Journal of Energy Storage 25 (2019) 100846

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Design and development of advanced smart energy management system integrated with IoT framework in smart grid environment

Prakash Pawar*, Panduranga Vittal K

Department of Electrical & Electronics Engineering, NITK Surathkal, India

A R T I C L E I N F O

Keywords:
Demand Response (DR)
Demand Side Management (DSM)
Internet of things (IoT)
Smart Energy Management Systems (SEMS)
ZigBee

A B S T R A C T

The day-to-day increased usage of power appliance by consumers is a growing concern in the energy sector, which creates an imbalance in the ratio of demand and supply. Demand-side energy management is an imperative tool to avoid significant deficiency from the supply end and improve energy efficiency. The trend in energy management lays focus on reducing the overall cost of electricity without limiting the consumption counterpart by instead choosing to reduce the power consumption during peak hours. The above issue seeks for design and development of a flexible and portable system to cover a wide variety of consumers for balancing the overall system. The design of smart energy management system is intended to replace the scenario of a complete power outage in a region with partial load shedding in a controlled manner as per the consumer's preference. Demonstration of experimental work is carried out assuming demand response event and also, considering the maximum demand limit constraint with different cases and changing the order of priority assigned to an appliance. Cost optimization algorithms based on time of usage and user comfort level with sensory information features are embedded within SEMS. Reliable ZigBee communication for home area network is established and also, an IoT environment is developed for data storage and analytics.

1. Introduction

The modern era has considerably increased the usage of power appliances. The research community has shown growing concern over minimizing the cause of environmental hazardous and alternative source of energy resources. The ever increasing demand for electricity consumption is a challenging issue to be addressed. Consumers in developing countries are affected severely due to the insufficient power supply from Utilities during peak hours, leading to frequent unscheduled load shedding. To adapt to the above situation, a consumer has to invest in fuel generators and battery storage with additional financial burden counterpart inversely affecting the economic growth of the country. The other end, Utilities have to invest huge amounts in developing infrastructure for the generation plants to withstand peak hours, subsequently leading it to be underutilized. To sustain a balance in energy supply and demand, there is a need for reliable power network within generation, transmission and distribution sector.

Smart Grid brings rapid transformation in the energy sector, enables demand side management system to quickly respond during outages, peak load shifting, and fault management. In addition, it facilitates consumer to employ alternative renewable sources for minimizing electricity cost and efficient utilization of available power sources.

Demand Response (DR) program in Demand-Side Energy Management(DSEM) is a viable solution to manage energy efficiently and in turn, benefit the consumer and Utilities [1]. Smart meters at the consumer's end have a crucial role to play in the power management of Energy sectors [2]. Bidirectional communication between consumer premises and the Utilities provide a greater opportunity in the energy management system [3]. Currently, Utilities provide different tariff rates based on the categories of consumers. The classification of consumers is mainly based on the usage of electricity and the business established in that region. Most commonly Energy sectors divide consumers into different categories as Domestic, Commercial, and Industrial customer [4]. For each category, there are different tariff rates with Time of Usage (ToU) and penalty charged considering demand limit and Power factor parameters. Tariff rates are low for residential customers and high for industrial customers, since industrial sector gives maximum profit for utilities, hence it is listed to be in the high priority section.

Load shedding due to insufficient power generation is one of the significant issues. There is a need for efficient utilization of available power in the best optimal way. In a conventional system when the available power from generating stations is less than the required demand from the consumer's end, the power distribution to some of the

* Corresponding author.
E-mail addresses: prakash.ee14fv10@nitk.edu.in (P. Pawar), vittal@nitk.edu.in (P. Vittal K).

https://doi.org/10.1016/j.est.2019.100846
Received 31 March 2019; Received in revised form 24 June 2019; Accepted 18 July 2019
Available online 30 August 2019

areas are tripped down. The load shedding is in the order of their preference by the utility end. The power consumption pattern is shifted to off-peak hours to balance the system and hence each affected area suffers the minimum possible blackout time. In recent years to overcome the issue of the complete blackout, a major area of research focuses on the design of a Smart Energy Management System (SEMS) for consumers which benefit Utilities as well as the end users [5]. Today, interests in energy management systems have grown significantly, now it is possible to optimize power utilization at consumer premises to get finer control of available resources [6,7]. The primary goal of the SEMS is to satisfy the user comfort with the available power and minimize the energy consumption and hence balance in the ratio of supply and demand. In demand-side energy management, during the peak consumption window, there are multiple constraints to schedule power optimally. In general, the appliance can be categorized as schedulable and non-schedulable [8]. Further, the schedulable appliance can be of interruptible or non-interruptible types. For example, a Washing machine can be considered as a schedulable non-interruptible appliance, and a pool pump can be a schedulable interruptible appliance [9,10]. Energy usage levels of Heat Ventilation Air Conditioning (HVAC) and other heating appliance(s) depend upon the weather condition in that region [11]. Nevertheless, environmental weather sensor data can also contribute to a greater extent in minimizing and scheduling the available power effectively. A comparative study of different literature published in the area of building energy management system is carried and listed in Table 1.

A considerable amount of literature focuses on algorithms deployed in demand side energy management framework associated with a DR strategy. In literature [12], authors propose a home energy management system to provide individual appliance usage details to the consumer and lets the consumer to make a decision. However, there is no automation mechanism to control an appliance operation. The authors in [13], have evaluated the effectiveness of Energy Management System (EMS) by considering power consumption data, ambient temperature, room temperature and consumer usage profile prior and after deployment of EMS system. It is reported that significant power reduction can be achieved by changing the TV usage pattern, avoiding standby power consumption and by varying the refrigerator capacities based on aforementioned constraints. In [14], authors Pedrasa et al. proposed an optimized model using Particle Swarm Optimization (PSO) scheduler, which emphasis on minimizing electricity cost and reducing peak load consumption for a domestic consumer. Furthermore, in [15] authors Ahmed et al. deployed algorithm for optimal real-time scheduling designed to shift the peak window and minimize the overall energy consumption by assigning priority to the appliances. In [16] Kuzlu et al. presented a hardware demonstration of the energy management system at the appliance level based on the DR program considering maximum demand limit constraint and also communication delay involved with energy management set up was evaluated.

In recent literature, various investigations have been carried out with environmental sensor data and user comfort integration to develop a more sophisticated energy management system. The authors in [17] Klein et al. presents a multi-agent-based comfort energy management system, which can dispatch the controls actions considering occupants and sensory information data. It coordinates with the occupants in the building and real world data like actual ambient temperature, user preference, and user schedules to maintain the user comfort and hence optimize the energy usage. In [18], Author's Doukas et al. developed a knowledge database with building energy characteristics and sensor feedback. Further, a rule set based intelligent system incorporated with expert knowledge is designed to create a reliable energy profile to control energy activities along with preserving consumer comfort and minimizing the electricity cost. Authors Sehar et al. in [11] presents an integrated environment to control appliances in a commercial building, i.e., Heating Ventilation and Air Conditioning (HVAC) demand to maintain individual user satisfaction considering their preference.

Table 1
Overview of research for Demand-Side Building Energy Management.

Authors	Proposed Approach	Parameters Considered	Appliances Type	Features incorporated
Jo et al. [32]	Linear transformation and optimization technique to find best optimal schedule.	User comfort features and thermal properties of appliances.	- Intended for use of Residential Consumer. - Heating and air conditioning appliances.	- Minimize inconvenience to consumer. - Reduce energy consumption. - Utilize available resources.
Yang et al. [33]	A Multi-agent system is developed to enable interaction between occupants and environment parameters.	Indoor environment, temperature, illumination level and user characteristics.	- Can be adopted for different building environment. - Considered HVAC and Lighting appliances.	- Satisfy occupants demand and minimize consumption. - Easily adopted into existing automation framework for add-on features.
Ogunjuyigbe et al. [34]	Consumer satisfaction based Genetic algorithm (GA) is used.	- Predefined budget allocation. - Consumer achieved satisfaction level.	- Focusing on residential consumer. - Home Appliances.	- Algorithm Controls based on user achieved satisfaction level and minimizes cost.
Tenfen and Finardi [23]	Mixed integer linear programming is used.	- Demand Response and load shedding features are included in EMS model.	- Focus on non-controllable loads in EMS model.	- Minimize the operational cost. - Measure the technical and economic impact of EM system on main grid.
Qureshi et al. [26]	Linear program and non-convex optimization problem using robust optimization method.	- Tracking temperature set-point level and load flexibility.	- Focus on HVAC appliance in a building environment.	A hierarchical control scheme providing ancillary service involved with building thermodynamics and flexibility in HVAC system.
Ghatikar et al. [31]	Linear optimization techniques and openADR communication tool is used.	- Real-Time Pricing & Peak day Pricing. - Glopal temperature set-ponts, dimming lights and plug loads.	Common Loads such as heating, cooling, and lighting systems	Enables integrated environment for energy providers and consumers to provide load flexibility, cost effective system.

Ogunjuyigbe et al. [19] suggested a demand-side load management technique that focuses on maximizing the user satisfaction level based on a certain rule at a possible minimum cost with a predefined budget by the consumer. In this case, the acquired data can be used for predictive analysis and further optimization in energy usage pattern [20].

Previous studies have suggested several optimal energy models for consumer-based on DR strategies and optimization approach. Author's Tenfen and Finardi in [23] proposed detailed modeling of optimal energy management to reduce the operational cost of the system, incorporated with shedding and scheduling of loads in demand side. In this work, authors also consider reducing the start-up, shutdown, and maintenance costs. In [24], authors Yin et al. present a novel DR estimation framework with regression models based on time of use and temperature set point for domestic and commercial consumers. The developed framework shows a DR potential and flexibility for peak load shed prediction. Authors Lagorse et al. in [21] developed a multi-agent EMS architecture for smart home energy management system with consumer intension and sensor feedback involving scheduling strategies and DR mechanism. Further, this technique has been implemented for renewable sources integrated with smart grid control. In [22] authors, Paterakis et al. focus on scheduling and controlling in-home appliances to provide economic advantages for residential energy management, modeled using mixed-integer linear programming. Furthermore, battery based Energy Storage System (ESS) considered along with DR strategy improved significantly in lowering the electricity cost.

In a recent work [25], authors Wang et al. proposed a novel supply based feedback control strategy. Global and local cooling distributors based on adaptive utility function are employed to properly distribute the chilled water/air flow among different zones to sustain the uniform thermal comfort. The proposed system helps resume operation quicker after the DR event and shows a significant reduction in power consumption. In [26], authors Qureshi et al. have proposed a hierarchical control scheme providing ancillary service for demand side management involved with building thermodynamics and HVAC system by tracking temperature level and load flexibility. The developed system provides flexibility in load scheduling and also minimum operational cost.

Several energy management frameworks are designed based on various communication technology, such as Wi-Fi, ZigBee, and powerline carriers [37]. The suitable communication mode between the consumer loads and Utility gateway is used to control the appliance with different operation strategy [27,28]. In [28] authors, Son et al. proposed a home EMS with key features involving real time data monitoring, intelligent control actions using power line communication. The designed system provides remote monitoring feature for better energy conservation with the use of statistical Reduce model, which examines the energy saving choices by including many different factors.

The Internet of Things (IoT) introduced in recent years has a wide range of application in the automation system. Integrating IoT environment in SEMS aids for remote monitoring and controlling at the appliance level for efficient energy management [29,30]. In a study [31], authors Ghatikar et al. developed new models using linear optimization techniques and communication open standards. This work presents a cost-effective solution to demand side energy management challenges by exploring communication technologies and information models for distributed energy system integration and interoperability.

Most of the energy management implementations discussed in the literature focus mainly on domestic consumers and are designed to schedule the appliance operations based on Utility signals assigned with fixed priority parameters. There is yet need of implementing a flexible energy management system with reliable communication, portable enough to include a wide variety of consumers that can manage power intensive loads to limit the household peak demand without much affecting the user satisfaction level and reducing overall electricity cost.

In this work, the proposed scheme emphasizes on design and development of real-time hardware prototype. Most of the energy management implementations discussed in the literature focus mainly on domestic consumers and are designed to schedule the appliance operation with fixed priorities. However, the preferences of the appliances change dynamically based on user convenience and environmental factors. Therefore, in this work, a flexible smart energy management system is proposed, which has user configurable priority feature, portable enough to include a wide variety of consumers without affecting the user comfort alongside involving cost optimization techniques. In addition, advanced self- diagnostic feature for reliable communication and ease of scalability at the appliance level is considered in the design of SEMS. Further, in this work, the IoT environment is integrated with the proposed SEMS for further data analytics usage and remote monitoring. Hardware demonstration of the prototype is set up in a laboratory environment and experiments are carried out with different configurable priority settings and demand limit constraints along with ToU and sensory information consideration. Nevertheless, the proposed smart energy management system can also be used to optimize the utilization of power generated by standalone systems like solar power plants, wind power plants, etc.

The content of this paper has been organized as follows: After this introductory section, a description of the proposed system and an overview of the proposed architecture is presented in Section-2. Proposed control method and implementation of different optimization algorithms are discussed in Section-3. In Section-4, details of the experimental setup and overall system framework is presented. Section-5 presents the results and discussions for the developed control schemes. Finally, Section-6 concludes the paper.

2. Description of the proposed system

This section describes the proposed Smart Energy Management System (SEMS) in detail with the algorithms embedded within the system.

2.1. Overview of proposed SEM system

The concept of proposed Smart Energy Management (SEM) system is shown in Fig. 1. The overall system comprises of an SEM unit that provides a monitoring and control functionalities for a consumer and another end Smart Sockets gather electrical parameters from appliances and perform local control based on the command signals received from the SEM unit.

SEM unit also acts as a gateway that provides an interface between the utility and a consumer. In such a scenario, the gateway receives the data of allocated maximum demand limit from Utility, which is used as an input for our SEM unit. Utility, on the other side collects energy consumption data from all the SEM units in a city and analyzes this data for updating the maximum demand limit of each household. Collected data would also be used for billing purpose, and an e-bill would be generated for each household.

2.2. The architecture of SEM gateway

In general, SEM Gateway comprises of the following modules,

I. *SEM Gateway (Central controller)*: The SEM acts as an intermediate gateway between the Utility and a consumer, it is used here as the main control unit which runs a decisive (power negotiation) algorithm that serves as a brain of the SEM system. It decides to switch ON/OFF selected end-user appliances based on the utility signal received, as well as homeowner's load priority settings. During peak load hours, the SEM unit warns consumer while switching on a high power consuming appliances to avoid high tariff charges. It is also responsible for collecting energy consumption data from all the load controllers through XBee modules and providing an LCD interface for homeowners to retrieve real-time energy consumption data and also with a provision to

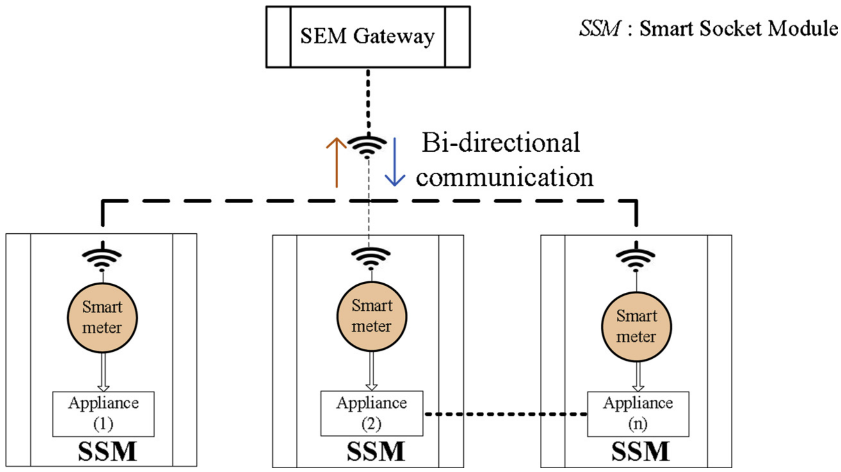


Fig. 1. Overview of proposed Smart energy management system.

configure the priority of an appliance as intended.

II. *SEM communication module*: Wireless communication is established between the coordinator (user end) and a router (appliance end) module. XBee Series- 2 devices are used here as a communication module, either end an XBee module is attached to enable communication within the SEM system. XBee module in a load controller is configured as a router (appliance end) and the other module it is configured as the coordinator (user end). Once the communication is established between the router and the coordinator within the SEM system, the SEM unit runs the power negotiation algorithm with the collected power consumption data and coordinator associated with it sends the controls signals to the router.

2.3. The architecture of a smart socket module (load controller)

A load controller provides an interface between the SEM unit and a selected appliance through Smart Socket Module(SSM). It provides basic power management functions (i.e., control, communicate).

Role of different Architecture module based on its function:

1 *A data collection and processing module*: The main task is to collects real-time electrical parameters such as RMS voltage and current values, further computes apparent power, real power, energy and power factor of an appliance. Hall effect based LEM sensors are used here for voltage and current measurement.
2 *A control module*: It is an electronic relay circuit used to switch a selected appliance ON/OFF, as per command sent by the SEM Gateway.
3 *A communication module:* It establishes a two-way communication path between a Smart Socket Module and the SEM Gateway.

The collected power consumption data from a load controller is to be sent to the SEM Gateway counterpart commands from the SEM unit is received by a load controller. Communication is established using Application Transparent (AT) mode, and each load controller communicates directly with the SEM unit. After collecting data from all load controllers, SEM unit runs the decisive algorithm and sends back control commands to individual load controller.

2.4. Communication within the SEM system

Generally, in an energy management system, communication modules are required at the end of both the master and slave node. One of the communication modules is integrated with the SEM Gateway and the other associated with each smart socket or load controller. The type of communication modules plays an important role in overall system performance in terms of data communication and power consumption. Various communication technologies are available such as Bluetooth (802.15.1), Wi-Fi (802.11/n), ZigBee (802.15.4), and Power Line Carrier (PLC), for a home area network either one or combination of these communication technologies can be deployed based on a range of communication and data rate. Based on an evaluation study of various communication technology [35], ZigBee finds a suitable candidate for our application, which has low cost, low power, and ease of deployment.

3. Proposed demand side energy management algorithms

The proposed SEMS control technique consists of smart socket unit for individual consumer appliances to communicate with the SEM Gateway (Central controller) using XBee modules in AT mode of communication. SEM gateway in the proposed technique receives the data of allocated maximum demand limit from utility and energy consumption data from all the smart sockets installed. Further, SEM uses a decisive algorithm for power negotiation to schedule the individual appliance optimally.

The proposed SEMS is embedded with the following algorithms in SEM Gateway and Smart Socket Module(SSM) to address demand side energy management for optimal energy usage.

1 SEM Gateway (Central controller)
  - *Decisive algorithm operation during Demand Response*
  - *Self-Diagnostic feature to handle non-responding appliance*
2 SmartSocket Module (Appliance end)
  - *Control actions dispatched at the appliance end*
  - *Cost Optimization Algorithm*

The decisive algorithm is the main component in the proposed SEMS technique, and it is deployed in the SEMS main controller (Gateway). Furthermore, all control actions are managed through the decisive algorithm.

3.1. Decisive algorithm operation during Demand Response

The decisive algorithm is the key element in the proposed SEMS technique, which considers the consumer priorities of appliances and operates the most critical appliances even when the utility allotted power is less than the maximum demand. The complete flowchart of the proposed SEMS technique with power negotiation algorithm is shown in Fig. 2. Further, stepwise explanation of the deployed algorithm is discussed in this section.

Step 1: The SEM decisive algorithm starts by gathering power

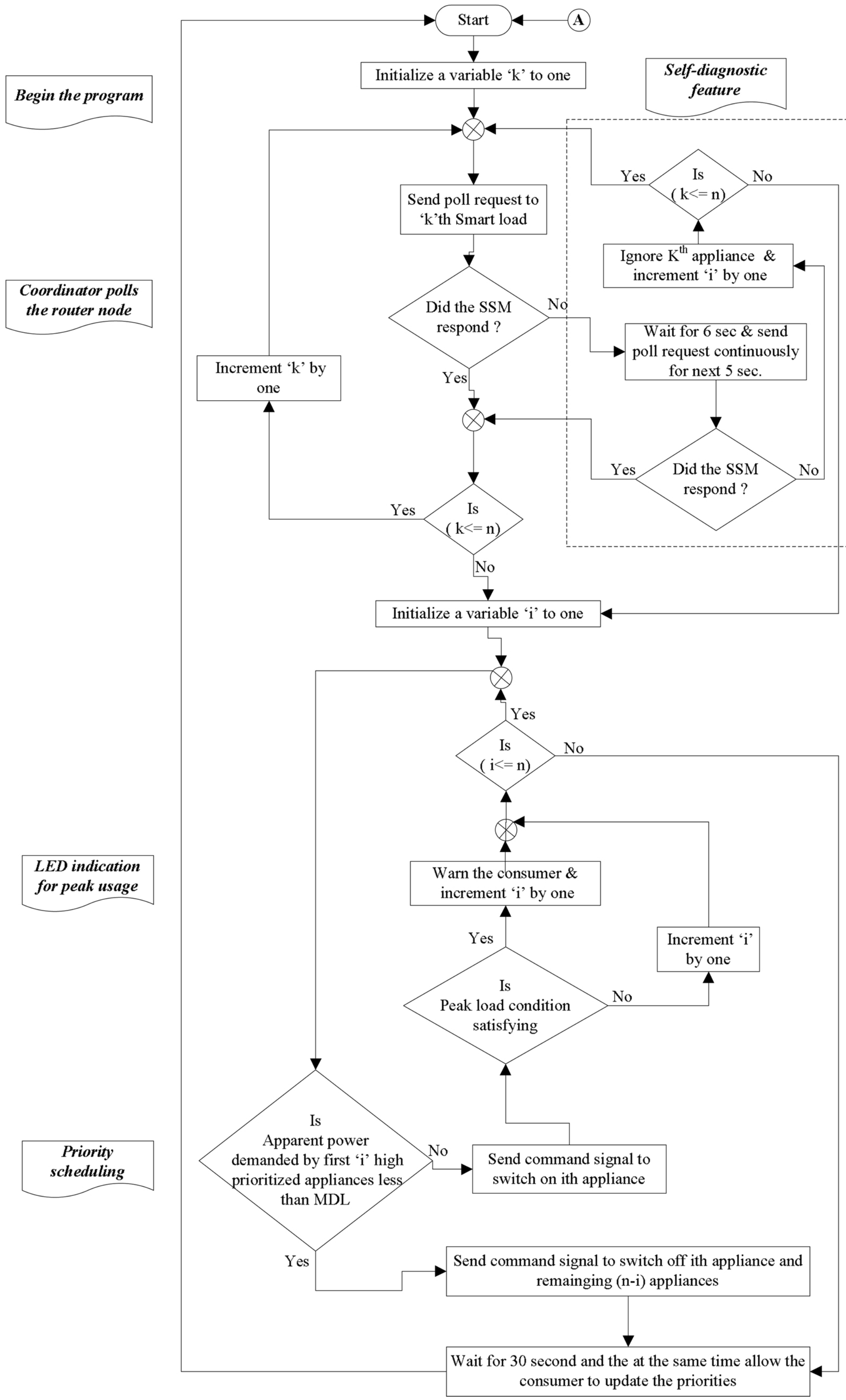


Fig. 2. Flowchart of Decisive algorithm with self-diagnostic capability.

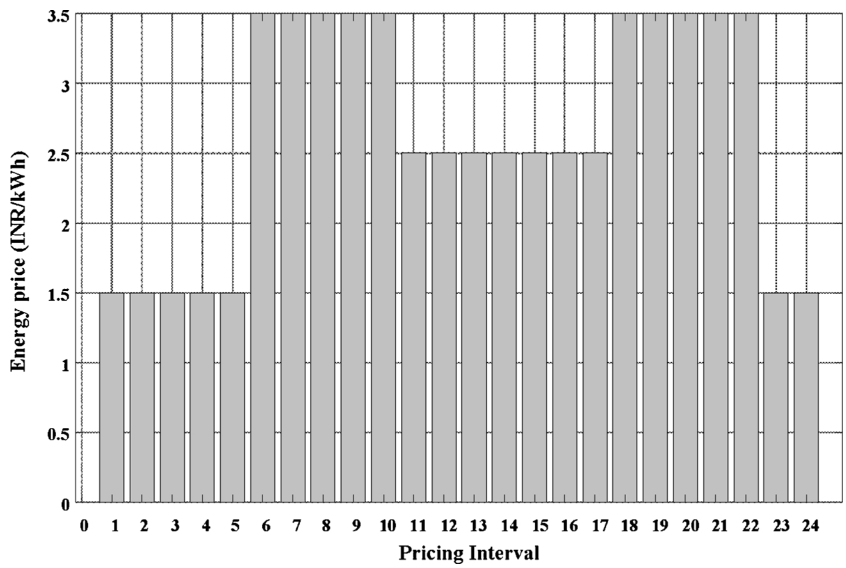


Fig. 3. The Approved ToU Tariff for consumers [22].

consumption data of all the appliances. This data collection would be done in a predefined order. If any load controller does not respond, the controller runs a self-diagnostic algorithm (explained in Section-3.2).

Step 2: The collected data of power consumption is arranged in the order of consumer's priorities, and then SEM Gateway checks for following demand limit violations.

- Total Apparent Power consumed > Maximum Demand Limit (MDL).

Step 3: SEM Gateway sends a command to switch ON the maximum number of high prioritized appliances such that the MDL is not violated and sends a command to switch OFF the remaining appliances.

Step 4: For any appliance which is switched ON, the decisive algorithm also checks for following peak load condition *(which may vary depending on user convenient)*.

- Total Appliance Power > $\frac{1}{4}$ (Maximum Apparent Power of previous month)

In the case of peak load condition being satisfied, the SEM Gateway sends a command signal to the load controller to warn the consumer about the high power consumption during peak load hours to avoid high tariff charges. In addition, the load controller warns consumer by switching on the buzzer and LED for one second.

Step 5: After sending respective command signals to all appliances, SEM Gateway would wait for 30 s before the next data sampling. Further, the consumer can update appliance priorities based on his/her convenience during the wait time. Then repeat steps 1–5.

Flow chart of the SEM decisive algorithm for 'n' number of loads in a household is shown in Fig. 2. It is to be noted that before running this algorithm, priorities of appliances are initialized with predefined settings. Also, two variables 'i' and 'k' are used in the flow chart. Variable 'i' increments in the order of priorities whereas 'k' increments in a predefined order to collect power consumption data of all appliances.

3.2. Self-diagnostic feature to handle non-responding appliance

SEM Gateway sends a request signal to each of the load controllers to collect its data. In normal operating conditions, the load controller responds immediately with the energy consumption data of such specific load. However, in some abnormal conditions where the XBee device in that load controller module becomes inactive temporarily, the sequence of data transfer might be disturbed, and load controller may not respond even after coming back to normal state. In such conditions, SEM Gateway waits for the prior set time of six seconds and then runs a self-diagnostic algorithm where it continuously polls the load controller for next five seconds and at the same time waits for its response. The load controller then responds with the relevant data if the inactivity was due to a temporary fault. SEM Gateway would then continue sending requests to other load controllers. In case, even after five seconds of continuous polling, if the load controller doesn't respond, SEM Gateway would assume that the load controller is permanently inactive and would ignore it for that event starts sending requests to other load controllers. Thus, few inactive load controllers would not affect the remaining system functionality.

3.3. Cost optimization algorithm

ToU tariff affects consumer's energy expenses to a significant extent. A load scheduling algorithm is developed with an objective of minimizing energy expenses. However, not all appliances are subjected to this algorithm. Appliances in a household are categorized as schedulable and non-schedulable appliances based on the willingness of the consumer to allow operation of an appliance to be schedulable. This algorithm runs in the load controller of all schedulable appliances. Hence all schedulable appliances are controlled by both SEM decisive algorithm running in the SEM unit and load scheduling algorithm running in the load controller of a schedulable appliance. The ToU Tariff of MESCOM for the fiscal year 2018 applicable to Low Tension (LT) industries (categorized as LT-5) [36] is mentioned in Fig. 3. The above-mentioned ToU tariff is considered for the design of load scheduling algorithm with an objective of cost optimization. SEM unit sends data of time to all schedulable appliances. Based on the time zone, the load controller of a schedulable appliance decides the status of the appliance. Based on consumer's daily usage, duration per day for which an appliance is required to be operated is predefined.

The algorithm is designed in such a way that appliance is operated to the maximum possible extent during 22:00 h to 06:00 h so that consumer would be benefitted with an incentive of Indian rupees ₹1/unit as presented in Fig. 4. During peak load hours, the appliance is forced to be switched OFF irrespective of the required duration of operation in order to avoid penalty. During non-peak load hours when neither incentive is offered, nor penalty is levied i.e., from 10:00 h to 18:00 h, appliance can operate if the required duration of operation is more than eight hours else it is switched OFF so that it would be

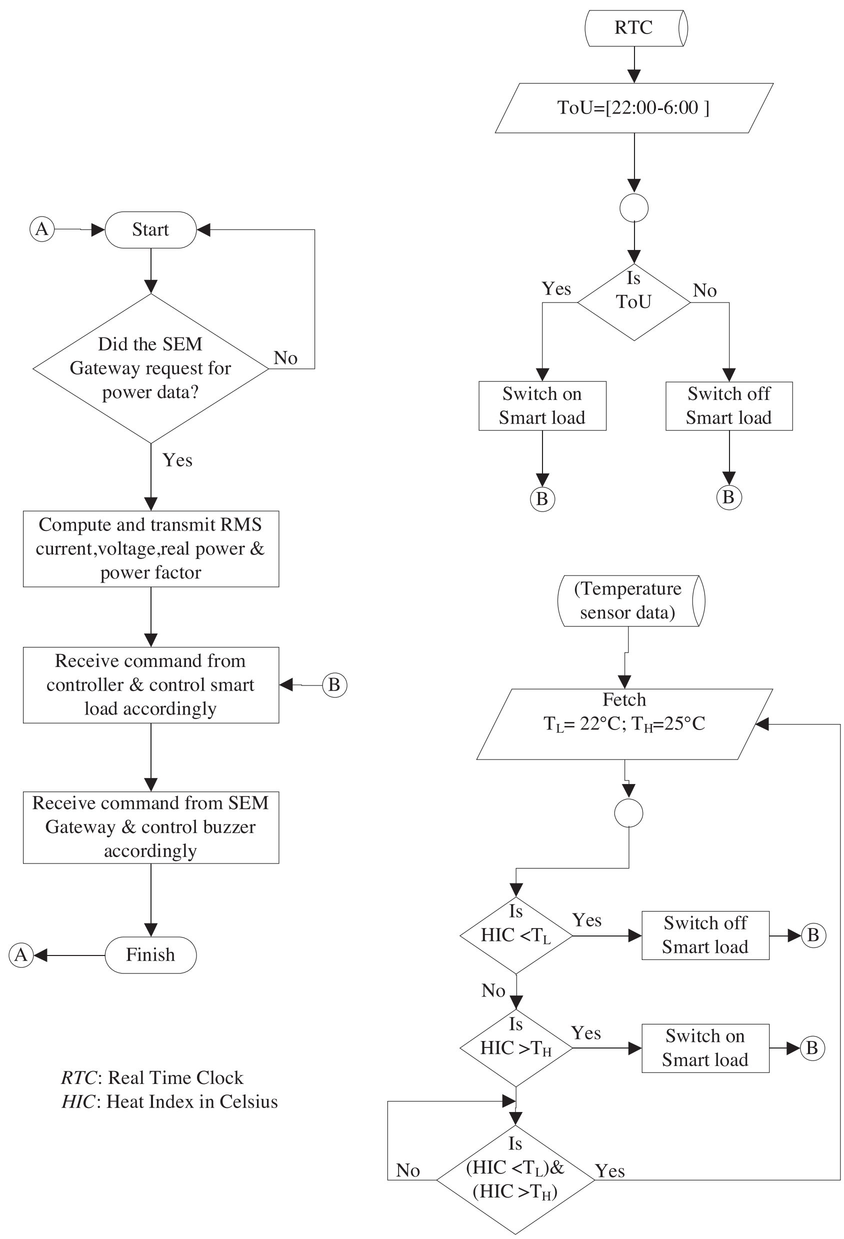


Fig. 4. Flowchart of algorithm deployed in the smart socket module.

scheduled to operate between 22:00 h and 06:00 h as incentive would be provided during this period. In case if on any day appliance could not be operated for required duration may be due to domination by SEM decisive algorithm which would happen if generated power is insufficient, the algorithm makes sure that this loss would be compensated in the next day by allowing it to operate for a longer duration. At 10:00 PM of every day, the required duration of the operation is updated by adding the previous day's pending requirement to the daily requirement.

3.4. Control actions dispatched at the appliance end

The internal details of the smart socket are discussed in detail in the following sections, the flowchart of the algorithm is shown in Fig. 4, and the role of the smart socket algorithm is as follows. The Smart Socket decisive algorithm keeps checking any request received from the coordinator end to send the power consumption data. Microcontroller unit associated with the smart socket computes and transmit RMS current, voltage, real power, and power factor parameters. Smart socket receives the command signal from the coordinator and controls the relay to switch the status of an appliance accordingly. Further, Smart Socket receives signals from the coordinator to indicate any warnings with the appliance usage.

4. Smart energy management system experimental setup

In this section, experimental design and development of SEMS is presented.

4.1. The overall system set-up

The overall SEM system is shown in Fig. 5, which is set up in the laboratory environment with actual loads: a lighting load, a fan, and a charging laptop. Algorithms deployed in SEM unit are designed to run the appliances in the order of assigned priority during the Demand Response (DR) event considering the maximum demand limit and scheduling the appliance considering the Time of Usage (ToU) to accommodate it in the minimum slab rate.

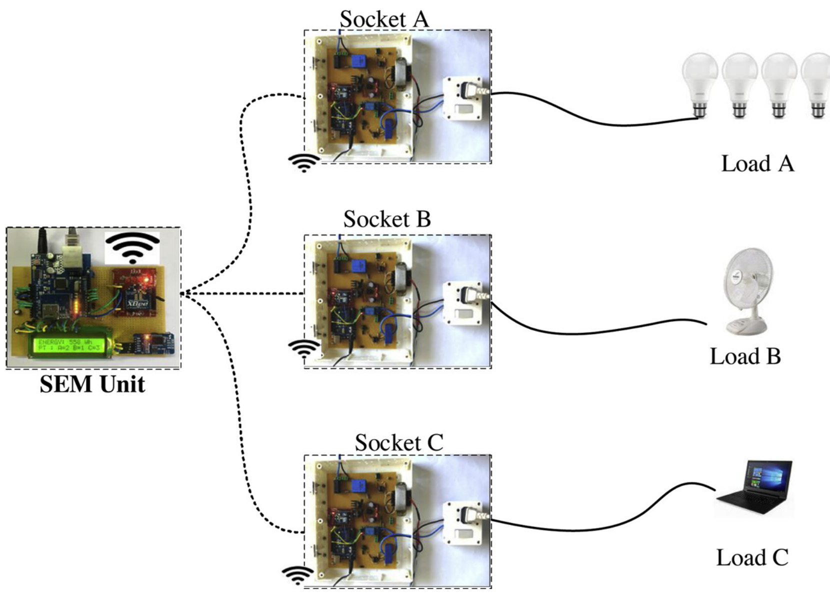


Fig. 5. Experimental setup of SEMS.

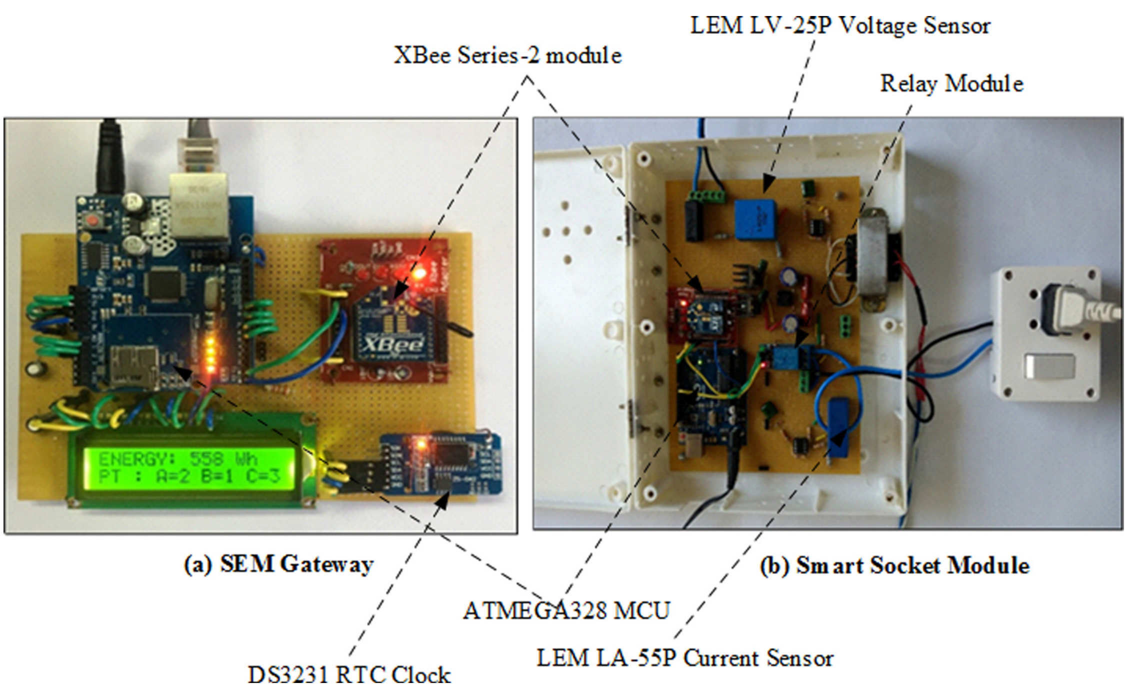


Fig. 6. Experimental setup of (a) SEM Gateway. (b) Smart Socket Module.

Actual loads are used in the experimental work in the laboratory environment, and an incandescent lighting bank is used as Load-A, which has the provision for vary the power consumption by switching on/off the status of the individual bulb within it. A fan appliance is used as Load-B in the setup, which has the provision for altering its speed and it is also, associated with humidity and a temperature sensor to demonstrate how the user comfort case is integrated with the algorithms deployed. A charging laptop is included as Load-C: this load is intentionally chosen to show the scheduling of chargeable loads considering the time of usage (ToU).

4.2. User end interface with the display unit

The SEM unit has the LCD display unit to display the essential electrical parameter such as energy consumption of the loads and the priority of the loads assigned. Switch buttons are included to change the priority of the appliance according to the consumer preference. The experimental laboratory setup of the SEM unit is shown in Fig. 6(a).

4.3. Smart socket module as a load controller

Three identical load controllers are used in the experimental setup which is named as smart socket as depicted in Fig. 6(b), these are used as general purpose socket built for switching the loads according to control signals received and sub-metering application to measure the basic electrical parameters for the loads connected. The module is associated with an ATMEGA328 microcontroller unit, measurement modules, i.e. voltage (LEM LV-25P) and current sensors (LEM LA-55P), a relay module with 20A range for switching actions and XBee series-2 module for bidirectional communication.

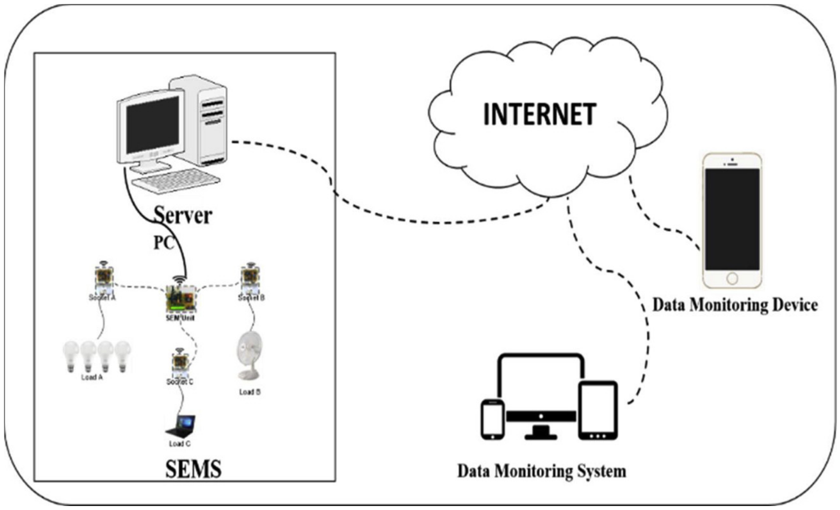


Fig. 7. IOT environment for energy monitoring system.

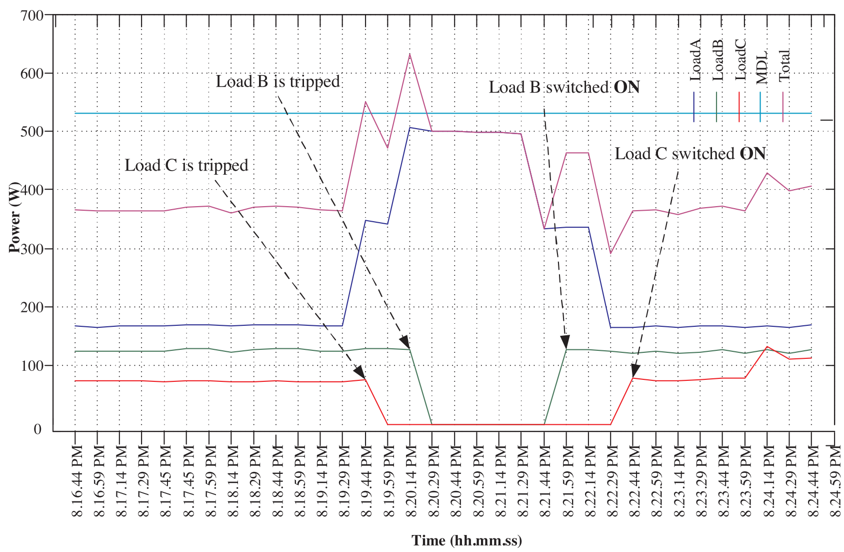


Fig. 8. Experiment to demonstrate running of higher priority appliance with MDL constraint.

Table 2
Power Consumption Data.

Appliance	Load a	Load b	Load c	Total
Appliance status	On (2-bulb)	On	On	
Priority	High	Medium	Low	
Apparent Power (W)	330	127	83	
Power Demanded (W)				540
Maximum Demand Limit (W)				530
Appliance status (After Power Negotiation)	On	On	Off	

4.4. SEM system communication modules

The SEM system uses two identical XBee modules for ZigBee communication: i) the XBee module with HEM unit, which is configured as the coordinator and ii) the XBee module in the smart socket, which is configured as a router at the load end. The Application Transparent (AT) mode of ZigBee communication is used in the experimental setup.

The coordinator in the SEM unit sends a broadcast data request message to the routers integrated with the smart socket in the predefined order, which collects all the power consumption data from the loads connected to the smart sockets. In turn, the router receives the control signal from the coordinator of the SEM unit. The data received from the router is in the format of the string. Further, it is converted to its equivalent decimal format to get the actual value of electrical parameters.

4.5. Configurable priority setting feature

Based on consumer's priority, the usage of appliances changes for every few hours. For example, in a day time, AC would be more important than lights whereas, during night time, light is more preferable than AC. So in order to give flexibility to the consumer in such situations of changing requirements, there is a provision for priority settings are made configurable and can be updated anytime by the consumer as per his/her needs. The priority of each load is displayed on an LCD screen on a real-time basis.

4.6. IOT environment with an energy monitoring system

A housing development of smart meters are used to monitor energy consumption in real time. The developed SEMS power data can be uploaded to the server by establishing a successful connection via an Ethernet shield. Further uploaded data can be accessed and monitored

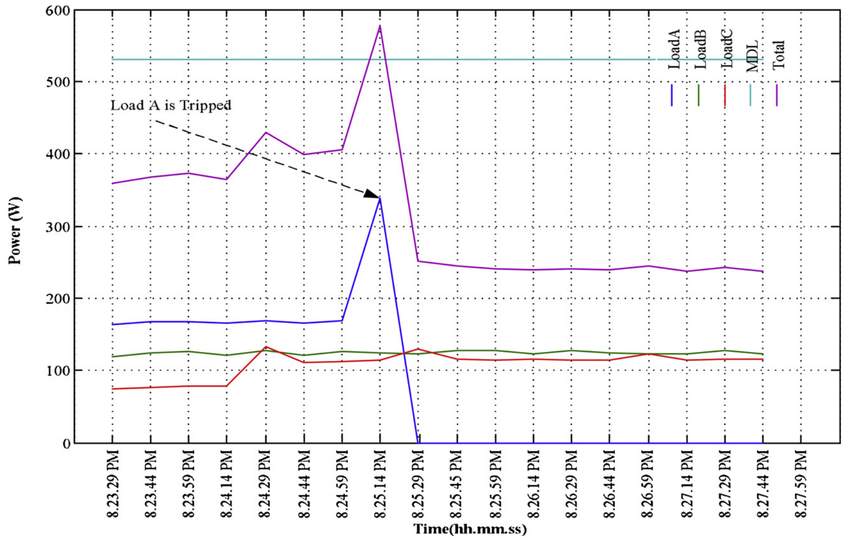


Fig. 9. Experiment to demonstrate running of higher priority appliance with a change in the order of priority considering MDL constraint.

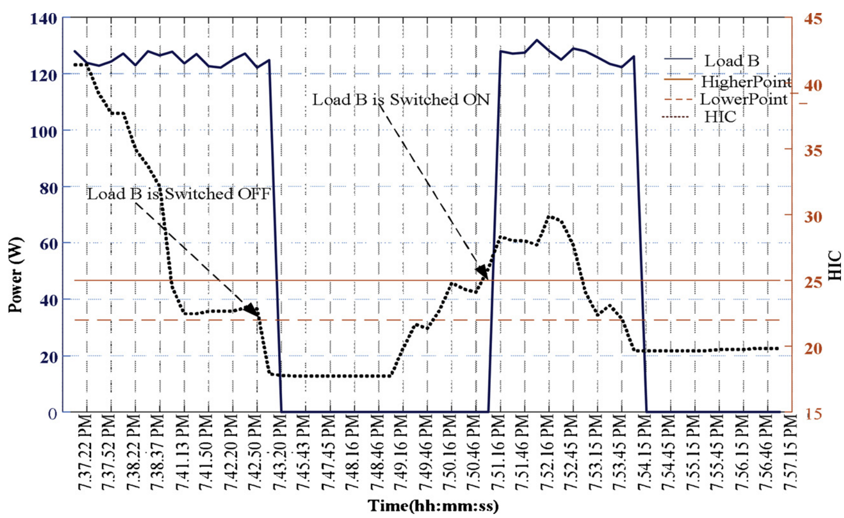


Fig. 10. Experiment to demonstrate user comfort setting with the sensed parameter.

using data monitoring system or data monitoring devices. The graphical view of the overall system is depicted in Fig. 7. On acquiring metering data extensively, it is possible to explore research on the management of energy systems. As of now, several research groups are exploring research areas like Real-Time Energy Management solutions, Big Data Analytics, Machine learning, and Energy Costing Solutions.

The energy monitoring system consists of a server and database management system for real-time monitoring and data acquisition. The server used is WAMP, and in the WAMP server, hostname is changed from localhost to "domain name" (Note: smart-meter web domain works only intra server system, otherwise, the user should enter the login path to enter into the website). Different names can be given to multiple databases in the server. In the web portal, only authorized person can be able to login into the webpage using login credentials. Further, results and trend graphs are presented in Section 5.5.

5. Demonstration and result analysis

In this section, results for different scenarios are demonstrated and are analyzed. Experiments are conducted by assigning an order of priority to an appliance with different configurations, user comfort case and cost optimization technique are demonstrated to prove the effectiveness of the energy management system.

5.1. Operation strategy of a load for configured priority

Case-I(a): Operation strategy with dynamic consumption of "Load a" (1-bulb).

In this case, incandescent bulb bank is considered as Load A, and it is assigned with the highest priority. A fan load is assigned with mid priority. Since battery charging is a schedulable load, it is assigned with low priority. In this case, SEM load scheduling operation is depicted in Fig. 8.

Stepwise execution of the load scheduling with configured priority is detailed below.

Step 1: SEM unit broadcast a data request signal in the form of the string "Ca".

Step 2: Load 'a' responds with its power consumption data i.e. RMS voltage, RMS current, power factor, apparent power, real power, reactive power, energy.

Step 3: SEM unit then broadcast a data request signal in the form of the string "Cb".

Step 4: Load 'b' responds with its power consumption data.

Step 5: SEM unit then broadcast a data request signal in the form of the string "Cc".

Step 6: Load 'c' respond with its power consumption data.

Step 7: From Table 2 it is observed that power demanded is less than

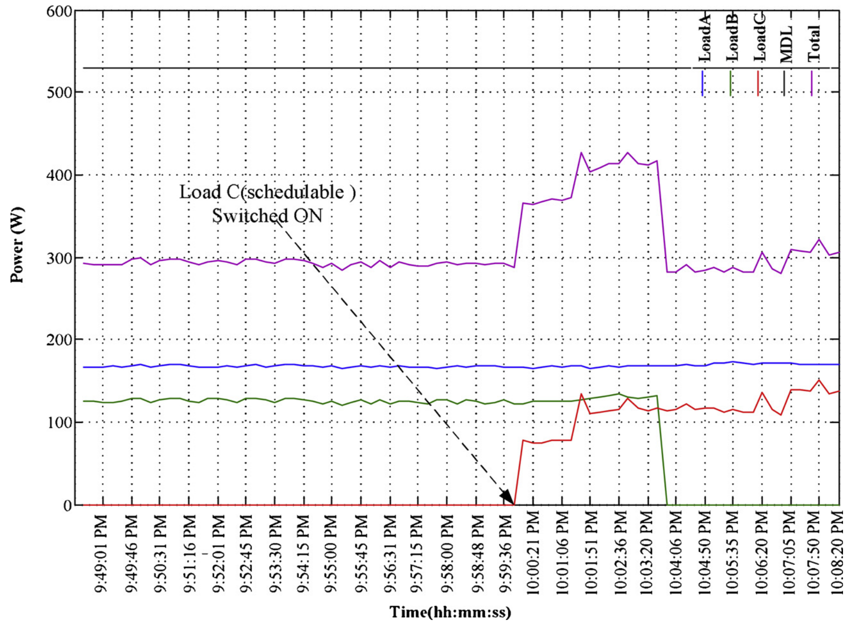


Fig. 11. Experiment to demonstrate scheduling operation with ToU.

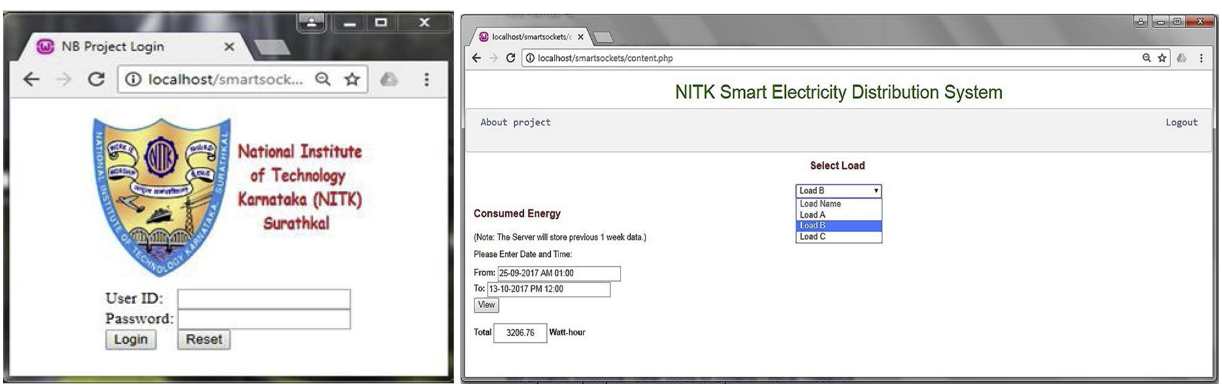


Fig. 12. (a) Login Portal (b) Load and Time selection webpage.

the maximum demand limit. Hence all three loads remain 'On' as per the decisive algorithm. Since total power demand is less than maximum demand limit, SEM unit switch ON relays of all the three loads using command signals in the form of strings "raah", "rbbh", "rcch".

In Fig. 8, it is shown maximum demand is set to be 530 W (i.e., input from the Utility). From the time period 8.16.44 PM to 8.19.44 PM, all the three loads were turned since the maximum power consumption is less than the maximum demand limit (MDL). At the instant 8.19.44 PM, extra incandescent bulbs in the bank are switched (i.e., two bulbs ON) so that the total power consumption exceeds the MDL. The proposed SEM controller immediately reacts to this scenario and turns off the battery charging load(Load-C). Further, at the instant 08.20.29 PM, the power consumption of lighting load is increased by switching the extra bulb (i.e., three bulbs ON). Since the lighting load alone consuming 497 W of 530 W MDL. Therefore, the controller switches off the second load (Load-B) as well to balance the supply and demand. Finally, when Load A consumption is decreased, Load B and Load C are turned ON in the order of priority. In this case, power consumption details and scheduling of appliances by SEM system, are listed in Table 2.

Case-I(b): Operation Strategy with Dynamic Consumption of "Load a" (2-bulb).

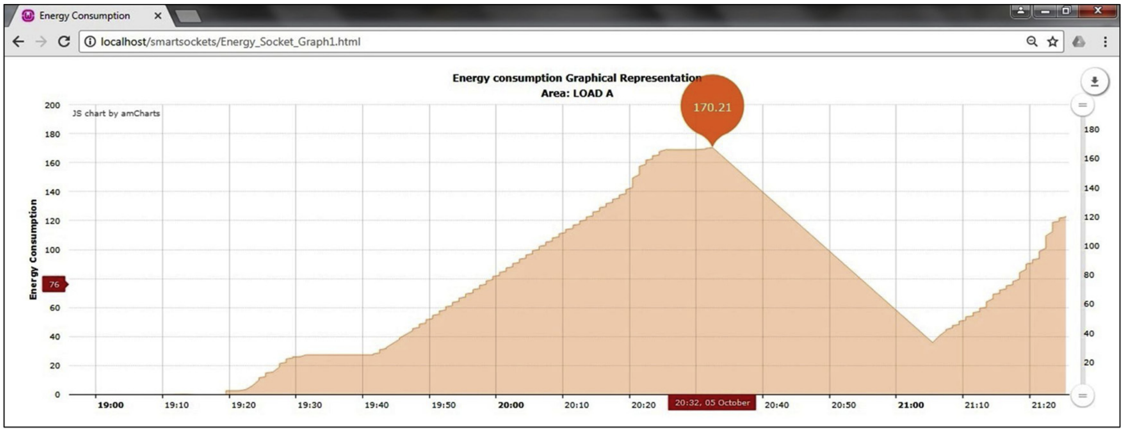
5.2. Case-II: load priority order –(Low) Load A — (Mid) Load B — (High) Load C

Similar to Case-I but with a change in the order of Load priorities, with the graphical demonstration shown in Fig. 9. SEM unit compares the total apparent power of all the three loads (330 + 127 + 083 = 540 W) with a maximum demand limit of 530 W. Since total power demand is more than the maximum demand limit and power demand of the first two priority loads (127 + 083 = 210 W) is less than the maximum demand limit, SEM unit send a commond signal to turn ON relays of Load-C and Load-B but turns OFF relay of Load-A.

Appliance operation based on Decisive algorithm with an assigned order of priorities is presented in the above Fig. 9. Consider the case, if the user wants to turn on all the three Loads. Initially, all the loads are turned since there is no violation of MDL. As Load A consumption is increased further, at instant 8:25:14 PM it is observed that Load A is itself tripped off to avoid MDL violation since it is assigned with lower priority in this case.

5.3. User preference setting with perceived sensor data

Most of the heating or cooling appliances are designed to operate at a fixed temperature or in a shorter range of temperatures which would force appliances to turn on or off frequently. For example, an air



(a)

SERIAL.NO	TIME	RMS VOLTAGE IN VOLTS	RMS CURRENT IN AMPS	APPARENT POWER DEMAND IN VA	POWER FACTOR	ENERGY IN WATT-HOUR	PRIORITY
107	2017-10-05 19:41:35	227.40	0.00	0.00	0.00	27.38	1
108	2017-10-05 19:41:50	226.22	0.77	174.32	1.00	27.98	1
109	2017-10-05 19:42:05	226.37	0.77	174.27	1.00	28.69	1
110	2017-10-05 19:42:20	225.80	0.77	172.98	1.00	29.44	1

(b)

Fig. 13. (a)Power consumption of the schedulable load (b) Power consumption trend graph.

conditioner attains the desired temperature according to the temperature set by the consumer. The compressor in the air conditioner is turned on and remains on until the room temperature decreases to be the same as the set temperature. Once the desired temperature is reached, the compressor turns off until the room temperature increases again. Air conditioner consumes a lot of power every time its compressor is turned on. This power is much greater than the power consumed by the air conditioner for continuous operation (long cycles). Thus, frequent short cycles affect the efficiency of the air conditioner. On the other hand, the efficiency of the air conditioner improves as it runs for more amount of time i.e., longer cycles.

In the proposed system, the consumer is given provision to set a larger range of temperatures to improve the efficiency of appliances, thereby reducing energy consumption. In case when the SEM unit sends a command signals to switch on a heating or cooling appliance, the load controller of that appliance also checks for comfort settings violation. Besides, controls appliance such that it always maintains the temperature within the range of consumer's comfort settings. In our case, data from humidity temperature sensor with the Heat Index in Celsius (HIC) is used as the threshold value. Further, upper limit (25 °C) and the lower limit (22 °C) are used to control the load status as shown in Fig. 10. At the instant 7.43.20 PM, room temperature is below 22 °C. Hence the controller turned off the fan load. Similarly, after some time (i.e., at 07.51.16 PM) temperature has crossed the upper limit (i.e., 25 °C), the controller turned on the fan load.

5.4. Scheduling considering ToU tariff

As explained in the earlier sections, appliances in the household can be categorized into two groups, such as schedulable and non-schedulable. To reduce the electricity cost during the ToU tariff, the proposed controller shifts the schedulable loads to peak off hours. In this case, the controller uses the input from the RTC module and peak hours information from the utility. Load scheduling characteristics for ToU tariff system is shown in Fig. 11. Here, peak-off hours start from the 10 PM, and hence the controller shifts the battery charging (i.e., schedulable load) to 10 PM so as to reduce the electricity cost.

5.5. IoT environment with energy monitoring system

The webpage is developed to display real-time energy consumption and other electrical parameters. The web portal is created in such a way that only an authorized person can be log into the webpage using login credentials. After successfully logging in, the user can access the smart meter data repository. For example: If a user wants to check the real-time energy consumption of any laboratory present on the webpage, the user needs to select that laboratory and specify the date and time, as shown in Fig. 12(a)&(b). By clicking view, it will enter into the next page, which displays the acquired electrical parameters. As shown in Fig. 13(b), different electrical parameters will be displayed on this page. At the end of the page, it will show the total energy consumption of the selected laboratory. In the main page, there is a provision for checking the trend graph of power consumption of a different load, as shown in Fig. 13(a).

The user needs to enter the login credentials in the login page, as shown in Fig. 11 After successfully logged in to the webpage, the user can enter into the main page. In the main page, the user can have all the privileges to select the different laboratories, check the real-time energy consumption, Power usage data, possible to view trend graph of energy consumption. If a user or guest wants to know the objective and project details can check it in about the project. The load wise power data such as RMS current, power demand, power factor, energy consumption, and assigned priority for a load of developed SEMS system is shown in Fig. 13(b). In addition, due time in hours for the schedulable load is also shown in the power data table.

6. Conclusion

The hardware prototype of SEMS is designed and developed in the laboratory environment, and experiments are carried out to demonstrate the effectiveness and working of the power optimization algorithms deployed in the controller. The wireless ZigBee communication is established using XBee series-2 modules between the SEM controller and smart socket unit. It is also incorporated with a new advanced self-diagnostic mechanism to form a reliable network. The first experiment demonstrates the novel configurable priority feature, wherein three different loads are considered. There is also a provision to change the priority order of an appliances according to the consumer requirement. Secondly, in this work, different experimental scenarios are exhibited to show the running of only higher priority appliance during DR event and under MDL constraint. Furthermore, cost optimization algorithms are deployed in the SEM controller, which schedules the operation of a particular appliance during the off peak hours. It considers ToU tariff and hence utilize the lower slab rate to minimize electricity cost. In order to avoid higher power consumption during peak hours, a warning is given to the consumer with a buzzer and LED indicators. Finally, to access the power consumption data of individual load, secure web portal associated with an IoT environment is developed. GUI is provided with power consumption plot to view power usage of an appliance daily and monthly basis and also, database is provided for the energy management system with a provision to use it for further data analytics.

References

[1] R. Deng, Z. Yang, M.-Y. Chow, J. Chen, A survey on demand response in smart grids: mathematical models and approaches, IEEE Trans. Ind. Informatics 11 (3) (2015) 1.
[2] M. Beaudin, H. Zareipour, Home energy management systems: a review of modelling and complexity, Renew. Sustain. Energy Rev. 45 (2015) 318–335.
[3] L. Gelazanskas, K.A.A. Gamage, Demand side management in smart grid: a review and proposals for future direction, Sustain. Cities Soc. 11 (2014) 22–30.
[4] G. Lilis, G. Conus, N. Asadi, M. Kayal, Towards the next generation of intelligent building: an assessment study of current automation and future IoT based systems with a proposal for transitional design, Sustain. Cities Soc. 28 (2017) 473–481.
[5] M. Kuzlu, M. Pipattanasomporn, S. Rahman, Review of communication technologies for smart homes/building applications, Proc. 2015 IEEE Innov. Smart Grid Technol. — Asia, ISGT ASIA, (2015), pp. 4–9 2016.
[6] L. Díaz-Vilariño, H. González-Jorge, J. Martínez-Sánchez, H. Lorenzo, Automatic LiDAR-based lighting inventory in buildings, Meas. J. Int. Meas. Confed. 73 (2015) 544–550.
[7] L. Barelli, G. Bidini, F. Bonucci, A. Ottaviano, Residential micro-grid load management through arti fi cial neural networks, J. Energy Storage 17 (December 2017) (2018) 287–298.
[8] Y. Huang, L. Wang, W. Guo, Q. Kang, Q. Wu, Chance constrained optimization in a home energy management system, IEEE Trans. Smart Grid 9 (1) (2016) 1.
[9] K.P. Kumar, B. Saravanan, Day ahead scheduling of generation and storage in a microgrid considering demand Side management, J. Energy Storage 21 (June 2018) (2019) 78–86.
[10] M. Zachar, P. Daoutidis, Energy management and load shaping for commercial microgrids coupled with flexible building environment control, J. Energy Storage 16 (2018) 61–75.
[11] F. Sehar, M. Pipattanasomporn, S. Rahman, Integrated automation for optimal demand management in commercial buildings considering occupant comfort, Sustain. Cities Soc. 28 (2017) 16–29.
[12] J. Han, C.-S. Choi, W.-K. Park, I. Lee, Green home energy management system through comparison of energy usage between the same kinds of home appliances, 2011 IEEE 15th Int. Symp. Consum. Electron. (2011) 1–4.
[13] T. Ueno, F. Sano, O. Saeki, K. Tsuji, Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data, Appl. Energy 83 (2006) 166–183.
[14] M.A.A. Pedrasa, T.D. Spooner, I.F. MacGill, Coordinated scheduling of residential distributed energy resources to optimize smart home energy services, IEEE Trans. Smart Grid 1 (2) (2010) 134–143.
[15] M.S. Ahmed, A. Mohamed, T. Khatib, H. Shareef, R.Z. Homod, J.A. Ali, Real time optimal schedule controller for home energy management system using new binary backtracking search algorithm, Energy Build. 138 (January) (2017) 215–227.
[16] M. Kuzlu, M. Pipattanasomporn, S. Rahman, Hardware demonstration of a home energy management system for demand response applications, IEEE Trans. Smart Grid 3 (4) (2012) 1704–1711.
[17] L. Klein, et al., Automation in Construction Coordinating occupant behavior for building energy and comfort management using multi-agent systems, Autom. Constr. 22 (2012) 525–536.
[18] H. Doukas, K.D. Patlitzianas, K. Iatropoulos, J. Psarras, Intelligent building energy management system using rule sets, Build. Environ. 42 (2007) 3562–3569.
[19] A.S.O. Ogunjuyigbe, T.R. Ayodele, O.A. Akinola, User satisfaction-induced demand side load management in residential buildings with user budget constraint, Appl. Energy 187 (2017) 352–366.
[20] E. Fabrizio, et al., Monitoring of a micro-smart grid: power consumption data of some machineries of an agro-industrial test site, Data Brief 10 (2017) 564–568.
[21] J. Lagorse, D. Paire, A. Miraoui, A multi-agent system for energy management of distributed power sources, Renew. Energy 35 (1) (2010) 174–182.
[22] N.G. Paterakis, O. Erdinç, A.G. Bakirtzis, J.P.S. Catalão, Optimal household appliances scheduling under day-ahead pricing and load-shaping demand response strategies, IEEE Trans. Ind. Informatics 11 (6) (2015) 1509–1519.
[23] D. Tenfen, E.C. Finardi, A mixed integer linear programming model for the energy management problem of microgrids, Electr. Power Syst. Res. 122 (2015) 19–28.
[24] R. Yin, et al., Quantifying flexibility of commercial and residential loads for demand response using setpoint changes, Appl. Energy 177 (2016) 149–164.
[25] S. Wang, R. Tang, Supply-based feedback control strategy of air-conditioning systems for direct load control of buildings responding to urgent requests of smart grids, Appl. Energy 201 (2017) 419–432.
[26] F.A. Qureshi, C.N. Jones, Energy & Buildings Hierarchical control of building HVAC system for ancillary services provision, Energy Build. 169 (2018) 216–227.
[27] D.-M. Han, J.-H. Lim, Design and implementation of smart home energy management systems based on zigbee, IEEE Trans. Consum. Electron. 56 (3) (2010) 1417–1425.
[28] Y.-S. Son, T. Pulkkinen, K.-D. Moon, C. Kim, Home energy management system based on power line communication, IEEE Trans. Consum. Electron. 56 (3) (2010) 1380–1386.
[29] F. Abate, M. Carratù, C. Liguori, V. Paciello, A low cost smart power meter for IoT, Measurement 136 (2019) 59–66.
[30] A.H. Alavi, P. Jiao, W.G. Buttlar, N. Lajnef, Internet of things-enabled smart cities: state-of-the-art and future trends, Measurement 129 (July) (2018) 589–606.
[31] G. Ghatikar, S. Mashayekh, M. Stadler, R. Yin, Z. Liu, Distributed energy systems integration and demand optimization for autonomous operations and electric grid transactions, Appl. Energy 167 (2016) (2020) 432–448.
[32] H. Jo, S. Kim, S. Joo, Smart heating and air conditioning scheduling method incorporating customer convenience for home energy management system, IEEE Trans. Consum. Electron. 59 (2) (2013) 316–322.
[33] R. Yang, L. Wang, Development of multi-agent system for building energy and comfort management based on occupant behaviors, Energy Build. 56 (2013) 1–7.
[34] A.S.O. Ogunjuyigbe, T.R. Ayodele, O.A. Akinola, User satisfaction-induced demand side load management in residential buildings with user budget constraint, Appl. Energy 187 (2017) 352–366.
[35] MaxStream, XBee — Series 2 OEM RF Modules, XBee S2, no. 801 (2007), pp. 1–60.
[36] K. Electricity, R. Commission, T. Order, Mangalore Electricity Supply Company Ltd. (2019), pp. 206–243.
[37] P. Pawar, K.P. Vittal, Design of smart socket for power optimization in home energy management system, 2nd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT Bangalore) (2017) 1739–1744.