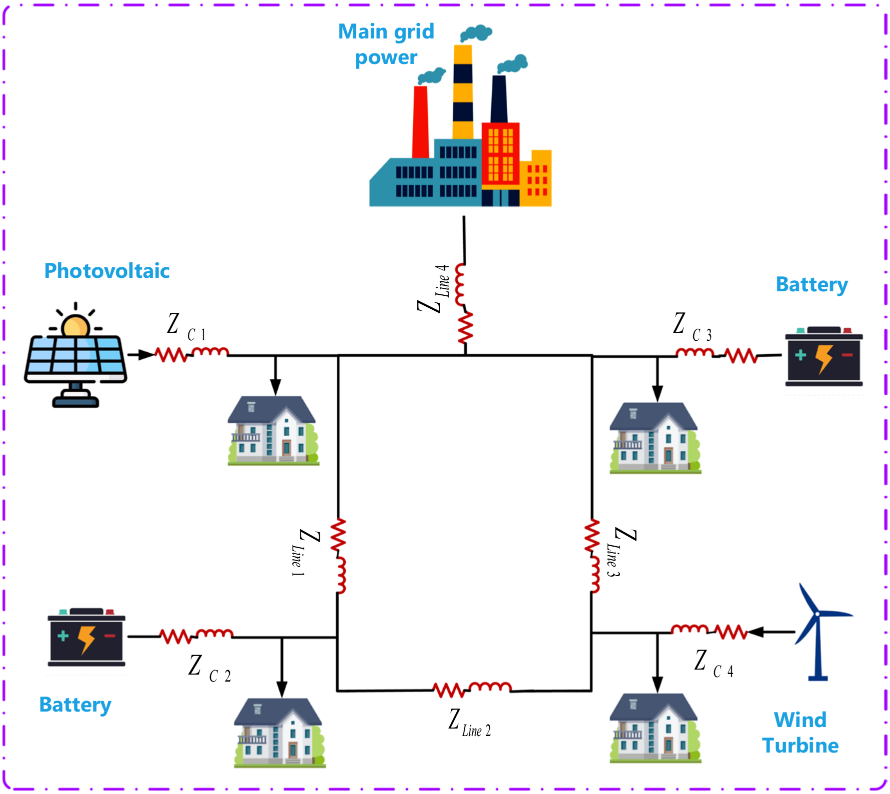


Fig. 1 Structure of proposed microgrid system

the MMG and the electricity grid CEMS should decide on an accurate and proper strategy based on load demand and the electricity price while considering the uncertainties. Accordingly, the stochastic optimal power management of MMG problem is considered as a bi-objective optimization problem for minimizing the operational cost and emission [31].

Real-time data transfer between MATLAB software and ThingSpeak framework are used to model proposed communication architectures. Because of the following benefits, ThingSpeak has been used to simulate real-time communication in cloud-based approaches [32]:

1. It enables two-way communication between the user and the simulated system, enabling real-time data sharing and remote control. MATLAB Real-time Toolbox facilitates communication between the simulated feeding model and the ThingSpeak IoT platform.
2. A platform for communication that enables online real-time data sharing between MATLAB and ThingSpeak.

3. Security—Each channel has its own ID and can be either public (visible by other users) or private. User authentication is enabled via username and password (seen by specific users).

2.1 Modeling of wind turbine

A wind turbine has an output power that mainly depends on its radius and the wind speed in the considered area. The other variables are constants, such as air density, or can be considered as constants by setting them to a value given by the control algorithm by implementing maximum power point algorithm (MPPT) [33–35] (Fig. 2):

$$P_m = \frac{1}{2}\rho A_t C_p(\lambda.\beta) V_w^3 \tag{1}$$

The performance factor (C_p) can be defined as;

$$C_p(\lambda.\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} + 0.0068\lambda \tag{2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

2.2 Modeling of photovoltaic

The installed maximum power and weather conditions affect how much power the PV panels can produce. The PV output power depends on the irradiance, the efficiency of the generation, the area of the panels and the optimal orientation depending on the location. The chosen PV technology has an efficiency $\eta_{PV} = 15\%$. The power produced by PV over a day is given as follows [33, 36]:

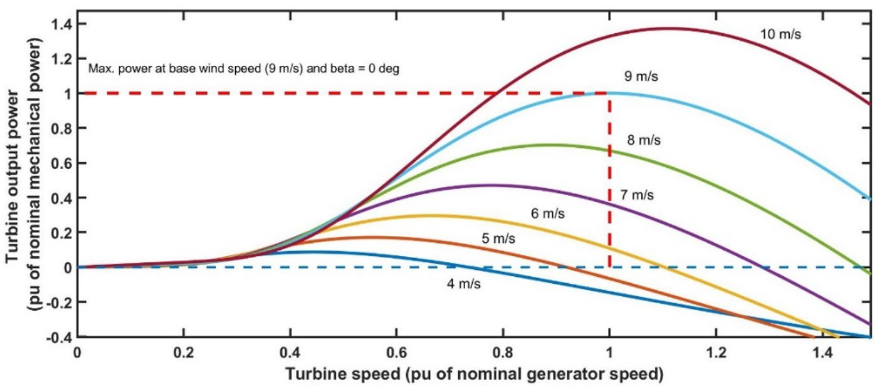


Fig. 2 Turbine power characteristics (pitch angle beta = 0 deg)

$$I = I_{ph;cell} - I_{0;cell}\left[\exp\left(\frac{q(V + IR_{s;cell})}{akT}\right) - 1\right] - \frac{V + IR_{s;cell}}{R_{p;cell}} \tag{4}$$

where I_{PH}, *the cell* is photocurrent (A), I_o, *the cell* is reversed leakage or the saturation current of the PV cell diode, *Id* is the cell is the current (A) computed by the Shockley diode equation of PV cell, q is the electron charge ($1.602 \times 10^{-19} C$), T is the temperature of the diode measured in Kelvin (K), k is the Boltzmann's constant ($1.38 \times 10^{-23} J/K$), R_p is the cell is parallel resistance of PV cell (Ω), R_s is the cell is the series resistance of PV cell (Ω),

2.3 Mixed integer linear programming

The problem is defined as a mixed integer linear programming, composed by real variables, $\mathscr{x}$, and binary variables, $\mathscr{y}$. The standard format for presenting this class of formulations is [36]:

$$\min_{\mathscr{x},\mathscr{y}} \mathscr{f}\,(\mathscr{x},\mathscr{y}) = \mathscr{a}^{T}\mathscr{x} + \mathscr{b}^{T}\mathscr{y} \tag{5}$$

The subject:

$$\begin{aligned} \mathcal{M}(\mathscr{x},\mathscr{y}) &= c \\ \mathcal{N}(\mathscr{x},\mathscr{y}) &\le d \end{aligned} \tag{6}$$

where $\mathscr{f}(\mathscr{x},\mathscr{y})$ is the objective function, and $\mathcal{M}(\mathscr{x},\mathscr{y})$, $\mathcal{N}(\mathscr{x},\mathscr{y})$ are the constraints, modelled as equalities and inequalities, which are used to limit the solution in a feasible region.

The objective function, which is the cost for absorbing energy from the n_d generators, is defined to minimize operating cost as [36]:

$$\mathscr{f}(\mathscr{x},\mathscr{y}) = \sum_{t=1}^{T}\sum_{i_d=1}^{n_d} \mathcal{P}_{\mathcal{M}}^{d}(i_d,t) * \mathcal{Q}(i_d,t) + \sum_{t=1}^{T}\sum_{i_{nd}=1}^{n_{nd}} \mathcal{P}_{\mathcal{M}}^{nd}(i_{nd},t) * \mathcal{Q}(i_{nd},t) \tag{7}$$

where $\mathscr{f}(\mathscr{x},\mathscr{y})$ is the total cost to be optimised. $\mathcal{P}_{\mathcal{M}}^{d}(i_{nd},t)$ and $\mathcal{P}_{\mathcal{M}}^{nd}(i_{nd},t)$ are the energy of the dispatch able and nondispatchable. $\mathcal{Q}(i_d,t)$ and $\mathcal{Q}(i_{nd},t)$ are unitary cost associated to those generators.

For various types of dispatchable generators, the formulation of the objective function might be taken into consideration. For instance, the utility power absorbed can be used as a dispatchable generator, ($\mathcal{U}_{g}^{d}(i_d,t)$ for $i_d = \{\text{utility}\}$) and the associated operating cost, $\mathcal{Q}(i_d,t)$ as a parameter that changes in terms of the time.

The optimization model defines the following constraints as equalities and inequalities in order to produce a workable optimal solution. The energy balance in the MG must always be maintained and can be expressed as [36].

$$\sum_{i_d=1}^{n_d} \mathcal{P}_{\mathcal{M}}^{d}(i_d,t) + \sum_{i_{nd}=1}^{n_{nd}} \mathcal{P}_{\mathcal{M}}^{nd}(i_{nd},t) + \sum_{k=1}^{n_k} \mathcal{P}_{\mathcal{ESS}}(k,t) = \sum_{i_l=1}^{n_l} \mathcal{P}_{l}(i_l,t) + \mathcal{P}_{losses}(t), \forall t \tag{8}$$

where $\mathcal{P}_{ESS}(k,t)$ is discharged/charged battery, $\mathcal{P}_{L}(i,t)$ is loads power and $\mathcal{P}_{losses}(t)$ is power loss.

Energy sources can be divided into two categories: dispatchable sources and non-dispatchable sources.

The power of the energy produced by the dispatchable sources can be characterized as [36],

$$\mathcal{P}^{d}_{\mathcal{M}}(i_d,t) = \mathcal{U}^{d}_{\mathcal{M}}(i_d,t) * \Delta t, \forall i_d, t \tag{9}$$

As a result, the energy produced by these generators can be expressed as,

$$\mathcal{P}^{nd}_{\mathcal{M}}(i_{nd},t) = \mathcal{U}^{nd}_{\mathcal{M}_{max}}(i_{nd},t) * \Delta t - \mathcal{U}_{curt}(i_{nd},t) * \Delta t, \forall i_{nd}, t \tag{10}$$

The flowchart of the proposed method is shown in Fig. 3.

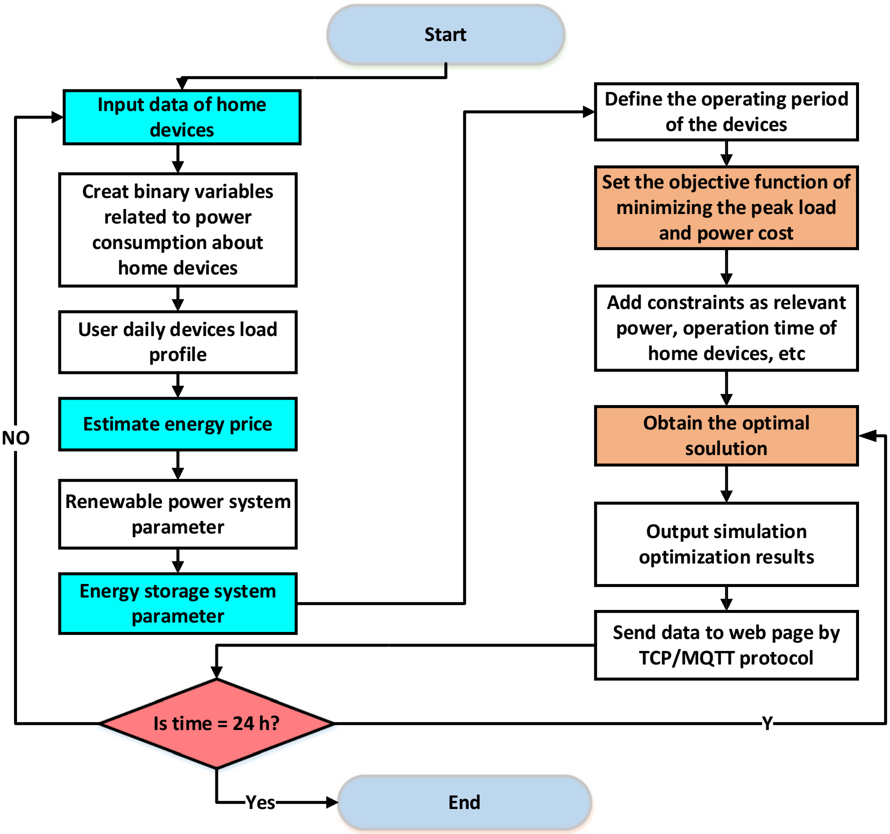


Fig. 3 Flowchart of proposed method

3 Proposed internet of energy communication platform

If there is a disruption, a smart MG's decentralized controller aids in controlling the working circumstances of the system. IoT technology can also be utilized for communication between smart home appliances, a central controller, or power management hubs. The IoT platform was suggested by the researchers as a means of data collection, monitoring, management, and control for the micro grid. This platform integrated and connected all appliances and energy sources. The energy supply layer, network layer, energy management layer, energy appliance layer, control system layer, and IoT service layer were important IoT platform layers, as shown in Fig. 4.

The creation of a distributed Internet of Energy (IoE) platform for energy management is a difficult task. The platform's functions are to connect to the IoE cloud for device tracking and management and to integrate the micro-grid tools into the communications system. The planned IoE communications network is made up of four distinct layers, as shown in Fig. 4. The descriptions of each stratum are provided below.

(a) *Agent layer*: The device or perception layer was referred to as the layer of different components [37]. Various IoT users are included in the device layer, which comprises of smart electric vehicles, smart homes, and transportation systems, along with DGs like PVs and the WTs. Additionally, this layer supported different kinds of sensors for measuring the real-time environmental and physical state of the components and the actuators needed for adjusting

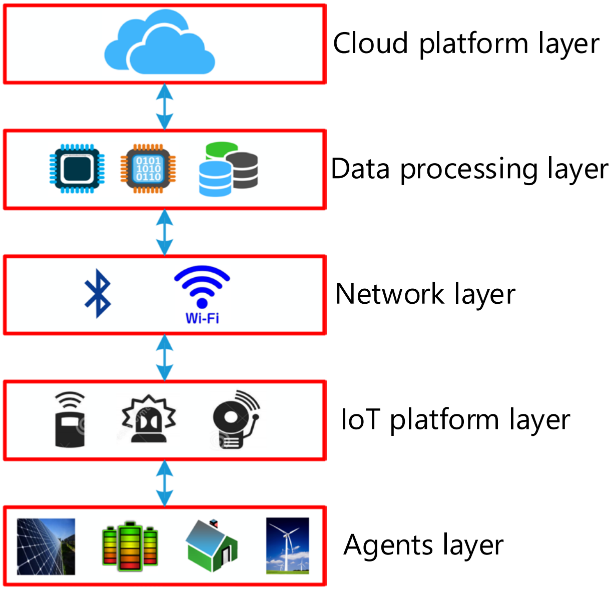


Fig. 4 Suggested architecture

them. Hence, WSNs and WSANs were seen to be an inseparable component of this layer. The WSNs are defined as sensors which sense the environmental data and transmit it to other smart devices or the upper layers through the wireless network.

(b) *IoT platform layer*: The sensors layer is the IoT platform layer. Additionally, this layer supports a variety of sensors that may be used to track the physical and environmental health of the connected agents and make real-time adjustments. The two parts of the sheet that cannot be separated are the wireless sensor and actor network (WSAN) and the wireless sensor network (WSNs). WSNs are a collection of sensors that are used to monitor the environment and broadcast their findings to other devices or higher layers over a wireless network.

(c) *Network layer*: Data from the fog and perception layers can be combined by the network layer before being sent to the upper layers for additional processing and storage. For distributed functionality existing on the component edges, it has the ability to transfer data to other smart devices. WIFI, Bluetooth, 3G/4G, Z-Wave, Zigbee, UMB, LoRa, and cellular networks are a few examples of communication technologies that are utilized in many contexts. These gadgets offer wireless communication capabilities and can be applied in a variety of ways.

(d) *Layer of data processing*: The definition of the data processing layer is the layer that permits the storage and processing of a sizable volume of data that was assembled from lower levels with the aid of potent processors [37].

(e) *Layer of cloud*: For the purpose of worldwide tracking, the cloud layer maintains historical data from distributed energy resources (DERs). The ability to keep historical data is one of the characteristics needed for IoE applications and services [38]. Virtualized servers are a component of the IoE cloud layer. Additionally, a new application interface with saved historical data for each DER has been introduced. The application interface to the cloud infrastructure supports the historical archive, which may save and maintain a large amount of data [39].

The hierarchic structure for smart homes with cyber layer, physical layer and control layer is presented in Fig. 5. The hybrid platform featured two communication layers. The Layer 1 devices in the intelligent building were found to transmit the MqTT messages to a built-in MQTT client (BMC), record the events/measures, and sign up for BMC's protection/control messages for MQTT. The interaction between the Cloud and the BMC was defined in layer 2 (global layer) using the HTTP POST/GET requests. In this system, every computer has a Wi-Fi module connected to a local portal. This made it possible to regularly write down the values of a particular and predetermined subject. Subscribing to the various topics after that, the BMC posts the values to the cloud channel. The planned algorithm for system resource allocation is implemented by the cloud interface MATLAB, which has access to all cloud data. Then, the algorithm's output is sent from a cloud to smart BMC appliances that keep track of it. The researchers found that the suggested design was durable in the event of any layer's communication failing (either global or local). Therefore, the BMC was built in such a way that it could serve as a local controller

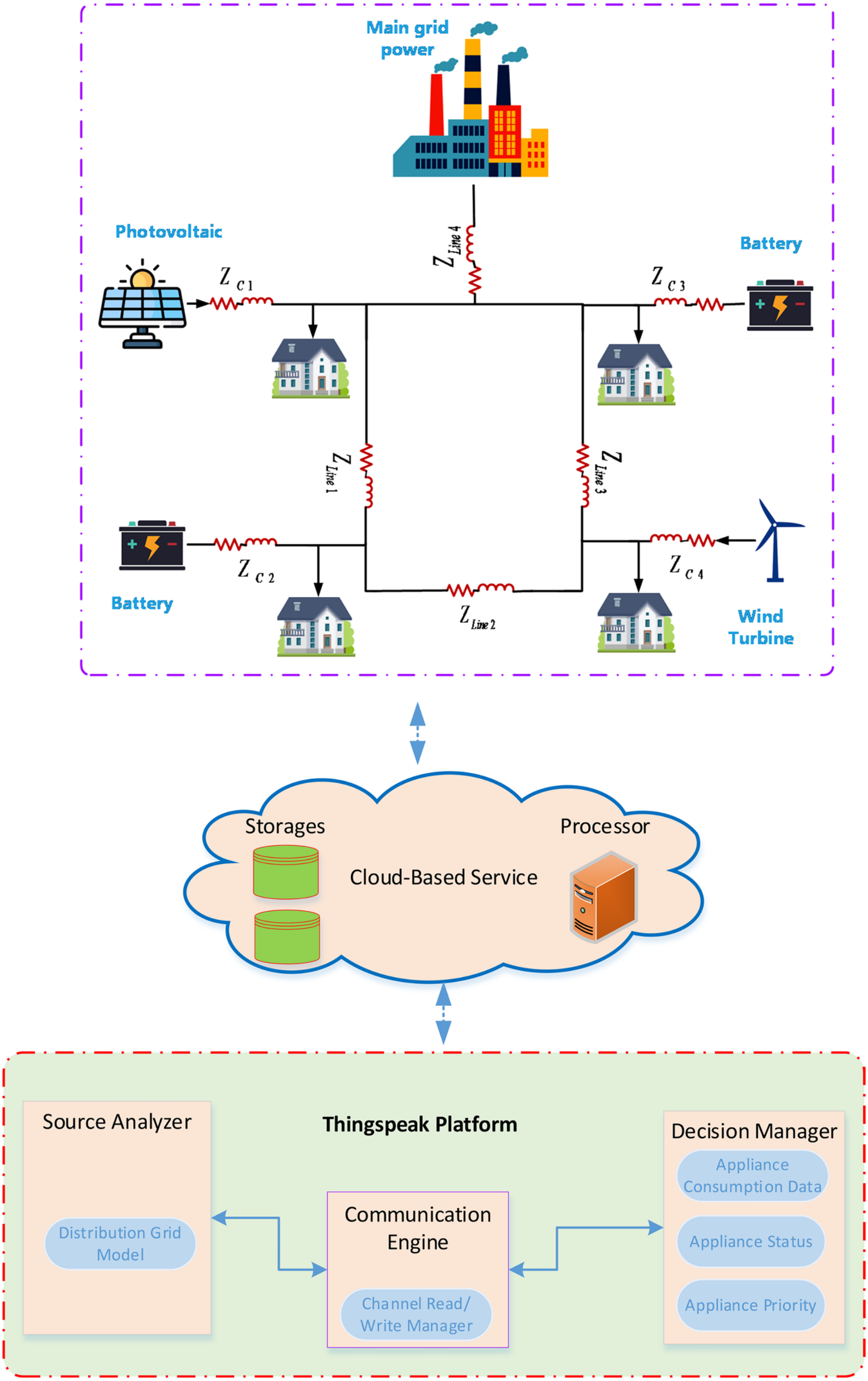


Fig. 5 Smart home proposed architecture of communication

(or backup controller) for all appliances in the building in the event of a communication connection breakdown or significant latency seen in the network. The Results section highlighted this BMC feature [40–43].

4 Simulations results

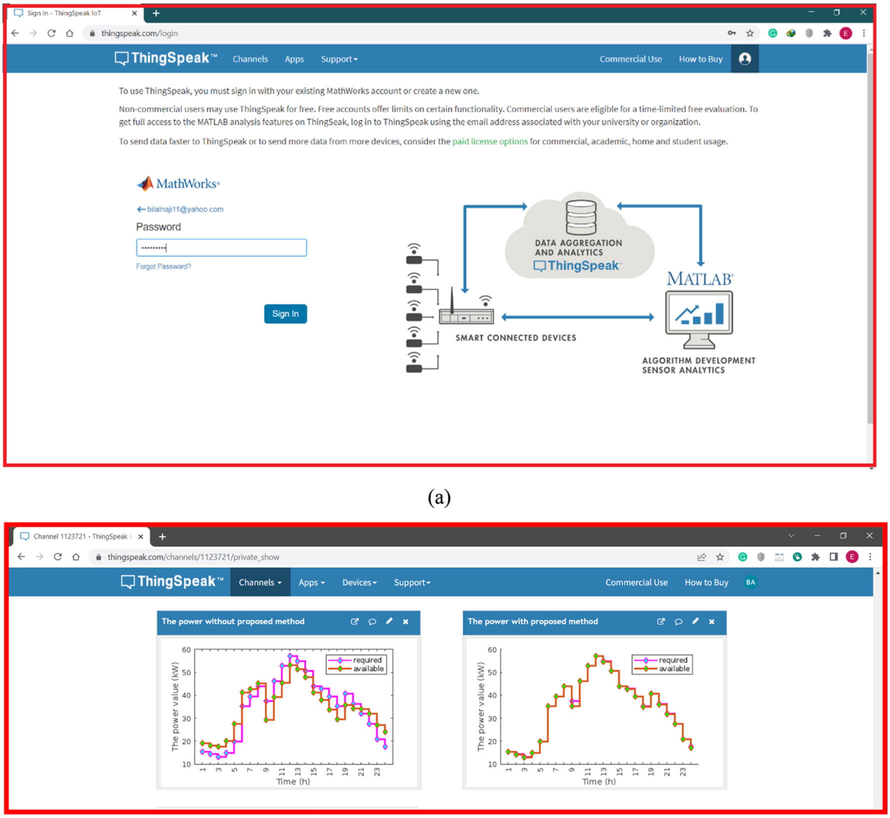
The simulation results of the suggested method for addressing the issue of the examined microgrid system's optimal power management are described in this part. Where the purpose is to reduce the microgrid system's operating expenses and emissions. Moreover, the results of power management of microgrid components are compared.

In this section, the performance of the recommended demand-side management system is tested using a microcontroller, and the results are discussed. For RTP, the analysis is completed, using mixed-integer-linear-programming. Table 1 shows the load appliances parameters [44].

This test introduces and discusses the results of smart EMS constructed using the suggested technique over a cloud-platform to control devices in micro grid. In this study, a Thing Speak platform is organized by a microcontroller, which serves as the main command and control unit. Between the main control unit and subscribing microgrid devices, MQTT serves as a broker. The User Interface (UI) for the Thing Speak platform that has been developed in this study is straightforward and practical, enabling home owners to engage with and obtain home energy management as a service via a cloud system. The dashboard and the UI flow architecture are illustrated in Fig. 6.

Table 1 Load appliances parameters [44]

Appliances	Power (KW)	Operational length (hour)	User defined time slot
Hairdryer	1.2	1	20:00–24:00
Blender	0.3	1	11:00–13:00
Lights	0.5	7	18:00–24:00
Laptop	0.1	2	08:00–17:00
TV	0.3	5	19:00–24:00
PC	0.3	2	08:00–22:00
Dryer	3.4	1	01:00–24:00
Washing machine	3	2	01:00–24:00
Vacuum cleaner	1.2	2	08:00–21:00
Steam iron	1.2	1	08:00–24:00
Air condition	3.5	6	10:00–18:00
Dishwasher	3	2	01:00–24:00
Water pump	2	5	01:00–24:00
Refrigerator	0.3	13	01:00–24:00



(a)

(b)

Fig. 6 User interface design platform (thing speak platform)

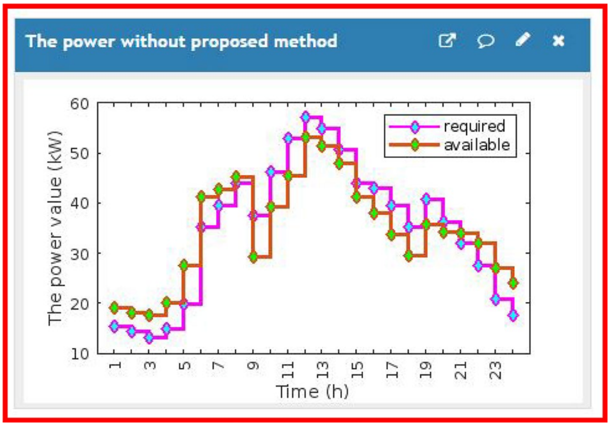


Fig. 7 Suggested graphical user interface of power without proposed method

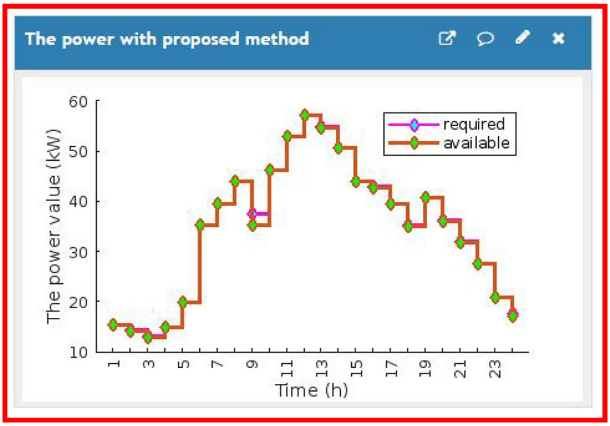


Fig. 8 Suggested graphical user interface of power with proposed method

The EMS includes a graphical user interface (GUI) to let consumers understand the total cost of microgrid devices and power consumption. Figures 7, 8 show the power consumption of all loads without and with corrective methods.

5 Discussion of results

In the RTP case, the price before applying the proposed method was 2002.77 (cent). However, after applying the mixed-integer-linear-programming optimization, the cost was found to be 1589.632. Comparing the suggested method with the conventional technique, the mixed-integer-linear-programming optimization

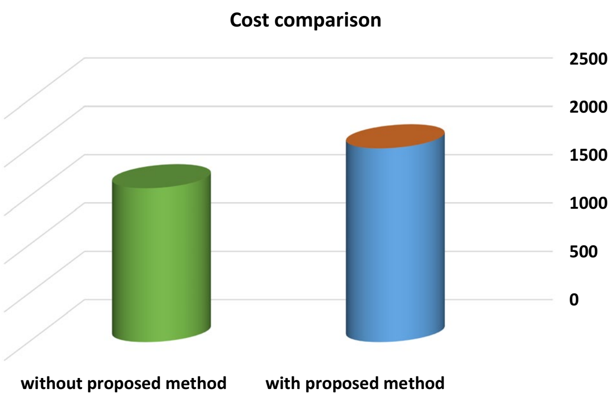


Fig. 9 Cost comparison between without proposed method and with proposed method

saved 19% per day. Figure 9 shows a cost comparison of price without the proposed EMS and with the proposed EMS.

6 Conclusion

A dramatic increase in domestic energy demand has motivated experts to implement energy-efficient domestic appliances and environments. With the development of IoT, where IoT devices are able to connect and communicate with each other, many distributed approaches using intelligent technologies have been proposed for improving the performance of smart applications. In this study, based on the advanced technologies of IoT, we present a new approach for smart HEMS based on Mixed-Integer-Linear-Programming. Message Queuing Telemetry Transport (MQTT) subscriber/publisher is adopted for cloud level messaging and HTTP TCP/IP for interactions between a cloud-server and the platform. A graphical user interface (GUI) is provided with plotting of power consumption to examine every appliance's power usage on daily basis and, further, a database is also provided for energy management which can also be used for further analysis of the data. The simulation results of this study demonstrate that the proposed system reduces the energy costs of residential facilities. Moreover, in future work, more complex conditions including more disturbance, faults, and islanding will consider and the proposed method will apply for precise microgrid monitoring.

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