

Energy Management System of a Zero Energy Building using Multi-Agent Systems

A Dissertation submitted in fulfillment of the requirements for the Degree
of

MASTER OF ENGINEERING

in

Power Systems

Submitted By

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2016

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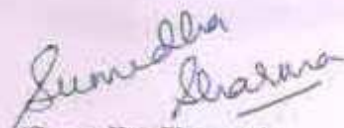
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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**Energy Management System of a Zero Energy Building using Multi-Agent Systems**", in fulfillment of the requirements for the award of the degree of **Master of Engineering in Power Systems**, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is an authentic record of my own work carried under the supervision of **Dr. Surya Prakash**. It refers to other researchers' work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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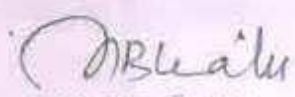
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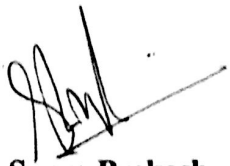

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Dr. Surya Prakash

ABSTRACT

Rising trend towards urbanization has resulted in the emergence of urban buildings as major energy consumers. This has increased the burden on the grid which may eventually result into severely interrupted power supply and outages. In order to assist the over-burdened grid, the concept of zero energy buildings (ZEBs), which consist of individual generation systems, has been developed. Traditionally, ZEBs have a negligible net energy consumption when accounted on an annual basis. However, this concept of annual energy accounting does not reduce the building's dependency on the grid. Thus, in order to minimize their grid-dependency, this work makes ZEBs self-sufficient by incorporating instantaneous power management techniques. Accordingly, a power management system has been designed which controls the instantaneous flow of generated power in the ZEB depending upon the load variations. This involves decentralized control of dispersed parameters which has been achieved through the technique of multi-agent system (MAS). For the purpose of simulations, agent models have been developed using JAVA Agent Development Framework (JADE). Extensive simulations have been performed and results have been obtained for optimal power management and load scheduling using Genetic algorithm (GA).

Keywords: *Energy management system, Genetic algorithm, hybrid energy system, multi-agent system, zero energy building.*

ACKNOWLEDGMENT

I take the privilege to offer my deepest sense of gratitude to my supervisor **Dr. Surya Prakash**, for his constant motivation, support, and personal attention, which have proved to be of immense help throughout my dissertation tenure. I would also take this opportunity to thank **Dr. Mukesh Singh** for his insightful comments and valuable suggestions. Under his guidance I successfully overcame many difficulties and learned a lot.

I am also thankful to **Dr. Prakash Gopalan**, Director of Thapar University, Patiala for providing the facilities for the completion of M.E. I express my deep sense of gratitude towards **Dr. Ravinder Agarwal**, Head of the Department of Electrical & Instrumentation Engineering, Thapar University, Patiala for constantly encouraging each student to put their best foot forward in whatever field of work they take up, and **Ms. Manbir Kaur**, Associate Professor & PG Coordinator for her motivational approach.

I extend my gratitude to the researchers and scholars whose hours of toil have produced the papers that I have used in the dissertation. Finally, I take this opportunity to express my indebtedness to my family who are my source of optimism. Their wisdom and endearment motivate me to strive for excellence and keep my morale high, always.

Sumedha Sharma
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LIST OF SYMBOLS

CO_2	Carbon dioxide
E_b	Energy stored in the battery
E_b^{max}	Maximum value of battery's stored energy
E_b^{min}	Minimum value of battery's stored energy
$\eta_{b_{in}}$	Charging efficiency of battery
$\eta_{b_{out}}$	Discharging efficiency of battery
ε	Error
FC	Signal sent by GA to fuel cell controller
Gap	Difference between the generation and demand
k	Priority factor
LM	Value of loads satisfied
LS	Value of loads shed
P_b	Power sent to battery
P_{bc}	Charging power supplied to the battery
P_{bd}	Power discharged from battery
P_G	Total generated power
P_g^f	Power generated from fuel cell
P_g^i	Power generated by the i^{th} source
P_g^s	Power generated from PV panels
P_g^w	Power generated from wind turbine
P_{grid}	Power exported to the grid
P_L	Total load of the building
P_l^i	Load of the i^{th} appliance
P_{net}	Net surplus power
P_{rated}^i	Rated power of the i^{th} appliance
PI_i	Priority index of the i^{th} appliance
SOC	State of charge of battery
SOC^{max}	Maximum value of battery's SOC
SOC^{min}	Minimum value of battery's SOC
Δt	Time interval

LIST OF ABBREVIATIONS

AC	Alternating current
BA	Battery agent
BESS	Battery energy storage system
DC	Direct current
DER	Distributed energy resource
EMS	Energy management system
GA	Genetic algorithm
GenA	Generation agent
ICT	Information and communication technology
JADE	JAVA Agent Development Framework
LA	Load agent
MAS	Multi-agent system
PV	Photo-voltaic
RE	Renewable energy
SG	Smart grid
ZEB	Zero energy building

Chapter 1

INTRODUCTION

The first AC power grid was conceived in 1886 as a centralized system, which offered only unidirectional flow of power. With time, the technologies employed, the fuels used, and the generation capacities evolved. Eventually, the interconnections and extent of the grid witnessed manifold development. However, the conventional electric grid which is in operation today operates on technologies developed in the 1970s. Conventionally, the grid allows a single-directional flow of power from the utility to the end-user. Furthermore, traditional utility structure is vertical integration, where a single utility enjoys monopoly over the different power delivery stages. Besides, its physical infrastructure, dates back in time and has high risks of failure. The tools and techniques developed to manage the delivery of electric power are obsolete and insufficient to handle modern power issues.

Today, the world is witnessing a rapid growth of population and modernization of technologies, which involve widespread electrification of conventional working methodologies. Consequently, there arises an ever-changing and continuously increasing power demand. Moreover, with the aging of the physical infrastructure of the grid, there are high chances of power outages in different parts of the grid. In order to be able to communicate these events occurring at the load-end, there emerges a need to introduce a bi-directional communication channel between the end-users and the utility. This has motivated research in the field of smart grids (SGs) which have a high potential to overcome the shortcomings of the conventional grid.

1.1 Smart Grid

SG is a technological evolution of the existing electrical grid. It incorporates information and communication technology (ICT) into the existing grid. This enables a two-way communication between the electric utility and the end-consumer. This is achieved through an improved digital infrastructure which replaces the conventional physical infrastructure, along with the use of improved digital and power electronics technologies. The structure of SG is basically a cyber-physical structure. A cyber-physical structure refers to one which is an amalgamation of a system's physical and computational elements. The cyber structure can be viewed as the convergence of the system's computation, communication, and control. The physical structure is the electrical infrastructure that a grid requires. However, in a SG, the electrical transmission lines and meters require the property of bidirectional communication. Accordingly, the basic idea of a SG has been illustrated in Fig. 1.1.

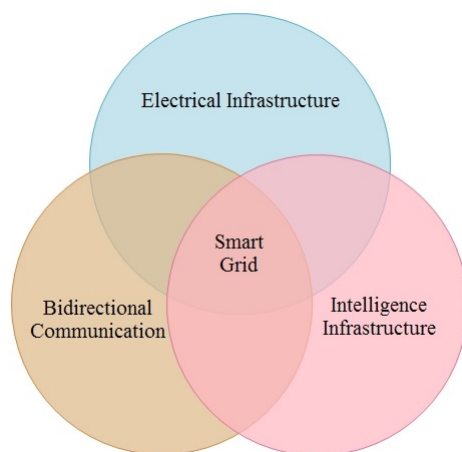


Figure 1.1: Smart grid

Due to the advantage of bi-directional communication, SGs make use of smart-metering infrastructure which enables the consumers to have an enhanced control over their electricity consumption and monthly billing. It keeps the consumers informed and empowers them to take efficient energy management decisions regarding power flow. The user can manage his power utilization by shifting heavy power-consuming tasks to the low demand period of the day. Moreover, the consumer is allowed to sell its surplus power to the grid and earn economic benefits in return. Thus,

this technology makes the existing grid more efficient, flexible, and reliable.

Among the prominent advantages of SGs is its ability to add power sources at the transmission and distribution level. These sources majorly constitute distributed energy resources (DERs). DERs are geographically dispersed sources of energy, and produce smaller quantities of power. These power generations can be aggregated to satisfy regular load demand. Along with DERs, SG can accommodate suitable energy storage systems. These minimize the power interruptions which are caused due to the irregular nature of DERs. SG technology, thus, leads to a sustainable lifestyle with minimum wastage and maximum utilization of clean energy. It further strengthens the economy and ensures returns on investments. Apart from empowering the consumer to manage and efficiently use energy, it adds reliability and intelligence to the grid, thus, leading us to an energy-secure world.

1.2 Renewable Energy

With the advent of the 21st century, global energy demand has witnessed an escalation. This can be attributed to the progressive penetration of technology into human life and growing trend towards urbanization. The urban population constituted 54% of the world population in 2014 and is expected to reach 66% by 2050 [1]. These rising trends reflect their impacts proportionately in the global energy demand. This is evident from the projections of the U.S. Energy Information Administration which has predicted the global energy consumption to rise by 56% from 2010 to 2040 [2]. Such a high growth in demand, calls for a rapid increase in energy production in order to minimize the energy demand-supply gap. However, increasing the production is constrained by the limited conventional fuel resources and the impacts they produce on the global climate. Approximately 21.3 billion tonnes of carbon dioxide (CO_2) is produced annually by burning of fossil fuels [3]. Emission of such large quantities of CO_2 indicates a high carbon footprint. Higher carbon footprints are a major cause of global warming, ultimately resulting in adverse climatic changes. Consequently, the period 2001-2010 has been recorded as the warmest decade by the U.S. Environmental Protection Agency's Climate Change Indicators Report [4]. Keeping these environmental concerns in view, while at the same time minimizing the demand-supply gap, has led to the widespread incorporation of renewable energy (RE) resources to produce electricity.

RE is the energy derived from resources which replenish themselves naturally within human time frame. RE sources are typically DERs, thus, appearing in nature as physically dispersed sources. The current exploitation of these sources is limited in the commercial market. This is credited to the high initial costs of power generation systems which employ RE sources. Moreover, due to intermittent nature of these sources, suitable energy storage systems are necessary for their extended consumption. Most commonly used RE sources include sun, wind, tides, geothermal heat, etc. These can be harnessed to produce comparatively small, and decentralized energy, which can be aggregated to cater to the rising power demand.

1.3 Integration of RE sources into SG

Due to the rising need to integrate RE sources into the power generation systems, there has arisen a need of a power system which can effectively integrate RE sources and storage systems, while at the same time offer rapid and wider control over its power flow. It is common knowledge that RE resources have high variability, which may become the biggest reason for variability as, and when the penetration of renewable resources into power generation systems increases. An estimation and trend of this variability, communicated to the grid would enable it to function reliably. Advanced techniques to store this energy can accommodate the fluctuations caused by intermittent power. Thus, SGs, which function on ICT, can be viewed as a solution to the constraints faced by the existing electric grid. The various features of SG-integration of RE sources are summarized in the following discussion.

1. Future energy sustainability: RE sources are making a significant contribution to climate protection, diversify resources, ease dependence on fossil resources, not produce any type of contamination, domestic energy carriers, and therefore contribute to regional value creation and help to secure employment. Hence, employment of renewables as future energy sources provides sustainability.
2. Empowering grid in peak hours: Integration of more renewables and storage support the SG with greater generation capacity. Increasing proportion of renewables in generation systems not only improves operational efficiency, but reduces peak demands.

3. Energy management: Smart-metering helps to adopt energy management techniques at consumer level such as demand-side management, demand response, flexible usage, leading to optimum utilization, and results into saving of energy.
4. Independent systems: RE systems work as isolated systems during grid failure and reduce impact on customer. Industrial and commercial consumers adopt grid-connected RE systems which help to reduce power demand. Further, isolated systems in residential areas conserve energy and minimize the load on the grid.
5. Upgrading electrical market: SG enables bi-directional energy flow. Such a power exchange provides an electronic platform to facilitate trading of electricity at national level. Having initiated RE trade since 2011, India ranks fourth for its market potential in RE.

Thus, it is concluded that RE sources offer a promising future to the global power sector [5]. Furthermore, they are widely available over the earth's surface and offer a carbon-free alternative to conventional fuels. Thus, in order to draw maximum benefits of these facts, techniques to harness RE at distributed locations have been developed. Moreover, integrating RE generation systems into individual buildings with ICT capabilities, is expected to satisfy their local energy demands while simultaneously avoiding the associated transmission losses. This is of importance because buildings' share of energy consumption constitutes 40% of the global energy [6], thus, increasing the burden on the grid. However, building-integration of RE-based generation systems is expected to reduce this burden. Implementation of such a scheme will allow buildings' local energy demands to be satisfied by the locally generated power. This has motivated research in the field of zero energy buildings (ZEBs).

1.4 Zero Energy Buildings

Existing literature lacks a uniformly accepted and consistent definition of ZEB. Traditionally, it may be defined as a building which has been evaluated to have minimum energy requirements. Torcellini *et al.* proposed four different ZEB definitions, depending upon whether the energy accounting is done on the supply-side, or consumer-side. Accordingly, four different classifications of ZEBs were proposed namely, site, source, emission, and cost ZEBs [7]. Apart from this, a recent

publication released by the United States Department of Energy defines ZEBs as energy-efficient buildings, in terms of the source energy. It describes ZEBs as buildings where the annual on-site generation of RE is either greater than, or equal to the energy that is delivered to it annually [8]. However, the energy required to serve its instantaneous loads is delivered by the utility grid and is mostly produced by using conventional fuels. This highlights the fact that the carbon footprints, as well as, grid dependency of these buildings is not reduced. Therefore, in order to diminish the grid dependency, the concept of a traditional ZEB needs to be modified. Consequently, this work suggests ZEBs to incorporate instantaneous energy accounting, rather than annual energy accounting. Thus, this work proposes an improved definition of ZEBs as buildings which are self-sufficient in terms of energy, that is, at each instant of time they produce as much power as is demanded by their loads, using RE sources.

Power generated by a single RE source in a ZEB is bound to be unreliable, due to the intermittent nature of RE sources. This problem can be eliminated by employing more than one source of power and a suitable battery energy storage system (BESS) in the ZEB. Development of such techniques has encouraged the integration of ZEBs in power systems. However, since multiple sources operate together to power the building, there arises a need for a control mechanism which ensures co-ordinated operation of the various generation sources. This has resulted in a lot of studies in the field of energy management systems (EMSs) for individual buildings [6], [9]. The authors in [10] have developed a scheduling scheme for managing energy in houses and buildings. It can be observed that this work is limited to development of EMS for conventional buildings and does not accommodate the concept of ZEBs. Similarly, in [11] the authors have developed a grid-connected home EMS for ZEB implementation. However, for ZEB implementation, annual energy accounting has been considered which does not minimize the power import of the buildings from the grid. Moreover, in both these works, cost minimization is the prime objective rather than energy sustainability. Another work in this regard can be observed in [12], where the authors have discussed the integration of zero grid impact buildings into the microgrid. However, in this work the prototype of the generation system is connected to a building with a load larger than its storage capacity. As a consequence, it is not possible to achieve a situation where no power is imported from the grid. Thus, the objective of energy independence, i.e. minimized grid dependency of a ZEB is not met. This, in turn, requires efficient power routing to maintain a cost-optimized and

uninterrupted supply of power to the loads. Consequently, there arises the need for a smart EMS which can control the instantaneous flow of power in the building. Accordingly, the proposed scheme employs a suitable EMS which makes it self-sufficient at all instances.

1.5 Energy Management System

Energy management of a ZEB involves a number of parameters such as real-time power availability, which in turn, is dependent upon weather conditions. Other parameters include real-time load requirement, storage level of batteries, etc. Therefore, design and control of the EMS of a ZEB takes into account a large number of entities [9], [13]. Moreover, centralized computation and decision making for such complex systems are strenuous and demand huge investments [14]. Consequently, semi-centralized or decentralized decision making is favored in such systems. This has motivated the incorporation of the concept of multi-agent systems (MASs) for development of the proposed EMS.

MAS refers to a network of software or hardware agents, interacting intelligently with each other within an environment. The potential of MAS when applied to the power engineering field is presented in [15]. Further, the authors have also highlighted the advantages of MAS over other distributed artificial intelligence techniques. Moreover, the authors in [16] have discussed the decision making approach, design, and implementation of MASs. Some existing works which inculcate MAS into EMS development are presented in [13] and [17]. In [13], the authors have presented a semi-centralized MAS based EMS for heating, cooling, electrical, and combined heat and power generation systems. However, the objective of energy management in the electrical system is to achieve net zero costs. It fails to enhance the energy efficiency of the electrical system. Moreover, the authors in [17], have developed an intelligent multi-agent control system for energy and comfort management. However, this work considers a microgrid which is grid-connected at all instants, except for grid disturbances or unacceptable tariffs. This does not reduce the burden on the grid. Further, this work requires the user to define load characteristics in a graphical user interface. This, however, complicates the EMS and reduces its user-friendliness.

The aforementioned discussion has motivated the author to develop a MAS based EMS for achieving energy sustainability of ZEBs. Accordingly, the proposed controller action include in-

stantaneous power dispatch, power routing as well as load scheduling. A lot of scheduling schemes have been used in the past. These include model predictive control based residential load scheduling technique as discussed in [18]. However, this scheme faces certain drawbacks such as operational difficulties, high cost of maintenance. Moreover, these controllers lack flexibility which can result in unprofitable and unreliable controllers [19]. Further, in [20], the authors have discussed an appliance scheduling algorithm for a home EMS. However, this scheme introduces a penalty term for minimizing the operational costs, rather than focusing on energy efficiency. Other scheduling techniques such as greedy algorithm have not been widely used for appliance or load scheduling. Besides, it suffers from certain disadvantages such as designing and verification difficulties [21]. Furthermore, in [22] Genetic algorithm (GA) has been used for demand-side management in SG environment, highlighting its robustness and accuracy.

As can be observed from literature, the advantages of using GA as a scheduling technique are manifold [23]. The basic advantage of using GA is that its solution can be suitably transformed for parallel processings on more than one computer systems [24]. Moreover, it is a multi-objective evolutionary algorithm. These advantages highlight its suitability to work in multi-agent environment. Further, since the environment in the proposed system is dynamic and the number of variables is large, GA appears as a suitable scheduling technique. As can be observed from [22], GA satisfactorily handles a large number of appliances, which other scheduling schemes fail to handle. Thus, the suitability of GA for load scheduling, as a part of the MAS-based EMS can be justified.

1.6 Motivation

It can be concluded from the above discussion that existing literature lacks a consistent definition of a ZEB. Most of these definitions focus on annual energy accounting which does not minimize the building's grid dependency. Moreover, limited work has been done in the field of energy management of ZEBs. Thus, this work proposes an instantaneous power management scheme for buildings which ensures energy sustainability of ZEBs. Further, traditional EMSs are centralized, lack operational flexibility, and do not ensure timely operation. Moreover, since instantaneous power management of a ZEB requires timely control and monitoring of a number of

distributed components, it appears as a multi-constrained and multi-objective problem. Thus, the technique of MASs has been successfully employed in designing the proposed EMS. Accordingly, a MAS-based EMS has been successfully designed and developed in this work. It effectively caters to the requirements of real-time power computations, for timely power management decisions for achieving the design objectives of ZEBs.

1.7 Objectives

The main objectives of this work are listed as follows.

1. The author has proposed a modified concept of ZEBs with minimized power import from the grid. These incorporate RE-based systems with sufficient generation and storage capabilities, to make the building energy independent.
2. MAS-based EMS has been designed, which controls the real-time power flow decisions in the dynamic environment of ZEBs, in a co-ordinated manner.
3. Intelligent agents have been developed using JAVA Agent Development Framework (JADE) which form a part of the MAS.
4. GA has been successfully employed to design a load scheduling algorithm, depending upon the conditions of real-time load requirements and power availability in the ZEB.

1.8 Dissertation Organization

The dissertation titled- Energy Management System of a Zero Energy Building using Multi-Agent Systems has been organized in five chapters. **Chapter 1** deals with an overview, literature survey, motivation, and objective of the dissertation. **Chapter 2** describes the detailed structure of the proposed system. **Chapter 3** discusses the materials and methods for illustrating the problem formulation of the proposed system. It includes the mathematical modeling, description of the current multi-agent system and a discussion on Genetic algorithm, along with the designed schemes and algorithms. **Chapter 4** provides the simulations and results of the proposed work. The conclusion of work has been mentioned in **Chapter 5**, followed by the list of publications and bibliography.

Chapter 2

SYSTEM DESCRIPTION

This work develops an efficient EMS for managing the power in a ZEB to minimize its grid dependency. The basic block diagram of the proposed system is illustrated in Fig. 2.1. As evident from the figure, the proposed system is essentially a ZEB which consists of residential loads and a power generation system. The purpose of the generation system is to harness power from the locally available RE sources. As can be observed from the figure, the proposed ZEB generates power through rooftop solar photo-voltaic (PV) panels, a domestic wind generator, and a fuel cell. Further, $M1$ and $M2$ are meters which measure the instantaneous power generated from PV and wind sources, respectively. The DC power generated from PV and fuel cell is converted to AC through suitable conversion devices. The fuel cell is turned on or off through a controller which is basically a switch, as shown in the figure. The power obtained from these sources is supplied to a common bus, called the home grid. This common bus is connected to the utility grid through a controllable switch. The ZEB also houses a suitable BESS to handle the issue of intermittent power created by the unpredictable nature of RE sources. A converter is used to convert the DC power delivered by the battery into suitable AC power. Moreover, a charge controller is used to control the charging and discharging rates of the BESS. The BESS as well as the loads of the building are also connected to the same home grid.

The loads contained in the ZEB are categorized into baseline, regular, and burst loads, as can be seen from the figure [25]. Baseline loads are appliances whose power requirements must be immediately met at any instant of time and are thus, non-schedulable. Consequently, these loads

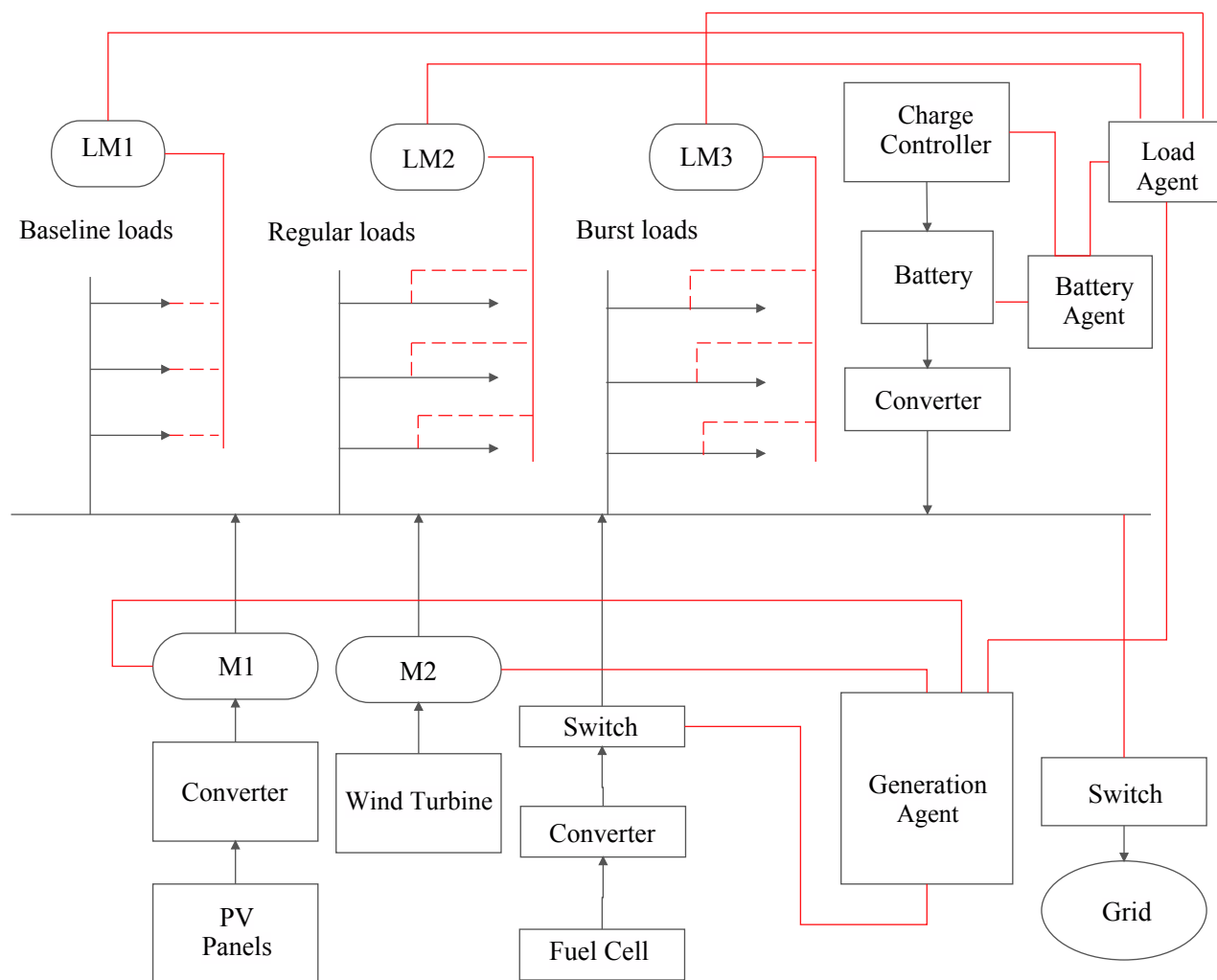


Figure 2.1: Detailed system diagram of the proposed scheme.

are given highest priority. Networking, lighting and cooking devices are examples of such loads. Regular loads are the category of loads that are always in operation and constantly demand power over a long time period. However, these loads can be interrupted intermittently, allowing manageable operation. Thus, these loads are second in order of priority. Examples of such loads are heat ventilation air conditioning systems, refrigerators, water heaters, etc. Burst loads are fixed duration loads and have high power requirements. Excess of such loads at any given instant contributes to peak loads. However, their time of use can be scheduled according to the availability of power. Thus, these loads are lowest in order of priority. Examples of these loads are clothes dryer, washing machine, etc. Further, the power demands from each of these load categories is measured through three load meters. These are *LM1*, *LM2*, and *LM3* for baseline, regular, and burst loads,

respectively.

The control and management of the different system components, as described above, requires a suitable EMS. Accordingly, the proposed scheme includes a MAS-based EMS which ensures co-ordinated system operation to maintain a suitable balance between the available and demanded powers. Three different agents have been identified and developed for the design of the EMS. These are the generation agent (GenA), load agent (LA), and battery agent (BA). These agents are software controllers which exist and operate in synchronism with each other. Each individual agent obtains information from its immediate environment which might be the power generation system, battery, loads, or other agents in its proximity. Based upon this information, the agent makes suitable decisions regarding power flow and load scheduling. The function of GenA is to control the generation of power in the ZEB, keeping in regard the real-time load requirements. The LA is responsible for taking suitable decisions for shedding the load when there occurs a shortfall of generated power and stored energy. BA deals with management of the energy storage of the battery, that is, it decides upon the charging, and discharging of the BESS. Furthermore, the system also comprises of a common platform, known as a database agent, which can be accessed by all other agents. Each agent writes its information which is required to be shared with other agents, on this database. This allows individual agents to read the information which they require for taking autonomous action. Thus, without having to undergo a series of requests and acknowledgments, the MAS allows a number of distributed and parallel processings in a short time.

Chapter 3

PROBLEM FORMULATION

The proposed work intends to achieve minimized grid dependency of a ZEB through efficient power management. This has led to the application of the concept of MAS in development of the proposed EMS. Thus, this chapter begins with the mathematical modeling of the proposed scheme. Accordingly, it highlights the design and objectives of individual agents. Furthermore, the algorithms developed for achieving the objectives of the proposed work have been elucidated.

3.1 Mathematical Modeling

The total power generated in the ZEB at any time instant t can be expressed as.

$$P_G(t) = \sum_{i=1}^n P_g^i(t) \quad (3.1)$$

where, $P_G(t)$ is total generated power and n is the number of power sources in the system.

In the proposed work, the ZEB consists of four power sources viz. PV arrays, wind generators, fuel cells, and a BESS.

Thus,

$$P_G(t) = P_g^s(t) + P_g^w(t) + P_g^f(t) + P_{bd}(t) \quad (3.2)$$

where, $P_g^s(t)$ and $P_g^w(t)$ are the powers generated from solar and wind sources, respectively, $P_g^f(t)$ is the power generated by the fuel cell, and $P_{bd}(t)$ is the power discharged from BESS.

It is common knowledge that power generation through fuel cells is relatively expensive as compared to PV and wind sources. Consequently, under normal operating conditions, only the solar and wind sources are allowed to generate power. In such a situation the fuel cell remains turned off. This means,

$$P_G(t) = P_g^s(t) + P_g^w(t) \quad (3.3)$$

The normal operating conditions can be categorized as Mode I and Mode II, as discussed below.

1. Mode I- During this mode, the powers generated by solar and wind sources are sufficient to satisfy the load.

$$P_g^s(t) + P_g^w(t) - P_L(t) = 0 \quad (3.4)$$

Here,

$$P_L(t) = \sum_{i=1}^N P_l^i(t) \quad (3.5)$$

where, $P_L(t)$ is the total demand, N is the number of loads, and P_l^i is the demand of the i^{th} appliance. Thus, the power gap between the generation and load, $P_{net}(t)$, maybe expressed as follows.

$$P_{net}(t) = P_G(t) - P_L(t) \quad (3.6)$$

From Eq. 4 and Eq. 6,

$$P_{net}(t) = 0 \quad (3.7)$$

In such a condition, there is no requirement to turn on the fuel cell. This is conveyed by a signal FC given to the switch controlling the fuel cell. The value of FC at this instant is

0. Since all the generated power is consumed by the load, the BESS and utility grid remain disconnected from the home grid during this mode.
2. Mode II- During this mode of operation, the power produced by the solar and wind sources is more than the load. That is, if

$$P_g^s(t) + P_g^w(t) > P_L(t) \quad (3.8)$$

then, from Eq. 3.6,

$$P_{net}(t) > 0 \quad (3.9)$$

where, P_{net} is the surplus power. This implies that there exists some net surplus power which is either fed to the BESS or supplied to the grid. This decision is taken after checking battery's real-time state of charge, $SOC(t)$. The $SOC(t)$ of BESS is also an indication of its stored energy at time t , $E_b(t)$.

$SOC(t)$ is subjected to the following constraint.

$$SOC^{min} \leq SOC(t) \leq SOC^{max} \quad (3.10)$$

where, SOC^{min} and SOC^{max} are the minimum and maximum limits of SOC , respectively.

Similarly, $E_b(t)$ is subjected to the following constraint.

$$E_b^{min} \leq E_b(t) \leq E_b^{max} \quad (3.11)$$

where, E_b^{min} and E_b^{max} are the minimum and maximum limits of $E_b(t)$, respectively.

If,

$$SOC(t) \geq SOC^{min}$$

\implies

$$E_b(t) \geq E_b^{min}$$

then the surplus power, $P_{net}(t)$ is fed to the grid. This means that the controlled switch connects the ZEB to the grid. However, if

$$SOC(t) < SOC^{min}$$

\implies

$$E_b(t) < E_b^{min}$$

then $P_{net}(t)$ is used to charge the BESS. The BESS will now be charged with round-trip efficiency [26].

$$E_b(t + \Delta t) = E_b(t) + (P_{bc}(t) \times \Delta t) \quad (3.12)$$

Here,

$$P_{bc}(t) = [P_G(t) - P_L(t)]\eta_{bin} \quad (3.13)$$

where, $E_b(t + \Delta t)$ is energy stored in BESS at the end of the time interval Δt , $P_{bc}(t)$ is the charging power supplied to the battery, and η_{bin} is round-trip efficiency of the BESS.

When BESS has charged to E_b^{max} , its $SOC(t)$ will become SOC^{max} . At this instant, it stops drawing $P_{bc}(t)$. The remaining surplus power is now supplied to the grid. This implies,

$$P_{grid}(t) = P_{net}(t) - P_{bc}(t) \quad (3.14)$$

where, $P_{grid}(t)$ is the power which is supplied to the grid at instant t .

3. Mode III- Under abnormal conditions which include weather irregularities and disturbances, the RE sources are not able to produce rated output. Moreover, during high load conditions, the generated power is not able to satisfy the load. In such conditions, the demand becomes greater than the generation. That is,

$$P_G(t) < P_L(t) \quad (3.15)$$

To overcome this power deficiency, the following steps are taken.

- (a) Additional power is generated by turning on the fuel cell. Accordingly, signal FC is given by GenA to the fuel cell controller. Here, the value of FC is 1. Thus, the fuel cell is turned on and $P_g^f(t)$ is supplied to the home grid.
- (b) Further, discharging the BESS provides the necessary power to cover the deficit. This occurs only when $SOC(t) > SOC^{min}$. In such a scenario, the battery is discharged according to the following equations [26].

$$E_b(t + \Delta t) = E_b(t) - (P_{bd}(t) \times \Delta t) \quad (3.16)$$

and,

$$P_{bd}(t) = [P_L(t) - P_G(t)]\eta_{b_{out}} \quad (3.17)$$

where, $P_{bd}(t)$ is the amount of power discharged from the battery and $\eta_{b_{out}}$ is the discharging efficiency of BESS.

The total power available at the home grid after steps 1 and 2 are carried out, is expressed by Eq. 3.2.

- (c) If the increased generation, as given by Eq. 3.2, is not sufficient to satisfy the loads, then the loads are shed. Scheduling loads based upon their priorities results in reduction of the demanded power. This is achieved through a GA-based load scheduling algorithm. It is discussed later in this chapter.

The controller action describing the above-mentioned modes of the ZEB is explained in Algorithm 1.

3.2 Multi Agent Systems based EMS

An *agent* is a hardware or software entity which is capable of performing autonomous action without any external interference, to satisfy its design objectives. However, agents tend to fail when placed in physical environments, which are generally dynamic and unpredictable. This has given

Algorithm 1 Proposed control scheme**Input:** $P_l^i(t)$, $P_g^s(t)$, $P_g^w(t)$, $SOC(t)$.**Output:** FC , $P_g^f(t)$, $P_{bd}(t)$, $P_{bc}(t)$, loads met LM , loads shed LS

```

1: Store  $SOC_{min}$ ,  $E_{max}$ ,  $\Delta t = 0.25$ .
2: for ( $t = 0, t \leq 24, t = t + \Delta t$ ) do
3:   if ( $\sum_{i=1}^{15} P_l^i(t) > (P_g^s(t) + P_g^w(t))$ ) then
4:      $FC(t) = 1$  and  $P_g^f = 1kW$ 
5:   else if ( $\sum_{i=1}^{15} P_l^i(t) < (P_g^s(t) + P_g^w(t))$ ) then
6:      $FC(t) = 0$  and  $P_g^f = 0kW$ 
7:   end if
8:    $E_b(t) = SOC(t) \times E^{max}$ 
9:   for  $E_b(t) \leq E^{max}$  do
10:    if ( $SOC(t) > SOC^{min}$ ) then
11:       $P_{bd}(t) = \eta_{b_{out}} \times (\sum_{i=1}^{15} P_l^i(t) - P_G(t))$ 
12:       $E_b(t + \Delta t) = E_b(t) - (P_{bd}(t) \times \Delta t)$ 
13:    else
14:       $P_{bd}(t) = 0$ 
15:    end if
16:  end for
17:  Compute  $P_G(t) = P_g^s(t) + P_g^w(t) + P_g^f(t) + P_{bd}(t)$ 
18:  Compute  $Gap(t) = P_G(t) - \sum_{i=1}^{15} P_l^i$ 
19:  if ( $Gap(t) > 0$ ) then
20:     $LS(t) = 0$  and  $LM(t) = P_G(t)$ 
21:     $Rem_P(t) = Gap(t)$ 
22:  else
23:    Obtain  $LS(t)$  and  $LM(t)$  from Algorithm 2.
24:     $Rem_P(t) = P_G(t) - LM(t)$ 
25:    if ( $SOC(t) > SOC^{min}$ ) then
26:       $P_b(t) = 0$  and  $P_{grid}(t) = Rem_P(t)$ 
27:    else
28:       $P_b(t) = Rem_P(t)$  and  $P_{grid}(t) = 0$ 
29:       $P_{bc}(t) = \eta_{b_{in}} \times P_b(t)$ 
30:       $E_b(t + \Delta t) = E_b(t) + (P_{bc}(t) \times \Delta T)$ 
31:    end if
32:  end if
33: end for

```

rise to the concept of *intelligent agents*, which perform flexible autonomous actions to achieve their objectives. The term flexibility, in this regard, refers to the three characteristics of an intelligent agent, described as follows.

1. Reactivity: It refers to the ability of an intelligent agent to perceive and respond to changes

in its environment in a timely manner.

2. Pro-activeness: It describes the goal-directed behavior of an intelligent agent, to take initiative in order to meet its design objectives.
3. Social ability: This refers to the characteristic of an intelligent agent to be able to interact and communicate with other agents in its vicinity.

For certain complex problems, independent intelligent agents may appear to be insufficient and incapable to achieve the desired goals. Thus, in order to solve intricate problems, more than one intelligent agent, working in close co-ordination with each other can be used. Such a mechanism constitutes a MAS. The basic ideology underlying the concept of MAS is to divide a complex problem into smaller and simpler parts. It then involves allocating each part to a different entity, each of which is an individual intelligent agent working in synchronization with other such agents of the distributed MAS.

As discussed in the previous chapter, the proposed system comprises of a number of distributed components which work in a synchronized manner to achieve the ultimate goal of energy independence of ZEB. This involves instantaneous power dispatch, power routing as well as load scheduling. For this purpose, three intelligent agents have been designed for the proposed system- GenA, LA, and BA. These have been discussed as follows.

1. Generation Agent- The function of the GenA is to track the instantaneous power generation of the ZEB. It interacts with the LA to receive the instantaneous load requirement, and accordingly decide upon switching the fuel cell on or off. Thus, GenA takes input data from the meters $M1$ and $M2$, as well as from LA. It finally takes a decision whether the generation needs to be increased by turning on the fuel cells or not. This is relayed to the fuel cell switch through a signal FC . To turn on the fuel cell, FC is 1. Similarly, to turn off the fuel cell, FC is 0. Fig. 3.1 depicts the basic structure of the GenA.

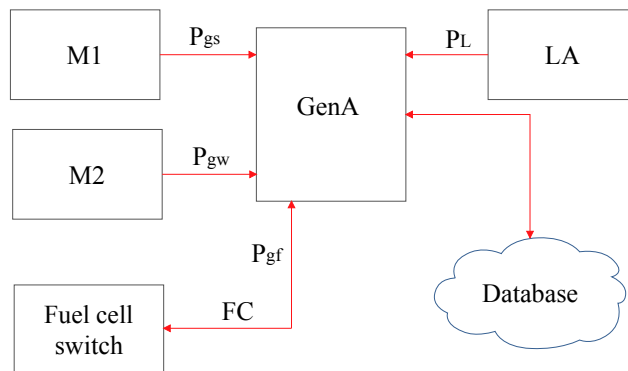


Figure 3.1: Generation agent

2. Load Agent- The function of LA is to analyze the instantaneous load connected to the home grid and communicate the same to GenA. Keeping in view the instantaneous power generated, demand, $SOC(t)$, and load priorities, LA takes suitable decision regarding load scheduling. It performs load scheduling through an algorithm based upon GA. Thus, LA takes inputs from GenA, BA, connected loads, and the load priorities decided by the user. The output of LA is the result of Algorithm 2, as discussed in the following subsection. Figure 3.2 shows the basic block diagram of LA.

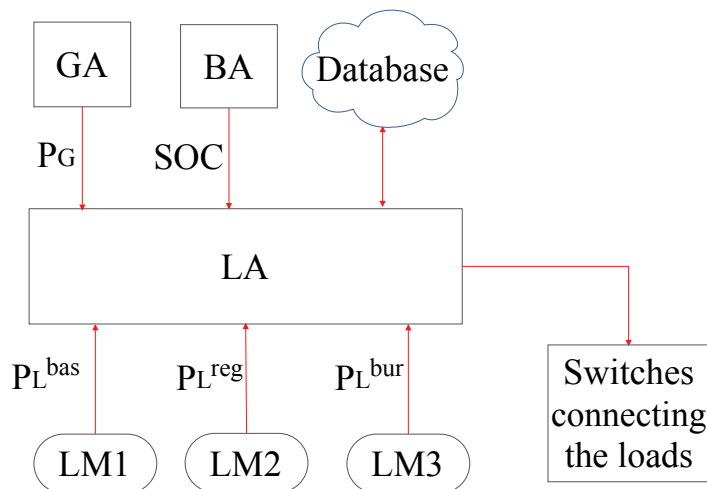


Figure 3.2: Load agent

3. Battery Agent- The prime function of BA is to determine the BESS's real-time $SOC(t)$. It further receives knowledge from other agents about the generated powers and loads. Fur-

thermore, in accordance with Algorithm 1, BA supervises the charge controller of the BESS for its charging and discharging, to satisfy the instantaneous loads

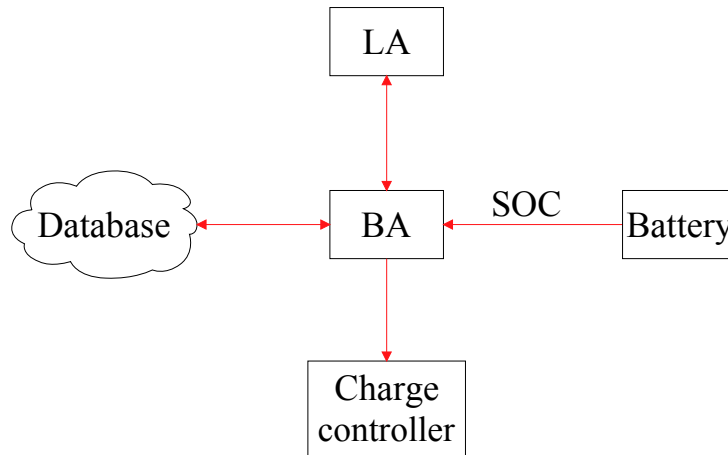


Figure 3.3: Battery agent

3.3 Genetic Algorithm based load scheduling

Load scheduling, as discussed before, is carried out when the power available at the home grid, as obtained from Eq. (3.2), is not sufficient to cater the instantaneous load requirements. Accordingly, loads are turned off or disconnected from the home grid in order of their priorities. The priorities of individual loads are decided depending upon the user preferences, time of use, and power demand. Accordingly, a priority index PI has been calculated for each appliance, as follows.

$$PI_i = \frac{P_{rated}^i}{\sum_{i=1}^N P_{rated}^i} \times k \quad (3.18)$$

where, P_{rated}^i is the rated power of the i^{th} appliance, N is the total number of appliances, and k is a priority factor which varies with the type of load. For baseline or high priority loads its value is chosen as 1. For regular or medium priority loads the value of k is chosen as $2/3$. Similarly, since the burst loads are of lowest priority, the value of k for such loads is chosen as $1/3$.

The objective of load scheduling in the proposed system is a maximization problem. It is basically a product of the load priority indices and their corresponding power demands, which can

be expressed as follows [27].

$$\sum_{i=1}^N PI_i \cdot P_l^i(t) \quad (3.19)$$

where, N is the total number of loads. Moreover, the objective is subjected to the following constraint.

$$P_G(t) - P_L(t) \geq 0 \quad (3.20)$$

The overall objective function for the designed load scheduling algorithm can be expressed as

$$f(P_L) = \sum_{i=1}^N PI_i \cdot P_l^i(t) + (P_G(t) - \sum_{i=1}^N P_l^i(t)) \quad (3.21)$$

The proposed load scheduling algorithm is based on GA. GA refers to a class of evolutionary search techniques which simulate biological evolution and genetic mechanism. It evolves better and returns fitter solutions with every generation. For a certain generation, the relative fitnesses of different individuals are evaluated. The fittest strings are selected as parents for that particular generation. The parents then undergo crossover and mutation, thus producing off-springs for the next generation. This process is repeated for a number of generations. The best individuals are selected and weaker ones are eliminated after several generations of evolution. The stepwise mechanism for the scheduling action of LA is presented in Algorithm 2. As can be observed from the algorithm, the user inputs required are P_G , PI_i , and number of loads (N). After the decision making, the algorithm returns outputs as LM and LS , which are the loads to be satisfied, and loads to be shed, respectively. Thus, based upon the real-time load and generation, a GA-based load scheduling algorithm has been developed as part of the EMS.

Algorithm 2 Load scheduling algorithm based on GA**Input:** $N, P_l^i \forall (i \in N), P_G(t), PI_i$, population size (ps).**Output:** $LS(t), LM(t)$.

```

1: Store  $\Delta t = 0.25$  and  $N$ .
2: Initialize  $Q = 0$ .
3: for ( $i = 1, i \leq N, i++$ ) do
4:   Store priority index  $PI_i$ 
5: end for
6: for ( $iteration \leq maximum\ iterations$ ) do
7:   Calculate fitness:
8:    $f(P_L) = \sum_{n=1}^{15} (PI_n \times P_l^n) + (P_G - \sum_{n=1}^{15} P_l^n)$ 
9:   Evaluate relative fitnesses of the population and perform selection.
10:  Create new strings by carrying out crossover among the selected population.
11:  Compute  $f(P_L)$  of the new population to eliminate undesirable changes in the population.
12:  Apply mutation to introduce variations and form new strings.
13:  Repeat 11.
14:  Check for convergence. Calculate  $\varepsilon = f(P_L)(1) - f(P_L)(ps)$ 
15:  if ( $\varepsilon \leq 0.001$ ) then
16:    Problem is converged.
17:  end if
18: end for
19: for ( $i = 1, i \leq ps, i++$ ) do
20:   Compute sum,  $t = \sum_{k=1}^N P_{lk}^i$ 
21:   if ( $t \leq P_g(t)$ ) then
22:      $A \leftarrow t$ 
23:   end if
24: end for
25:  $z \leftarrow maximum\ value\ of\ A$ 
26: Find index ( $j$ ) of  $A$ , for  $A = z$ .
27: Optimal power available for the individual loads is:
28: for ( $k = 1, k \leq 15, k++$ ) do
29:   Display  $P_{lk}^j$ 
30:   if ( $P_{lk}^j < P_{lk}^{min}$ ) then
31:      $P_{lk} \leftarrow 0$ 
32:      $Q = Q + P_{lk}$ 
33:   else
34:      $R = R + P_{lk}$ 
35:   end if
36: end for
37: Display results,  $LM = R$  and  $LS = Q$ .

```

Chapter 4

SIMULATION AND RESULTS

4.1 Simulation Parameters

For the purpose of simulations, a residential ZEB has been considered. The ZEB includes a generation system consisting of PV panels, wind generators, and fuel cells. Further, a suitable BESS is also provided to store energy. SOC^{max} and SOC^{min} are assumed to be 100% and 25%, respectively. The details of the generation system are listed in Table 4.1.

Table 4.1: Specifications of the ZEB power generation system

S.No.	Source	Rating
1	PV panels	2.4 kW
2	Wind turbine-generator unit	5 kW
3	Fuel cells	1 kW
4	BESS	4 kWh

The proposed ZEB comprises of a variety of residential loads. It has been assumed that the load and generated power remain constant for a period of 15 minutes. The list of equipments and the power ratings of each of these appliances have been mentioned in Table 4.2. Moreover, the table also depicts the average duration for which each appliance is operated on one particular day. The data for the same has been obtained from [28]. Furthermore, these loads have been categorized as baseline, regular, and burst loads, as discussed in earlier chapters. This categorization has been presented in Table 4.3.

Table 4.2: Load specifications of the ZEB

S.No.	Appliance	Qty.	Power rating (Watts)	Duration (Hours)
1	Lighting	6	228	2.5
2	Radio	1	11	6
3	CD Player	1	35	4
4	Television	1	113	4
5	DVD/VCR	1	32	0.427
6	Computer	1	64	2.2
7	Washing Machine	1	130	1
8	Refrigerator	1	473	24
9	Electric Oven	1	1193	0.25
10	Toaster	1	1182	0.25
11	Microwave	1	1080	0.1
12	Electric water heater	1	575	9.2
13	Fans	3	111	6.9
14	Air cooler	1	235	3.95
15	Air conditioning	1	1834	1.575

Table 4.3: Categorization of ZEB loads

Regular loads	Baseline loads	Burst loads
Refrigerator	Washing machine	Computer
Water heater / geyser	Electric oven	Lighting
Air conditioner	DVD/VCR	Fans
Cooler	Television	Microwave
	CD player	Toaster
	Radio	

4.2 Results and Discussions

The following segment discusses the results obtained after performing the simulations on the proposed system. In the proposed system, a residential ZEB, including a power generation system, has been considered. As described in the previous chapters, the generation system comprises of a wind turbine, solar PV panels, and a fuel cell. For the purpose of simulations, wind and solar power curves for a particular day have been considered, as depicted in Fig. 4.1. This figure also shows the total availability of power generated using these two sources. Apart from the generation

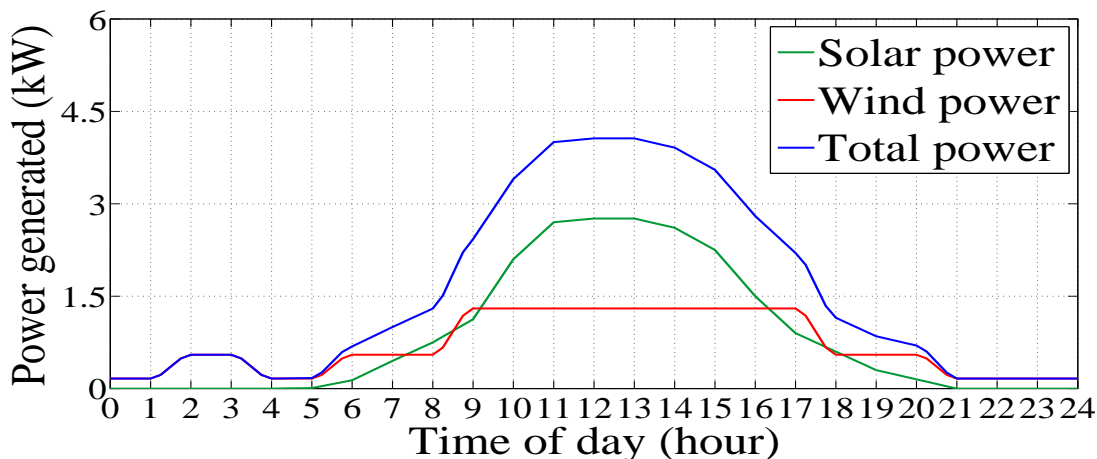


Figure 4.1: Power generated from wind and PV sources.

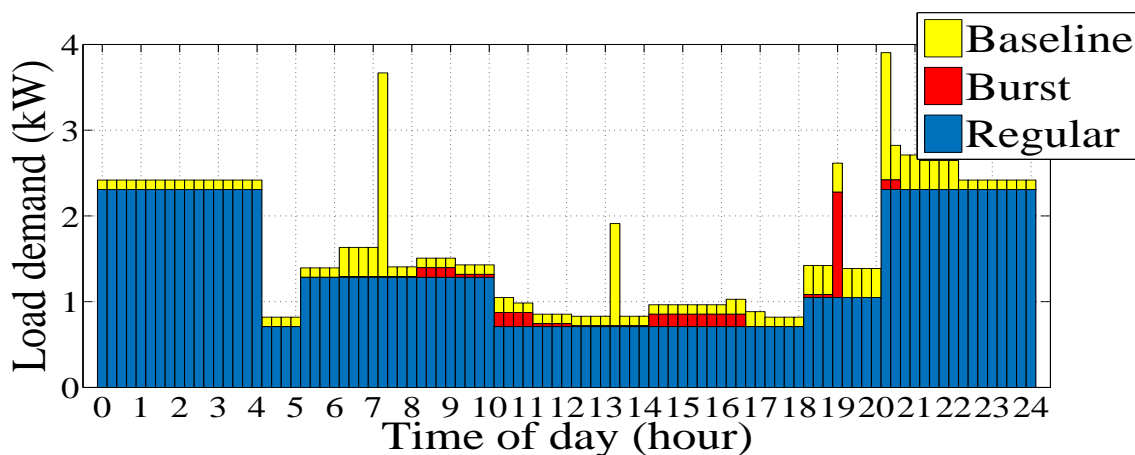


Figure 4.2: Hourly load variation.

system, the ZEB also includes residential loads. As mentioned before, these have been categorized as baseline, regular, and burst loads. The share of each category of loads in the total power demanded throughout the day has been illustrated in Fig. 4.2.

The power demanded by the appliances varies throughout the day. This value, $P_L(t)$ as calculated by Eq. (3.5), is communicated by LA to GenA. Similarly, the power generated in the ZEB differs with time due to intermittent nature of RE sources. This is again computed by GenA which receives $P_g^s(t)$ and $P_g^w(t)$, according to Eq. (3.3). As a result, there exists a gap between the power generation and demand at every instant of time. This gap is calculated by GenA and is illustrated in Fig. 4.3. The purpose of this work is to effectively manage the power in a ZEB by minimizing the gap between generation and demand. This is achieved through a suitably designed controller which is a decentralized EMS based on MAS. Thus, in accordance with Algorithms 1 and 2, the

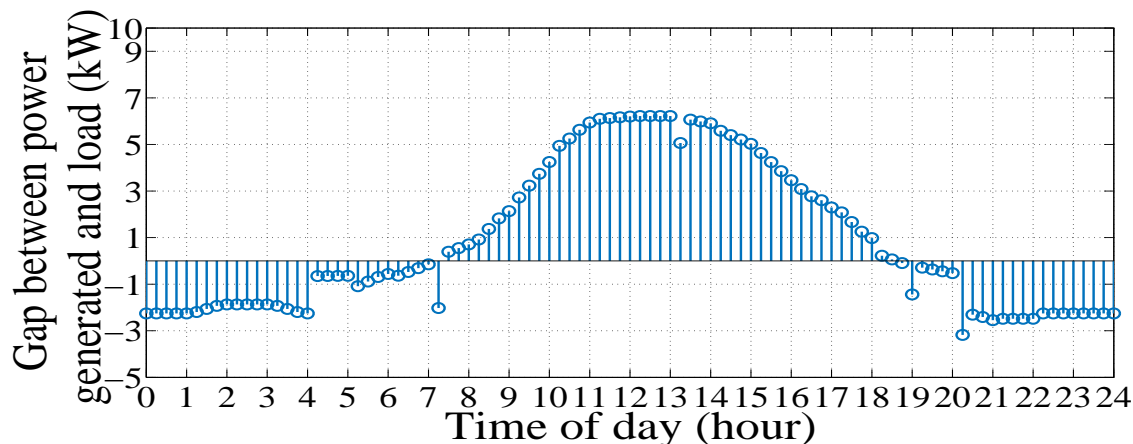


Figure 4.3: Gap between power generation and demand.

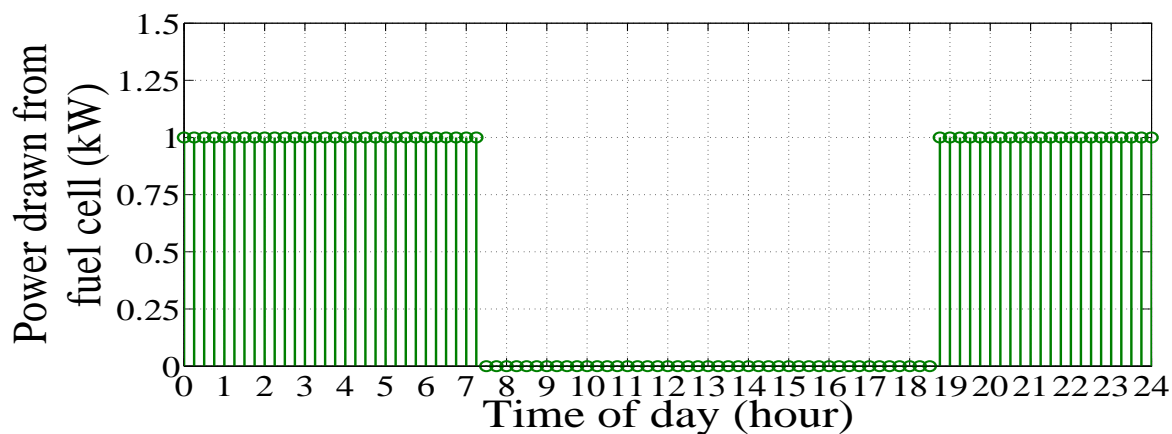


Figure 4.4: Power drawn from fuel cell.

MAS-based EMS efficiently manages the power in the ZEB to achieve its self-sustainability and minimize its grid dependency. For the purpose of illustrating the controller action, the following cases have been discussed.

1. Case I- $P_g^s(t) + P_g^w(t) < P_L(t)$ and $SOC(t) > SOC^{min}$

Consider the instant of 0715 hours, when the available power is less than the generated power. This results in a power deficiency of 2.024 kW. This corresponds to the operation of ZEB in Mode III, as described in Chapter 3. At this instant, according to step 4 of Algorithm 1, GenA sends FC of value 1, and turns the fuel cell on. Now, the fuel cell supplies an instantaneous power of 1 kW. The power drawn from the fuel cell over a complete day has been plotted in Fig. 4.4. To further increase the generation, battery's $SOC(t)$ is checked.

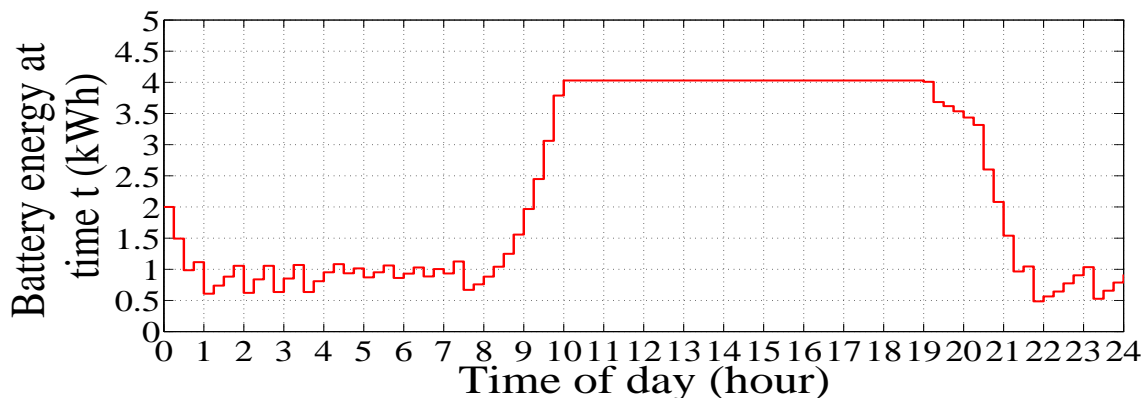


Figure 4.5: Battery energy at the beginning of the interval.

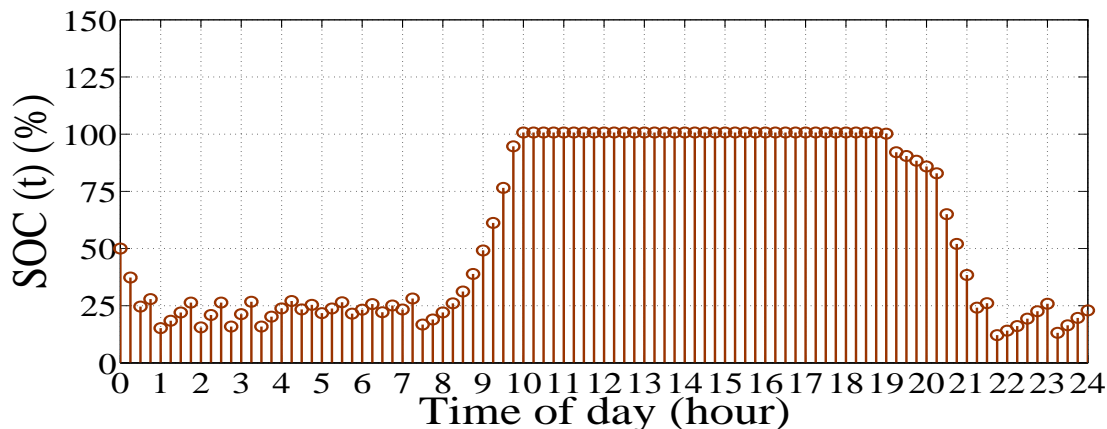


Figure 4.6: Battery SOC at the beginning of the interval.

Accordingly, BA receives the $SOC(t)$ from the battery. At this particular instant, the $SOC(t)$ is 28.14%. According to step 8 of Algorithm1, this corresponds to stored energy of 1.1256 kWh. This implies that $SOC(t) > SOC^{min}$, and $E_b(t) > E_b^{min}$. Thus, the BA signals the charge controller to discharge the BESS. Consequently, the battery discharges according to Eqs. (3.16)-(3.17). It supplies an instantaneous power of 1.8212 kW for a period of 15 minutes, after which the controller again checks the system conditions. At the end of this interval, the battery energy, $E_b(t + \Delta t)$ is 0.67 kWh. The variation of battery energy at the beginning of the intervals is depicted in Fig. 4.5. Similarly, battery $SOC(t)$ at the beginning of each interval is shown in Fig. 4.6. The power discharged from the battery at instants of power deficiency and $SOC(t) > 25\%$ is plotted for time intervals of 15 minutes in Fig. 4.7. The battery's energy at the end of each interval is illustrated in Fig. 4.9.

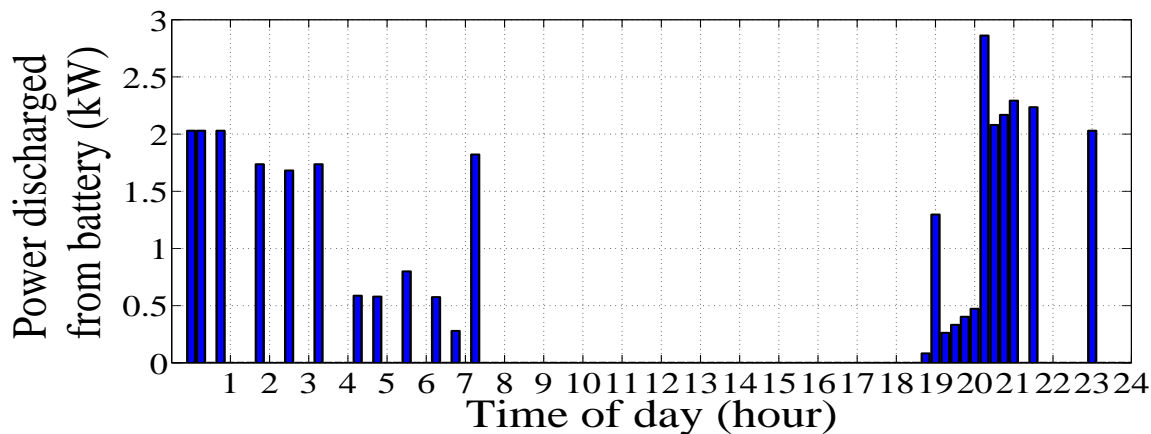


Figure 4.7: Power discharged from battery.

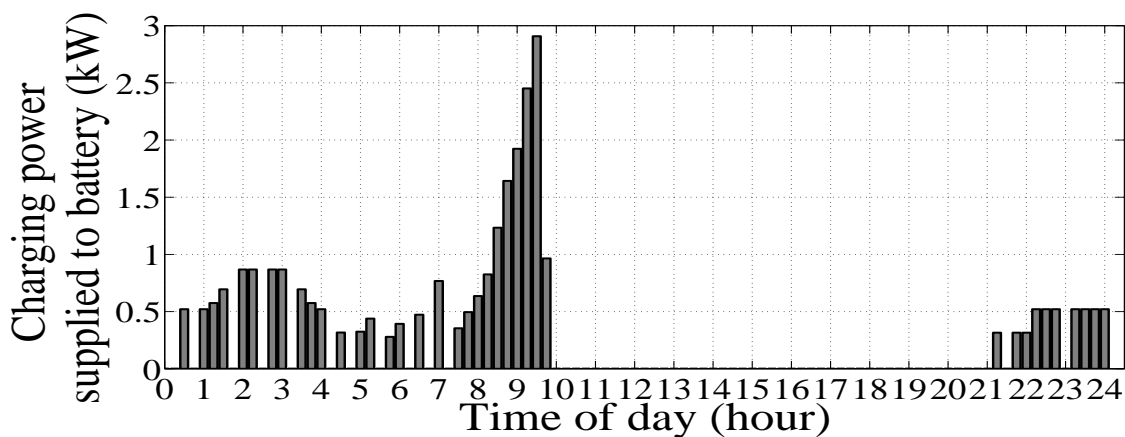


Figure 4.8: Charging power supplied to battery.

Now, with the fuel cell and battery turned on, the net power generation is increased as compared to that generated using only wind and solar sources. This can be observed from Eq. (3.2). The power which is now generated at the instant of 0715 hours is 4.4645 kW. The variation of the increased power, $P_G(t)$, throughout the day is shown in Fig. 4.10. The GenA again computes the gap between $P_G(t)$ and $P_L(t)$, which has been plotted in Fig. 4.11. As can be observed from this figure, the gap is now changed to 0.79756 kW. The positive sign indicates that the power generated now is greater than the load. This highlights the fact that during this interval, there is no requirement for load shedding, and all the loads are satisfied.

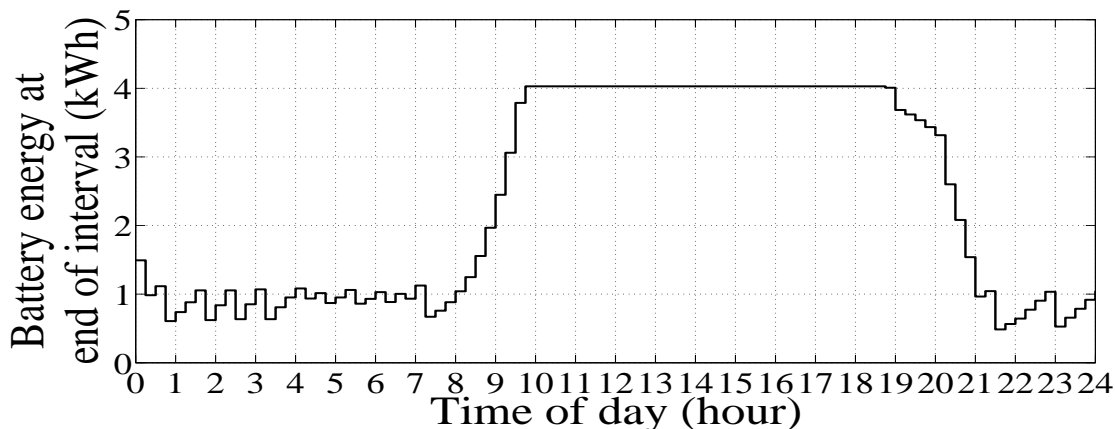


Figure 4.9: Battery energy at the end of the interval.

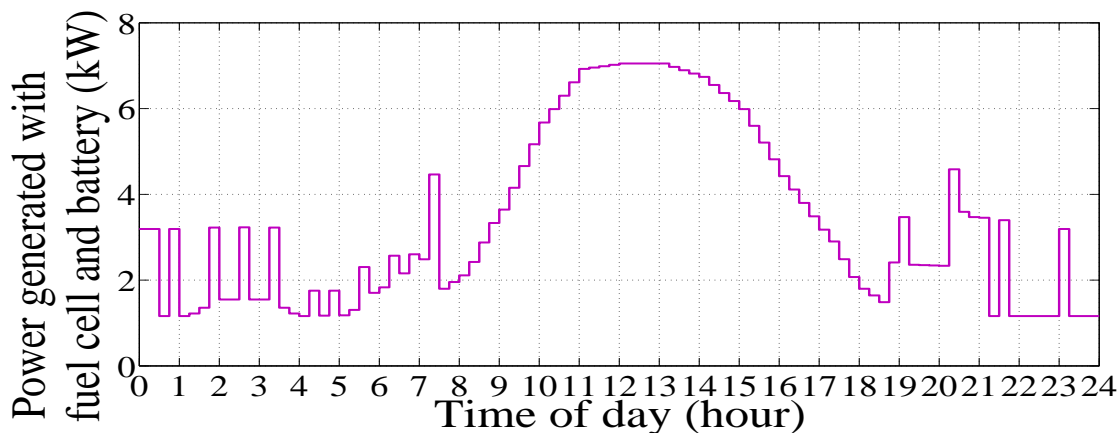


Figure 4.10: Total generated power with fuel cell and battery in operation.

Consequently through Algorithm 1, LA returns the value of LM as $P_L(t)$. Further, no loads are required to be shed at this instant i.e., LS is 0. This is indicated in step 20 of Algorithm 1. Furthermore, the power supplied to loads during each interval are plotted in Fig. 4.12.

During the considered time period, after satisfying the loads a power of 0.7975 kW remains surplus. The net surplus power remaining after supplying the loads at the end of each interval is illustrated in Fig. 4.13. This power can either be supplied to charge the battery or can be exported to the grid, as discussed in Mode II of chapter 3. The controller takes this decision based upon the current system conditions. At the considered interval, since the battery's $SOC(t) > SOC^{min}$, it does not require to be charged. Thus, BA disconnects the battery from the home grid as $P_{bc}(t)$ is 0. From Eq. (3.14), it is observed that $P_{grid}(t)$ is same as $P_{net}(t)$, implying that all the surplus power is exported to the grid. Therefore, the home grid gets

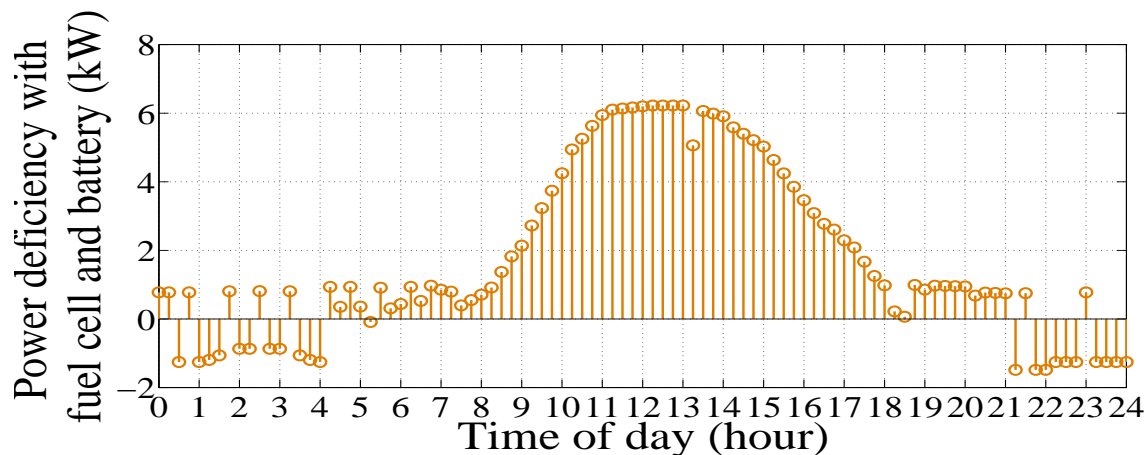


Figure 4.11: Deficiency in power with fuel cell and battery in operation.

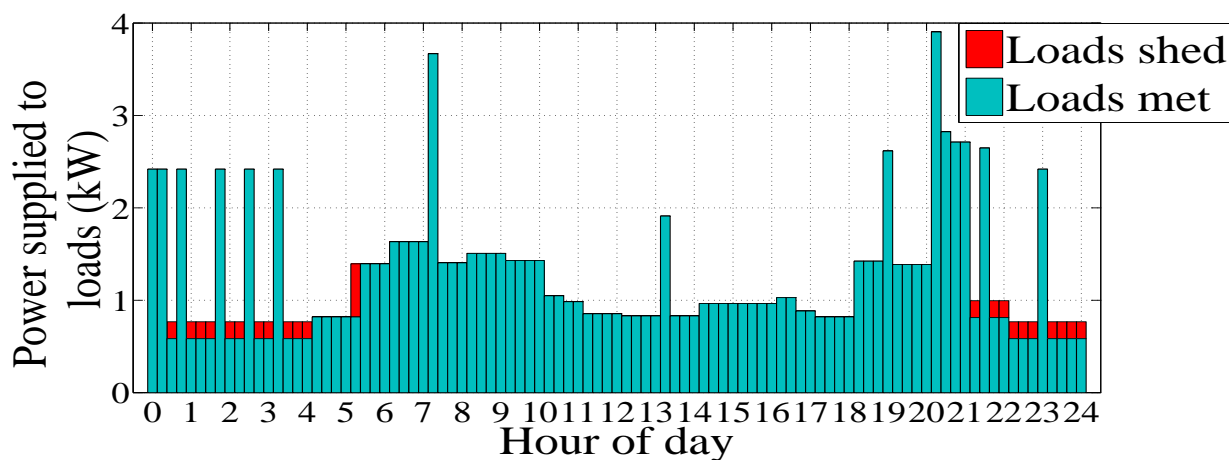


Figure 4.12: Power supplied to loads.

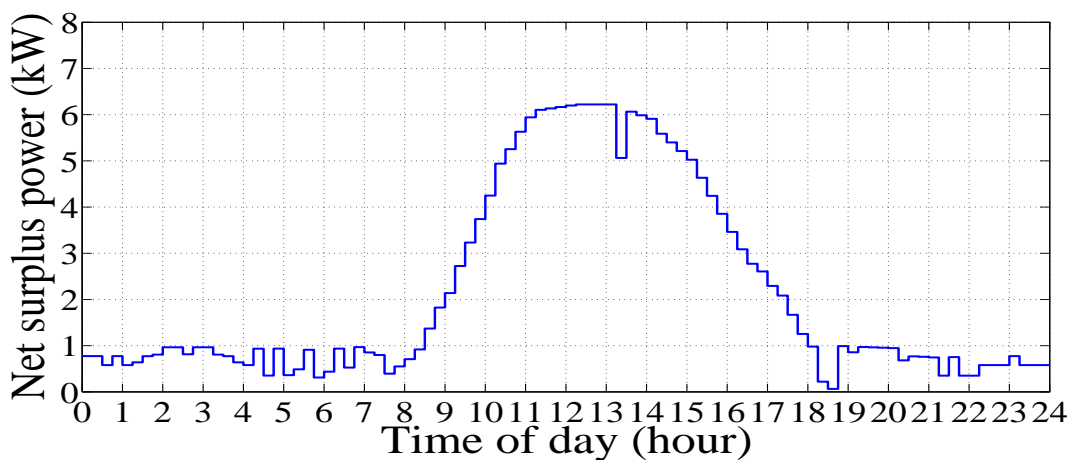


Figure 4.13: Power remaining at the end of the interval.

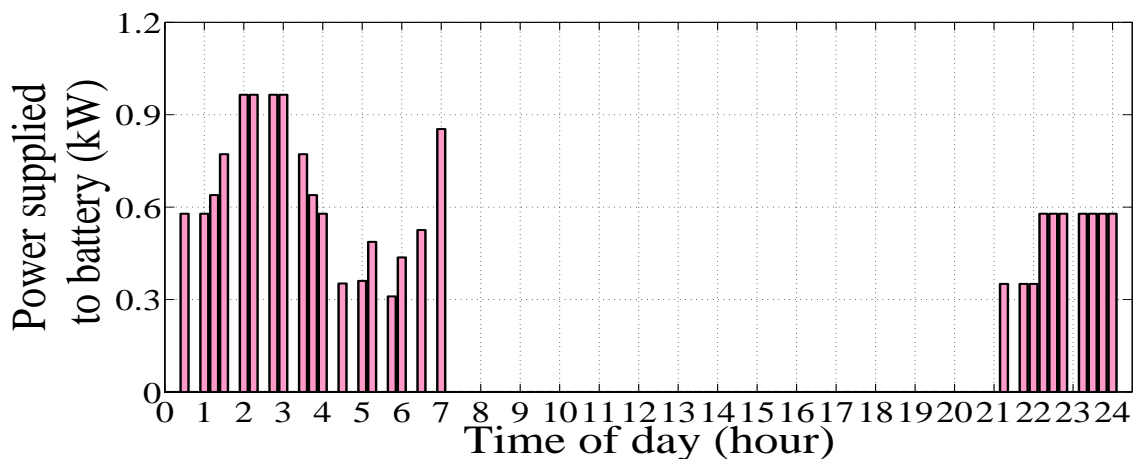


Figure 4.14: Power supplied to battery.

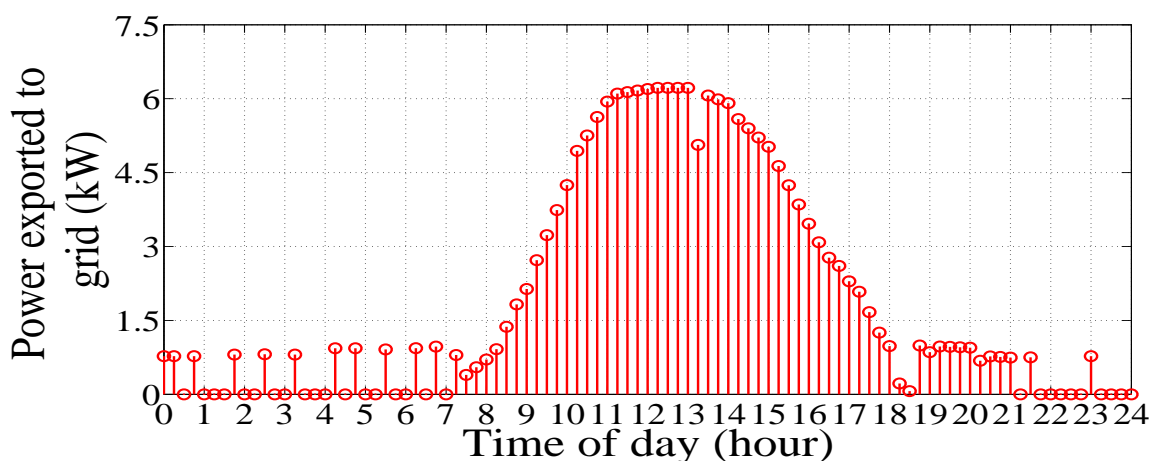


Figure 4.15: Power supplied to grid.

connected to the utility grid. The variation of $P_{grid}(t)$ with time throughout the day has been shown in Fig. 4.15. Therefore, at the instant of 0715 hours the power generated using wind and PV sources is insufficient to meet the loads. Accordingly, EMS turns on the fuel cell and discharges the BESS, resulting in a surplus power at the end of this interval, which is exported to the grid.

2. Case II- $P_g^s(t) + P_g^w(t) < P_L(t)$ and $SOC(t) < SOC^{min}$

In another case, at 2215 hours, the generated power from wind and solar sources is 0.1626 kW, whereas the load requirement is 2.418 kW. Thus, fuel cells are turned on by the signal FC equal to 1 from GenA. Now, the battery's initial storage at the beginning of the interval

is 0.6436 kW and its $SOC(t)$ is 16.09 %. This highlights the fact that it cannot be further discharged to meet the load requirements. As a result, there arises a need for scheduling the loads, since the total power generated by turning on the fuel cells is 1.1626 kW, which is still lesser than the demand. Thus, LA schedules the loads through Algorithm 2 which returns LS equal to 0.1834 and LM equal to 0.584. The results of the algorithm turns off the air-conditioner, which has a requirement of 0.1834 kW. Now, the demand is reduced to 0.584 kW. At this instant, there occurs a resulting gap of 0.5786 kW, and $SOC(t) < SOC^{min}$. Thus, in accordance with Algorithm 1, $P_{net}(t)$ is used to charge the battery according to Eqs. (3.12)-(3.13). This is depicted in Fig. 4.8.

3. Case III- $P_g^s(t) + P_g^w(t) > P_L(t)$ and $SOC(t) > SOC^{min}$

For validating the results for different power conditions, another instant of 1100 hours is now considered. At this time, sufficient power is obtained from solar panels. As a result, the total power generated in ZEB is 6.9259 kW as can be observed from Fig. 4.1. $P_L(t)$ which is now communicated by LA to GenA at this instant is 0.984 kW. This can adequately be satisfied by the generated power from ZEB's generation system. Thus, for this interval as can be obtained from Algorithm 1, there is no requirement of turning on the fuel cells. Consequently, GenA sends FC of value 0, to the fuel cell switch and it remains disconnected. Further, as can be seen from Fig. 4.5 and Fig. 4.6, BESS is charged to its rated capacity, which means that the SOC is 100 %. Thus, at this instant, BESS remains disconnected, implying that $P_{bc}(t)$ is 0. Thus, the surplus power, which is calculated using Eq. (3.6), is supplied to the grid. This corresponds to step 26 of Algorithm 1. The surplus power, $P_{net}(t)$ at this time is 5.942 kW as can be observed from Fig. 4.13.

4. Case IV- $P_g^s(t) + P_g^w(t) > P_L(t)$ and $SOC(t) < SOC^{min}$

The next considered instant for explaining the obtained results is 0800 hours. At this point of time, the generation is greater than the load by 0.706 kW. This indicates that there is no requirement of the fuel cell. Accordingly the GenA sends signal FC of value 0 to the fuel cell controller. This implies that during this interval, $P_g^f(t)$ is 0 kW, as can be justified from step 6 of Algorithm 1. Now, a surplus power of 0.706 kW remains after serving the loads. This is diverted according to the decision taken by the controller, which is described in Algorithm

1. In accordance with step 10 of the designed algorithm, $SOC(t)$ of the BESS is checked by BA. It is observed from Fig. 4.6 that at this instant, $SOC(t) < SOC^{min}$ and has a value of 22.062 %. Consequently, the surplus power, as calculated by GenA, is supplied to charge the battery. This is carried out in accordance with steps 28-30 of Algorithm 1. Further, since no deficiency of power occurs in this case, LA satisfies all loads by diverting power accordingly into the appliances. This indicates that for this particular situation, LM is $P_L(t)$, and LS is 0.

The results obtained in the above-described cases illustrate the fact that the designed controller is satisfactorily able to handle the various situations of power variations in the ZEB. Thus, the co-ordination of MAS and GA result in a suitable EMS for achieving energy-sustainability and energy independence of the ZEB.

Chapter 5

CONCLUSION

In this work, the author has proposed a system to minimize the grid dependency of buildings by incorporating RE based generation system in individual buildings, making them ZEBs. Further, a control scheme has been designed to achieve the goal of instantaneous power independence of ZEBs. Since, power management of ZEBs appears as a multi-objective problem which involves decisions regarding power dispatch, power routing, and load scheduling, the controller has been designed on the scheme of a MAS. Three intelligent agents have been designed for this purpose using the JADE platform, namely GenA, LA, and BA. Moreover, for load scheduling LA manages the loads through a scheme based upon GA. The designed algorithm satisfactorily disconnects the load in case of power deficiency. Simulation results for the four cases explained in the previous chapter depict that the proposed scheme minimizes the grid import of the building. Instead, the ZEB exports power to the grid during hours of high power generation from RE sources. Thus, a significant burden on the grid is reduced through careful and judicious management of the available power resources and the loads. The proposed system, thus, appears as an effective and energy-efficient solution to the problem of instantaneous power management in self-sustainable ZEBs.

The future work in this regard would include development of the hardware component of the proposed system. Further, interfacing of the software agents with the physical environment of the building is a major concern that demands a dedicated research.

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1. S. Sharma, A. Dua, S. Prakash, N. Kumar, and M. Singh, A novel central energy management system for smart grid integrated with renewable energy and electric vehicles, in Transportation Electrification Conference (ITEC), 2015 IEEE International, Aug 2015, pp. 16. doi: 10.1109/ITEC-India.2015.7386923
2. S. Sharma, A. Dua, M. Singh, N. Kumar, S. Prakash, “Fuzzy rough set based energy management system for self-sustainable smart city”. Manuscript submitted to *IEEE Systems Journal*.
3. S. Sharma, M. Singh, S. Prakash, “Energy management system of a zero energy building using multi-agent systems”. Manuscript under preparation.

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M.E.- Power Systems	Thapar Institute of Engg. and Technology	Thapar Institute of Engg. and Technology University	8.74*

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