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Stability and Power Control for Smart Home Energy Management System

by

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Abstract

Smart home is a place that equipped with information technology and computing, it can accept as well as respond to the resident's request. The purpose is to provide resident a comfortable, convenient, safe, and joyful life through managing various technologies at home. Smart home system is a thought that supports control of several different systems in a household (e.g., heating, air conditioning, security, lighting, and audio/video systems) and acknowledged under the term smart homes. In this way, the worst condition of energy shortage could happen due to increasing number of consumer electronics and their attractive functions according to the advancement of smart homes. These increased power consumption resources have been forcing the human to search methods for managing power to reduce power consumption in home because power used in the home is a typical example of consumptive one. The high power required by home appliances makes our homes one of the most critical areas for the impact of power consumption. The residential areas are one of the main power consumers today, reducing power in home would contribute significantly to the environment. As more and more home appliances and consumer electronics are deployed, the power consumption in home area (i) tends to increase and (ii) leads an increase in the risk of power blackout. As a result, an intelligent smart home energy management system is needed for smart homes, which is responsible for observing and handling the working operations of home appliances.

This dissertation concerns research of technological issues for design and implementation, evaluation and stability problems. These problems are important application domains of smart homes. The overall objective of this dissertation is to develop the application of power and stability control for smart homes, which reduces the risks of peak power consumption to prevent power blackout and maintain power system stability in the presence of time delay. The stability analysis problem treated in this research is to determine the upper bound for time delay so that the system is globally stable.

Design and implementation part addresses the basic components for proposed system model such as smart home energy management system, smart electric sensors, power provisioning controller and smart appliances. Then the system is designed with the characteristics of sensing and computation, adaptability, autonomy and executing timeliness. The performance of the system is analyzed in terms of home appliance power consumption patterns, priority rule for available power sharing among appliances and stable region identification for which the system is stable. The simulation results show the appliance power consumption behavior when the available power supply is limited. Simulation results also help in defining stable/unstable and overshoot/non-overshoot region. The stability analysis verifies that the system stability is dependent on some time delay. Moreover, the peak power consumption of heterogeneous home appliances can be guaranteed for maintaining available power limit.

To evaluate the proposed system, the validation of the system is shown with both simulation and experiment results. First, the real house based power control simulator is developed with Visual Studio. Second, the stability analysis has been carried out for overall power system with MATLAB.

This proposed research can help the development of smart home system to prevent power blackout and guarantee the maximum power consumption within the available power limit. Moreover, it can provide optimal system design of power assignment among home appliances and implementation of stability test with delay consideration. This research can give better solutions for inhabitants who are seeking to get maximum appliance utilization with fast system response and customer satisfaction.

keyword : home energy management system, power control, stability control, power provisioning controller, smart electric sensor.

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List of Abbreviations

ICT	Information and Communication Technology
SHemS	Smart Home Energy Management System
SHA	Smart Home Appliance
SES	Smart Electric Sensor
PPC	Power Provisioning Controller
HA	Regular Home Appliance
HGW	Home Gateway
ICPM	Instantaneous Consuming Power Message
SPM	Suggested Power Message
LMI	Linear Matrix Inequalities
EBPA	Equal Based Power Assignment
RBPA	Ratio Based Power Assignment
PBPS	Priority Based Power Sharing
PBFP	Priority Based Final Power

List of Symbols

$D_i(t)$	Instantaneous consuming power level of ith SHA at time t
$S_i(t)$	Suggested power level for ith SHA at time t
m	No. of SHAs
n	No. of Sub-breakers
SYNC	Synchronization message
t_{SYNC}	Transmission time of SYNC message
τ_{SYNC}	Propagation delay of SYNC message
$t_{PROC-PPC}$	Processing time at PPC
t_{ICPM}	Transmission time of ICPM
τ_{ICPM}	Propagation delay of ICPM
t_{SPM}	Transmission time of SPM
τ_{SPM}	Propagation delay of SPM
T_c	Communication Interval
τ	Communication delay
a_i	Response speed of ith SHA
$\frac{b_i}{a_i}.u$	Final steady state value of ith SHA
$\frac{1}{a_i}$	Time constant
$R(t)$	Remaining power
P	Total available power for all SHAs
l	Divider of available power
D_i^{max}	Maximum consuming power of ith SHA
t_{min}	LMI constraint
$F(x)$	Negative-definite matrix

$r_i(t-\tau)$	Individual remaining power of ith SHA
F_i	Final power level of ith SHA
$F_i^{(n)}$	Final power level of ith SHA for interval n
D_{init_i}	Initial power demand of ith SHA for interval
G_{pri_i}	Given Priority of ith SHA
C_{pri_i}	Calculated Priority of ith SHA
N_{pri_i}	Normalized Priority of ith SHA
$ER(t)$	Estimated remaining power
D_i^{min}	Minimum consuming power of ith SHA

Chapter 1

Introduction

The electricity network is facing many problems, from deregulation and load increase; which is caused by the fact that the system was not designed to operate at that level. Such problems lead to major events and paralyze the electricity system. The increasing demand and aging infrastructure made it difficult to keep the system up to date and this made the system complex; to overcome such complexity. It is necessary to come up with a major solution to such problems; in other words the grid has to be made more modern and smarter, generating the electricity, transmitting and distributing in a smarter way.

Deregulation of the power utility industry, being a reality today, has resulted in competition in every aspect of power systems; be it in power generation, or in transmission or in energy consumption, management of electric energy is of utmost importance.

Sensing and communication technologies, smart meters for example, are essential to support the development, integration and deployment of flexible, safe, reliable and efficient power distribution management systems. Smart metering is a subject that is attracting much more attention. Smart metering is delivering many benefits in a lot of respects. The design, control, management and optimization of these new distributed energy sources and technologies, their integration into existing energy distribution networks, pose significant technological challenges to ensure their reliability and safety, and to improve and maximize their competitiveness. As a consequence, smart meters forward the signal to home devices intelligently configured in houses by communicating with them in a wireless or wired way to accomplish end-to-end transfer of information and power usage adjustment intended for home appliances.

In addition to the AMI technologies, effective energy management within smart homes also has to be taken into account in the context of underlying infrastructures in smart grids. From the perspective of power consumption reduction and efficiency, a platform-centralized energy management system for home plays a key role in automatic supervision of energy-aware smart appliances.

Smart Grid is a new electrical grid that uses ICT to gather and ac on information about the behaviors of suppliers and consumers in an automated way to improve the efficiency of the production, transmission, distribution and consumption of electricity. Advancements of smart grid is driven by the technologies, (1) integrated communication, (2) automated control, (3) intelligence sensing and measurement. Real time monitoring of the stability and efficiency of smart grid and its appliances are to be accomplished through two main tasks:

1. Exchange of information obtained from distributed sensing and measurement.
2. Dissemination of management and control messages to the appliances.

The efficiency, reliability and stability of the smart home is expected to be significantly improved via home energy management system (HEMS). Sensors are the most essential part of the HEMS, used to connect individual home appliance to the energy management system. Smart home is viewed as end user of smart grid. Smart home is incorporating a communications network that connects the key electrical appliances and services, and allows them to be remotely (both within and outside the home) controlled, monitored or accessed.

Applications of smart home system are:

- Environment monitoring system
- Health care system
- Entertainment system
- Security and safety system
- Stability and power control of smart home system

The proposed system of Smart Home Energy Management System (SHemS), is responsible for collecting data from appliances using sensors, and then optimizing power supply by using the information obtained from sensors. Embedding intelligence in the form of stability and power management for SHemS to meet the problems of improved reliability, efficiency and user satisfaction to cope with the system dynamics is a challenging task.

Design and implementation of maximum consuming power control and implementation of stability test will play a vital role in keeping the total household power consumption below a certain limit, while considering customer preferences and allowing the customer more flexibility to operate their appliances. This dissertation deals with design, implementation and evaluation of stability and power control for smart home environment.

1.1 Research Problems and Motivations

Extensive research efforts have been made to develop a variety of monitoring and controlling applications in smart home environment such as peak power control, lighting control, environmental monitoring, energy management, home appliance control, security control, etc. In this dissertation, stability and power control are considered one of the important research problem of the smart home environment.

Smart home technologies are viewed as end users of smart grid. Smart home system is a home or residence, which responds to the needs of customers to provide comfort, convenience, security and entertainment [1].

It is already convinced that the number of home appliances in smart homes has significantly increased compared to the past. The high power required by home appliances makes our homes one of the most critical areas for the impact of power consumption. The real time monitoring of power consumption of appliances is an important factor for future intelligent home where intelligent home is dedicated to the seamless infusion of technology with day to day living to create a lifestyle totally unique for each individual [2].

As the residential areas are one of the major power consumers today, thus reducing power in home would contribute greatly to the environment. As more and more home appliances are introduced with attractive features, the power consumption at home

- Tends to grow

- Leads to increase the risk of instability

of the whole power system [3]. In this way, we have to face the worst situation of energy shortage.

The balancing of energy use is a challenging fundamental issue for the efficient behavior of an electrical system. Son and Moon [4] state that a HEMS is the technology to manage and balance the home energy use. The HEMS plays a vibrant role in recognizing the efficient and versatile control of consuming power among home appliances in smart homes. Pipattanasomporn et al. [5] quote that the HEMS is a networked system and it is responsible for monitoring and managing the working operations of home appliances, and helping smart homes to reduce power consumption based on the specific set of requirements. However, nowadays the HEMS is a display-type of device that contains high processing unit to monitor and control the energy management in the home environment. On the other hand, the introduction of smart meter (SM) technologies is incorporated into the home gateway, which is totally different from other research works.

A smart energy management system for smart home system is needed which is responsible for collecting data from appliances using sensors, and then optimizing power supply by using the information obtained from sensors. Embedding intelligence in the form of stability and power management for smart energy management system to meet the problems of improved reliability, efficiency, and user satisfaction to cope with the system dynamics is a challenging task. Smart home system needs the basic components, like smart sensors, intelligent controller, communication infrastructure, and smart home appliances.

1.1.1 Peak Power Consumption

> “Peak power consumption is defined as the highest power requirement occurring in a given time period (e.g., an hour, a day, a month, season, or year) or a period during which the customer power demand needs to be curtailed to alleviate a system stress condition”.

In recent years, the demand for electricity has increased in households with the use of various appliances. This raises a concern to many developed and developing nations with the immediate demand increase of electricity by appliances. There is a need for consumers to track their daily power usage in houses. The total amount of power consumed in an individual household is referred as power consumption. The consumption of power is an important aspect of electricity supply. Customers should be aware of preserving energy for future use. With daily usage of electricity, the energy patterns have been slowly varying. This variation of consumption patterns can be caused by unnecessary utilization of power by inhabitants such as increase of appliances in respective households and careless attitude in utilization of home appliances. These factors may show greater impacts on end users. As the power supplied by energy companies is vast, most of the people are neglecting energy and its savings. The importance of consumption is declining in the mindset of utilities. The energy utilities should play a major role in advancing the smart meter technology and should make people participate in reducing energy consequences by creating awareness about the impact of their current level of consumption. An effective energy management system for home to provide load reduction during stress conditions.

1.1.2 Power Blackout

Electricity as an easy to use power is one of the most generally used energy all over the world. Electric power system is the elementary requirement for daily life and its failure will possibly paralyze the smart homes. The severe accidents by a large scale blackout have been well documented and many struggles have been done for avoiding such a large scale blackout [6], [7], [8]. On contrary, the blackout in smart homes is also a serious problem, but no investigation study has been done for blackout prevention for home. It causes mental stress for the home user, and makes the smart homes unstable. The future smart homes should be stable completely. For this purpose, there is a great need to introduce smart energy management system for smart homes that shows a dynamic role in attaining reduction in extreme consuming power.

1.2 Organization of the Thesis

Chapter 2 describes the preliminaries and related work for the proposed system. This chapter includes the definition and technologies for smart grid, smart home system and its applications in real life, importance of home energy management system particularly for reducing power consumption in residential area and introduction of SM.

Chapter 3 proposes a system design and architecture for maximum consuming power control and power blackout prevention for smart home system. The proposed system consists of Smart Electric Sensors (SESs), Power Provisioning Controller (PPC) and Smart Home Appliances (SHAs). The real time monitoring and measuring of power consumption levels of SHAs through SES is a key and an integral part of smart homes. A SES is used to connect individual SHA to the power management system but with a communication delay. The proposed SHemS is analyzed to illustrate the impact of SES, for two important properties of smart home system, preventing blackout and maintaining power system stability. Simulation results show the SHA power consumption behavior when the available power supply for appliances is limited. Simulation results help in observing the effects of system parameters to the total available power for power distribution among SHAs and border estimation for stability.

Chapter 4 gives a comprehensive review of stability control for SHemS. This chapter explains the introduction of continuous and discrete time delay systems. The solution approaches for continuous and discrete time delay systems are Linear Matrix Inequalities (LMIs) and calculation of Eigen values respectively. It also explains the effects of communication delay on system stability and also analyzes whether such delays can reduce the stability margin and determine how much stability margin might be reduced. Lyapunv-Kasovskii (L-K) stability theorem is used to compute the stability parameters of the system and derive upper bounds of delay for continuous time delay system. Simulation results help in evaluating the stability theorem in MATAB (LMI toolbox) and identifying the stable region and also the possible ranges of delay for which stability is guaranteed.

Chapter 5 demonstrates the power control for SHemS. This chapter is divided into two parts named power assignment criteria and power control schemes. In power assignment criteria, the focus is on achieving optimal system model for SHemS. The specific research targets are to achieve SHA maximum power satisfaction level and get faster response time of the proposed system by applying two different power assignment criteria': Equal Based Power Assignment (EBPA) criteria and Ratio Based Power Assignment (RBPA) criteria. The two power assignment criteria also analyze in simulation environment to check total available power distribution, effects of change in SHA response speed and effects of system parameters on stability. In second part (power control schemes) of this chapter, PPC computes suggested power level for SHAs according to SHA priority defined by home user. This part proposes a system to control maximum power consumption in detailed transient behavior considering heterogeneous smart appliances with different time constant. In order to guarantee the maximum power limit, the computation of remaining power and reassign it to SHAs as their temporal targets have been done. Simulation results show the effectiveness of our proposed system in managing maximum power consumption.

Chapter 6 describes the implementation of proposed SHemS in smart home system. The proposed system is modified with more practical aspects of implementation in this chapter. A practical SHA model is introduced by setting minimum consuming power level of SHAs. The system architecture includes circuit breaker model protection mechanism and stability implementation. Priority schemes also modified according to the new additions. Simulation results help in analyzing the overall system behavior and effectiveness of system parameters for stability and power control.

Chapter 7 summarizes the work done in this research study. Areas for future work and developments are suggested.

1.3 Dissertation Focus and Scope

A system of smart homes refers to a residence that is equipped with computing and information technology, which responds to the needs of the occupants and provides comfort, convenience, security and entertainment [9]. Smart homes expect to control numerous diverse systems in a household domain. Air-conditioning, audio/video, heating, lighting, security and health care, such systems could be found in smart homes [10].

In particular, the research objectives are summarized as follows:

1. To develop an effective design and architecture of SHemS, which consists of a PPC, SESs, SHAs, regular appliances (HAs) and wired/wireless communication networks. To analyze and observe the behavior of SHAs.

    - Maximize home appliance performance

  - Reduce system response time
  - Live in better and smarter life-style which leads to increase the quality of life with customer satisfaction

2. Implement the stability test for continuous time delay system, i.e., Lyapunov-Krasovskii (L-K) stability theorem with LMIs. To identify the stability region for the upper bound of communication delay.

3. Implementation of stability analysis for discrete time delay system, i.e., calculation of Eigen values to identify system stability with SHA priority.

4. Study the different power assignment criteria to optimize system design depending on application types. The proposed system also maintains the maximum power of the smart home appliance that does not exceed the limit by introducing two power control schemes based on SHA priority. The basic objective is to achieve customer's or home owner satisfaction level.

5. Implementation of SHA power management model with additional features and also the protection mechanism with circuit breaker model.

1.4 Dissertation Contribution

The contribution of this dissertation fall in following different parts concerning respectively design and implementation, evaluation and stability problem of SHemS. This dissertation can help in the development of smart energy management system and give better solution for inhabitants for the maximum home appliance utilization with minimum response time and achieving home user satisfaction. In this dissertation, the following specific contributions are made for advancements in the state of the art of this research area.

1. Proposal of a novel system design and architecture for smart home system for black-out prevention and implementation of stability test. Through simulation, the result show that the appliance power consumption behavior when the power supply is limited.

2. Consideration of communication delay is also unique in this research and is found to be main factor of the system stability.

3. None of the research work in past perform the stability analysis for smart home systems. Therefore, there is a great need to propose a system design and architecture for stability control.

4. Implementation of stability theorem is also applicable to other research areas, e.g.,

    - Data feedback in health care systems
    - Data exchange in large-scale data systems
    - Air traffic control systems, and so on.

5. Both theoretical and practical aspects have been considered for stability control for the first time for smart home system.

6. The detailed analysis of power waveform is also omitted in many studies which is one of the novelties of this research.

7. Overshoot mechanism has been proposed to eliminate the power overshoot.

8. Practical appliance model is introduced by considering the minimum consuming power level of an appliance.

9. Circuit breaker model has been utilized towards more practical implementation.

Chapter 2

Preliminaries

2.1 Introduction

The need for electricity has been growing rapidly in recent years as a result of economic activities, weather, and population growth. Though technological advances allow the storage of electricity, it is still not viable to store electricity in large quantities. Therefore, electricity must be generated at the moment that it is demanded. Additionally, the electricity demand varies significantly overtime on an hourly, daily, as well as seasonal basis. Power systems often encounter unexpectedly high demand levels due to various reasons, such as extreme weather conditions. The power system needs to continuously balance the supply and the demand for reliable power delivery across the transmission grid.

2.2 Overview of Smart Grid

The “Grid ”refers to the method by which energy is generated, transmitted, and distributed to homes and business. The electricity industry was conceived over 50 years ago when the load and generation was less; now in the information age, with a digital society where demand is very high, the electricity infrastructure has been forced to its limits which had not been anticipated; in addition, the electricity demand continues to grow. So the focus of the question has become what needs to be done from a technology prospective to meet that growing demand for electricity. With the aging power grid and the increasing electricity demand, the deficiencies of the old power grid infrastructure, i.e., lack of automated analysis and control, poor visibility, and lack of environment awareness, have become too significant to be neglected [11]. Consequently, a new concept for the next generation electric power system, smart grid, has emerged. A smart grid is characterized by a two-way flow of electricity and information to create an automated and widely distributed energy delivery network that enables integration, effective cooperation, and information interchange among the many interconnected elements of the electric power grid. In smart grid, real-time monitoring and control of large-scale power grid and its intelligent appliances are of most importance to facilitate self-healing, where sophisticated communications and controls across the grid are required to accomplish the two tasks [12]: Exchange of information obtained from distributed sensing; Dissemination of management and control messages to electric equipment and appliances.

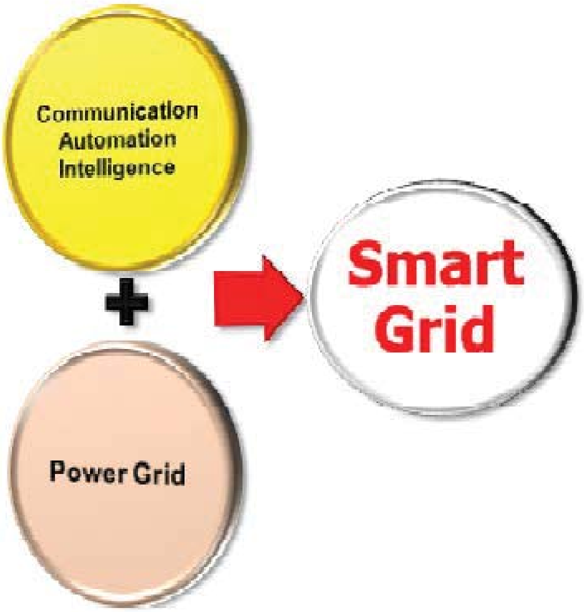


Figure 2.1: Smart Grid.

In different domains of smart grid communications, different communication technologies are preferred to meet the specified requirements. For communication access in smart grid, both wired and wireless communication technologies should be considered. Smart meters/sensors can help to monitor the peak load through customer participations and to control various intelligent appliances and industry electricity consumption [13].

In order to promote the success of smart grid system, the communication techniques need to satisfy strict requirements, i.e., high reliability and low latency. High communication quality and energy efficiency is expected with the consideration of deployment costs and bandwidth constraints. As a result, the communication network for smart grid needs to be customized to meet the challenges posed by smart grid applications. Overall, smart grid will be complex adaptive systems under semi-autonomous distributed controls for improved efficiency, reliability, stability and safety [14]. Reliable and real-time information is the key factor for trustworthy power delivery in smart grid [11]. Performance degradation, such as delay and power outage, will disturb the stability of smart grid system. Hence, an effective mechanism needs to be applied to satisfy the communication requirements of smart grid systems.

2.3 End-user Applications and Benefits

The end-user applications of smart grid are as follows:

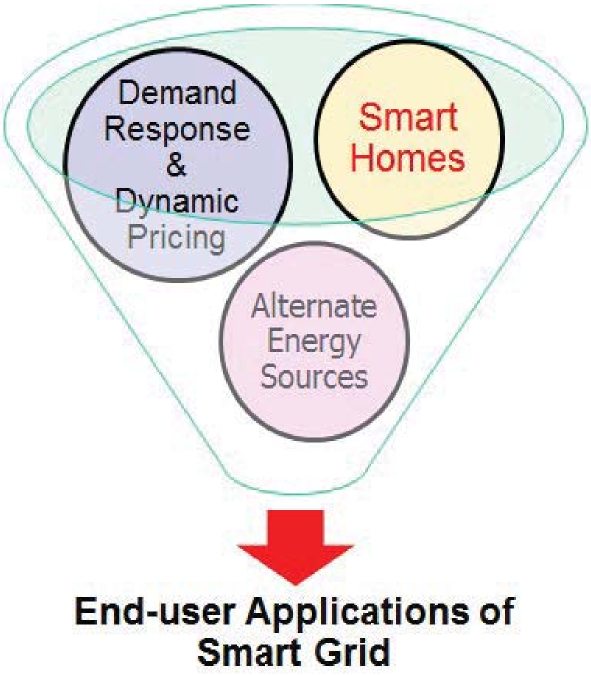


Figure 2.2: End-user applications.

The benefits of smart grid are:

1. Customer satisfaction

2. Improved reliability
3. Production sustainability
4. Energy distribution efficiency
5. Demand management by utilities
6. End-user control over energy use
7. Quicker response to outages
8. Real time pricing for electricity
9. Integration of clean energy

2.4 Smart Grid Technologies

The increasing complexity of the conventional grid due to population growth and advancements in technology and infrastructure contribute immensely to instability, insecurity, inefficiency and environmental energy sustainability. This calls for the use of Information and communication technologies (ICT) to take care of the reliability impact of smart grid resources such as renewable energy, demand response, energy storage and electric transportation [15]. The use of smart grid technologies will have a societal impact in the near future [16], since it will not be only affecting network operators and grid users, but also individual homeowners [17]. With the envisioned transition from a hierarchically controlled grid to a distributed controlled one [18], end users will become increasingly aware of their energy consumption patterns and can accordingly decide to balance their lifestyle and business requirements as an active customer of the grid [19]. Smart grid can be said to be a system of information and communication applications integrated with electric generation, transmission, distribution and consumer technologies which will enable consumers to manage their usage and chose economically between efficient offerings, utilize automation and alternative resources to maintain delivery system reliability and stability.

The basic concept of a smart grid is to include monitoring, analysis, control, and communication capabilities to the conventional grid system to maximize the throughput of the system and reduce the energy consumption. The smart grid provides opportunities for utilities to move electricity around the system as efficiently and economically as possible. It will also offer homeowners and businesses to use electricity as reasonably as possible. It is to achieve reliability, efficiency and optimization in operation, planning, demand response, as well as utilization of diverse resources [20] - [22]. With the above concept of a smart grid, there is a great assurance of power quality and reliability of power system.

A smart grid will:

- ***Be able to heal itself*:** Smart grid expects and instantly responds to system problems in order to mitigate or avoid power outages and power quality.

- ***Motivate consumers to actively participate in operations of the grid*:** Improved system reliability will create benefits for consumers. However, perhaps the most significant benefits arise from more empowerment and individual control over energy use and monthly bills. Smart grid can provide a new set of tools for consumers to manage their usage and total energy bills. Smart grid technology makes it easier and cheaper for consumers to see their electricity use and to have access to value-enhancing dynamic pricing, if they desire it. Finally, by connecting prices and quantity of usage, customers will be transformed from passive to active, engaged participants in electricity markets.

- ***Enable electricity markets to flourish*:** Significant increases in bulk transmission capacity will require construction of new transmission lines before improvements in transmission grid management proposed by smart grids can make a difference. Such improvements are aimed at creating an open marketplace where alternative energy sources from geographically distant locations can easily be sold to customers wherever they are located. Intelligence in distribution grids are not required to enable small producers to generate and sell electricity at the local level using alternative sources such as rooftop-mounted photo voltaic panels, small-scale wind turbines, and micro hydro generators.

- ***Accommodate all generation and storage options*:** It accommodates a wide variety of generation options.

- ***Run more efficiently*:** Increased asset utilization made possible by smarter energy management means more efficient power plant operation and fewer peaking units.

- ***Resist attack*:** Smart grid technologies better identify and respond to natural or man-made disruptions. One of the most important issues of resist attack is the smart monitoring of power grids, which is the basis of control and management of smart grids to avoid or mitigate the system-wide disruptions like blackouts. Real-time information enables grid operators to isolate affected areas and redirect power flows around damaged facilities. New technology of state monitor is needed to achieve the goals of the smart grids.

- ***Enable higher penetration of intermittent power generation sources*:** There will be increase in the amount of renewable energy resources as climate changes and environmental concern. These are for the most part intermittent in nature. Smart Grid technologies will enable power systems to operate with larger amounts of such energy resources since they enable both the consumers and suppliers to compensate for such intermittency.

2.5 Smart Home System

Smart home is an integration of home automation equipment, home securities, home communication and other attractive features based on advanced technologies, such as combined automation, combined networks and communication technologies [23], [10]. Smart home was first officially introduced by American Association of House Builders in 1984 [9]. The free dictionary defines smart house is a highly automation house in which not only audio/video entertainment facilities are networked, but also air conditioner and lighting control are networked as well. Network service can be accessed everywhere in house, such that home appliances at any place may be interconnected with other devices [24]. Aldrich [9] defined a smart home is a place that equipped with computing and information technology, and can accept as well as reply resident's request. The purpose is to provide resident a comfort, convenient, safety, and joyful life through managing various technologies at home and outside world. The Japanese government defines smart home is an information house. Currently, special attention is paid on energy saving and carbon emission reducing. It is expected to control energy usage efficiency through connecting electrical appliances and related devices in house with information network. A common definition of Smart Home is of an electronic networking technology to integrate devices and appliances so that the entire home can be monitored and controlled centrally as a single machine [25].

2.6 Components of Smart Home System

To be considered a Smart Home, the technology used must employ all the following elements: intelligent control, home automation and internal network [26]. The intelligent control is provided by a control system, comprised of two types of elements: sensors, which will monitor, control and report the status of the home environment, and a control agent (human or software based) which acts on the information provided by the sensors. The home automation function is fulfilled by electrical or electronic devices; called actuators that will interact and modify the environment by accomplishing specialized tasks. These tasks often work towards a more complex goal defined by the user of the system. The purpose of the home network is simply to ensure that all the components can receive and send instructions to each other. Figure 4 provide a simple example on how all three elements interact.

1. **Control system** is a critical part of a Smart Home as it determines usability, reliability and overall effectiveness of the solution provided. These systems are written as a piece of software that is run on a home computer or embedded in an electronic device. These software systems offer the ability to control a subset of the home appliances from a centralized location. The basic idea of home automation is to employ sensors and control systems to monitor a dwelling, and accordingly adjust the various mechanisms that provide heat, ventilation, lighting, and other services. By more closely tuning the dwelling's mechanical systems to the dweller's needs, the automated intelligent home can provide a safer, more comfortable, and more economical dwelling. For example, the electronic controller of an automated home can determine when the dwellers have gone to bed and turn off the lights and

lower the thermostat; it can monitor fire alarms; it can anticipate hot water usage and optimize the operation of the water heater.

2. **Sensors** are used to measure the electrical energy. It senses all the consumption generated inside the residents. It also gives broader understanding to the energy utilities so that overall energy usage customs of the habitants can be altered. Finally, the real-time measuring and monitoring of power consumption levels of home appliances through sensors is a key and an integral part of smart home system.

3. **Actuators** are electrical or electronic devices that can control a household appliance. When they come as a separate device, they need to be electrically coupled with the appliance and can control it by executing some simple commands, such as switching it on or off. When they are embedded within the appliance itself, they can be more sophisticated and provide more value added to the user.

4. **Home network technology** can be subdivided into three main areas, depending on the communication media used: Power line and Wireless. Power line systems plug in directly to the house electrical network (electrical mains) and do not require additional cabling. This technology is the oldest of the three and, though simple to configure and cheaper than other solutions, it may lack scalability and considered the least reliable due to its susceptibility to electrical interferences. Wireless systems do not require any wires to operate. This technology can be further subdivided into Radio Frequency (RF), and Infrared (IR). It is the most recent and is increasingly becoming more popular as costs per unit decrease.

5. **Smart home appliances** A smart home energy management system for smart homes must have smart home appliance to meet the challenges of smart grid. Smart home appliances ($SHAs$) have following feature: compact OS installed, able to send and receive data, able to enter data into the computer, have processing ability, can be controlled remotely and have different power consumption modes to operate.

2.7 Summary

Smart grid is a term referring to the next generation power grid in which the electricity distribution and management is upgraded by incorporating advanced two-way communications and pervasive computing capabilities for improved control, efficiency, reliability and safety. A smart grid delivers electricity between suppliers and consumers using two-way digital technologies. It controls intelligent appliances at consumer's home or building to save energy, reduce cost and increase reliability, efficiency and transparency. A smart grid is expected to be a modernization of the legacy electricity network.

It provides monitoring, protecting and optimizing automatically to operation of the interconnected elements. It covers from traditional central generator and/or emerging renewal distributed generator through transmission network and distribution system to industrial consumer and/or home users with their smart appliances. A smart grid is characterized by the bidirectional connection of electricity and information flows to create an automated, widely distributed delivery network. It incorporates the legacy electricity grid the benefits of modern communications to deliver real-time information and enable the near-instantaneous balance of supply and demand management.

Chapter 3

Architecture and Design of Smart Home System

3.1 Introduction

Smart home system also called smart homes constitute a branch of ubiquitous computing that involves incorporating smartness into dwellings for comfort, health care, safety, security, and energy conservation[23]. Remote monitoring systems are common components of smart homes, which use telecommunication and web technologies to provide remote home control[10]. A smart homes is a home assembled with home automation system. In smart homes, the occupant can remotely control or program the automated home electronic devices by entering a signal command. Smart homes offer a better quality of life by introducing an occupant on vacation can use a touch tone phone to provide a home security system, control temperature measures, switch appliances on or off, control lighting, program a home theater or entertainment system and perform many other tasks [27]. A home automation system integrates electrical devices in a home with each other. Devices may be connected through a computer network to allow control by a personal computer, and may allow remote access from the Internet. Through the integration of information technologies with the home environment, systems and appliances are able to communicate in an integrated manner which results in convenience, energy efficiency and safety benefits[1].

Automation in a smart environment can be viewed as a cycle of perceiving the state of the environment, reasoning about the state together with task goals and outcomes of possible actions, and acting upon the environment to change the state. Sensors monitor the environment and make information available through the communication network. The database stores this information while other information components process the raw information into more useful knowledge (e.g., action models, and patterns). New information is presented to the decision-making algorithm upon request or by prior arrangement. The decision action is communicated which record the action and communicate it to the physical components or actuators or device controllers, thus changing the state of the world and triggering a new perception [28].

Home automation may include centralized control of lighting, HVAC, appliances, security locks of gates and doors and other systems, to provide improved convenience, comfort, energy efficiency and security. Home automation for the elderly and disabled can provide increased quality of life for persons who might otherwise require caregivers or institutional care [29]. Home automation has become popular in recent years due to the accessibility through the portable devices such as smart phone and tablet connectivity. The concept of the "Internet of Things"is closely attached with the popularization of home automation. Other automated tasks may include setting the power consumption control to a blackout prevention setting and restoring the normal setting when the peak power consumption scenario begin.

Nowadays, home automation systems are varied as an Internet-controlled by allowing the user to control appliances and consumer electronics remotely.

3.2 Motivation

Over the past several decades, electric power systems have encountered more frequent stress conditions due to ever-increasing electricity demand [30]. Transmission line outages have been a common cause of system stress conditions, which are likely to occur during critical peak hours. Such events will cause a supply-limit situation where cascading failures and large-area blackouts are possible. These situations have been envisioned to deal with such unexpected supply limit events by selectively curtailing system loads, whereby regaining balance between electricity supply and demand [31].

As more and more home appliances and consumer electronics are deployed, power consumption in home area tends to grow rapidly. Although advanced integrated circuit (IC) and hardware technology enhances the power efficiency of home appliances and consumer electronics, the current energy crisis and greenhouse effect require more efficient energy management in all areas. The need for electricity has been growing rapidly in recent years as a result of addition of home appliance at home to make life comfortable for the user. These advances are becoming the cause of energy shortage. As the consumed energy increased the available energy limit for energy management system decreased, which makes the whole system susceptible to outage [3]. An energy management system is facing energy consumed peak hours in which whole power system should be stable all the times. For this purpose, it is necessary to monitor all the appliances through sensors in real time to ensure that energy management system for home is working properly. The main motivation of this research is the stability issue for smart home system. The stability issue has not been studied yet by the community of home networks. The proposed modeling approach will help in future to prove stability of energy management systems for homes during peak hours of energy consumption which would be the milestone in the history for home networks with increase in home appliances to keep the user comfort at the first priority.

To reduce maximum consuming power, it is essential to know how power is consumed. Consequently, power consumption monitoring is needed. The real time checking of instantaneous consuming power of appliances can be positively achieved by sensors [4]. Secondly, it is compulsory to manage and control the all appliances to apply power reduction schemes. To deal with these issues, a simple and effective smart energy management system for smart homes is proposed.

3.3 Preliminaries

3.3.1 Home Energy Management System (HEMS)

A HEMS is responsible for monitoring and managing the operation of in-home appliances, and providing load shifting and shedding according to a specified set of requirements[32]. Different algorithms and models [33]-[36] can be used, depending on load (An end user device or customer that receives power from the electric system) types and requirements.

Various HEMS hardware applications are proposed in [37], [38]. Several papers in the literature focus on controlling low power consumption appliances, such as refrigerators, coffee makers, lighting, and other plug loads. These appliances are not suitable for peak power analysis as they have no significant impact on the overall household power consumption. Issues of optimal appliance scheduling to minimize household energy consumption are also the topic of previous work [35], [36]. For controlling and managing the home appliances, a number of HEMS were suggested and established [39]. The previous HEMS monitors and controls the home devices, and show home energy consumption information. HEMS in [40], is clarified with its complete goals that must be satisfied by HEMS and also offer strategies for the system growth to reduce power consumption at home. In general, priority of the appliances is also an important study in HEMS [41].

It is responsible for collecting data from appliances using sensors, then optimizing power supply by using the information from sensors [42]. A conventional power management system focused only on power consumption monitoring and standby power reduction strategies [43]. With the increasing power demand by appliances for intelligent and personalized services, smart energy management system is required in smart homes to support smart devices. Furthermore, smart home exploits various sensors (e.g. smart meters or smart electric sensors) to improve overall energy efficiency and resident's satisfaction. In the overall scenario, the sensor measures the real time instantaneous consuming power levels of appliances.

3.3.2 Applications of HEMS

In general, HEMS has three main applications named power consumption, generation and storage. A brief description of these mentioned applications are given below.

- ***Power Consumption*:** A HEMS is a system that includes all the necessary elements to achieve reduction of electricity consumption in home environments. One of its main elements is the ability to communicate and manage the power consumption of home appliances and offers to users the specific tools to reduce their power consumption. The power consumption profile of residential area represents an important challenge and sets the foundations for enabling the intelligent controller. In order to empower residential consumers and give them the necessary means for change they must become better informed about their electricity use. Power consumption is invisible to most consumers. There is little knowledge about how their electricity is being consumed or how this consumption affects their lives [44]. Academics like [45] feel that supplying consumers with electricity consumption feedback is one way that can be addressed. This feedback can be provided in a variety of ways, but one way that is becoming increasingly popular is the use of in-home displays. Advancements in home displays can provide consumers with real time updates on the amount of electricity consumed. Power consumption management by HEMS helps in educating electricity consumers through the provision of their electricity consumption feedback. This also enables consumers through the system automated control of the household thermostat, pool pump, lighting, and select household appliances and consumer electronics.

HEMS today is highly affected by variations in the use of energy during a day. The energy use during the night is very low, but the use of energy increase significantly during a couple of hours in the afternoon and evening (called peak hours) when people come home from work. This is because people turn ON the lights, TV, computers, start cooking etc., which all consume energy. Adding intelligence to the existing HEMS will make it possible to monitor the energy use and thereby know how and when the energy will be used. By having a two way communication inside home domain between all parts of HEMS it will be possible to control the power consumption more efficiently.

- ***Power Generation*:** Power generation that feeds into the distribution grid, rather than the bulk transmission grid, whether on the utility side of the meter, or on the customer side. This is not a new phenomenon. Prior to the advent of alternating current and large-scale steam turbines during the initial phase of the electric power industry in the early 20th century, all energy requirements, including heating, cooling, lighting, and motive power, were supplied at or near their point of use. At the same time the system of central generation was evolving, some customers found it economically advantageous to install and operate their own electric power and thermal energy systems.

  Over the years, the technologies for both central generation and distributed improved by becoming more efficient and less costly. Today, advances in new materials and designs for photo-voltaic panels, micro-turbines, reciprocating engines, thermally activated devices, fuel cells, digital controls, and remote monitoring equipment, among other components and technologies, have expanded the range of opportunities and applications for modern generators. These generators have made it possible to tailor energy systems that meet the specific needs of consumers. These technical advances, combined with changing consumer needs, and the restructuring of wholesale and retail markets for electric power, have opened even more opportunities for consumers to use power generators to meet their own energy needs, as well as for electric utilities to explore possibilities to meet electric system needs with distributed generation.

In order to solve global environmental problems, renewable energies such as solar and wind will be widely used. This means that the future energy supply will be influenced by fluctuating renewable energy sources. Electricity production will follow the weather conditions. Photo-voltaic is the process of converting solar energy to direct current. The most common application of this technique is solar cells grouped into larger solar panels. Micro-combined heat and power units are home sized versions of the larger combined heat and power units used in power plants. They are typically generating heat as their main product and electricity is generated as a by-product.

For reasons of reliability, distributed generation resources would be interconnected to the same transmission grid as central stations. Various technical and economic issues occur in the integration of these resources into a grid. Technical problems arise in the areas of power quality, voltage stability, harmonics, reliability, protection, and control. Behavior of protective devices on the grid must be examined for all combinations of distributed and central station generation which is still not solved. A large scale deployment of distributed generation may affect grid-wide functions such as frequency control and allocation of reserves. As a result smart grid functions, virtual power plants and grid energy storage are needed to the grid.

The coexistence of multiple energy sources which have versatile dynamic properties and electrical characteristics have impact on safety, efficiency, control and stability of

HEMS. Technical issues associated with HEMS are interconnection and the islanding mode. Interconnection of micro grid with main grid is complex; complexity in interconnection is effected by the types of power generation, number of generating sources, location of points of interconnection and level of penetration of micro grid system with main grid.

- ***Power Storage*:** Power storage system is expected to play an important role in the future smart grid. Some relevant applications are given below.

  First, storage system installed in customer side substations can control power flow and mitigate congestion, or maintain voltage flow in the appropriate range.

  Secondly, storage systems can support the electrification of existing equipment to integrate it into the smart grid. Electric vehicles (EVs) are a good example since they have been deployed in several regions, and some argue for the potential of EVs as a mobile, distributed energy resource to provide a load-shifting function in a smart grid. EVs are expected to be not only a new load for electricity but also a possible storage medium that could supply power when the electricity price is high.

  A third role expected for power storage is as the energy storage medium for HEMS in homes and buildings. With a HEMS, residential customers will become actively involved in modifying their energy spending patterns by monitoring their actual consumption in real time. HEMS in general will need storage system, for example to store electricity from local generation when it is not needed and discharge it when necessary, thus allowing the HEMS to function optimally with less power needed from the grid.

  A basic service that must be provided by power utilities is to keep supply power voltage and frequency within tolerance, which they can do by adjusting supply to changing demand. Frequency is controlled by adjusting the output of power generators; storage systems can provide frequency control functions. Voltage is generally controlled by taps of transformers, and reactive power with phase modifiers. Storage systems located at the end of a heavily loaded line may improve voltage drops by discharging electricity and reduce voltage rises by charging electricity.

  Consumers may possess appliances needing continuity of supply, such as fire sprinklers and security equipment. Storage system is sometimes installed as a substitute for emergency generators to operate during an outage. Semiconductor and liquid-crystal manufacturers are greatly affected by even a momentary outage (e.g. due to lightning) in maintaining the quality of their products. In these cases, storage system technology such as batteries and capacitors can be installed to avoid the effects of a momentary outage by instantly switching the load off the network to the storage system supply. A portable battery may also serve in an emergency to provide power to electrical appliances.

3.3.3 HEMS Objectives and Requirements

As stated in [4], HEMS consists of a group of objectives and requirements. The main objective of HEMS is to reduce the energy consumption. In particular, the HEMS has following objectives:

1. ***Easy to deploy:*** It has to be taken into consideration that HEMS should be easy to deploy into houses because deploying new cables or infrastructure is not the best solution. This requires using already installed communication systems, such as wireless communication or power line communication which will minimize the costs and gain user acceptance.

2. ***Interoperability:*** In order to monitor and manage appliances efficiently a home network has to be introduced where devices can exchange information and commands without interoperability conflicts.

3. ***Data security:*** Security has to be incorporated into HEMS in terms of data encryption and authentication to protect the system against external threats. However, security issues will not be analyzed as they are out of scope of this research.

4. ***Auto-configuration:*** HEMS is going to be used by users that may not have enough knowledge to perform difficult network configuration tasks. Taking into consideration that users may add or change their home appliances, HEMS should provide easy to use configuration tools or in the best case the network should be auto-configurable.

5. ***Display energy consumption:*** One of the HEMS goals is to monitor energy consumption. This information should be available to users through the user interface.

6. ***User friendly interface:*** The user interface should provide information about the current consumption and also previous consumptions, providing daily, monthly and even annual reports. Additionally, it can offer the possibility to compare the electricity consumption between months or even compare it to other sources, such as average consumption. This option could be a new service provided by the smart grid through the smart meter. This interface should also provide management options, where the users can modify their preferences and control their appliances. User preferences are related to the strategy used to reduce energy consumption and can vary from system to system.

7. ***Intelligent and context-aware:*** HEMS should have intelligence to facilitate efficient energy management. This can be achieved by creating a context-aware system. A context-aware system is capable of collecting information from the environment, or context, and react accordingly.

8. ***Communication with smart meter:*** Enabling this communication will provide the user with real-time price and billing status, energy consumption information, as well as possible services that may arise.

9. ***Smart planning:*** Automatic peak load management provides smart planning for reducing energy consumption.

3.3.4 Smart Meter (SM)

SM is a subject that attracts much more attention. Smart metering is obtaining many benefits in a lot of aspects. Many benefits are available, especially on improving the energy efficiency. The smart metering is the combination of power system, telecommunication and several technologies. SM has countless benefits like it can enhance reliability, remotely read interval meeting, with the meter capable of daily reads, quality of supply and outage detection to improve consumer supply services, ability to control connection and disconnection remotely and apply supply capacity limits to manage emergency situations and quicker restoration. It can give customers more control over their everyday energy usage, opportunity for lower bills and can improves customer service and allows for a more proactive workforce [46]. A SM system employs several control devices, various sensors to identify parameters and devices to transfer the data and command signals. In future electricity distribution grids, smart meter would play an important role in monitoring the performance and the energy usage characteristics of the load. Collection of energy consumption data from all consumers on a regular basis allows managing electricity demand more efficiently and also to advise the consumers about the cost efficient ways to use their appliances. In light of this, smart meters can be used to control light, heat, air conditioning and other appliances [47]. SM can be programmed to maintain a schedule for operation of the home appliances and control operation of their devices accordingly. In addition, integration of smart meters helps utility companies in detecting unauthorized consumption and electricity theft in view of improving the distribution efficiency and power quality.

3.3.5 Focused Area of Smart Home System

Smart home technologies are viewed as end users of smart grid. A home is incorporating a communications network that connects the key electrical appliances and services, and allows them to be remotely (both within and outside the home) controlled, monitored or accessed. Smart home system is a home or residence, which responds to the needs of customers to provide comfort, convenience, security and entertainment. Applications of smart home system are: environment monitoring system, health care system, entertainment system, security and safety system and stability and power control of smart home system.

The focused area of this particular research is stability and power control aspects of smart home system.

3.4 Proposed Architecture of Smart Home Energy Management System (SHemS)

SHemS is responsible for collecting data from appliances using sensors, and then distributing power supply by using the information obtained from sensors. Embedding intelligence in the form of stability in power management for SHemS to meet the problems of improved reliability, fast system response, and user satisfaction to cope with the system dynamics is a challenging task. In this section, the focus of study is system design and analysis of SHemS for blackout prevention and implementation of stability test.

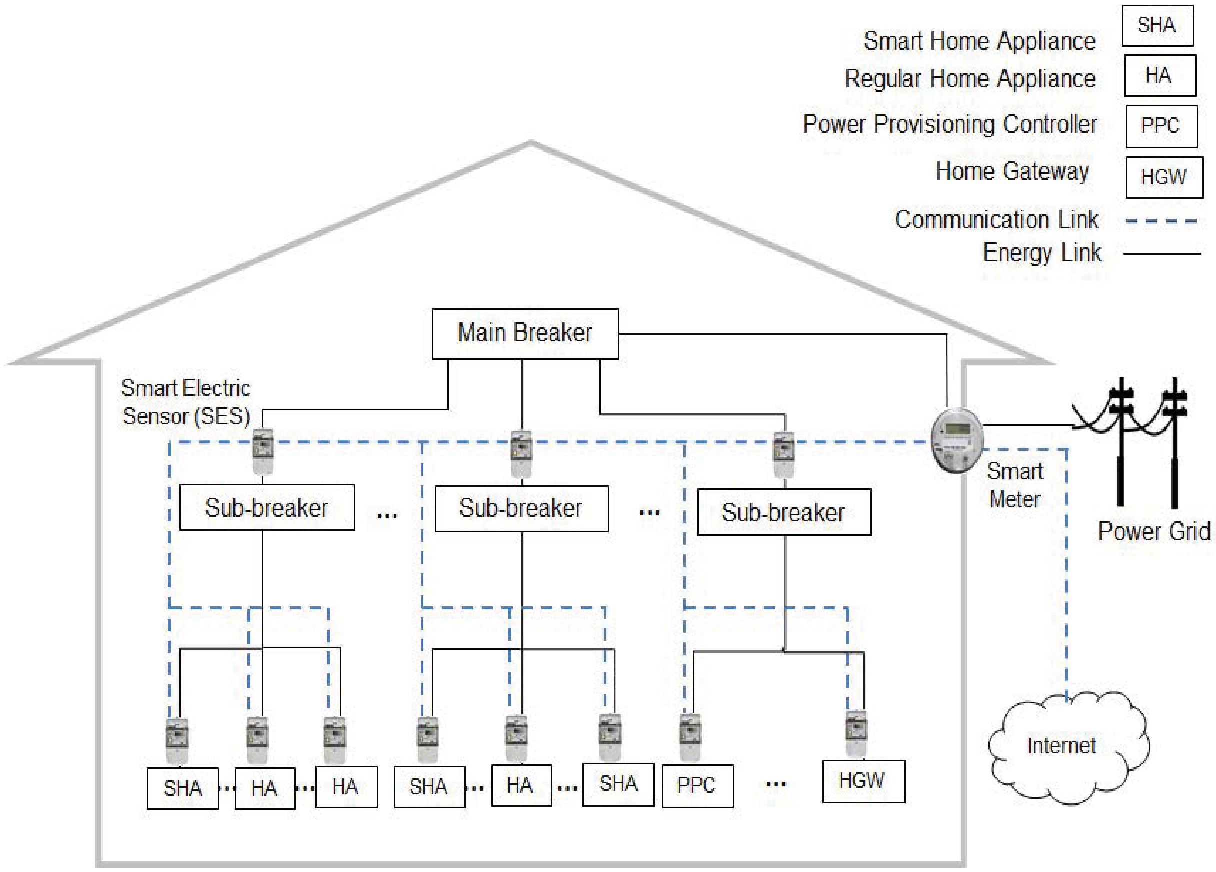


Figure 3.1: Proposed system architecture for SHemS.

3.4.1 Components of SHemS

The proposed SHemS consists of basic components, like smart electric sensors (SESs), power provisioning controller (PPC), communication infrastructure, and smart home appliances (SHAs) as depicted in Figure 3.1.

1. **Main breaker:** a circuit breaker that has feeder connects to the sub-breaker.
2. **Sub-breaker:** a branch circuit breaker that connects to the outlets, lighting, and other loads.
3. **SES:** a sensor that is used to measure real-time information of power consumption level.
4. **PPC:** a processing unit that is used to monitor and control the power consumption level.
5. **HGW:** a home gateway system communicates with PPC, SES and appliances over a local communication network.
6. **HA:** is a regular home appliance that cannot control its power consumption, only ON/OFF mode.
7. **SHA:** is a home appliance that can control its power consumption according to the suggested power from PPC.

In over all scenario, the use of SES will help in measuring the real-time power consumption levels of SHAs and send this information to PPC then based on this information PPC will provide the remaining power information to the appliances, but with a communication delay.

3.5 Proposed System Model

The efficiency, reliability and stability of the smart energy management system are expected to be significantly improved with the help of SES. It introduced a paradigm shift in the analysis of power system. Large scale usage of sensors with home appliances leads to a great rise of communication over wired and wireless links, which also requires an intelligent controller, which referred to as PPC.

In this chapter, the simulation results help in better understanding of how proposed system work and what is the relationship between system parameters with each other. For proposed system design and analysis, the focused area is management of power consumption of HEMS for stability, fast system response to get saturation and user satisfaction.

Stability is one of the most important issues in a system design. In proposed system, there are two key parameters (i) communication delay (ii) divisor of available power and these parameters effect the critical system behaviors such as stability and overshoot of energy waveform. User satisfaction would be represented by SHA priority given by the user. Priority will be used in PPC to manage power consumption and user satisfaction.

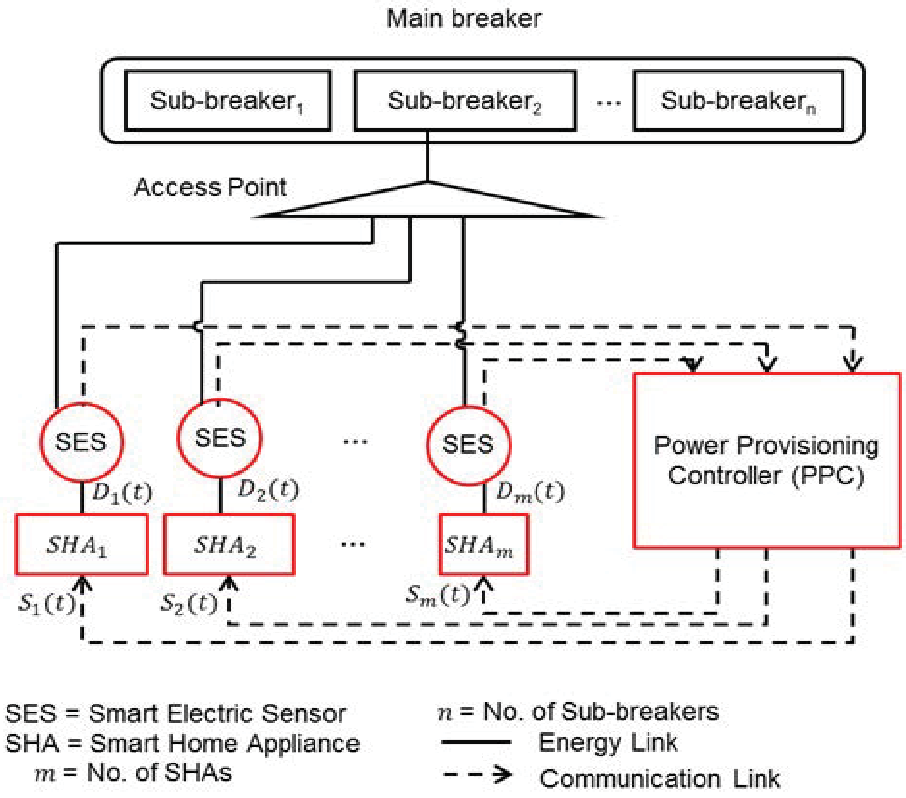


Figure 3.2: Proposed system model for SHemS.

In proposed system model given in Figure 3.2, main breaker of the home is the breaker that the feeder wire associates to. Main breaker is designed to trip if the amperage rating exceeds the value labeled on the breaker. Main breaker is further divided into sub-breakers. Sub-breakers are used to extend feed for multiple branch circuits in whole residential area. From here, the sub-breaker connects to outlets, lighting and other loads via individual circuit breakers. The proposed system model for SHemS consists of m SHAs $m = \{SHA_1, SHA_2, ..., SHA_m\}$, SESs and a PPC.

3.5.1 Smart Electric Sensor (SES)

A SES is used to connect individual SHA to the SHemS. For proposed model of SHemS, SES is responsible for collecting and measuring ON/OFF status and the information about instantaneous consuming power levels of SHA called $D_i(t)$ from all SHAs and sends this information to PPC.

3.5.2 Power Provisioning Controller (PPC)

The functions of PPC are to compute remaining power for SHAs, calculate the suggested power level ,($S_i(t)$), for SHAs and finally send $S_i(t)$ to corresponding SHA.

3.5.3 Smart Home Appliance (SHA)

This research assume that the home appliance is a smart home appliance (SHA) with communication unit and processing unit. SHA has the ability to change its power consumption level upon receiving the "suggested power level ($S_i(t)$) "from the PPC, which performs intelligent computing upon receiving the information ($D_i(t)$) from the SESs.

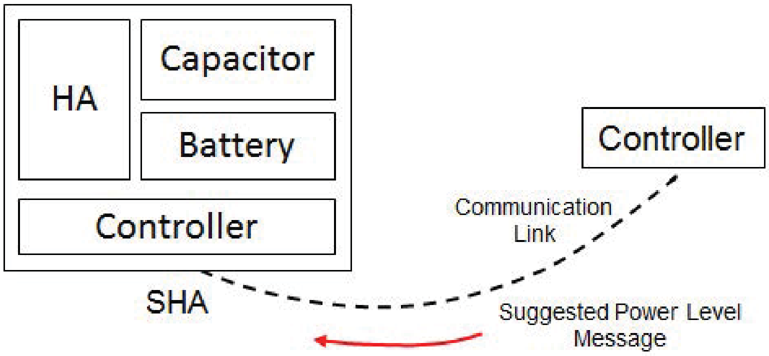


Figure 3.3: Message handshaking in between a SHA and a controller in the SHemS.

Upon receiving a message from a controller, SHA can control its power consumption based on the suggested power level from the controller.

The proposed SHemS assume to have SHA, a SHA has following features:

1. Can change its power consumption according to control signal from controller
2. Compact OS installed

3. Able to send and receive data

4. Can be controlled remotely

5. Different power consumption modes to operate

3.5.4 Interaction of appliances with SES

SES is used to measure the instantaneous consuming power level of appliances (SHA and HA). Upon receiving a message from SES, PPC computes a next suggested power level based on the knowledge of instantaneous consuming power level of the SHA. in case of regular appliance (HA), PPC sends ON/OFF information to corresponding HA.

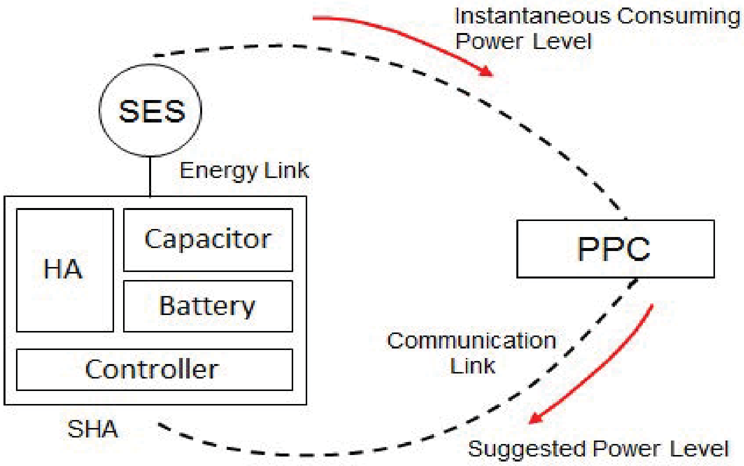


Figure 3.4: Interaction of SHA with SES.

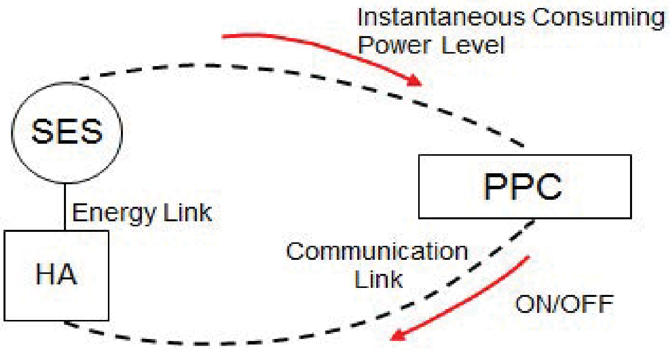


Figure 3.5: Interaction of HA with SES.

3.5.5 Communication Media and Message Exchange Procedure

The proposed system works with message exchanges between SHAs, SES and PPC. The message exchange procedure consists of two phases which are given below:

1. ***Synchronization Phase:*** In this phase, SYNC message is sent from PPC to SESs with the purpose of time synchronization for all SESs.

2. ***Communication Phase:*** Communication phase consists of exchange of two messages named as:

   ICPM: A message that is sent from SES to PPC and contains information of instantaneous consuming power level $D_i(t)$ of ith SHA.

   SPM: A message that is sent from PPC to SHA and contains information of suggested power level $S_i(t)$ of ith SHA.

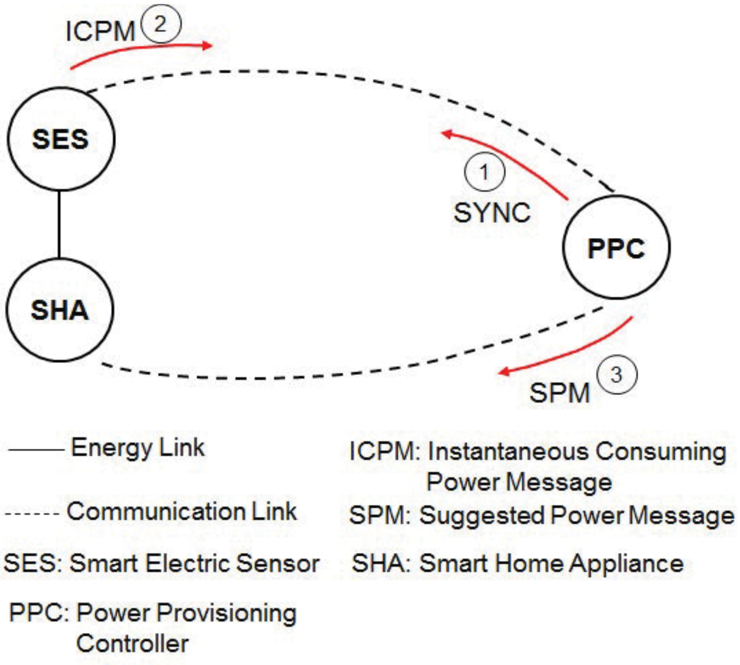


Figure 3.6: Message exchange procedure.

3.5.6 Message Operation Timeline

The message operation timeline of proposed system named communication interval (T_c), can be defined as sequential communication between SHAs, SESs and PPC. A communication interval starting from T_{n-1} and ending at T_n as depicted in Figure 3.7. The interval starts by the PPC by sending a synchronization message (SYNC) to SESs.

1. $t_{SYNC} + \tau_{SYNC}$: transmission time and propagation delay of SYNC message.
2. $t_{ICPM} + \tau_{ICPM}$: transmission time and propagation delay of ICPM.
3. $t_{proc-PPC}$: the time required for processing at PPC.
4. $t_{SPM} + \tau_{SPM}$: transmission time and propagation delay of SPM.

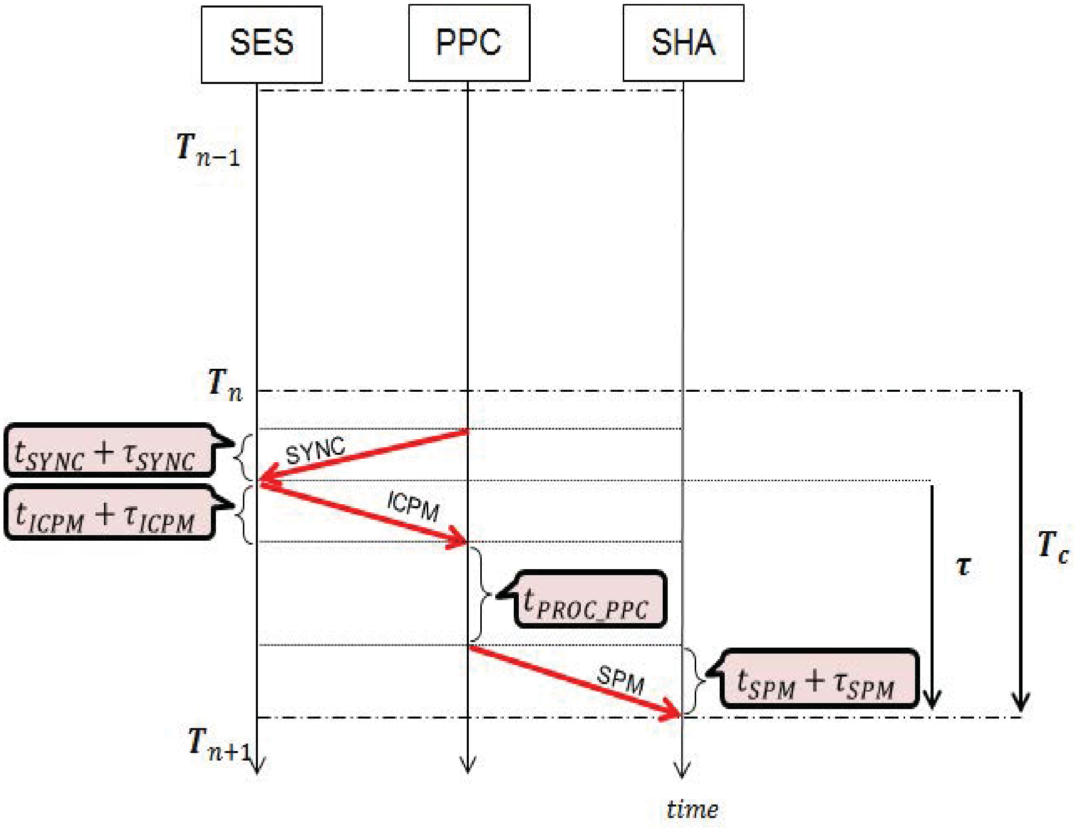


Figure 3.7: Message operation timeline.

$$T_c \geq t_{SYNC} + \tau_{SYNC} + t_{ICPM} + \tau_{ICPM} + t_{proc-PPC} + t_{SPM} + \tau_{SPM} \tag{3.1}$$

The proposed SHemS also consider the communication delay which is the total time of sending ICPM, SPM with both transmission and propagation delay and processing time at PPC as given below:

$$\tau = t_{ICPM} + \tau_{ICPM} + t_{proc-PPC} + t_{SPM} + \tau_{SPM} \tag{3.2}$$

3.5.7 Power Consumption Derivation of SHA

In proposed system model of SHemS, SES is responsible for collecting information about instantaneous consuming power level, $D_i(t)$, from SHA and sends this information to PPC.

$$D(t) = \sum_{i=1}^{m} D_i(t) \tag{3.3}$$

Then the functions of PPC are to compute remaining power $R(t)$ available for SHAs, divide the remaining power by l, and send this information i.e., $S_i(t)$ to SHAs. Where, l is the designer's parameter also called divisor of available power. The transfer of information of instantaneous consuming power level of m SHAs from SES to PPC and then available remaining power level from PPC to SHA happen with some communication delay τ. In proposed modeling, the total power available for all SHAs is denoted as P, thus remaining power R can be represented as:

$$R(t) = P - D(t) = P - \sum_{i=1}^{m} D_i(t) \tag{3.4}$$

$$R(t) = P - \sum_{i=1}^{m} D_i(t) \tag{3.5}$$

Where $D_i(t)$ is the instantaneous consuming power level of ith SHA at time t. On the other hand, assume that each SHA has its own maximum consuming power level D_i^{max} , and it behaves based on the first order state equation given by:

$$\dot{D}_i(t) = -a_i \cdot D_i(t) + b_i \cdot u \tag{3.6}$$

where,

$$b_i \cdot u = \begin{cases} a_i \cdot D_i^{max}, & \text{if } S_i(t) + D_i(t) \geq D_i^{max} \\ a_i \cdot (S_i(t) + D_i(t)), & \text{if } S_i(t) + D_i(t) < D_i^{max} \end{cases} \tag{3.7}$$

with

$$S_i(t) = \frac{R(t-\tau)}{l} \tag{3.8}$$

Note that, in above first order state equation model, $\frac{b_i \cdot u}{a_i}$ is the final steady state value of the ith SHA, and $\frac{1}{a_i}$ is the time constant, i.e., the time required for the power to reach 63% of the final steady state value (see Figure 3.8).

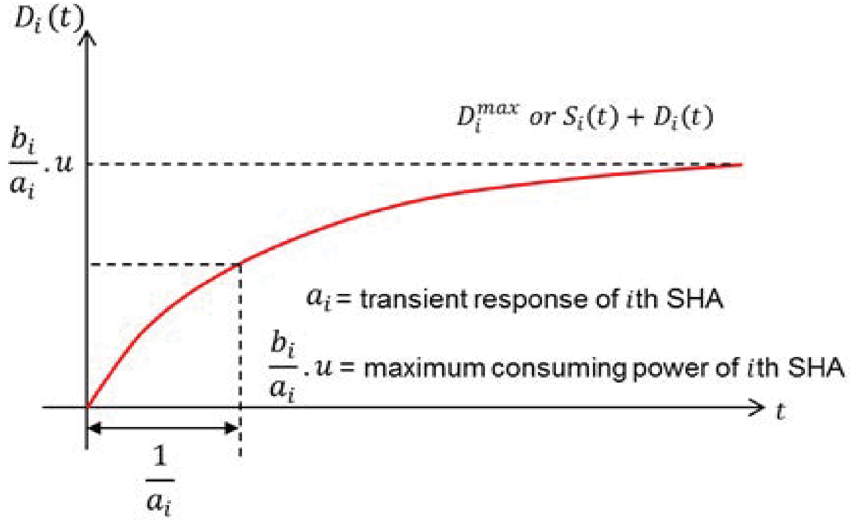


Figure 3.8: Simplified first-order power consumption derivation of SHA.

In proposed model, $S_i(t) + D_i(t)$ is considered as an available power assigned to each SHA, where $S_i(t)$ is the delayed version of the remaining power divided by a designer's parameter l. If this available power is larger than D_i^{max}, the SHA manages its own power towards its maximum consuming power level. On the other hand, if the available power for SHA is less than D_i^{max}, then the SHA reduces its performance to $S_i(t) + D_i(t)$.

3.6 Simulation Scenario and Objectives

Each SHA has the parameter a_i and D_i^{max}, which decides the response speed and maximum consuming power level of a SHA, respectively. The remaining power R is divided by a designer's parameter l, and the information on the remaining power is fed back to each SHA with a communication delay τ.

For simulation scenario setting of proposed system, three SHAs are considered. These SHAs are attached with one SES. The maximum consuming power levels of three SHAs are $D_1^{max} = 1kW$, $D_2^{max} = 0.7kW$, and $D_3^{max} = 0.5kW$. The total available power for SHAs is assumed to be $2kW$.

The main simulation objectives are to maintain the maximum power limit of all SHAs and to observe the effects of system parameters to the total power available respectively. The detailed objectives are to analyze the power distribution among SHAs with same turn ON time, power distribution among SHAs with different turn ON time, effects of system parameters on stability and finally the border estimation for stability.

3.7 Effects of System Parameters on Stability

Stability is one of the most important issues in a system design. At first, the case when all three SHAs are turned ON at the same time has been considered with the same SHA parameter $a_i = 10 (i = 1, 2, 3)$.

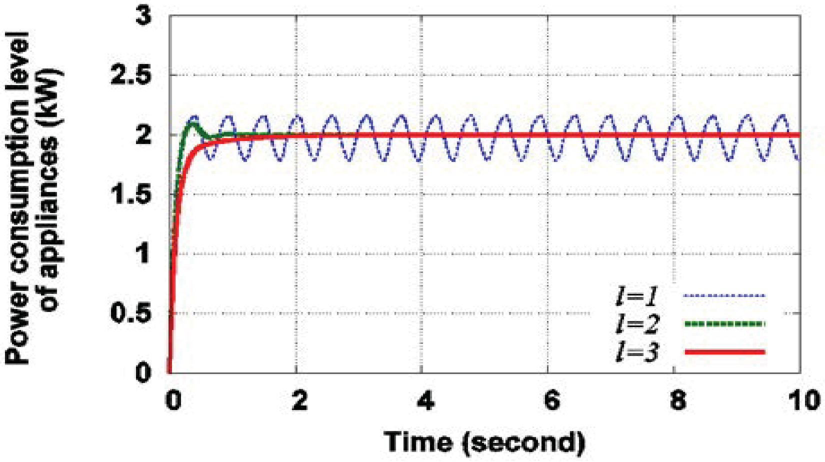


Figure 3.9: Total power characteristics for $l = 1$ (unstable), $l = 2$ (overshoot), and $l = 3$ (stable) with $\tau = 0.2$.

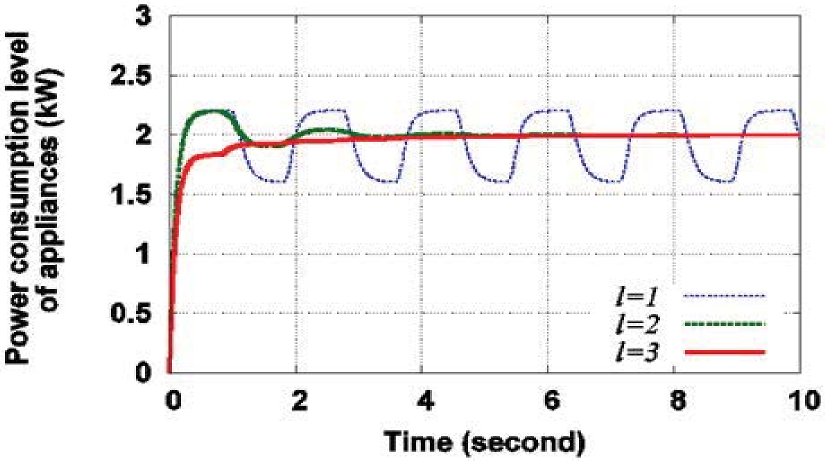


Figure 3.10: Total power characteristics for $l = 1$ (unstable), $l = 2$ (overshoot), and $l = 3$ (stable) with $\tau = 0.8$.

From Figure 3.9 and 3.10, the total power characteristics of the proposed system showed three convergence behaviors; stable, unstable, and overshoot.

The proposed system in simulation environment shows that as the value of system parameter l increases system becomes more stable.

3.8 Border Estimation for Stability

The border estimation of l to get stable/unstable and overshoot/non-overshoot regions also considered and the results are given in Table 3.1.

Table 3.1: Border estimation for stable/unstable, overshoot/non-overshoot region.

τ	a_i	*Stable/Unstable*	*Overshoot/Non-overshoot*
0.2	3	$l = 0.72$	$l = 1.22$
0.2	10	$l = 1.24$	$l = 1.90$
0.2	30	$l = 1.49$	$l = 2.30$
0.4	3	$l = 1.12$	$l = 2.00$
0.4	10	$l = 1.45$	$l = 2.20$
0.4	30	$l = 1.56$	$l = 2.35$
0.8	3	$l = 1.48$	$l = 2.23$
0.8	10	$l = 1.60$	$l = 2.29$
0.8	30	$l = 1.72$	$l = 2.31$

The table 3.1 gives, the border values of stable and overshoot are l=0.72 and l=1.22, respectively for which the system get stable within 10 seconds. For the first case with $\tau = 0.2$, when a larger value than 1.22 is used the system is stable and has no overshoot. If l is in between 0.72 and 1.22, the system is stable but has overshoot in total power consumption characteristics, and the system becomes unstable when l is smaller than 0.72. Table 3.1 can also presented with border explanation as depicted in Figure 3.11, for clear understanding.

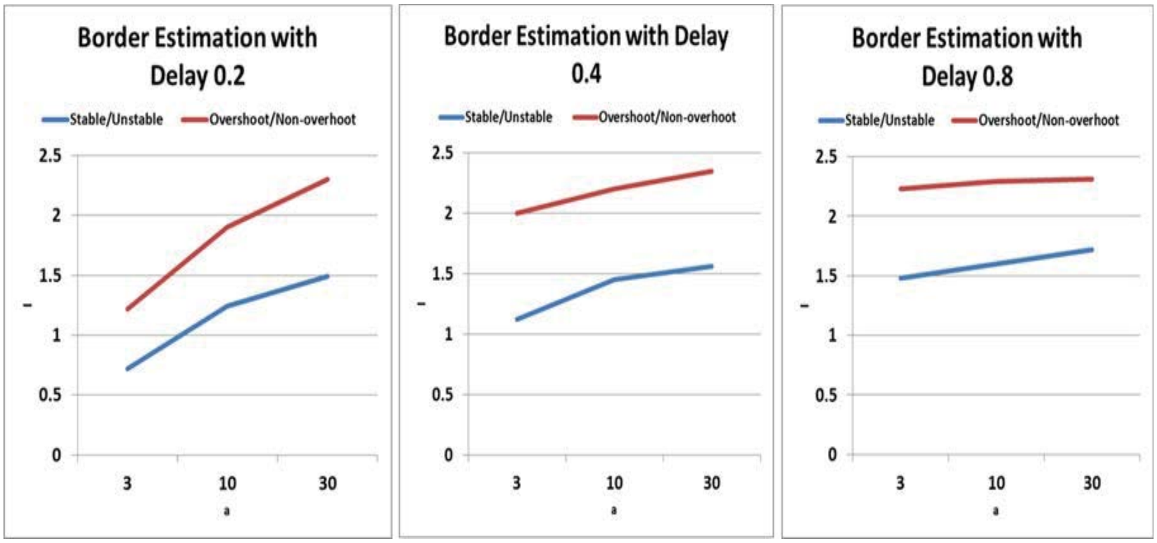


Figure 3.11: Border estimation for stable/unstable, overshoot/non-overshoot.

The border in l for stable/unstable and overshoot/non-overshoot increases as a_i increases and as τ increases. So the parameter l need to decide carefully by estimating the maximum communication delay τ and the maximum speed of SHAs.

3.9 Power Distribution Criteria

In this section, total available power distribution has been analyzed. At first, power distribution is analyzed with same Turn ON time of SHAs. Second, SHAs are analyzed with different Turn ON time.

3.9.1 Power Distribution with Same Turn ON Time

As the second simulation results, now the proposed system will test for the criteria that how the remaining power is distributed among SHAs. In these simulations, $D_1^{max} = D_2^{max} = D_3^{max} = 1kW$ for all SHAs and the total available power for all SHAs is $2kW$. The effect of SHA parameter a_i to the final available power sharing among SHAs is observed at first with both same value and different value assignment for SHA response speed. The behavior of the system with these criteria are given in Figures 3.12 and 3.13.

As in Figure 3.12, all three SHAs have same value for a_i and D_i^{max}. The proposed system showed that all three SHAs shared the remaining power equally. However, in

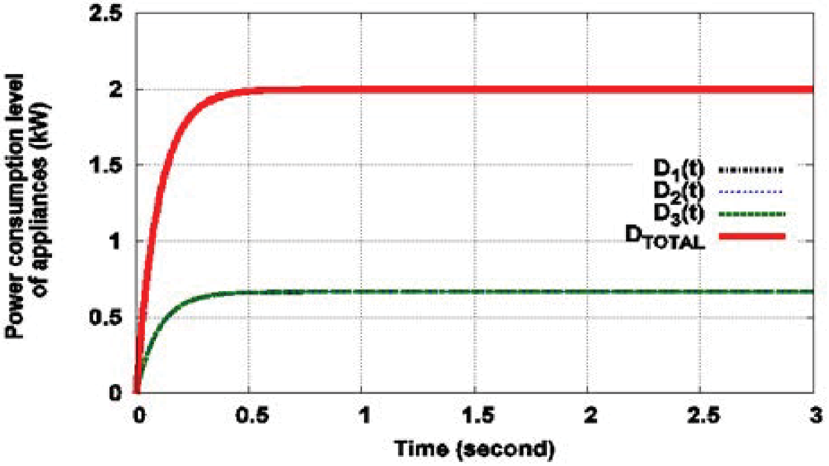


Figure 3.12: Power consumption behavior of SHAs for $a_i = 10$ (same turn ON time).

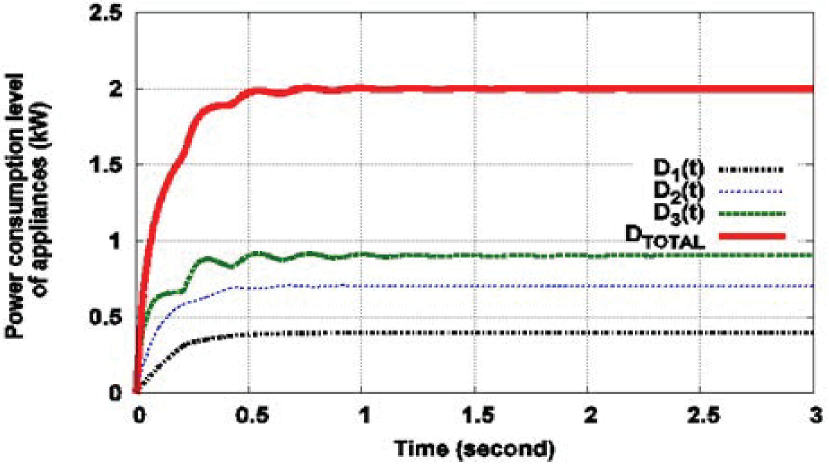


Figure 3.13: Power consumption behavior of SHAs for $a_1 = 3$, $a_2 = 10$, and $a_3 = 30$ (same turn ON time).

Figure 3.13, the situation when the value of time constant a_i is different and D_i^{max} is analyzed. In this scenario, the conclusion can be stated that the SHA with small time constant takes more power from the available power level.

3.9.2 Power Distribution with Different Turn ON Time

Now, the effects of turn ON timing to the final available power sharing has been tested with same SHA response spees $a_i = 10$.

In Figure 3.14, 3.15 and 3.16, all three SHAs have same $D_i^{max} = 1.0kW$ and $a_i = 10$. The conclusion in this situation can be derived that SHA which turned ON first can use

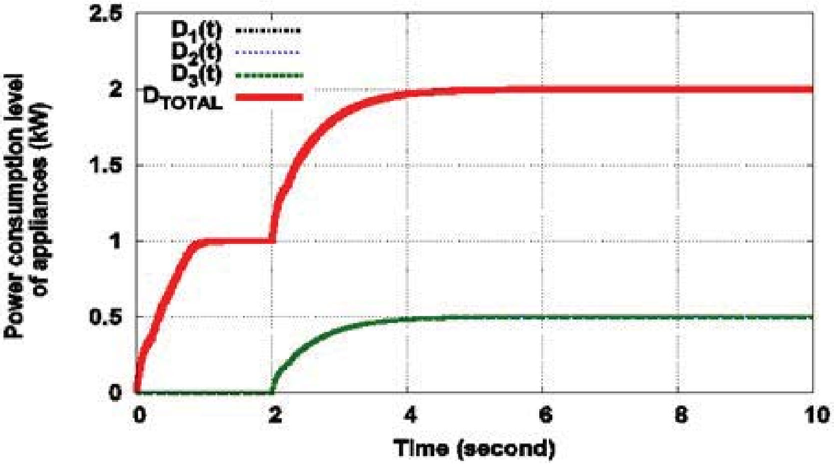


Figure 3.14: Power consumption behavior of SHAs with different turn ON timing ($t = 0$ for SHA_1, $t = 2$ for SHA_2 and SHA_3).

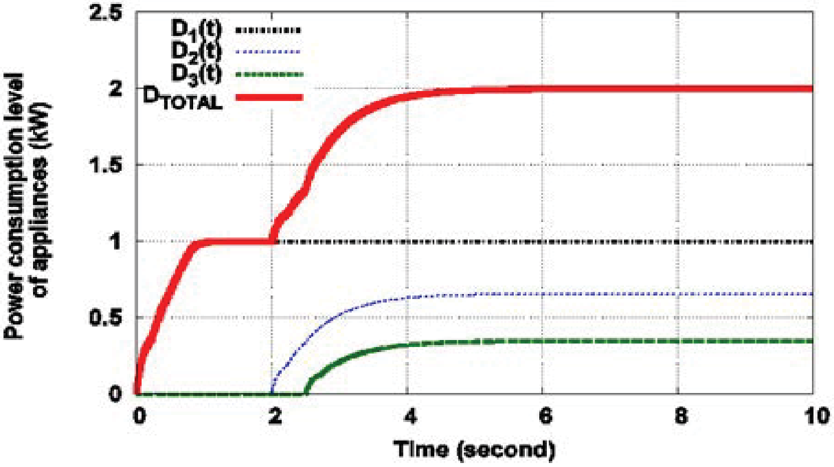


Figure 3.15: Power consumption behavior of SHAs with different turn ON timing ($t = 0$ for SHA_1, $t = 2$ for SHA_2 and $t = 2.5$ for SHA_3)

more available power and the last turned ON SHA have the smallest part of available power. As from two types of simulations, the final available power sharing among SHAs is determined by the speed of each SHA and by the turn ON timing in current system design.

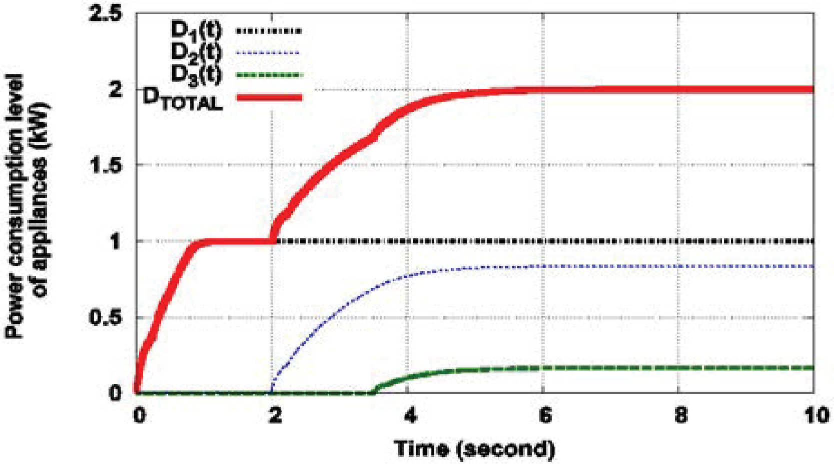


Figure 3.16: Power consumption behavior of SHAs with different turn ON timing ($t = 0$ for SHA$_1$, $t = 2$ for SHA$_2$ and $t = 3.5$ for SHA$_3$

3.10 Summary

The introduction of SES has brought a paradigm shift in the analysis of power consumption of SHAs in smart homes. In this chapter, the effect of SES that provides access to power supply and demand, but with some communication delay has been studied. The main objectives of this chapter are to prevent power blackout in home and maintain power stability of smart homes by proposing a system design based on PPC, SHAs and SESs. To reach these objectives, the proposed system design in simulation environment is analyzed. The simulation results showed the dependency of system parameters a_i (SHA response speed), D_i^{max} (SHA maximum consuming power level), l (divisor of available power) and τ (communication delay in information transfer between SES to PPC, processing at PPC and sending suggested power level from PPC to SHAs) in system behavior such as stable/unstable, overshoot/non-overshoot.

From simulation analysis, the border estimation table representing the stable/unstable and overshoot/non-overshoot regions is calculated which helps in concluding that the border in l for stable/unstable and overshoot/non-overshoot increases as a_i increases and as τ increases. So, the value of system parameter l should be decided carefully by estimating the maximum communication delay τ and the maximum speed of SHAs. Couple of experiments showed that how the remaining power is distributed to SHAs and what is the effect of turn ON timing of the SHAs to the final available power sharing.

From two types of simulations of proposed system, the final available power sharing among SHAs is determined by the speed of each SHA and by the turn ON timings.

Chapter 4

Stability Control for Smart Home Energy Management System

4.1 Introduction

Stability is one of the most important issues in the system design. The ability to maintain stable operation in the presence of delays is referred as System Stability. Stability of time-delay systems became a formal subject of study in the last ten to fifteen years. There has been a surge of research activities and henceforth a proliferation of new techniques and results; a cursory glance of the large numbers of articles published during this period. It is clear that advances in numerical methods and control theory, especially the theory of robust stability and control, have contributed much to make the progress possible. The techniques and methods found in robust stability are quadratic stability, small gain theorem, structured singular value, linear matrix inequalities (LMIs). Efficient numerical algorithms for solving LMI problems, which form a special category of optimization problems, have become an enabling tool that led the stability problems to be posed as LMI conditions and thus rendered solvable computationally. It is fair to conclude that these concepts and techniques have helped revitalize the field and by now have been routinely used in the study of time-delay systems.

The major objectives of this chapter are to: (i) study the effects of system parameters on stability (ii) analyze whether the delays can reduce stability margin (iii) determine how much stability margin might be reduced. In order to study the stability, the proposed system is linearized to be linear time delay system which is easy to study the aspect of stability. Lyapunov-Krasovskii (L-K) stability theorem is used to compute the stability parameters of the system.

In particular, bounds of delay are derived using Linear Matrix Inequalities (LMIs) approach. LMI package or toolbox in MATLAB is used to evaluate stability theorem for proposed SHemS.

4.2 Stability Analysis

One of the primary requirements to be satisfied by any system is that it should be stable. The notion of stability of systems can be defined in many ways. But in a general sense, a stable system should have an output which in many ways resembles the desired output of the system. Under the action of disturbances generated inside the system due to uncontrollable phenomena or those acting from outside to disturb the output, the output should remain close to the desired value.

Every system, for small amount of time has to pass through a transient period. Now the system will reach to its intended steady state after passing through transients is the stability analysis. Stability is the most important system specification. If a system is unstable, transient response and steady state error are most important. An unstable system cannot be designed for a specific transient response or steady state error requirement. There are many definitions for stability, depending upon the kind of the system or the point of view.

4.3 Importance of Stability

4.3.1 Controllability

A control system is said to be completely state controllable if it is possible to transfer the system from any arbitrary initial state to any desired state in a finite time period. That is, a control system is controllable if every state variable can be controlled in a finite time period by some unconstrained control signal. If any state variable is independent of the control signal, then it is impossible to control this state variable and therefore the system is uncontrollable.

4.3.2 Observability

A control system is said to be observable if every initial state ($x(0)$) can be determined from the observation of output ($Y(k)$) over the finite number of sampling periods. The system, therefore, is completely observable if every transition of the state eventually effects every element of the output vector. In the state feedback scheme, we require the feedback of all state variables. In practical, however, some of the state variables are not accessible for direct measurement. Then it becomes necessary to estimate the immeasurable variables in order to implement the state variable feedback scheme.

Some of the methods to implement stability are:

1. Routh Hurwitz Criterion
2. Nyquist Criterion
3. Bode Plot Method
4. Lyapunov's method etc.

Among these, the first three can be applied to linear time invariant systems whereas the last one is more general and can be applied to study the stability of linear and nonlinear systems. In this chapter, Routh Hurwitz Criterion and Lypunov's methods would be discussed.

4.4 Preliminaries

4.4.1 Routh-Hurwitz Stability Criterion

The stability of a feedback system is directly related to the location of the characteristic equation of the system transfer function. The Routh Hurwitz method is introduced as a useful tool for accessing system stability. The technique allows us to compute the number of roots of the characteristic equation in the right half plane without actually computing the values of the roots. Thus we can determine stability without the added computational burden of determining characteristic root locations. This gives us a design method for determining values of certain system parameters that will lead to closed-loop stability.

It was discovered that all coefficient of the characteristic polynomial must have the same sign and non-zero if all roots are in the left half plane. This criterion is a method for determining whether a linear system (the system will meet superposition property is called linear system) is stable or not by examining the locations of the roots of the characteristic equation of the system. Consider the characteristic equation.

$$1 + GH(s) = D(s) = a_n s^n + a_{n-1} s^{n-1} + ... + a_1 s + a_0 = 0 \tag{4.1}$$

By using this method, how many closed-loop system poles are in the left half plane, in the right half plane, and on the jw-axis can be noticed easily. The number of poles in each section of the s-plane can be identified, but cannot find their coordinates.

The method requires two steps:

1- Generate a data table called Routh table

2- Interpret the Routh table to tell how many closed loop system poles are in the left half plane, the right half plane, and on the jw-axis.

1. ***Why we study this method: :*** When modern calculators and computers can tell us the exact location of system poles why we are still using this criterion. The power lies in design rather than analysis. For example, if we have an unknown parameter in the denominator of a transfer function, it is difficult to determine via a calculator the range of this parameter to yield stability. Routh Hurwitz criterion can yield a closed-form expression for the range of the unknown parameter.

2. ***Stability Conditions:*** To determine whether the system is stable or not, check the following conditions: Two necessary but not sufficient conditions that all the roots have negative real parts are

   a) All the polynomial coefficients must have the same sign.

   b) All the polynomial coefficients must be nonzero.

   If condition (1) is satisfied, then compute the Routh-Hurwitz array as follows: where $a_i' s$ are the polynomial coefficients and coefficients in the rest of the computed using the following pattern:

$$b_1 = \frac{a_{n-1} a_{n-2} - a_n a_{n-2}}{a_{n-1}} \tag{4.2}$$

Table 4.1: Routh-Hurwitz Array

s^n	a_n	a_{n-2}	a_{n-4}	a_{n-6}
s^{n-1}	a_{n-1}	a_{n-2}	a_{n-5}	a_{n-7}
s^{n-2}	a_{n-1}	a_{n-2}	a_{n-5}	a_{n-7}
s^{n-3}	a_{n-1}	a_{n-2}	a_{n-5}	a_{n-7}
s^{n-4}	a_{n-1}	a_{n-2}	a_{n-5}	a_{n-7}
...	...	...	...	...
s^1	...	...	...	...
s^0	...	...	...	...

$$b_2 = \frac{a_{n-1}a_{n-4} - a_n a_{n-5}}{a_{n-1}} \tag{4.3}$$

$$b_3 = \frac{a_{n-1}a_{n-6} - a_n a_{n-2}}{a_{n-2}} \tag{4.4}$$

$$c_1 = \frac{b_1 a_{n-3} - a_{n-1}b_2}{b_1} \tag{4.5}$$

$$c_2 = \frac{b_1 a_{n-5} - a_{n-1}b_3}{b_1} \tag{4.6}$$

The necessary condition that all roots have negative real parts is that all the elements of the first column of the array have the same sign. The number of changes of sign equals the number of roots with positive real parts.

Special Case 1: The first element of a row is zero, but some other elements in that row are nonzero. In this case, simply replace the zero elements by ϵ, complete the table development, and then interpret the results assuming that ϵ is a small number of the same sign as the element above it. The results must be interpreted in the limit as $\epsilon \to 0$.

Special Case 2: All the elements of a particular row are zero. In this case, some of the roots of the polynomial are located symmetrically about the origin of the s-plane, e.g., a pair of purely imaginary roots.

The zeros row will always occur in a row associated with an odd power of s. The row just above the zeros row holds the coefficients of the auxiliary polynomial. The roots of the auxiliary polynomial are the symmetrically placed roots. Be careful to remember that the coefficients in the array skip powers of s from one coefficient to the next.

3. ***Auxiliary Polynomial:*** The roots of auxiliary equation may be one of the four cases:
   1-A pair of real roots of opposite sign
   2-A pair of roots located on the imaginary axis
   3-The non-repeated pairs of roots located on the imaginary axis
   4-The repeated pair of roots located on the imaginary axis
   Hence, total stability can be determined from the roots of $P(s) = 0$, which can be out of four types shown above.

4. ***Change in criterion of stability in special case:***
   After replacing a row of zeros by the coefficients of $\frac{dP(s)}{ds}$, complete the Routh's array. But now, the criterion that, no sign change in the 1st column of array for stability, no longer remains sufficient but becomes a necessary. This is because though $P(s)$ is a part of original characteristic equation, $\frac{dP(s)}{ds}$ is not, which is in fact used to complete the array. So, if sign change occurs in first column, system is unstable with number of sign changes equal to number of roots of characteristic equation located in right half of s-plane.
   Key Point: But if there no change, system cannot be predicted as stable and in such case stability is to be determined by actually solving $P(s) = 0$ for its roots. From the locations of roots of $P(s) = 0$ are always dominant roots of characteristic equation. Auxiliary polynomial is always the part of the original characteristic equation. This means the roots of the auxiliary equation are some of the roots of the original characteristic equation. Not only is this but the roots of auxiliary equation the most dominant roots of the original characteristic equation, from the stability point of view. The stability can be predicted from the roots of $P(s) = 0$ rather than the roots of characteristic equation as the roots of $P(s) = 0$ are the most dominant from the stability point of view. The remaining roots of the characteristic

equation are always in the left half and they do not play any significant role in the stability analysis.

4.4.2 Lyapunov Stability Criterion

Lyapunov stability plays an important role in the stability analysis of control systems described by state space equations. Lyapunov equations appear in many different engineering and mathematical perspectives such as control theory, system theory, optimization, power systems, signal processing, linear algebra, differential equations, boundary value problems, large space flexible structures, and communication. It is named after the Russian mathematician Alexander Mikhailovitch Lyapunov. Lyapunov's direct method is a mathematical interpretation of the physical property that if a system's total energy is dissipating, then the states of the system will ultimately reach an equilibrium point. The basic idea behind the method is that, if there exists a kind of continuous scalar "energy "functions such that this "energy "diminishes along the system's trajectory, then the system is said to be asymptotically stable. Since there is no need to solve the solution of the differential equations governing the system in determining its stability, it is usually referred to as the direct method.

> A system has an asymptotically stable equilibrium state, the stored energy of the system displaced within a domain of attraction decays with increasing time until it finally assumes its minimum value at the equilibrium state.

Lyapunov Stability Theory An equilibrium state is stable if whenever the initial state is near that point, the state remains near it, perhaps even tending towards the equilibrium point as time increases. Consider the autonomous system $\dot{x} = f(x), x_{eq} = 0$ is an equilibrium point of above equation.

Note: What if the equilibrium point $x_{eq} \neq 0$?.

Solution There is no loss of generality by this assumption. A shifted coordinates system in the form $y = x - x_{eq}$ can always select. The derivative of y is given by $\dot{y} = \dot{x} = f(y + x_{eq}) = 0$. The system described by the means of the new variable has the equilibrium at the origin.

Lyapunov Function According to his definition of stability, so called stability in the sense of Lyapunov, one can check the stability of a system by finding some functions, called Lyapunov function. Lyapunov stability method specialized for the linear time invariant systems, has more theoretical importance than practical value and can be used to derive and prove other stability results. For linear system, Lyapunov function can be chosen to be quadratic. There is no general procedure for finding a Lyapunov function for nonlinear systems, but for linear time invariant systems, the procedure comes down to the problem of solving the matrix Lyapunov equation. Since linear systems are mathematically very convenient and give fairly good approximations for nonlinear systems. Therefore, the solutions of the Lyapunov matrix equations give insight into the behavior of dynamical systems. Lyapunov functions have been effectively utilized in the synthesis of control systems.

To find $V(x)$, called a Lyapunov function, which must satisfy the following requirement.

1. V is continuous.
2. $V(x)$ has a unique minimum at x_{eq} with respect to all other points in D (neighborhood).
3. Along any trajectory of the system contained in D the value of V never increases.

Positive Definite Function A continuously differentiable function V is said to be positive definite in a region U of R^n that contains the origin if

1. $V(0) = 0$
2. $V(x) > 0 \; \forall x \neq 0$ and $x \in U$
3. $V(x)$ is said to be positive semi definite if $V(x) \geq 0 \; for \; \forall x \neq 0$ and $x \in U$.
4. Conversely, if condition (2) is replaced by $V(x) < 0$, then $V(x)$ is said to be negative definite, system called asymptotically stable.
5. $V(x)$ is said to be negative semi definite if $V(x) \leq 0$.

4.4.3 Lyapunov-Krasovskii (L-K) Stability Theorem

The presence of delays can have an effect on system stability and performance, so ignoring them may lead to design flaws and incorrect analysis conclusions. Stability is classified as delay-independent if it is retained irrespective of the size of the delays, and delay-dependent if it is lost at a certain delay value. In general the former condition is more conservative as in most cases bounds on the expected value of the delay exist.

The investigation of the stability properties of linear time-delay systems is usually performed using time-domain (Lyapunov based) methodologies, which account to construct simple L-K stability theorem by solving an appropriate set of LMIs. The stability conditions that can be obtained in this way are often conservative even though the existence of complete quadratic L-K functionals necessary and sufficient for stability is known, and so is their structure. The reason is that use of the complete functional yields infinite dimensional LMI conditions that are difficult to verify algorithmically with current tools; researchers have concentrated on other structures that yield simple finite dimensional LMI conditions.

The L-K Stability Theorem is used to discuss the stability of the system. Here the proposed system is restricted to use L-K functional, and aim at arriving at stability criteria which can be written in the form of LMI. In practice, there are systems which require feedback to improve the system performance, and the feedback channels involve delays. In these cases, the delay-independent stability criteria are clearly insufficient. In many cases, it is more desirable that the system does not have a delay, and the presence of delay is indeed detrimental to system stability and performance.

4.4.4 Time Delay Systems

Time delay systems (TDS) are also called system with aftereffect or time-delay. Systems with delays frequently appear in engineering. One reason is that real processes are full of time delays. Another reason is that time-delay systems are often used to model a large class of engineering systems, where transmission of information is involved. Typical examples of time-delay systems are communication networks, chemical processes, tele-operation systems and so on. Normally, the presence of delays makes systems less productive, less optimal and less stable. From the control point of view, it makes system analysis and controller design much more complicated. Since 1980s, the robust control of time-delay systems has attracted a lot of attention. Various robust control problems have been solved, but mostly for systems with a single delay.

Another active topic in time-delay systems is the stability analysis. The stability of dynamical systems involve delayed states which is the problem of both theoretical and practical interests. As time-delays are frequently encountered in many processes and very often are the cause for instability of the system. A number of techniques for stability analysis of linear systems with time-delay in the state variable have been reported in the literature over the past decades. Criteria for global uniform stability which is independent of the size of the time-delay have been proposed by a number of investigators [48]-[50]. Since for these stability criteria the time-delay is allowed to be arbitrary large, these stability results are, in general, conservative for many important applications. Recently, increasing attention has been devoted to the development of methods for delay-dependent stability analysis, i.e. stability criteria which depend on the size of the time-delay [51]-[52].

This chapter is concerned with the problem of stability analysis of linear systems with delayed state. We consider the case of single, time-delay and attention will be focused on developing delay-dependent stability criteria based on LMIs. The LMI approach developed in this chapter has few advantages over the existing methods of delay-dependent stability analysis such as [53]-[54].

This chapter will explore the time domain approaches of stability analysis. An advantage of time domain method is the ease to handle non-linearity and time-varying uncertainties. However, in order to illustrate the basic ideas, this chapter will concentrate on the stability problem of linear time invariant systems with single delay.

$$\dot{x}(t) = A_0 \cdot x(t) + A_1 \cdot x(t-\tau) \tag{4.7}$$

where A_0 and A_1 are given $n \times n$ real matrices. The usual initial condition is in the form of

$$x_t = \phi \tag{4.8}$$

4.4.5 Linear Matrix Inequalities (LMIs)

The L-K Stability Theorem is used to discuss the stability of the proposed system. Stability analysis can be easily and efficiently achieved by efficient numerical methods such as LMI-Toolbox in MATLAB. After transforming the given problem into LMI problem, there is a need to specify the decision variables in the LMIs. Then the solution can be made numerically by using the available solvers such as $feasible$ *solution problems* ($feasp$), etc. In other words, the question that can be posed here is there any limit on delay? If delay becomes excessive, it may be possible for the system to become unstable. In particular, LMIs help in derivation of an upper bound on time delay for which stability can be guaranteed.

The theory of LMIs has been attracting the attention of research communities for a decade especially from researchers in the control systems community. The concept of LMIs and its applications are based on the fact that LMIs can be applied to linear programming problems which can easily be solved by computers [55].

1. **A General Introduction to LMIs** LMIs can be generally described as:

   $$F(x) = F_0 + x_1F_1 + \ldots + x_mF_m < 0 \tag{4.9}$$

   where $x = [x_1, \ldots, x_m]$, is the coefficient vector of a polynomial. It is also referred to as decision vector. The F_i is Hermitian matrix. If the LMI matrix $F(x)$ is a negative-definite matrix, the solution set is convex, i.e.,

   $$F[\alpha x_1 + (1-\alpha)x_2] = \alpha F(x_1) + (1-\alpha)F(x_2) < 0 \tag{4.10}$$

   where $\alpha > 0, 1-\alpha > 0$. The solution is also referred to as the $feasible$ *solution*. From two such LMIs $F_1(x) < 0$ and $F_2(x) < 0$, a single LMI can be constructed such that,

   $$\begin{bmatrix} F_1(x) & 0 \\ 0 & F_2(x) \end{bmatrix} \tag{4.11}$$

2. **Classification of LMI Problems** LMI problems can be classified into three typical problems, i.e., the $feasible$ *solution* problems, *linear objective function minimization* problems and the generalized *eigenvalue problems*. In this particular research, feasible solution problem is considered.

3. **Stability Solution Problem** The stability solution problems also called feasible solution problems in optimization, i.e., for the inequality $F(x) < 0$. The feasible solution problem is to find the solution $F(x) < t_{min}I$, where the minimum t_{min} is a scalar also called LMI constraint which is to be found. If $t_{min} < 0$ can be found, there exist solutions to the original problem, otherwise there is no feasible solution.

4. **LMI Problem Solutions With MATLAB** MATLAB LMI Toolbox provides a set of convenient functions to solve problems involving LMIs. In general, problems involving LMIs are solved in two stages in MATLAB. First, need to define the LMIs in the problem. This stage includes the specification of the decision variables in the LMIs and defining the LMIs based on these decision variables. In the second stage, the problem is solved numerically using the available solvers. If the problem includes minimization of a function with a vector form of decision variables, one need to convert the matrix form of decision variables into the vector form using additional functions. The following procedures are used to describe LMIs in MATLAB:

   (a) Create an LMI model: An LMI framework can be established with $setlmis([])$ function. So, a framework can be established in MATLAB workspace.

   (b) Define the decision variables: The decision variables can be declared by $lmivar()$ function, with $P = lmivar(key, [n1, n2])$, where key specifies the type of the decision matrix, with $key = 2$ for an ordinary $n_1 \times n_2$ matrix P, while $key = 1$ for an $n_1 \times n_1$ symmetrical matrix.

   (c) Describe LMIs in partitioned form: The LMIs can be described by the $lmiterm()$ function and its syntax is quite complicated.

   $$lmiterm([k, i, j, P], A, B, flag) \tag{4.12}$$

   where k is the number of the LMIs. Since an LMI problem may be described by several LMIs, one should number each of them. If an LMI is given $G_k(x) > 0$, then k should be described by $-k$. A term in a block in the partitioned matrix can be described by $lmiterm()$ function, with i, j representing respectively the row and column numbers of the block. P is the declared decision variables, and the matrices A, B indicate the matrices in the term APB. If flag is assigned as s, the symmetrical term $APB + (APB)^T$ is specified. If the whole term is a constant matrix, P is set to 0, and matrix B is omitted.

   (d) Solve the LMI problem: For the declared model G, the feasible solution problems can be solved as the following form

   $$[t_{min}, x] = feasp(G, options, target) \tag{4.13}$$

The solution x thus obtained is a vector, and the *dec2mat*() function can be used to extract the matrix.

4.5 Stability Theorem for SHemS

A power system is continually subjected to change its load and operating conditions. It is essential that the system posses the ability to maintain stable operation when subjected to delays. Basically the proposed system (SHemS) is non-linear system but for the detailed analysis for stability, consideration of linear system has been taken into account. Because of the powerful tools available for the linear system. The non-linear system situation would be more complex and difficult to solve. The first step in analyzing a nonlinear system is usually to linearize it.

4.5.1 Linearization

At first, the power consumption derivation equation of SHA (described in previous chapter) has been considered.

$$\dot{D_i}(t) = -a_i \cdot D_i(t) + b_i \cdot u \tag{4.14}$$

For linearization, different modes are assigned to the situations as "Normal Mode Operation" and "Limited Mode Operation".

$$b_i \cdot u = \begin{cases} a_i \cdot D_i^{max}, & \text{if } S_i(t) + D_i(t) \geq D_i^{max} \\ a_i \cdot (S_i(t) + D_i(t)), & \text{if } S_i(t) + D_i(t) < D_i^{max} \end{cases} \tag{4.15}$$

When the available power for all SHAs is more than the specified SHA maximum consuming power level is called "Normal Mode Operation" otherwise "Limited Mode Operation".

First, the case when all m SHAs operate in "Normal Mode" has been considered. In this situation all SHAs have enough available power to operate till their maximum consuming power level, so that no SHA will disturb the working of the other SHA. The system equation can be represented in matrix notation as:

$$\begin{bmatrix} \dot{D_1(t)} \\ \vdots \\ D_m(t) \end{bmatrix} = \begin{bmatrix} -a_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & -a_m \end{bmatrix} \begin{bmatrix} D_1(t) \\ \vdots \\ D_m(t) \end{bmatrix} + \begin{bmatrix} a_1 \cdot D_1^{max} \\ \vdots \\ a_m \cdot D_m^{max} \end{bmatrix} \tag{4.16}$$

In above case, the proposed system is stable all the times and no need to apply stability test because SHAs can be operated independently.

In second case, all m SHAs operate in the "Limited Mode". In this situation, one SHA behavior will effect the other SHA behavior because available power for SHAs is not enough for their maximum consuming power level.

$$\dot{D}_i(t) = -a_i \cdot D_i(t) + a_i \cdot (S_i(t) + D_i(t))$$

$$\dot{D}_i(t) = -a_i \cdot D_i(t) + a_i \cdot S_i(t) + a_i \cdot D_i(t)$$

$$\dot{D}_i(t) = -a_i \cdot D_i(t) + a_i \cdot \frac{R(t-\tau)}{l} + a_i \cdot D_i(t)$$

$$\dot{D}_i(t) = -a_i \cdot D_i(t) + a_i \cdot \frac{P - \sum_{i=1}^{m} D_i(t-\tau)}{l} + a_i \cdot D_i(t) \tag{4.17}$$

The system equation can be represented in matrix notation as:

$$\begin{bmatrix} \dot{D}_1(t) \\ \vdots \\ \dot{D}_m(t) \end{bmatrix} = \begin{bmatrix} -a_1 + a_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & -a_m + am \end{bmatrix} \begin{bmatrix} D_1(t) \\ \vdots \\ D_m(t) \end{bmatrix} +$$

$$\begin{bmatrix} \frac{-a_1}{l} & \cdots & \frac{-a_1}{l} \\ \vdots & \ddots & \vdots \\ \frac{-a_m}{l} & \cdots & \frac{-a_m}{l} \end{bmatrix} \begin{bmatrix} D_1(t-\tau) \\ \vdots \\ D_m(t-\tau) \end{bmatrix} + \begin{bmatrix} P_1 \\ \vdots \\ P_m \end{bmatrix} \tag{4.18}$$

where,

$$P_i = a_i \cdot \frac{P}{l} \tag{4.19}$$

Note that the coefficient matrix in the first term becomes a zero matrix. Third, the case when k SHAs work with "Normal Mode Operation"and $m-k$ SHAs work with "Limited Mode Operation", where, m is the total no. of SHAs. Then system equation in matrix notation is as follows:

$$\begin{bmatrix} \dot{D}_1(t) \\ \vdots \\ \dot{D}_k(t) \\ \dot{D}_{k+1}(t) \\ \vdots \\ \dot{D}_m(t) \end{bmatrix} = \left[\begin{array}{ccc|c} -a_1 & \cdots & 0 & \\ \vdots & \ddots & \vdots & \mathbf{0} \\ 0 & \cdots & -a_k & \\ & & & \\ & \mathbf{0} & & \mathbf{0} \\ & & & \end{array}\right] \begin{bmatrix} D_1(t) \\ \vdots \\ D_k(t) \\ D_{k+1}(t) \\ \vdots \\ D_m(t) \end{bmatrix} +$$

$$\begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \\ \frac{-a_{k+1}}{l} & \cdots & \frac{-a_{k+1}}{l} \\ \vdots & \ddots & \vdots \\ \frac{-a_m}{l} & \cdots & \frac{-a_m}{l} \end{bmatrix} \begin{bmatrix} D_1(t-\tau) \\ \vdots \\ D_k(t-\tau) \\ D_{k+1}(t-\tau) \\ \vdots \\ D_m(t-\tau) \end{bmatrix} + \begin{bmatrix} a_1 \cdot D_1^{max} \\ \vdots \\ a_k \cdot D_k^{max} \\ P_{k+1} \\ \vdots \\ P_m \end{bmatrix} \tag{4.20}$$

4.6 Delay Dependent Stability Analysis for SHemS

The stability analysis for proposed linear TDS is dependent on delay (τ). The comparison can be made between proposed system model with delay in (4.16) and given linear TDS with single delay in (4.7). The two equations can be compared easily, where $A_0 = -a_i$, $A_1 = a_i$, $x(t) = D(t)$, $x(t-\tau) = D(t-\tau)$ and $\dot{x}(t) = \dot{D}(t)$ with delay (τ), the delayed term needs to be analyzed for the stability analysis of the proposed system. For this purpose, proposed system equation can be written with initial condition as follows:

$$\dot{D}(t) = A_0 \cdot D(t) + A_1 \cdot D(t-\tau) \tag{4.21}$$

$$D_t = \phi \tag{4.22}$$

where A_0 and A_1 are given $n \times n$ real matrices. As the delayed term grows from zero, the system performance can deteriorate and system is in danger of losing stability. There is no loss of generality by rewriting the equation 4.21 as:

$$\dot{D}(t) = (A_0 + A_1) \cdot D(t) + A_1 \cdot (D(t-\tau) - D(t)) \tag{4.23}$$

The term $A_1 \cdot (D(t-\tau) - D(t))$ considered as a delay term to the nominal stable system $\dot{D}(t) = (A_0 + A_1) \cdot D(t)$. In order to reflect the fact that the delay grows from zero as τ increases from zero. This can be solved by “Model Transformation”in combination with delay-independent stability for distributed delay problem, which helps in deriving a simple delay-dependent stability criteria. The delay-independent stability for distributed delay is given by:

$$\dot{D}(t) = A_0 \cdot D(t) + \int_{-\tau}^{0} A(\theta) \cdot D(t+\theta) d\theta \tag{4.24}$$

4.6.0.1 Model Transformation

Consider system 4.21 with 4.22, where the initial function is given as $\phi \in \mathcal{C}([-\tau, 0], \mathbb{R}^n)$. With the consideration that

$$D(t-\tau) = D(t) - \int_{-\tau}^{0} \dot{D}(t+\theta) d\theta \tag{4.25}$$

$$= D(t) - \int_{-\tau}^{0} [A_0 \cdot D(t+\theta) + A_1 \cdot D(t-\tau+\theta)] d\theta \tag{4.26}$$

for $t \geq \tau$, we can write 4.21 as:

$$\dot{D}(t) = [A_0 + A_1] \cdot D(t) \tag{4.27}$$

$$+ \int_{-\tau}^{0} [-A_1 A_0 \cdot D(t+\theta) - A_1 A_1 \cdot D(t-\tau+\theta)] d\theta \tag{4.28}$$

with initial condition

$$D(\theta) = \psi(\theta), -\tau \leq \theta \leq -\tau \tag{4.29}$$

$$\psi(\theta) = \begin{cases} \phi(\theta), & -\tau \leq \theta \leq 0 \\ 4.21 \quad \text{with} \quad 4.22, & 0 < \theta \leq \tau \end{cases} \tag{4.30}$$

The system explains by 4.21 and 4.22 already exists in 4.28 and 4.29 without initial condition 4.30. As it is a time invariant system, and for stability the initial time can be shifted as:

$$\dot{y}(t) = \bar{A}_0 \cdot y(t) + \int_{-2\tau}^{0} \bar{A}(\theta) \cdot y(t+\theta) d\theta \tag{4.31}$$

$$\psi(\theta) = \begin{cases} \bar{A}_0 = A_0 + A_1, \\ \bar{A}(\theta) = -A_1 A_0, \quad \theta \in [-\tau, 0] \\ \bar{A}(\theta) = -A_1 A_1, \quad \theta \in [-2\tau, -\tau] \end{cases} \tag{4.32}$$

with initial condition

$$y(\theta) = \psi(\theta), -2\tau \leq \theta \leq 0 \tag{4.33}$$

Let, $R(\theta) = \bar{A}(\theta) \cdot y(t+\theta)$. Now the proposed system 4.20 and 4.21 have been transformed by 4.30 and 4.31. Clearly the stability of the original system is the same as stability of transformed system.

Theorem 1[82]: Power model described in equation (4.21) is asymptotically stable if there is an existence of a real symmetric matrix $P > 0$ such that:

$$\begin{bmatrix} M & -PA_1A_0 & -PA_1^2 \\ -A_0^TA_1^2P & -P & 0 \\ -(A_1^2)^TP & 0 & -P \end{bmatrix} < 0 \tag{4.34}$$

where $M = \frac{1}{\tau}(P\hat{A}_0 + P\hat{A}_0^T + 2P)$ and $\hat{A}_0 = A_0 + A_1$.

Proof: The proof is established by showing that $V = D^TPD$ where P is positive definite is a Lyapunov function. This in turn is shown by using 4.34, the existence of symmetric matrix by theorem 1 and the existence of symmetric matrix $R(\theta)$ in transformed model that along with P satisfies the conditions:

$$P\hat{A}_0 + \hat{A}_0^TP + \int_{-2\tau}^{0} R(\theta)d\theta < 0 \tag{4.35}$$

$$\begin{bmatrix} pP - R(\theta) & P\hat{A}(\theta) \\ \hat{A}^T(\theta)P & -P \end{bmatrix} < 0 \tag{4.36}$$

$0 \leq \theta \leq 2\tau$

With the help of theorem 1, the time delay system in 4.20 is stable provided by the delay (τ) is such that theorem 1 is satisfied.

4.7 SHemS Stability Evaluation with LMI

The evaluation process of L-K stability theorem depends on three types of parameters: one SHA parameter, two system parameters and a LMI constraint parameter. SHA parameter has the parameter a_i which decides the response speed of the SHA. System parameters consists of designer's parameter l (also called divider of available power) and communication delay τ. The LMI constraint is t_{min}. In order to find the stable region, the value of t_{min} is calculated and observed. If $t_{min} < 0$ can be found, there exist solutions to the original problem (stable region), otherwise there is no feasible solution. In case of stable region identification, the maximum stable delay can be found based on the stable region analysis. The dependency of system parameters on stability is also investigated. The stability theorem evaluation has been done with LMI Lab in MATLAB. Maximum stable delay calculation depends on following parameters a_i, l, and τ.

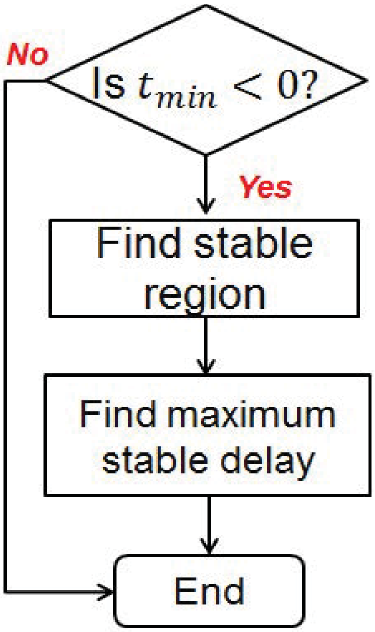


Figure 4.1: Stable region identification.

4.8 Evaluation Cases

The evaluation of stability theorem include three different cases which are as follows:

1. **Case-1:** The value of SHA parameter a_i is same while the value of system parameter l is different.
2. **Case-2:** The value of SHA parameter a_i is different while the value of system parameter l is same.
3. **Case-3:** The values of SHA parameter a_i and system parameter l both are different.

4.8.1 Case-1:

SHA parameter a_i is same for all SHAs in other words the value is fixed in each calculation of stable region while the system parameter l changes. In this case, the value of a_i for all SHAs is fixed to $3, 5, 7, 9$ and change system parameter l from 1 to 25.

The calculation results show the identification of stable region in Figure 4.2. The value of SHA parameter a_i is same as $a_i = 3$while the value of system parameter l is different. The stable region of given problem depends on the value of l. It is not easy to spot the

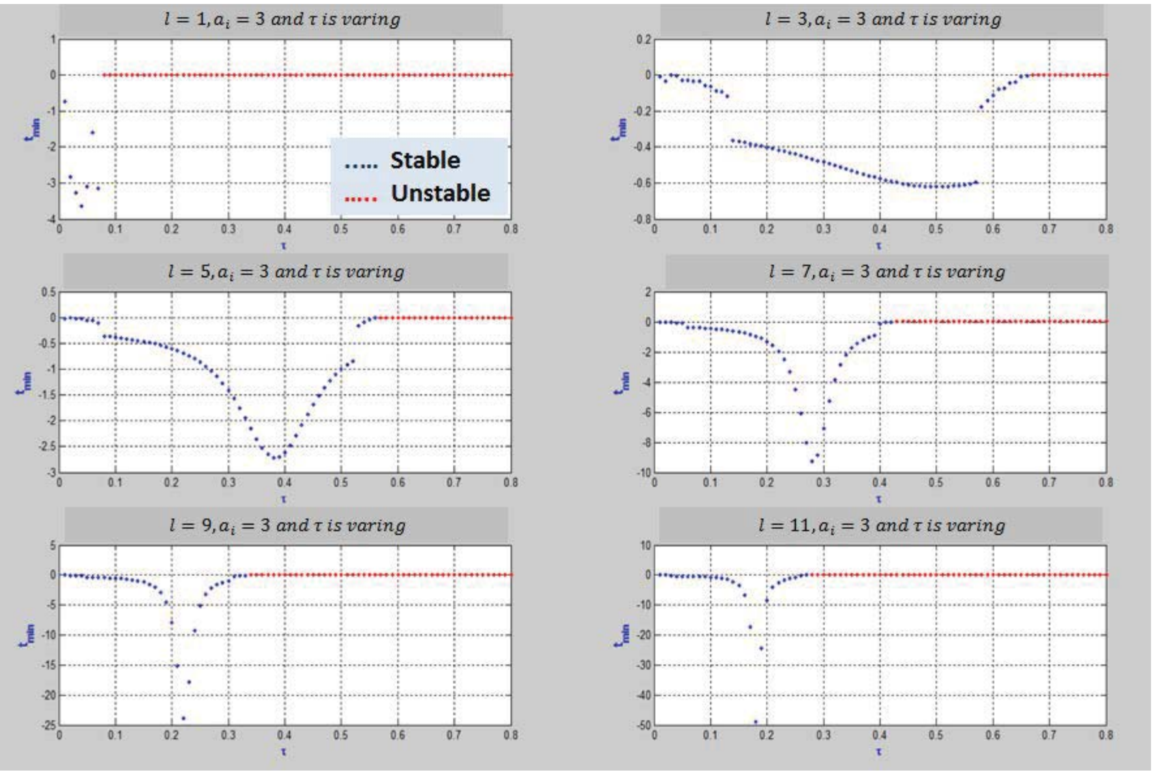


Figure 4.2: Case-1: Stable/unstable region identification of $a_i = 3$ for all SHAs with $l = 1, 3, 5, 7, 9, 11$.

variation of stable region in Figure 4.2. So, the calculation is repeated for different values of l and the results are summarized in Figure 4.3.

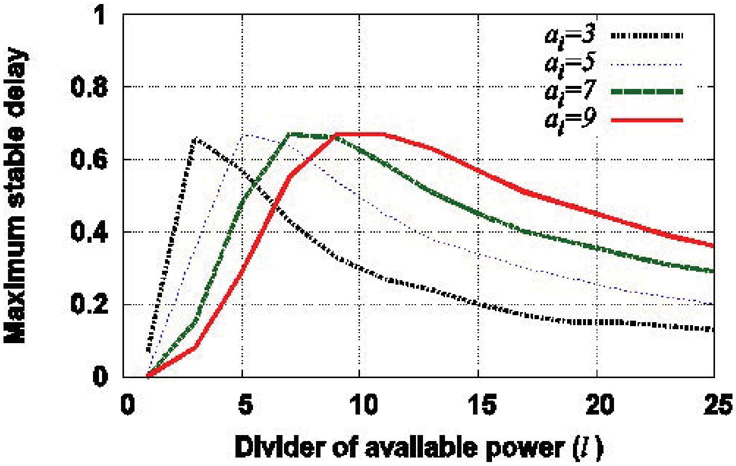


Figure 4.3: Case-1: Maximum stable delay.

In Figure 4.3, before l reaching some specific value, the stable region becomes larger as l increases. After l reached the specific value, the region becomes smaller as l increases.

This calculation is repeated for for $a_i = 5, 7, 9$ respectively. The value of maximum stable delay keeps changing with the change in system parameter l. When $a_i = l$, maximum stable delay is reached.

4.8.2 Case-2:

In this case, SHA parameter a_i is keep changing for all SHAs with fixed system parameter value of l. The value of l is kept same for all SHAs to $3, 5, 7, 9$ and change of a_i is varying from 1 to 25.

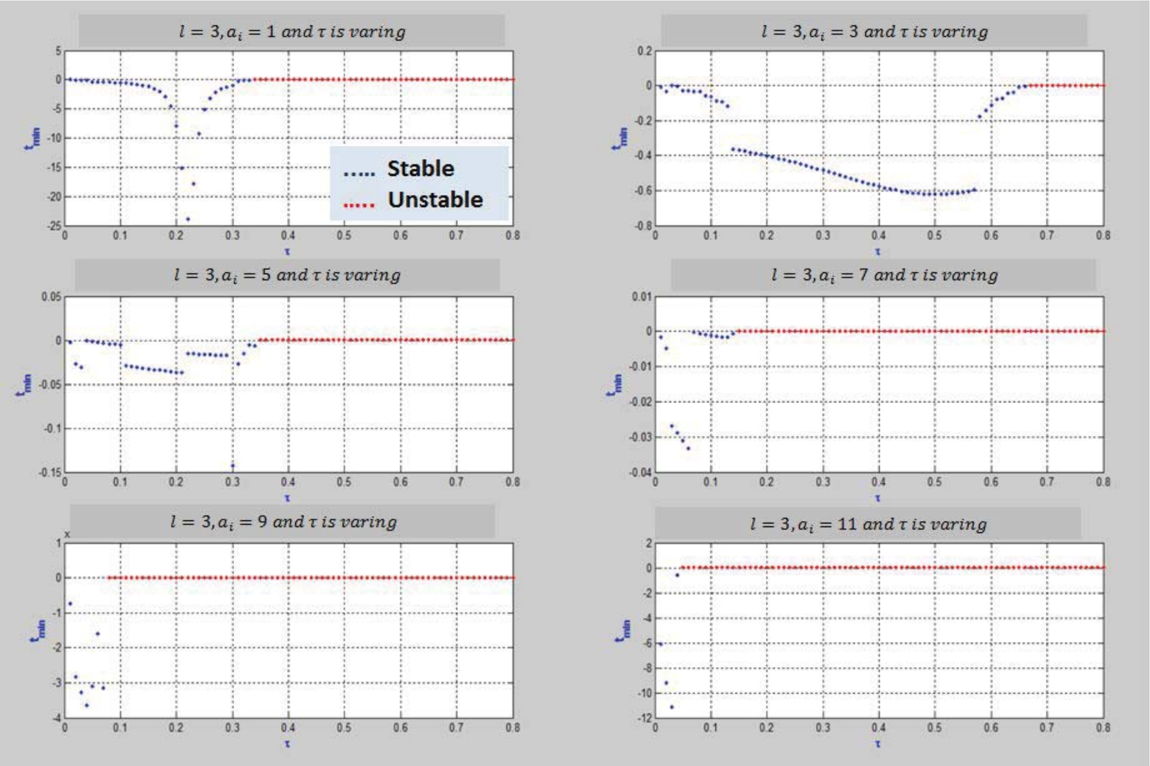


Figure 4.4: Case-2: Stable/unstable region identification of $l = 3$ for all SHAs with $a_i = 1, 3, 5, 7, 9, 11$.

The calculation results show the identification of stable region given in Figure 4.4. In this case for stable region identification, $l = 3$ is fixed and analyzed with different values of SHA parameter $a_i = 1, 3, 5, 7, 9, 11$. The stable region of given problem depends on the value of a_i. It is not easy to spot the variation of stable region in Figure 4.4. So, the calculation is repeated for different values of a_i and the results are summarized in Figure 4.5.

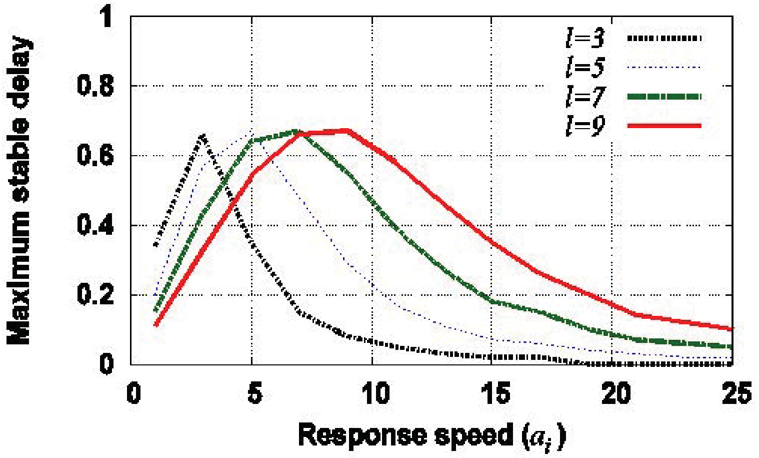


Figure 4.5: Case-2: Maximum stable delay.

From the Figure 4.5, before a_i reaching some specific value, the stable region becomes larger as a_i increases. After a_i reached the specific value, the region becomes smaller. For a fixed l the value of maximum stable delay keeps changing with the change in system parameter a_i. When $a_i = l$, maximum stable delay is reached.

4.8.3 Case-3:

The change of system parameter value of l with different values for SHA parameter a_i from one to another for all SHAs is analyzed. In this case, system parameter l changes from 1 to 20. The calculation results show the identification of stable region given in Figure 4.6, 4.7, 4.8, and 4.9. Four different combinations of a_i have been considered which are as follows:

- $a_1 = 1$, $a_2 = 3$, $a_3 = 5$
- $a_1 = 3$, $a_2 = 5$, $a_3 = 7$
- $a_1 = 5$, $a_2 = 7$, $a_3 = 9$
- $a_1 = 7$, $a_2 = 9$, $a_3 = 11$

It is not easy to spot the variation of stable region in Figure 4.6, 4.7, 4.8 and 4.9. So, the calculation is repeated for different values of l and the results are summarized in Figure 4.10. The conclusion can be stated as: if the values of SHA parameters a_i are different

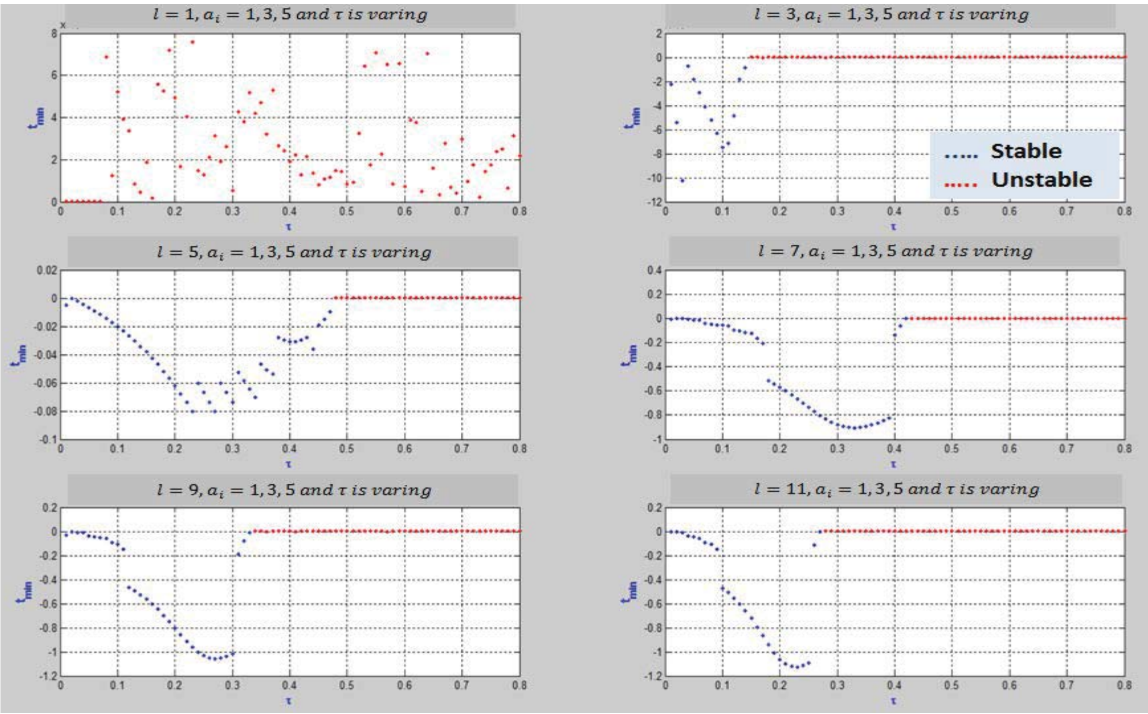


Figure 4.6: Case-3: Stable/unstable region identification of different $a_i = 1, 3, 5$ for all SHAs with $l = 1, 3, 5, 7, 9, 11$.

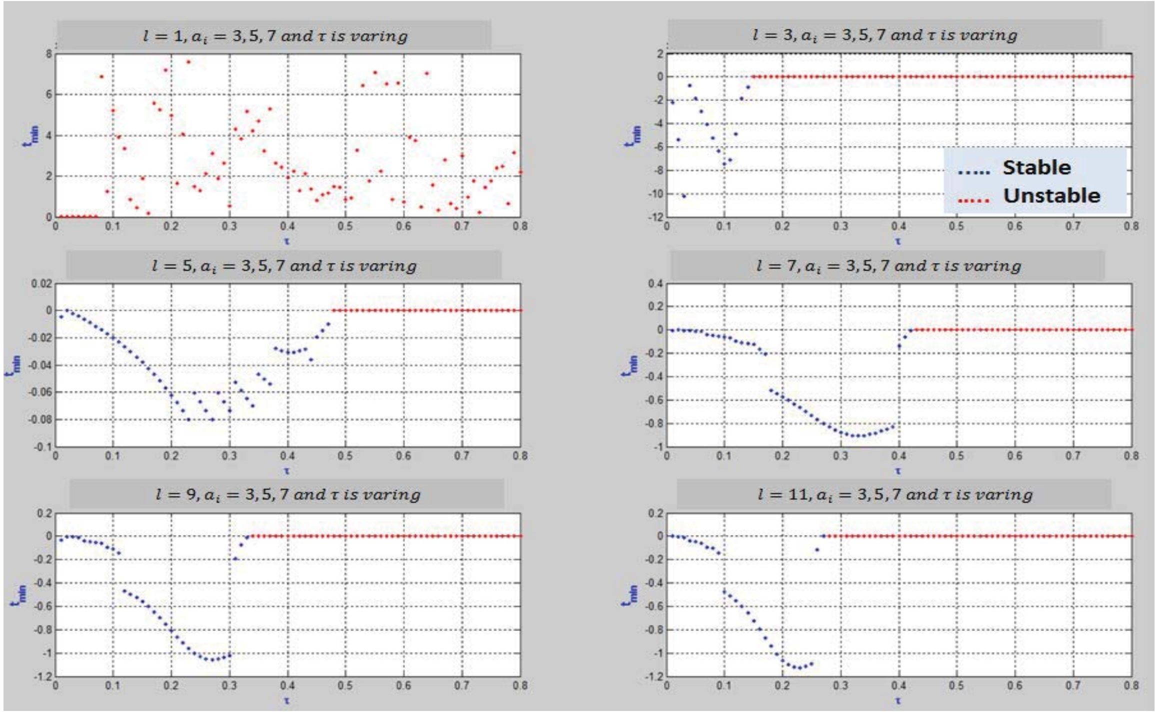


Figure 4.7: Case-3: Stable/unstable region identification of different $a_i = 3, 5, 7$ for all SHAs with $l = 1, 3, 5, 7, 9, 11$.

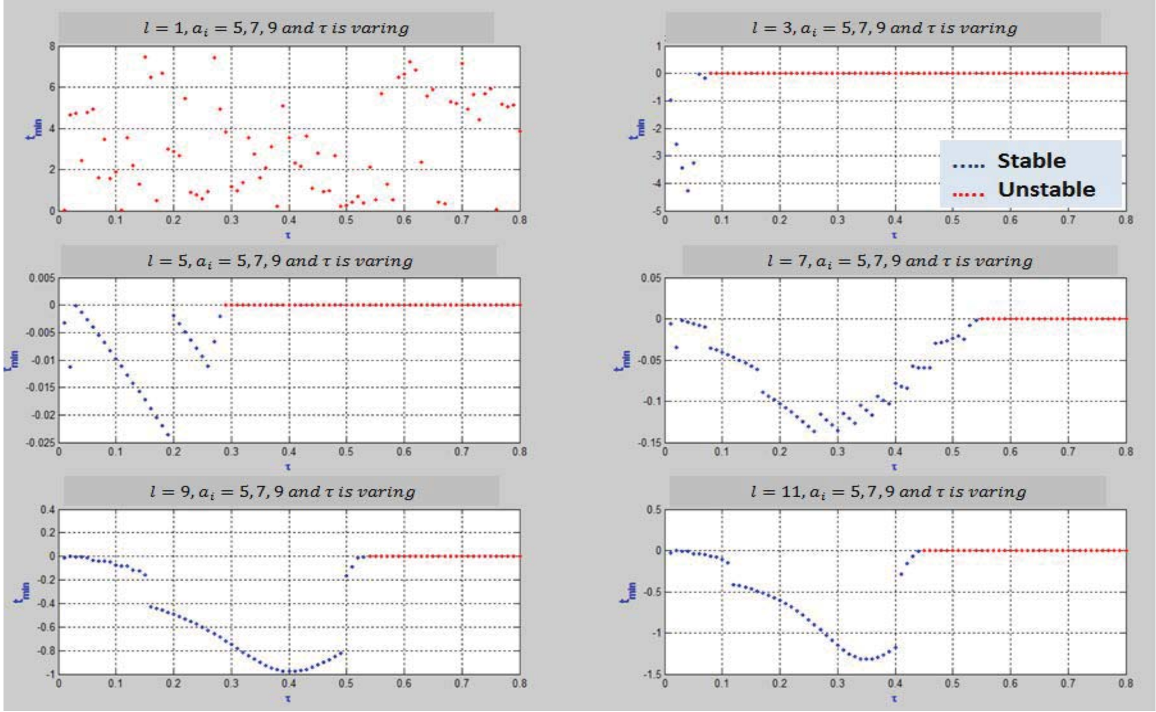


Figure 4.8: Case-3: Stable/unstable region identification of different $a_i = 5, 7, 9$ for all SHAs with $l = 1, 3, 5, 7, 9, 11$.

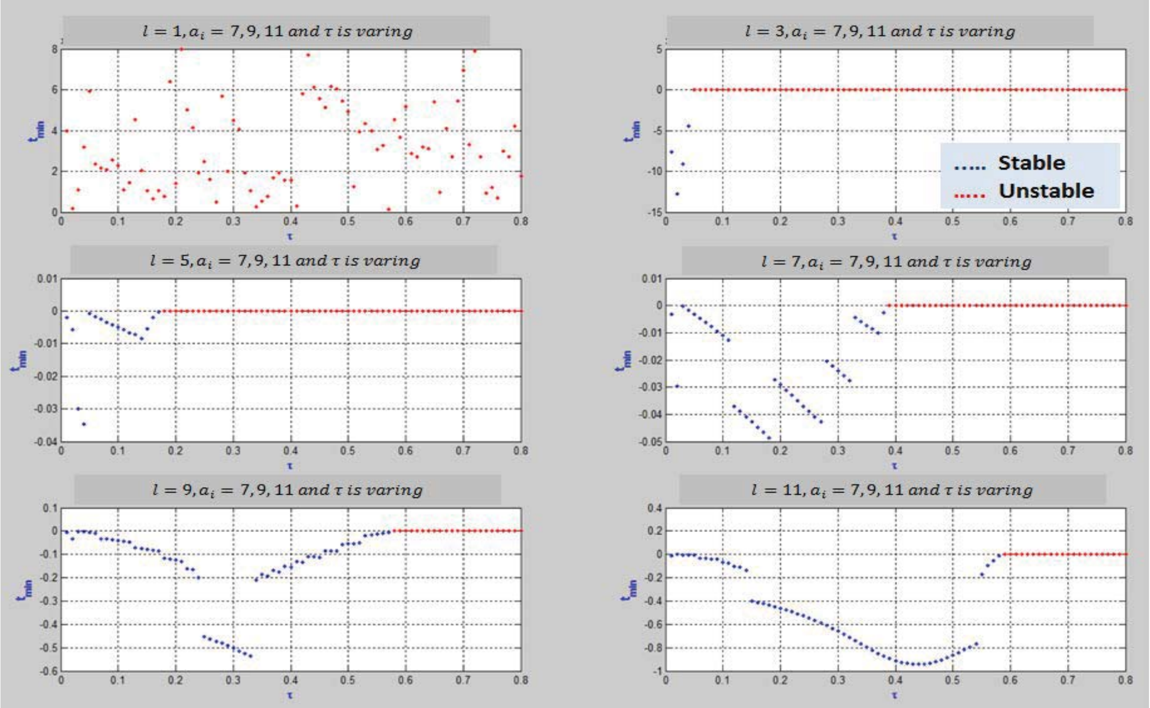


Figure 4.9: Case-3: Stable/unstable region identification of different $a_i = 7, 9, 11$ for all SHAs with $l = 1, 3, 5, 7, 9, 11$.

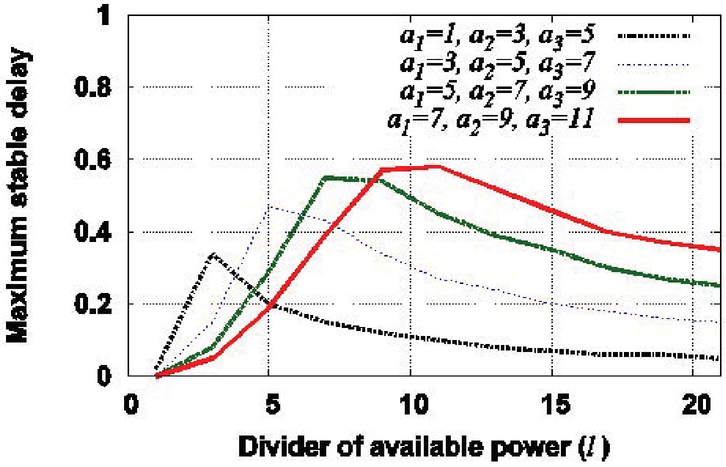


Figure 4.10: Case-3: Maximum stable delay.

from one another, maximum stable delay is different depending on the combination of a_i. The average $(a_i) = l$ give maximum stable delay.

4.9 Summary

The efficiency, reliability, and stability of the smart home system is expected to be significantly improved via smart home energy management system, and smart electric sensor is the most essential part of the energy system used to connect individual SHA to the energy management system.

Stability is one of the most important issues in a system design. In proposed system, each SHA has the parameter a_i which decides the response speed, the remaining power $R(t)$ is divided by a designer's parameter l. The information on the remaining power is fed back to each SHA with communication delay τ. There are two key parameters (i) communication delay and (ii) divider of available power and these parameters effect the critical system behaviors such as stability and overshoot of energy waveform. Therefore, there is a need to carefully design these parameters so that system would be stable and has no overshoot.

Lyapunov-Krasovskii (L-K) Stability Theorem is used as a tool to check system stability. The application of L-K stability theorem is studied by an appropriate formulation of LMI approach. The stability theorem is evaluated with the help of LMI package in MATLAB. The following conclusions are made: If the value of SHA parameter a_i is same for all SHAs, the value of maximum stable delay is almost same with any value of system parameter l. If the value of SHA parameter a_i is different from one SHA to another, the value of maximum stable delay occur when average $(a_i) = l$.

Chapter 5

Power Assignment Criteria for Smart Home Energy Management System

5.1 Introduction

There is a tendency to consume electrical energy simultaneously by home appliances leading to frequent demand peaks. Nowadays the number of appliances in modern residences has significantly increased as compared to the past. If the power demand is not met with the limited available power supply, this could lead to major power blackout. Efficient power consumption, intelligent power monitoring and interactive control of power consumption in smart homes are the key factors of sustainable development, reduction of power demand peaks and activities related to avoidance of blackout effects. Due to the continuous increase of residential electricity demand, energy consumption and management in households have received more attention in recent years.

The proposed SHemS consists of smart electric sensors (SESs) and power provisioning controller (PPC) and smart home appliances (SHAs). The PPC and SES are used to control and maintain stability with complete power waveform behavior examination. In this chapter, the main focus of study is on achieving optimal system model for smart homes to reduce the risks of power blackout by applying two different criteria of power assignment for the SHAs. A comparative study has been conducted which show the drastic change in the system behavior by changing the power assignment criteria. Simulation results also help to observe critical system behaviors such as stability and overshoot of energy waveform.

5.2 Motivation

To achieve the energy efficiency of smart homes [56], [57], which use technology to make all electronic devices in a house act “smart” or more automated, issues on both communication technologies and energy management methods in the home domain need to be addressed. On one hand, with millions of smart meters [58], sensors, and automatic control devices need to be deployed in electric power distribution grids close to residential and commercial buildings [4], which is characterized by involving a large number of intelligent machines sharing information and making collaborative decisions without direct human intervention. Issues on energy efficiency, reliability, and security of residential areas were discussed in [59] and comparisons of communication technologies and network architectures in home area networks were investigated in [60] and [61], respectively.

Due to an increase in home appliances the overall power consumption in home tends to grow and leads an increasing risk of losing stability [62]-[64]. A home energy management system is a part of the smart grid on consumption side. It is employed to get data from appliances using smart meters and sensors, and then to optimize power supply and management by using this information [65]. A conventional HEMS focus on power consumption monitoring and standby power reduction [66].

With the increasing demand for intelligent and personalized services, context-aware systems have been implemented in a smart home system to support reasoning and learning mechanisms [67]. In recent years, context-aware systems have been gradually applied to HEMS to improve energy efficiency and resident satisfaction [68], [56]. According to the user activities and requirements, these systems can reason the adaptive services by analyzing events and managing policies [69]. In Smart-Grid systems, demand-response and dynamic pricing mechanisms are introduced to curb peak power demands down below the maximum possible power supply [70].

For controlling and managing appliances, a number of energy management systems were proposed and developed. In [38], the author proposed a method to display power consumption information to the user explaining its overall goals that must be fulfilled. It also provides guidelines for the system development to reduce power consumption. In

[71], a research study showed that the feedback on power consumption to power users is effective to reduce total power usage. Pipattanasomporn et al. [5] proposed in-home appliance priority and customer comfort level settings. Gill et al. [72] proposed ZigBee based home automation system, composed of home network devices and an intelligent home gateway. Facchinetti et al. [73] presented a method for scheduling to balance the power usage in smart home system.

5.3 System Model

In particular, the focus is on achieving optimal system model for SHemS with the application of two different suggested power assignment criteria to distribute the total available power among SHAs. A comparative study has been conducted which shows the change in SHA behavior by changing suggested power assignment criteria. In the overall scenario, the SES measures the real time instantaneous consuming power levels of SHAs and sends this information to PPC. Based on this information, PPC computes the suggested power level for the SHAs. For further assumption, a communication delay (τ) is the total time of sending information from the SES to PPC, the processing time at the PPC and the sending information from the PPC to the corresponding SHA.The presence of communication delay raises the question of stability of the proposed system. The dynamics of the behavior of SHAs changes with the change in value of system parameters and introduces critical system events like stable/unstable and overshoot/non-overshoot.

Due to the communication delay and the processing time at PPC, each SHA receives its suggested power level ($S_i(t)$) from PPC which can be calculated by two different power assignment criteria given as:

1. Equal Based Power Assignment (EBPA) Criteria
2. Ratio Based Power Assignment (RBPA) Criteria

These power control criteria are used as approximated power control system models based on continuous time models for proposed SHemS. The main objectives of these power control criteria are to maintain stability and achieve fast system response.

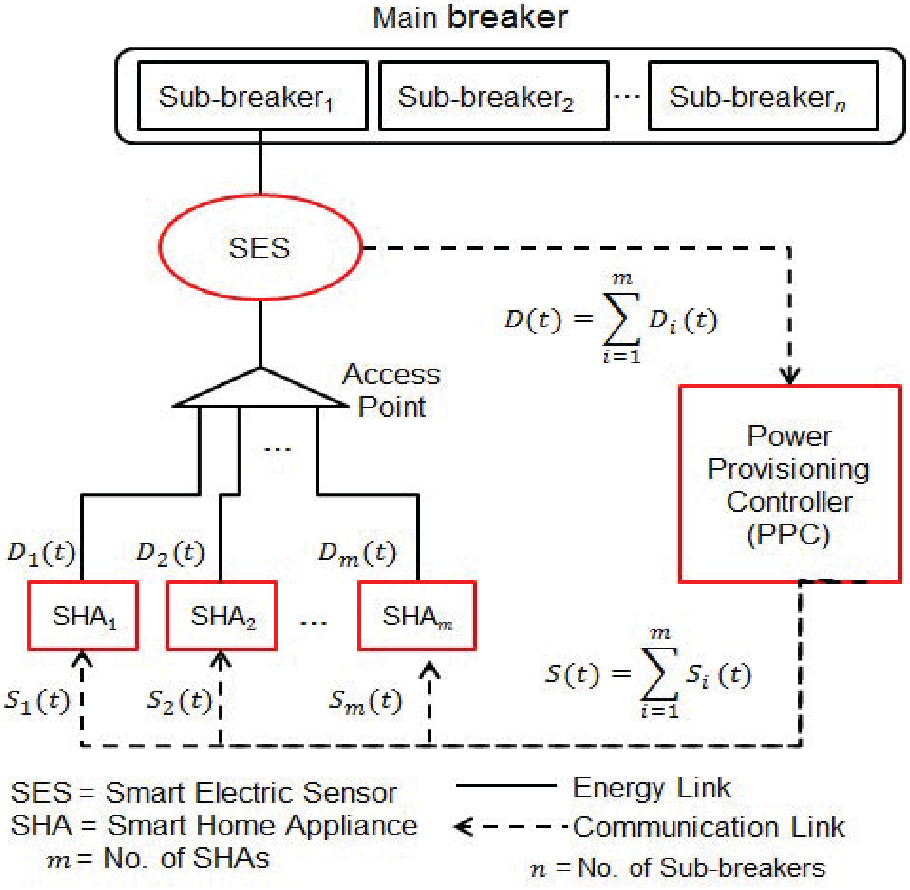


Figure 5.1: System Model.

5.4 Equal Based Power Assignment (EBPA) Criteria

In EBPA criteria, the total power P is distributed among SHAs equally based on system parameter l. Where, l is the designer's parameter also called divisor of remaining power $R(t)$ which is available for all attached SHAs. A SHA can change its power consumption level upon receiving the "suggested power level, $S_i(t)$" from PPC, that performs intelligent computing upon receiving the information of "instantaneous consuming power level, $D_i(t)$" of each SHA from SES. The transfer of information of $D_i(t)$ from SES to PPC and then suggested power level for each SHA from PPC to SHA with some communication delay τ.

In this criteria, PPC computes "suggested power level" for each SHA based on following criteria:

$$S_i(t) = \frac{R(t-\tau)}{l} \tag{5.1}$$

In this criteria, PPC divides the total remaining power by l, and sends this information i.e. $S_i(t)$ to the SHAs. Where, m is the total no. of SHAs and it should be $m \leq l$ (concluded from previous chapter).

5.4.1 Simulation Environment and Setup

For simulation of proposed power assignment criteria, each SHA is associated with a_i and D_i^{max} which decide the response speed and maximum consuming power level. The information of suggested power level is fed back to each SHA with communication delay ($\tau = 1.0$ second) from PPC. In the simulation execution with EBPA criteria, the system parameter value is $l = 3$, the suggested value that can achieve system stability from previous study [81].

For simulation, three SHAs are attached with one SES for clarity of explanation (see Figure 5.1). The total power available for all SHAs is $P = 2kW$. The total simulation execution time is 10 seconds. A computer simulation is conducted to analyze proposed power assignment criteria. The values used for a_i and D_i^{max} parameters are different for each simulation execution.

5.4.2 Simulation Objectives

The main objectives of simulation are to analyze the proposed system behavior with different PPC power assignment criteria to check (i) Total available power distribution among SHAs (ii) Effects of change in SHA response speed (iii) Effects of different turn ON timing and (iv) Effects of system parameters on power overshoot.

5.4.3 Effects of Change in SHA Response Speed

At first, all three SHAs are turned on at the same time. The response speed and maximum consuming power level for all SHAs are kept same as shown in the Figure 5.2. All three SHAs share the available power equally with $l = 3$. In this case, the proposed system show the stable behavior without any power overshoot. Obviously the total available power ($P = 2kW$) is not sufficient for all three SHAs to reach maximum consuming power level required by SHAs. Accordingly, the SHAs will saturate at the maximum

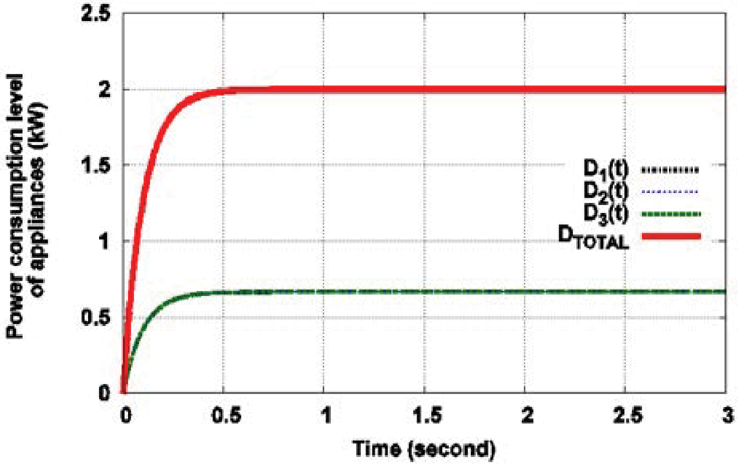


Figure 5.2: Power consumption behavior of EBPA criteria with $a_i = 10$ and $D_i^{max} = 1.0$ kW (for SHA $i = 1, 2, 3$).

power level lower than the SHAs maximum consuming power level. This is the total power distribution evenly among SHAs.

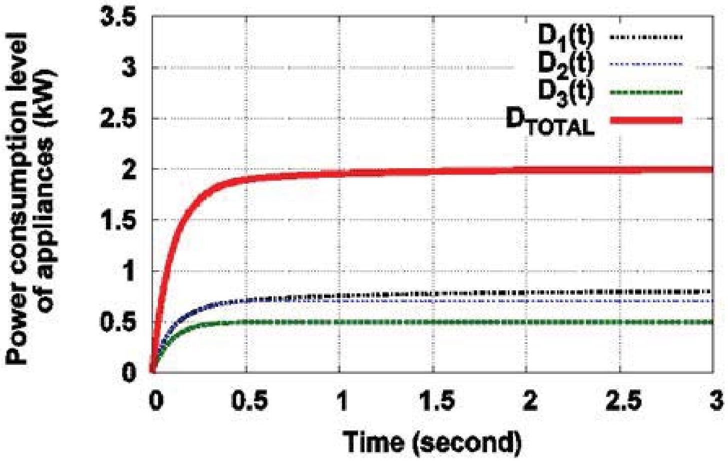


Figure 5.3: Power consumption behavior of EBPA criteria with $a_i = 10$ and $D_i^{max} = 1.0, 0.7, 0.5$ kW (for SHA $i = 1, 2, 3$).

In second experiment, the SHAs have different D_i^{max} and the same a_i . The two SHAs with smaller D_i^{max} reach to their required maximum consuming power level (see Figure 5.3). The remaining SHA saturates at a level lower than its required maximum consuming power. In this case, system is stable all the times and there is no power overshoot.

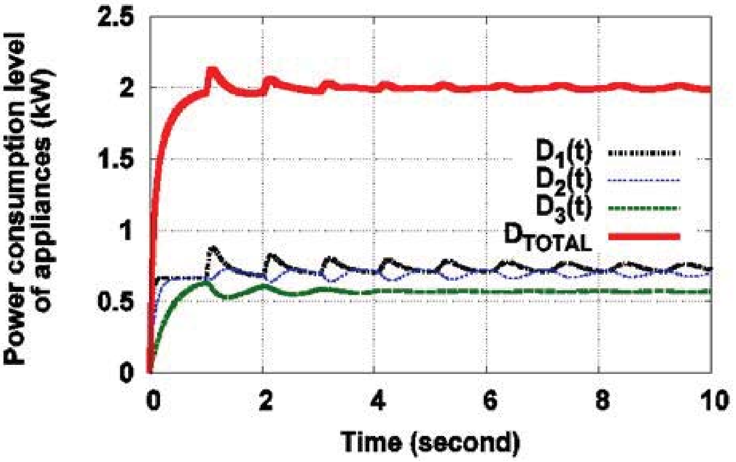


Figure 5.4: Power consumption behavior of EBPA criteria with $a_i = 30, 10, 3$ and $D_i^{max} = 1.0, 0.7, 0.5$ kW (for SHA $i = 1, 2, 3$).

5.4.4 Effects of Power Overshoot

In experiment result given in Figure 5.4, the proposed system observe overshoot with different a_i for SHAs. Both the response speed and maximum consuming power levels are different for all SHAs. As with this result of EBPA criteria, the conclusion can be made that if the time constant for each SHA is different with same or different maximum consuming power levels, the proposed criteria cannot guarantee maximum power limit.

For overall conclusion, with the same D_i^{max} or different D_i^{max}, if the system parameter a_i is the same, then the system will be stable all the times with EBPA criteria.

5.4.5 Effects of Turn ON Timings of EBPA Criteria

Next in experiment, the effects of turn ON timing of the SHAs are observed on the final available power sharing. The three SHAs having: $a_i = 30, 10, 3$ and $D_i^{max} = 1.0, 0.7, 0.5$ kW while the turn ON times are $t = 0$, $t = 2.0$, and $t = 3.5$ seconds. In this experiment the SHAs have different a_i and D_i^{max} values from each other. The SHA which is turned ON first was found to use more available power while the last turned ON SHA gets the smallest part of available power (see Figure 5.5).

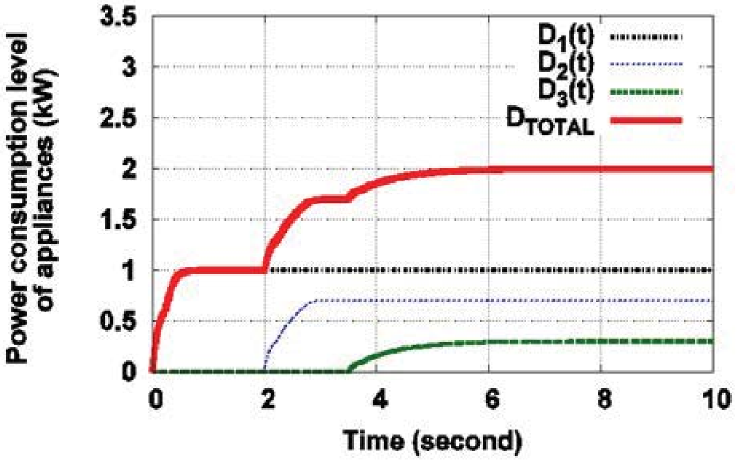


Figure 5.5: Testing the effect of turn ON time with EBPA criteria.

5.5 Ratio Based Power Assignment (RBPA) Criteria

In this criteria, "suggested power level" calculation have been modified to include a new factor r_i which is the individual remaining power of a SHA. It can be calculated as:

$$r_i(t-\tau) = D_i^{max} - D_i(t-\tau) \tag{5.2}$$

In RBPA criteria, the total power P is distributed among SHAs according to the need of the each SHA based on $r_i(t-\tau)$. A SHA can change its power consumption level upon receiving the "suggested power level, $(S_i(t))$" from PPC, that performs intelligent computing upon receiving the information of "instantaneous consuming power level $(D_i(t))$" of each SHA from SES. The transfer of information of $D_i(t)$ from SES to PPC and then suggested power level for each SHA from PPC to SHA with some communication delay (τ).

In this criteria, PPC computes "suggested power level" for each SHA based on following criteria:

$$S_i(t) = \frac{r_i(t-\tau)}{\sum_{i=1}^{m} r_i(t-\tau)} \cdot R(t-\tau) \tag{5.3}$$

The same system model as given in Figure 5.1 has been considered for this power control criteria. The functions of PPC are to calculate the total remaining power for the SHAs and also the individual SHA remaining power, $r_i(t-\tau)$, that a SHA needs to reach to its maximum consuming power level.

5.5.1 Simulation Environment and Setup

For simulation of proposed power assignment criteria, each SHA is associated with a_i and D_i^{max} which decide the response speed and maximum consuming power level. The information of suggested power level is fed back to each SHA with communication delay ($\tau = 1.0$ second) from PPC.

For simulation, three SHAs are attached with one SES. The total power available for all SHAs is $P = 2kW$. The total simulation execution time is 10 seconds. A computer simulation is conducted to analyze proposed power control criteria. The values used for a_i and D_i^{max} parameters are different for each simulation execution.

5.5.2 Effects of Change in SHA Response Speed

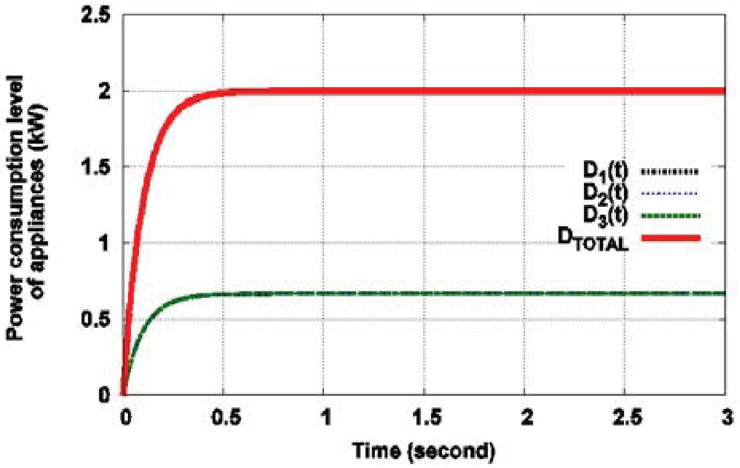


Figure 5.6: Power consumption behavior of RBPA criteria with $a_i = 10$ and $D_i^{max} = 1.0$ kW (for SHA $i = 1, 2, 3$).

At first, all three SHAs are turned on at the same time. The response speed and maximum consuming power levels for all SHAs are kept same as shown in the Figure 5.6. All three SHAs share the available power according to each SHA need. In this case, the proposed system show the stable behavior without any power overshoot. Obviously the total available power ($P = 2kW$) is not sufficient for all three SHAs to reach maximum consuming power level required by SHAs. Accordingly, the SHAs will saturate at the maximum power level lower than the SHAs maximum consuming power level. This is the total power distribution among SHAs based on their individual requirement to reach

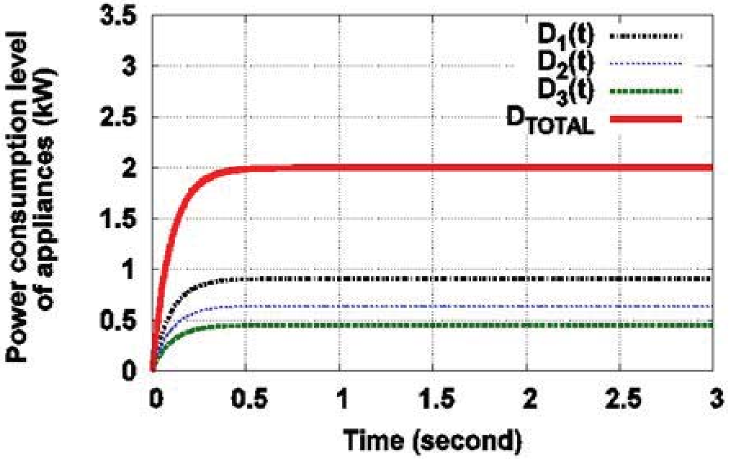


Figure 5.7: Power consumption behavior of RBPA criteria with $a_i = 10$ and $D_i^{max} = 1.0, 0.7, 0.5\ kW$ (for SHA $i = 1, 2, 3$).

maximum consuming power level.

In second experiment, the SHAs have different D_i^{max} and the same a_i. Although none of the SHA reach to its maximum consuming power level but each SHA take enough part from available power to reach its maximum consuming power level (see Figure 5.7). In this case, system is stable all the times and there is no power overshoot.

5.5.3 Effects of Power Overshoot

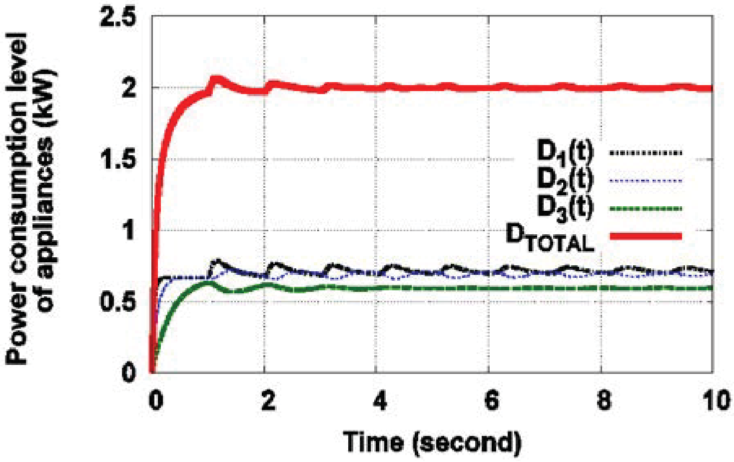


Figure 5.8: Power consumption behavior of RBPA criteria with $a_i = 30, 10, 3$ and $D_i^{max} = 1.0, 0.7, 0.5\ kW$ (for SHA $i = 1, 2, 3$).

In this experiment result of RBPA criteria, the system encounter power overshoot

(Figure 5.8). Both with same or different D_i^{max} the proposed criteria observe power overshoot. As both simulation results are nearly same so only one is presented here. The conclusion can be made that if the time constant for each SHA is same, the maximum power limit can be maintained. However, if the time constant for each SHA is different the proposed scheme cannot guarantee maximum power limit.

For overall conclusion, with the same D_i^{max} or different D_i^{max}, if the system parameter a_i is the same then the system will be stable in either of the proposed power assignment criteria.

5.5.4 Effects of Turn ON Timings of RBPA Criteria

Next in experiment, the effects of turn ON timing of the SHAs are observed on the final available power sharing. SHAs having: $a_i = 30, 10, 3$ and $D_i^{max} = 1.0, 0.7, 0.5\ kW$ while the turn ON times are 0, 2.0, and 3.5 seconds. In this experiment the SHAs have different a_i and D_i^{max} values from each other. In Figure 5.9, RBPA is shown, both having the same values of system parameters. The SHA which is turned ON first was found to use more available power while the last turned ON SHA gets the smallest part of available power.

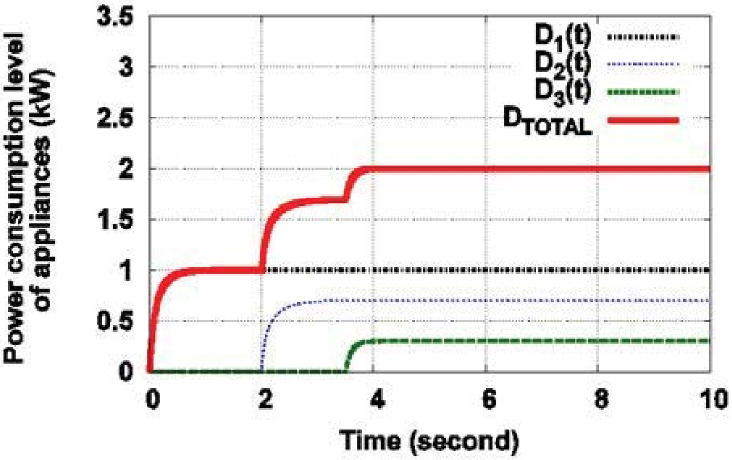


Figure 5.9: Testing the effect of turn ON time with RBPA criteria.

5.6 Comparative Study of EBPA and RBPA Criteria

A comparative study has been conducted which shows the change in SHA behavior by changing suggested power assignment criteria (see Table 5.1). In proposed system design

Table 5.1: Border estimation for overshoot/non-overshoot and stable/unstable

Power assignment Criteria	a_i	D_i^{max}	Overshoot/ or not?	Stable Time
RBPA	$a_i = 10$	$D_i^{max} = 1.0$	No	Stable all the time
		$D_1^{max} = 1.0$ $D_2^{max} = 0.7$ $D_3^{max} = 0.5$		
	$a_1 = 30$ $a_2 = 10$ $a_3 = 3$	$D_i^{max} = 1.0$	Yes	Stable at $t = 2.13s$
		$D_1^{max} = 1.0$ $D_2^{max} = 0.7$ $D_3^{max} = 0.5$	Yes	Stable at $t = 1.49s$
EBPA	$a_i = 10$	$D_i^{max} = 1.0$	No	Stable all the time
		$D_1^{max} = 1.0$ $D_2^{max} = 0.7$ $D_3^{max} = 0.5$		
	$a_1 = 30$ $a_2 = 10$ $a_3 = 3$	$D_i^{max} = 1.0$	Yes	Stable at $t = 2.08s$
		$D_1^{max} = 1.0$ $D_2^{max} = 0.7$ $D_3^{max} = 0.5$	Yes	Stable at $t = 2.00s$

for smart homes, there are two main contributions (i) communication delay and (ii) comparison between two suggested power assignment criteria for SHAs. These contributions affect critical system power behavior, stable/unstable or in other words overshoot/non-overshoot. Therefore, there is a need to choose the communication delay carefully so that the system would be stable with no power overshoot.

From table 5.1, the 1st row of RBPA and EBPA criteria have the same behavior (see Figures 5.2 and 5.6). All three SHAs share the available power equally with same values of system parameters a_i and D_i^{max}. In these cases, the system show stable behavior without any power overshoot.

The 2nd row of RBPA is similar to the above situation. Now the SHAs have different D_i^{max} but the same a_i, still the suggested power level is less than the required maximum consuming power level of each SHA (see Fig. 5.3 and 5.7). In this case again there is no power overshoot.

Only the 3rd and 4th rows of RBPA assignment criteria encounter power overshoot. The 3rd has same D_i^{max} but different a_i while the latter is vice versa. The 4th row of RBPA behavior can be seen in Figure 5.8, the other one was omitted for sme result observed.

In the 2nd row of EBPA, (like 2nd row of RBPA) the SHAs have different D_i^{max} and the same a_i. The two SHAs with smaller a_i reaches to their maximum required consuming power level (see Fig. 5.4). The remaining SHA saturates at a level lower than its required maximum consuming power level.

Finally both the 3rd and 4th rows of EBPA encounter power overshoot. Both have different a_i, the former has same D_i^{max} while the latter has different values of D_i^{max}. As with the 3rd and 4th rows of RBPA, only the 4th row of EBPA behavior shown in Figure 5.4.

The conclusion can be made that if the time constant for each SHA is same, the maximum power limit can be maintained. However, if the time constant for each SHA is different the proposed scheme cannot guarantee maximum power limit.

Also, with same D_i^{max} or different D_i^{max}, if the system parameter a_i is the same, then the system will be stable in either of the proposed power assignment criteria.

5.7 Effects of Communication Delay with EBPA and RBPA Criteria

Different communication delay (τ) values, SHA response speed (a_i) and maximum consuming power level (D_i^{max}) were tried and still similar behavior was observed. From 3rd and 4th rows of RBPA and EBPA having different values of the system parameter a_i causes the proposed system to experience power overshoot regardless of having same or different D_i^{max} values. With EBPA, power overshoot happens faster than with the RBPA criteria. On the other hand, RBPA (as compared to EBPA criteria) takes less time to recover to stability after power overshoot first happens.

In last experiment, the effect of different delays have been tested to the final available power sharing. In Figure 5.10 and 5.11 the total consumed power is shown for different delay values for both EBPA and RBPA criteria respectively.

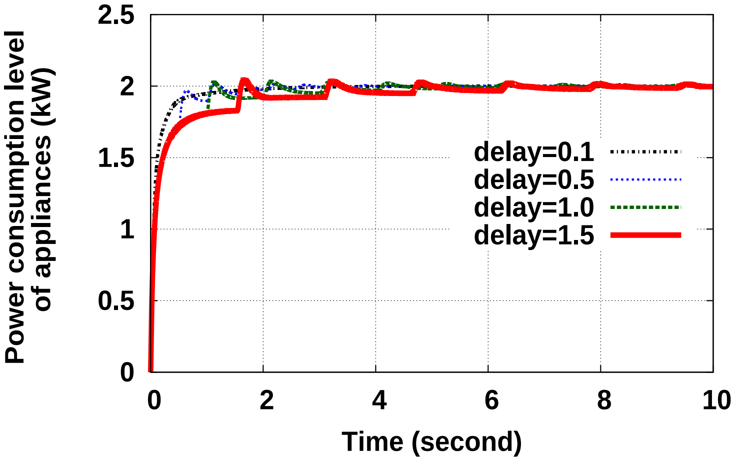


Figure 5.10: Testing the effect of delay with EBPA criteria.

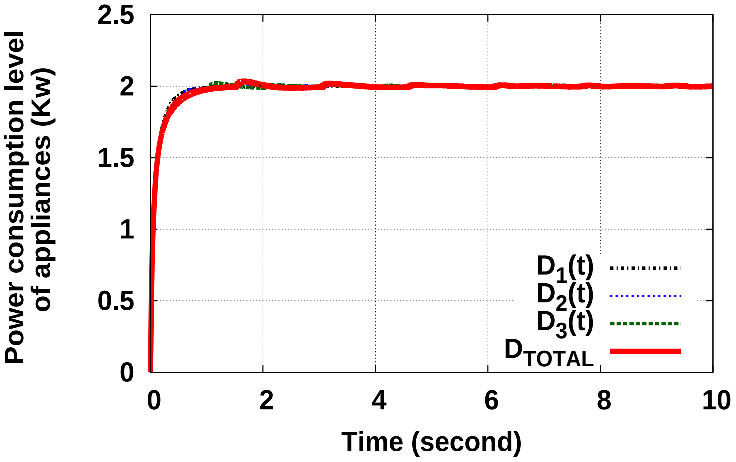


Figure 5.11: Testing the effect of delay with RBPA criteria.

For the different communication delay values the other system parameters are kept same as in the previous experiment. Only the turn ON time is changed to the beginning of the simulation. With the EBPA criteria the effects of communication delay causes more changes in the system total consumed power. While in the case of RBPA criteria the changes are quite less. In both power assignment criteria, the very small delay saves the system from having overshooting. As the communication delay starts growing to a more practical range both proposed criteria starts to exhibit overshooting at different times and with different overshooting duration and magnitudes.

5.8 Summary

In summary, the smart homes can be defined as a residence equipped with computing and information technology which anticipates and responds to the needs of the occupants, working to promote their comfort, convenience, security and entertainment through the management of technology within the home. The stability of smart home system can be significantly improved via SES and PPC.

The use of SES measures the instantaneous consuming power level from the SHAs. The functions of PPC are to gather ON/OFF status from each SHA, instantaneous consuming power $D_i(t)$ from SESs and calculate the remaining power and suggested power level for all SHAs.

In proposed system design for smart homes, there are two key contributions; first communication delay and second two suggested power assignment criteria for SHAs. The simulation results show that the dependency of system parameter a_i (SHA response speed) in the system behavior such as stable/unstable, in other words overshoot/non-overshoot for both of the proposed power assignment criteria. Also notice the effect of different turn ON timing on total power consumption distribution for both of the proposed power assignment criteria.

Chapter 6

Power Control Schemes for Smart Home Energy Management System

6.1 Introduction

There is a tendency to consume electrical energy simultaneously by home appliances leading to frequent demand peaks. Nowadays the number of appliances in modern residences has significantly increased as compared to the past. If the power demand is not met with the limited available power supply, this could lead to major power blackout. Efficient power consumption, intelligent power monitoring and interactive control of power consumption in smart homes are the key factors of sustainable development, reduction of power demand peaks and activities related to avoidance of blackout effects.

Due to the continuous increase of residential electricity demand, energy consumption and management in households have received more attention in recent years. The highlight of the proposed SHemS is its ability to control maximum consuming power of the SHAs based on SHA priority. In this chapter, the main focus is to achieve optimal system model for power control by apply different power control schemes. The proposed SHemS consists of SESs, SHAs and a PPC. The PPC and SESs are used concurrently to control and maintain stability and complete power waveform behavior examination. The role of PPC is to gather ON/OFF status from each SHA and instantaneous consuming power level from SES, and to send control signal back to each SHA. After gathering information along with SHA priority, PPC computes a final target power level for each SHA is not a hard task. However, when ON/OFF status of SHAs change, there is a need to reassign an amount of consuming power from one SHA to another, and the transient behavior due to such reassignment of power is not simple. This chapter proposes a system to control the maximum total power consumption in detailed transient behavior considering heterogeneous SHAs with different time constants. In order to guarantee the maximum power limit, the remaining power is computed, and reassign to SHAs as their temporal target power levels. Simulation results show the effectiveness of proposed system in managing maximum power consumption.

6.2 Motivation

The objective of moving to the smart homes is enhancing comfortable and environment-friendly unique lifestyle for each individual. But this way leads to the worst situation of energy shortage. The high power required by SHAs makes our home one of the most critical areas for the impact of power consumption. The maximum power consumption of the appliances in the user's residence should not exceed a certain power limit. In [76], [77], and [78] several approaches were provided and compared to reduce peak power consumption. In these existing studies, there is a lack of power assignment analysis among appliances and effects on home appliance behavior. In [79] and [40], communication between appliances and controller is held through message exchange but there is a lack of consideration for communication delay in message exchange procedure in the overall system scenario. This is the important contribution and was found to be main factor of the system stability. Kato et al. [80] developed the energy on demand system for single commercial utility power source and proposed demand negotiation algorithm for power sharing scheme to control overall power consumption but there is a lack of detailed power waveform analysis.

For proposed scenario of SHemS the SHAs considered to have different priority levels. The high priority SHAs are always allowed to use power until their maximum consuming power levels. Conversely, the low priority SHAs have to restrict their operation according to the remaining power. Though, with the change in ON/OFF status of SHAs, there is a need to reassign a part of consuming power from one SHA to another SHA, as a result the transient behavior due to reassignment of power is not simple. This chapter offers a system to control the maximum total power consumption in detailed transient behavior considering different SHAs with different time constants. In order to guarantee the maximum power borderline, the remaining power is calculated, and reassign to SHAs as their temporal target power levels. Simulation results show the efficiency of proposed system in managing maximum power consumption.

In general, priority of the SHAs is also an important study in HEMS, but the transient behavior issues for detailed analysis are neglected in many research studies. To control and maintain stability the detailed behavior analysis is very important. So, priority issue in proposed system to control maximum power consumption below the certain power limit has been considered. Communication delay and communication interval between SES and PPC are also key factors in system stability and performance criteria that we should consider as well.

To balance the power consumed and supply of the SHAs, two types of power control schemes have been proposed based on the SHA priority. These are as follows:

1. Priority Based Final Power (PBFP) Scheme
2. Priority Based Power Sharing (PBPS) Scheme

These two power control schemes are practical power control models for proposed SHemS based on discrete time models. The main objective of these power control schemes is to achieve user's satisfaction through SHA priority.

6.3 System Model

In proposed power control schemes of SHemS, SHAs considered to have different priority levels. The aim of the proposed system is to implement a control algorithm for maximum power consumption of SHAs based on SHA priority so that total power consumption does not exceed a certain limit. The proposed system model consists of SHAs, SESs and PPC. An example of such a system is illustrated in Figure 6.1.

There is an assumption that each instantaneous consuming power $D_i(t)$ of SHA is modeled by the first order state equation,

$$\dot{D}_i(t) = -a_i \cdot D_i(t) + a_i \cdot F_i \tag{6.1}$$

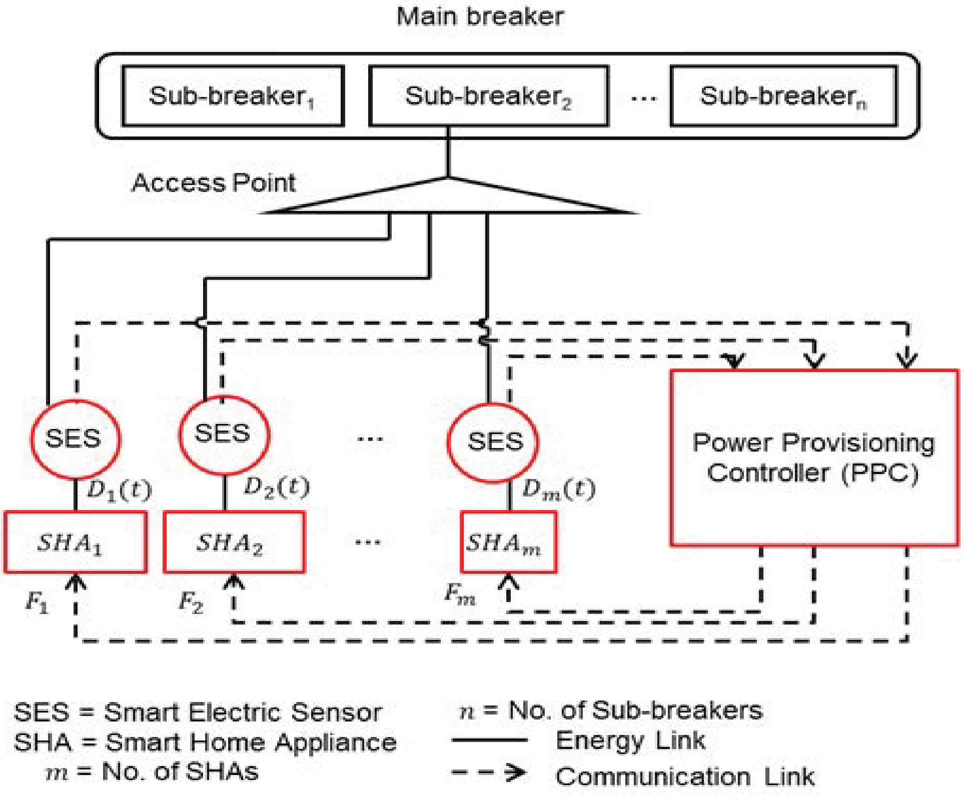


Figure 6.1: System model.

where parameter a_i decides the response speed, and F_i decides the steady state response (also named as “final power level”). It is clear that with the assumption that

$$D_i(0) = D_{init_i}, \tag{6.2}$$

$D_i(t)$ will be given as

$$D_i(t) = (D_{init_i} - F_i) \cdot e^{-a_i \cdot t} + F_i \tag{6.3}$$

Each SHA has maximum consuming power level D_i^{max}. SESs will help in measuring the instantaneous consuming power levels of SHAs, $D_i(t)$ and send this information to PPC. The functions of PPC are to collect both ON/OFF status from each SHA and instantaneous consuming power level $D_i(t)$ from SES. After gathering information, along with SHA priority, PPC computes a final power level for each SHA, F_i. Upon receiving a message from PPC, each SHA behave according to the final power level. Additionally consider that a communication delay $(\tau)[s]$ is the total time of the sending information from the SES to the PPC, the processing time at PPC, and the sending information from the PPC to the corresponding SHA.

6.4 System Control for Maximum Consuming Power

As the proposed schemes work with message exchange between SHAs, SESs and PPC. For this purpose, an interval T_c is defined for consecutive communications between SHAs, SESs and PPC. In Figure 6.2, two time variables are considered, one is global time t and other is local time x in each interval.

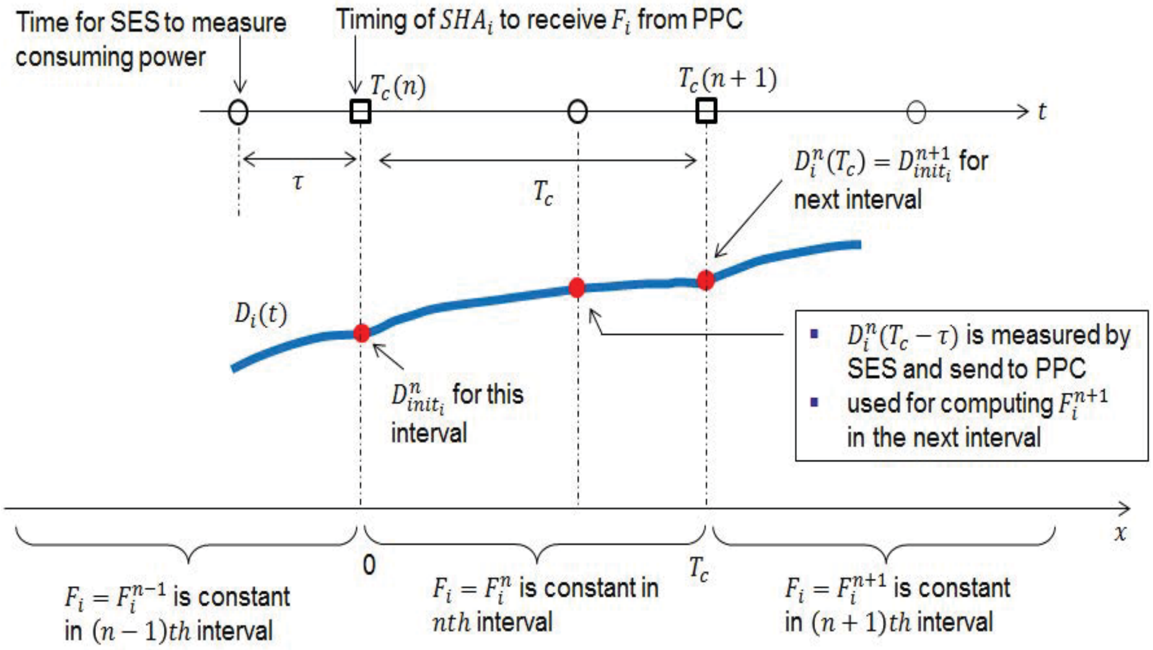


Figure 6.2: Time variables consideration.

An interval starting at nT_c and ending at $(n+1)T_c$ is called "interval n" and all variables related to interval n are denoted with superscript (n), such as:

$$D_i^{(n)}(x) = \left(D_{init_i}^{(n)} - F_i^{(n)}\right) \cdot e^{-a_i \cdot x} + F_i^{(n)} \tag{6.4}$$

Note that $D_{init_i}^{(n)}$ is the initial value $D_i^{(n)}(0)$ of the interval n, and is the same with the last value $D_i^{(n-1)}(T_c)$ of the previous interval $n-1$. T_c is a designer's parameter but $\tau \leq T_c$ is more realistic and should be considered because if $\tau > T_c$, PPC needs to compute another information which would overlap with the other information. When the communication interval n starts, each SHA receives the information of final power level $F_i^{(n)}$ from PPC, and the last value $D_i^{(n-1)}(T_c)$ is used as $D_{init_i}^{(n)}$ for this interval. Final power level $F_i^{(n)}$ would remain constant during this interval.

6.5 Priority Based Final Power (PBFP) Scheme

In this proposed PBFP criteria for smart homes to control maximum power consumption by SHAs based on SHA priority. The role of PPC is to gather ON/OFF status from each SHA and instantaneous consuming power level from SES, and to send control signal back to each SHA. After gathering information, along with SHA priority, computes a final target power level for each SHA is not a hard task. However, when ON/OFF status of SHAs change, there is a need to reassign an amount of consuming power from one SHA to another, and the transient behavior due to such reassignment of power is not simple.

6.5.1 Final Power Level

As PPC assigns final power level $F_i^{(n)}$ for the SHAs which can be calculated as:

$$F_i^{(n)} = \begin{cases} D_i^{max}, & \text{if } P_{limit} - \sum F_j^{(n)} \geq D_i^{max} \\ 0, & \text{if SHA is OFF} \\ P_{limit} - \sum F_j^{(n)}, & \text{if } P_{limit} - \sum F_j^{(n)} < D_i^{max} \end{cases} \tag{6.5}$$

The above equation works with priority, if the priority of ith SHA is higher than the other turned ON SHAs, PPC assigns final power level to the ith SHA as its maximum consuming power level $(i.e. D_i^{max})$. On the contrary, the remaining power is assigned to the lower priority SHAs. In proposed criteria, the total power available limit for all SHAs is P_{limit} and total consuming power at time x in the interval n can be denoted as:

$$\begin{aligned} P^{(n)}(x) &= \sum_{i=1}^{m} D_i^{(n)}(x) \\ &= \sum_{i=1}^{m} \left(D_{init_i}^{(n)} - F_i^{(n)} \right) \cdot e^{-a_i \cdot x} + F_i^{(n)} \end{aligned} \tag{6.6}$$

$$P^{(n)}(0) = \sum_{i=1}^{m} D_{init_i}^{(n)} \tag{6.7}$$

$$P^{(n)}(\infty) = \sum_{i=1}^{m} F_i^{(n)} \tag{6.8}$$

At first, consider the case when all SHAs have same a_i.

$$\begin{aligned} P^{(n)}(x) &= \sum_{i=1}^{m} \left\{ \left(D_{init_i}^{(n)} - F_i^{(n)} \right) \cdot e^{-a \cdot x} + F_i^{(n)} \right\} \\ &= \left\{ \left(\sum_{i=1}^{m} D_{init_i}^{(n)} - \sum_{i=1}^{m} F_i^{(n)} \right) \cdot e^{-a \cdot x} + \sum_{i=1}^{m} F_i^{(n)} \right\} \end{aligned} \tag{6.9}$$

If

$$\sum_{i=1}^{m} D_{init_i}^{(n)} \leq P_{limit} \tag{6.10}$$

and

$$\sum_{i=1}^{m} F_i^{(n)} \leq P_{limit} \tag{6.11}$$

then

$$P^{(n)}(x) \leq P_{limit} \tag{6.12}$$

for $0 \leq x < \infty$.

6.6 Simulation Objective and Scenario

The objective of the simulation is to observe and verify the system behavior and try to show that the power limit is maintained appropriately. Simulation results also show the effectiveness of SHA priority on total available power distribution among SHAs and to achieve home owner satisfaction level. There are two key parameters in simulation scenario and they are (i) communication interval and (ii) communication delay. Simulation results also help in observing the effects of these key parameters on system overall behavior.

For the simulation scenario of experiment, three SESs attached with three SHAs. The maximum consuming power levels of three SHAs are $D_1^{max} = 1.0\ kW$ (highest priority), $D_2^{max} = 0.7\ kW$ (2nd highest priority), and $D_3^{max} = 0.5\ kW$ (lowest priority). The total power limit for SHAs is $P_{limit} = 1.5\ kW$.

6.6.1 Effects of SHA Response Speed

Simulation results for effects of SHA response speed can noticed from Figure 6.3 and Figure 6.4. It can be noticed that if the time constant for each SHA is same, the maximum power limit can be maintained appropriately. However, if the time constant for each SHA is different the proposed scheme for calculating final power level cannot guarantee maximum power limitation (Figure 6.4). So, there is a need to introduce the concept of reassignment of actual remaining power.

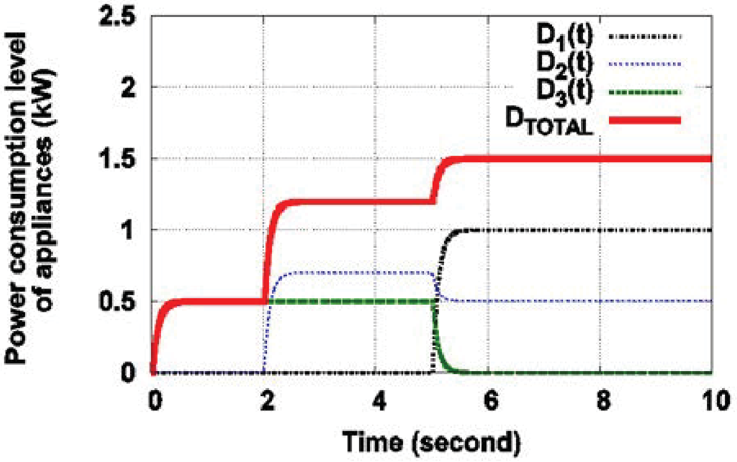


Figure 6.3: Power consumption behavior of SHAs with $a_i = 10$, turn ON time of SHA_1 is $t = 5$, turn ON time of SHA_2 is $t = 2$, and turn ON time of SHA_3 is $t = 0$.

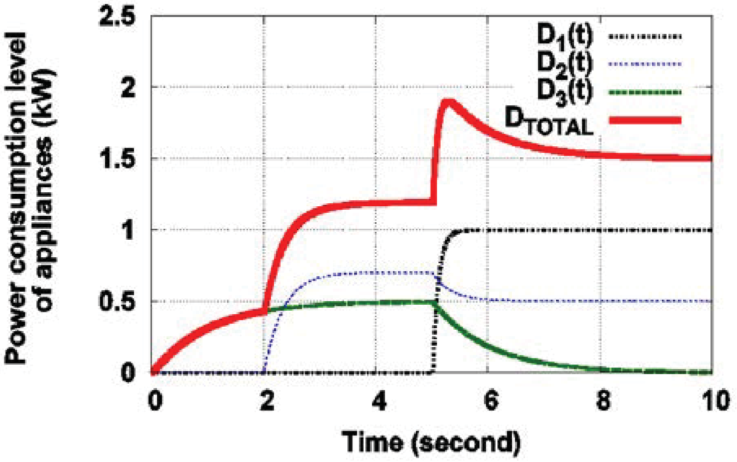


Figure 6.4: Power consumption behavior of SHAs with $a_1 = 10$, $a_2 = 3$, and $a_3 = 1$, turn ON time of SHA_1 is $t = 5$, turn ON time of SHA_2 is $t = 2$, and turn ON time of SHA_3 is $t = 0$.

6.6.2 Effects of Communication Delay and Interval

In this case the simulation is presented to observe the effects of system parameters, communication delay τ and communication interval T_c, to the total power consumption waveform. As for the first experiment in this section, investigate the power consumption behavior of SHAs when communication delay is fixed to $\tau = 0.2$ and communication interval changes to $T_c = 0.21$, $T_c = 0.45$, and $T_c = 0.75$, and the result is shown in Figure 6.5.

As in next simulation result, investigate the power consumption behavior of SHAs when communication interval is fixed to $T_c = 0.5$ and communication delay changes to $\tau = 0.05$, $\tau = 0.25$, and $\tau = 0.49$, and the result is shown in Figure 6.6.

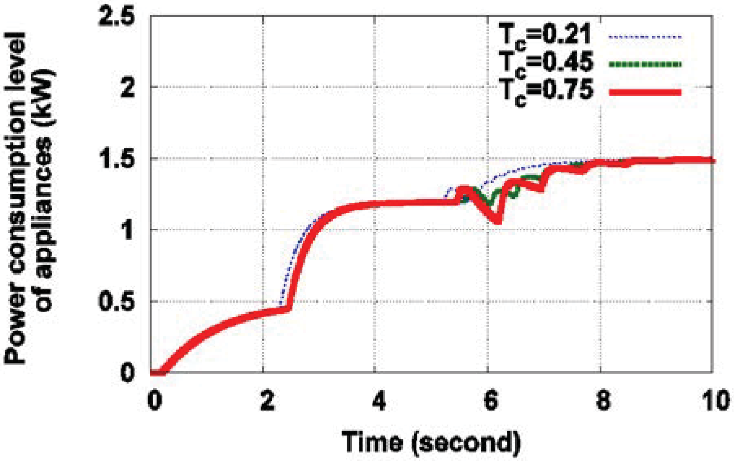


Figure 6.5: Total power consumption behavior with different T_c and fixed $\tau = 0.2$. Three SHAs have $a_1 = 10$, $a_2 = 3$, and $a_3 = 1$, respectively, and turn ON time of SHA_1 is $t = 5$, turn ON time of SHA_2 is $t = 2$, and turn ON time of SHA_3 is $t = 0$.

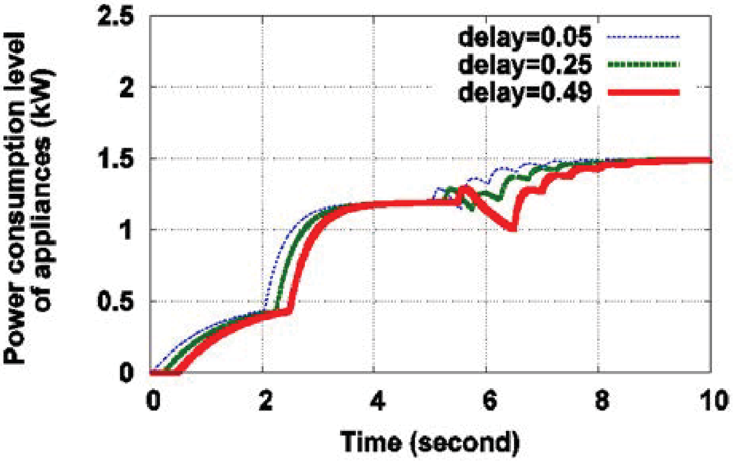


Figure 6.6: Total power consumption behavior with different τ and fixed $T_c = 0.5$. Three SHAs have $a_1 = 10$, $a_2 = 3$, and $a_3 = 1$, respectively, and turn ON time of SHA_1 is $t = 5$, turn ON time of SHA_2 is $t = 2$, and turn ON time of SHA_3 is $t = 0$.

From Figure 6.5, proposed system showed the power consumption behavior which does not change by changing the system parameter T_c. The detailed waveform of power consumption of SHAs is obviously different depending on the value of system parameters but the envelope of total power consumption waveform is remained same for different T_cs. On the other hand, from Figure 6.6, the information found that the parameter communication delay (τ) affects not only the detailed waveform but also the envelop of power consumption waveform. The larger τ tends to slow down the changing speed of the envelope.

When a SHA reduces its power, the power decreasing speed of SHA can be determined by the system parameter a_i. However, when a SHA increases its power, the power increasing speed of SHA depends on remaining power. If the remaining power is sufficient, SHA can achieve its maximum increasing speed which is determined by system parameter a_i, but if the remaining power is not enough, the increasing speed slows down. Therefore, total power consumption limit does not exceed the available power limit.

6.7 PBFP Scheme with Overshoot Control

In order to solve the overshoot problem observed with ideal power level algorithm, detailed power assignment algorithm has been proposed. In this algorithm, the ideal power level defined in the previous section (denoted as $F^{(n)}_{ideal_i}$) is considered as overall final power level, while the final power level for each interval $F_i^{(n)}$ is computed based on the estimation of the actual remaining power at the beginning of the interval.

6.7.1 Detailed Power Assignment Algorithm

As PPC only knows the information of $D_i(t-\tau)$ in order to assign $F_i^{(n)}$ for the next interval thus PPC has to guess remaining power based on the $D_i(t-\tau)$ and $F_i^{(n-1)}$ and takes the maximum value. By taking the maximum value, the worst case remaining power of the system estimation is considered which reassigns to the SHAs based on the SHA priority.

In order to keep the maximum power limit, the remaining power is always estimated. For the proposed system, estimated remaining power is given by:

$$remain = \sum_{i=1}^{m} max\left\{D_i(t-\tau), F_i^{(n-1)}\right\} \tag{6.13}$$

Considering the robustness of the proposed system and ability to maintain the maximum power level, the worst case remaining power is used with this estimation. For which the maximum power consumption between the power limit is guaranteed. The estimated actual remaining power is assigned to each SHA. The pseudo code for computing $F_i^{(n)}$ is as follows:

```
if $\left(\left(F_{ideal_i}^{(n)} - F_i^{(n-1)} \geq 0\right)$
 and $\left(F_{ideal_i}^{(n)} - F_i^{(n-1)} \leq remain\right)\right)$ then
  $F_i^{(n)} = F_{ideal_i}^{(n)}$;
  $remain = remain - \left(F_{ideal_i}^{(n)} - F_i^{(n-1)}\right)$;
else
  if $\left(\left(F_{ideal_i}^{(n)} - F_i^{(n-1)} \geq 0\right)$
   and $\left(F_{ideal_i}^{(n)} - F_i^{(n-1)} > remain\right)\right)$ then
    $F^{(n)} = F_i^{(n-1)} + remain$;
    $remain = 0.0$;
  else
    if $\left(F_{ideal_i}^{(n)} - F_i^{(n-1)} < 0\right)$ then
      $F_i^{(n)} = F_{ideal_i}^{(n)}$;
    end if
  end if
end if
```

6.7.2 Effects of Power Overshoot Control

The main goal of this chapter is to prevent the situation when total power consumption of all SHAs in smart home exceeds the available power limit. PPC calculates the remaining power and reassigne to SHAs according to their priority. Considering the robustness of the proposed system and the ability to maintain the maximum power, the worst case remaining power is used. With this estimation, the maximum power consumption between the power limit is guaranteed (see Figure 6.7).

The proposed system is analyzed in simulation environment and verified that the total power limit for SHAs is maintained appropriately. From simulation results, It is

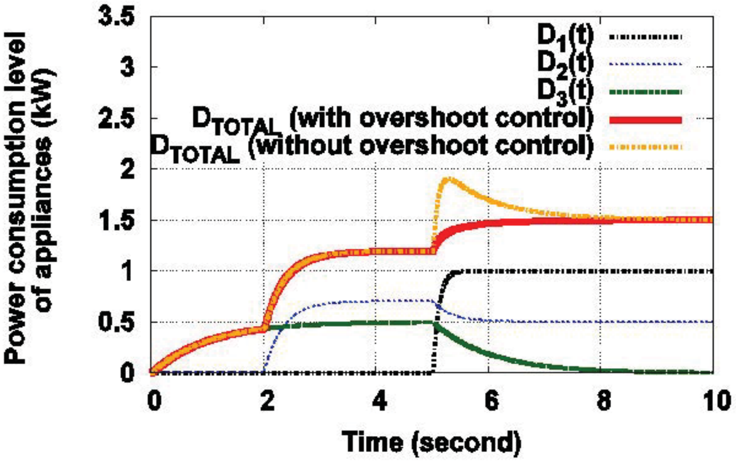


Figure 6.7: Total power consumption behavior with overshoot control. Three SHAs have $a_1 = 10$, $a_2 = 3$, and $a_3 = 1$, and turn ON time of SHA_1 is $t = 5$, turn ON time of SHA_2 is $t = 2$, and turn ON time of SHA_3 is $t = 0$.

identified that the change of system parameter T_c does not affect the envelope of the detailed consuming power waveform, but the communication delay τ affects the changing speed of the envelope. This shows the robustness of the proposed system against the communication interval but there is a need to carefully manage the communication delay.

6.8 Priority Based Power Sharing (PBPS) Scheme

The center notion of our proposed system is priority of a SHA. SHA priority is used to share total available power among all active (attached) SHAs. This is because some of SHAs are more important than the others in home. To satisfy this significant criterion, priority is given to each SHA. At first, the system will choose the higher priority SHAs and suggests higher satisfaction power level for them as compared to lower priority SHAs. To calculate suggested power level for each SHA, a priority based power sharing (PBPS) scheme has been proposed, which allows the home user to operate their SHAs according to their corresponding priority level.

Initially, a home user assigns given priority G_{pri_i} for each SHA. The proposed SHemS use two other types of priorities; calculated priority C_{pri_i} and normalized priority N_{pri_i}. The first C_{pri_i} changes with each iteration according to the ON/OFF status and SHA satisfaction power level based on its maximum consuming power level (D_i^{max}), it can be represented as:

$$C_{pri_i} = \begin{cases} 0, & \text{if } D_i(t) = D_i^{max} \\ G_{pri_i}, & \text{if } D_i(t) < D_i^{max} \end{cases} \tag{6.14}$$

The second priority is called, normalized priority N_{pri_i} which can be calculated as:

$$N_{pri_i}(t) = \frac{C_{pri_i(t)}}{\sum_{i=1}^{m} C_{pri_i(t)}} \tag{6.15}$$

If $\sum_{i=1}^{m} C_{pri_i}(t) = 0$, states either all SHAs are OFF or have been completely satisfied with their maximum consuming power level. If $\sum_{i=1}^{m} C_{pri_i}(t) > 0$, then some SHAs are still not completely satisfied and PPC will keep tuning the suggested power level, $S_i(t)$ as:

$$S_i(t) = \begin{cases} D_i^{max}, & \text{if } R(t) \cdot N_{pri_i} + D_i(t) \geq D_i^{max} \\ R(t) \cdot N_{pri_i} + D_i(t), & \text{if } R(t) \cdot N_{pri_i} + D_i(t) < D_i^{max} \end{cases} \tag{6.16}$$

The initial value of the suggested power level $S_i(t)$ is assumed zero. The initial value of remaining power $R(0)$ can be deduced which would be equal to the total available power P. In each iteration, the tuned suggested power level is refined and PPC re-compute the calculated priority, the normalized priority and remaining power. If $R(t) = 0$, states that there is no more power to distribute among SHAs and some SHAs cannot be totally shared. In this situation, SHA will receive its current calculated final suggested power level. If $R(t) > 0$ and $\sum_{i=1}^{m} C_{pri_i}(t) > 0$, the PPC need to keep tuning $S_i(t)$ until $R(t) = 0$ or $\sum_{i=1}^{m} C_{pri_i}(t) = 0$, and send last $S_i(t)$ to the SHAs.

6.8.1 Simulation Objective and Scenario

The objective of the simulation is to verify the system behavior and try to show that the power sharing criteria based on PBPS scheme. For simulation scenario of proposed system, three SHAs attached with three SESs has beeen considered. Throughout the simulation, both the communication delay (τ) and synchronization time (t_{SYNC}) are assumed to be 0.02 seconds.

The maximum consuming power levels for all three SHAs are same as $D_i^{max} = 0.7kW$ and total power available for all SHAs is $P = 1.5kW$. It is obvious that, the total power available is not enough for three SHAs to reach their maximum consuming power level at the same time.

6.8.2 Effects of SHA Priority

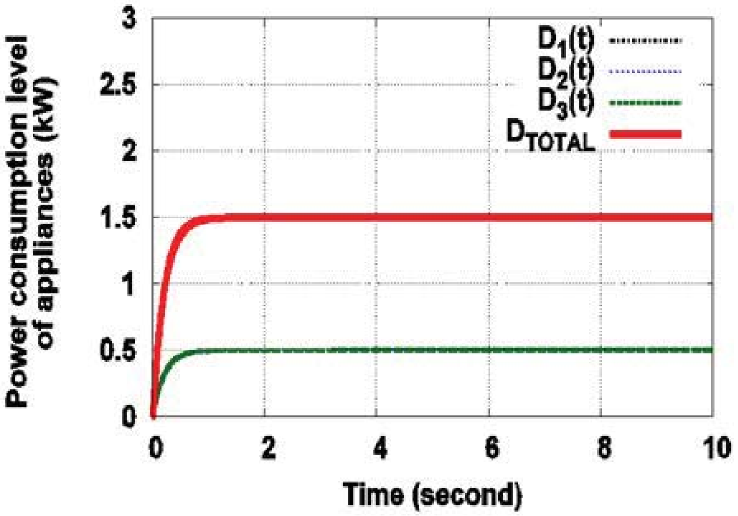


Figure 6.8: Power consumption behavior of SHAs with $a_i = 7$ and same turn ON time for all SHAs with same priority for all SHAs $G_{pri_i} = 5$.

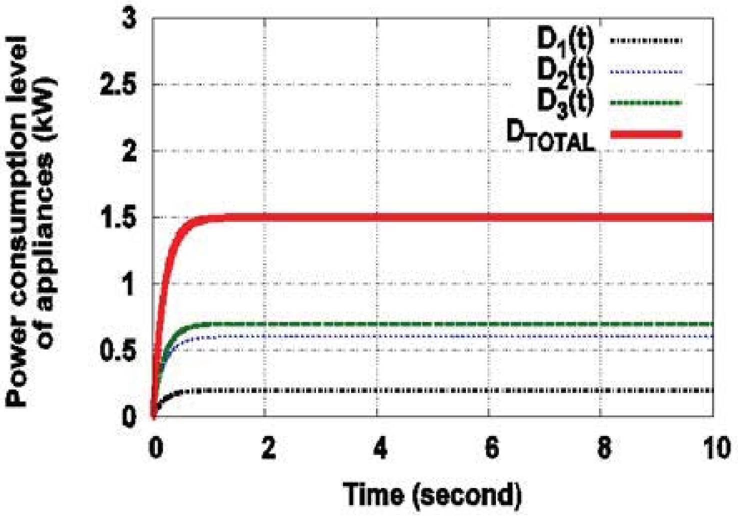


Figure 6.9: Power consumption behavior of SHAs with $a_i = 7$ and same turn ON time for all SHAs with same priority for all SHAs $G_{pri_1} = 1$, $G_{pri_2} = 3$, and $G_{pri_3} = 7$ respectively.

In Figure 6.7, all three SHAs have same value of a_i, D_i^{max} and the given priority G_{pri_i}

and shared the available power equally. However, in Figure 6.8, the situation when G_{pri_i} is different for each SHA is considered. In this scenario, the SHA with high priority takes more power from the available power (i.e., PPC satisfied the SHA more).

6.8.3 Effects of Turn ON Timing on SHA Priority

Next, the effects of the turn ON time of the SHAs to the total available power sharing has been considered as depicted in Figure 6.10, 6.11 and 6.12. In Figure 6.10, before turning ON the higher priority SHA, the already running lower priority SHAs are assigned and reached high power level; the remaining power will be unsatisfactory for the newly turned ON high priority SHA. In this case, PPC suggests the lower priority SHAs to release some power for the high priority SHA to reach better satisfaction level.

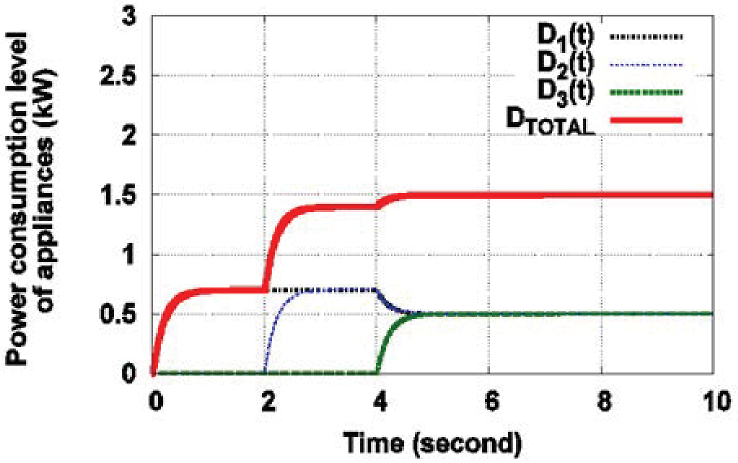


Figure 6.10: Power consumption behavior of SHAs with $a_i = 7$ different priorities for SHAs are $G_{pri_1} = 1$, $G_{pri_2} = 3$, and $G_{pri_3} = 7$, respectively and turn ON time of SHA_1 is $t = 0$, SHA_2 is $t = 2$ and SHA_3 is $t = 4$.

If the response speed for each SHA is same, the maximum power limit can be maintained. However, if the response speeds are different, the proposed PBPS scheme cannot guarantee maximum power limitation. At time $t = 4s$ overshoot is visible. Since the rate of change of instantaneous consuming power level of a SHA which is turned ON later is faster than the rate of change of instantaneous consuming power level of a SHA which is losing power for the higher priority SHA, power overshoot is noticed (as shown in Figure 6.12).

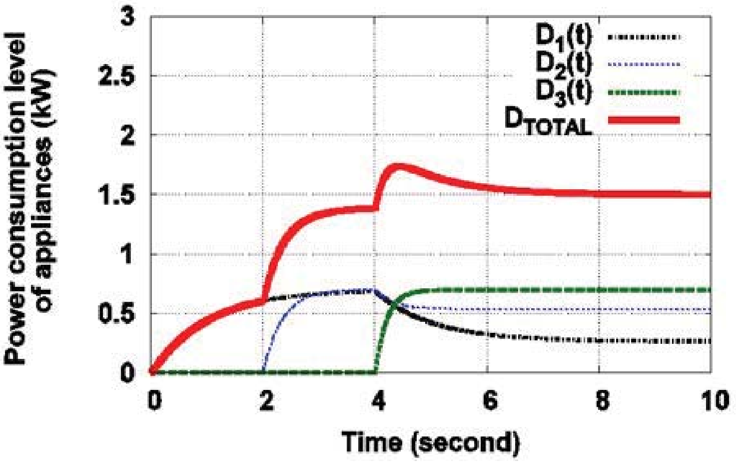


Figure 6.11: Power consumption behavior of SHAs with $a_1 = 1, a_2 = 3, a_3 = 10$ different priorities for SHAs are $G_{pri_1} = 1$, $G_{pri_2} = 3$, and $G_{pri_3} = 7$, respectively and turn ON time of SHA_1 and SHA_2 is $t = 0$ and SHA_3 is $t = 4$.

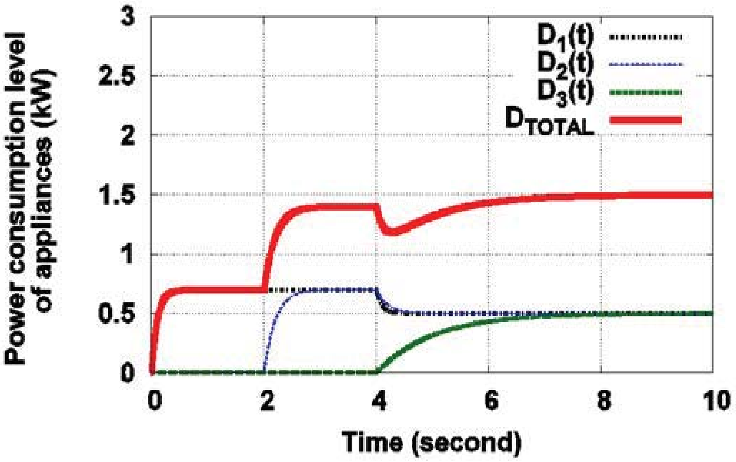


Figure 6.12: Power consumption behavior of SHAs with $a_1 = 10, a_2 = 3, a_3 = 1$ different priorities for SHAs are $G_{pri_1} = 1$, $G_{pri_2} = 3$, and $G_{pri_3} = 7$, respectively and turn ON time of SHA_1 is $t = 0$, SHA_2 and SHA_3 is $t = 4$.

On the contrary, if the rate of change of instantaneous consuming power level of a SHA which is turned ON later is slower than the rate of change of instantaneous consuming power level that is losing power, no overshoot is experienced (as shown in Figure 6.13).

As from the simulations it is visible that the maximum power limitation with PBPS scheme cannot guaranteed. So, there is a need to introduce the concept of limiting the reassignment of remaining power by proposing PBPS scheme with power overshoot control.

It is clear that the proposed overshooting control kept the maximum consuming power level below the total available power limit by delaying the saturation of the newly turning ON SHA.

6.9 PBPS Scheme with Power Overshoot Control

In order to solve the power overshoot problem observed with PBPS scheme, the proposed maximum consuming power control that is designed to guarantee the total power consumption below the specified limit. The $D_i(t)$ will be modified as:

$$D_i(t) = (D_i(t-\tau) - Ls_i(t)) \cdot e^{a_i \cdot (\tau)} + Ls_i(t) \tag{6.17}$$

In this algorithm, the suggested power level defined in the previous section $S_i(t)$ is considered as initial suggested power level, while the limited suggested power level for each interval, $Ls_i(t)$ can be calculated as in Figure 6.13. Where, $ER(t)$ (estimated remaining power) is calculated as:

$$ER(t) = \sum_{i=1}^{m} max(D_i(t-\tau), Ls_i(t-\tau)) \tag{6.18}$$

PPC has to guess remaining power level based on the $D_i(t-\tau)$ and $Ls_i(t-1)$ by taking their maximum. For sake of the robustness of our proposed system and ability to maintain the maximum power level, the estimated remaining power is used. The proposed modifications to control overshoot depend on three inputs: the suggested power level $S_i(t)$ from the previously proposed PBPS scheme, the limited suggested power level from previous interval $Ls_i(t-1)$ together with the $D_i(t-\tau)$ from SES.

Considering the case, new suggested power level is more than or equal to the old limited suggested power level. This situation reveals that the SHA should increase power in the next interval, depending on the estimated remaining power level available. The PPC will set limited suggested power level as suggested power level. If the amount of increase is more than the estimated power level, PPC gives all the estimated remaining power to this SHA and there would be no more power for the remaining SHAs.

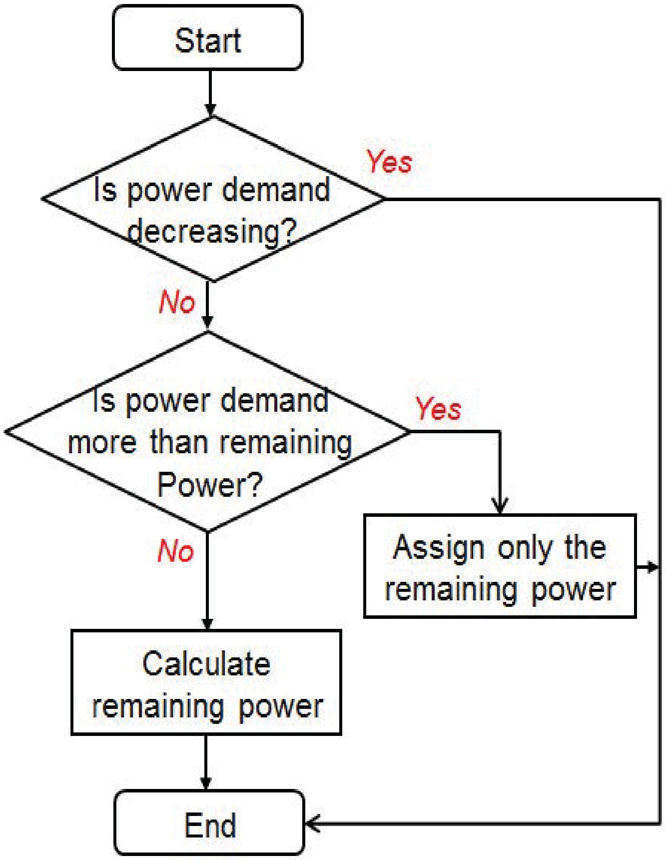


Figure 6.13: Calculation of limited suggested power Ls_i.

6.9.1 Effects of Power Overshoot Control

The case, when the new suggested power is less than the old limited suggested power level, means that the SHA should decrease power in the next interval. In this case, PPC sets the limited suggested power level as suggested power level. The released power will not be used in this interval to provide the safety margin to avoid overshoot.

In Figure 6.14, comparison is shown between the system with and without power overshoot control (PBPS scheme) using the same parameters as in Figure 6.11. It is clear that the proposed power overshoot control kept the maximum consuming power level below the total available power limit by delaying the saturation of the newly turning ON SHA.

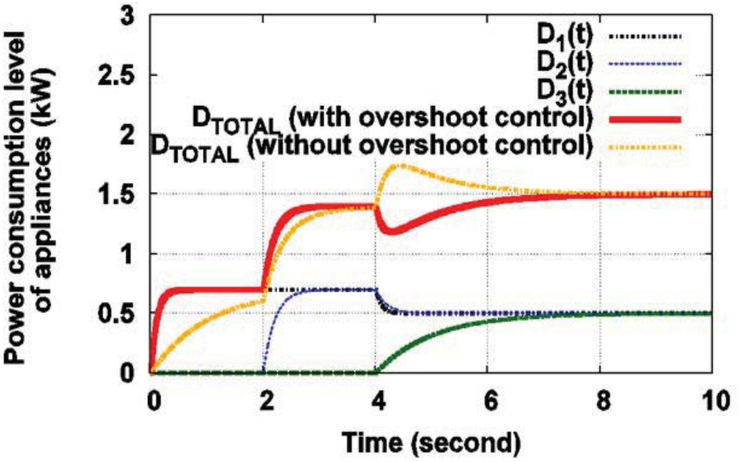


Figure 6.14: Power consumption behavior of SHAs with $a_1 = 1, a_2 = 3, a_3 = 10$ different priorities for SHAs are $G_{pri_1} = 1, G_{pri_2} = 3, G_{pri_3} = 7$, respectively and turn ON time of SHA_1, SHA_2 is $t = 0$, and SHA_3 is $t = 4$

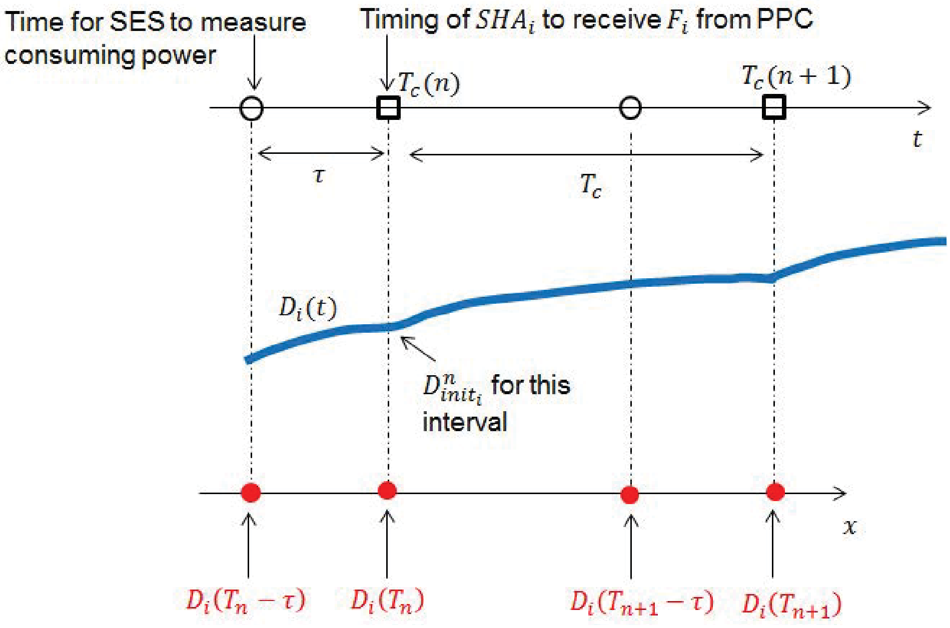


Figure 6.15: Discrete time stability model

6.10 Discrete Time Stability Analysis

For discrete time stability model, the proposed system will focus on four points: $D_i(T_n - \tau)$, $D_i(T_n)$, $D_i(T_{n+1} - \tau)$ and $D_i(T_{n+1})$ (see Figure 6.15).By considering the power consumption equation of SHA given as:

$$\dot{D}_i(t) = -a_i \cdot D_i(t) + a_i \cdot F_i \tag{6.19}$$

The final target power level can be calculated as:

$$F_i = \begin{cases} D_i^{max}, & \text{if } R(nT-\tau)\cdot N_{pri_i} + D_i(nT-\tau) \geq D_i^{max} \\ R(nT-\tau)\cdot N_{pri_i} + D_i(nT-\tau), & \text{if } R(nT-\tau)\cdot N_{pri_i} + D_i(nT-\tau) < D_i^{max} \end{cases} \tag{6.20}$$

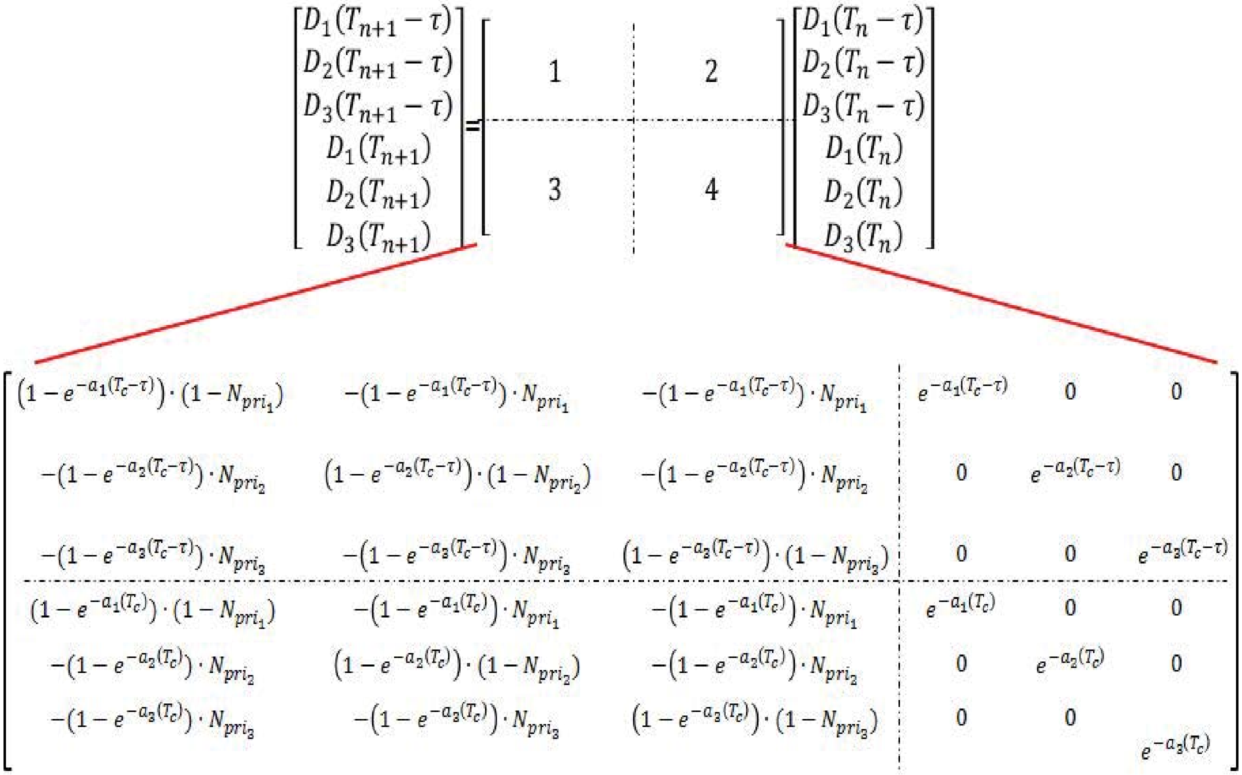
SHA power consumption derivation with PBPS scheme can be described as:

$$\dot{D}_i(t) = -a_i \cdot D_i(nT-\tau) + a_i \cdot [R(nT-\tau)\cdot N_{pri_i} + D_i(nT-\tau)] \tag{6.21}$$

At interval T_n and T_{n+1}, initial point of interval $D_{init_i} = D_i(T_n)$

$$\begin{aligned} D_i(T_{n+1}-\tau) &= e^{-a_i(T_c-\tau)}\cdot D_i(T_n) - (1-e^{-a_i(T_c-\tau)})\cdot N_{pri_i}\cdot \sum D_j(T_n-\tau) \\ &= +(1-e^{-a_i(T_c-\tau)})\cdot D_i(T_n-\tau) + (1-e^{-a_i(T_c-\tau)})\cdot PN_{pri_i} \end{aligned} \tag{6.22}$$

The system equation of three SHAs in matrix notation can be presented as:



$$\begin{bmatrix} D_1(T_{n+1}-\tau) \\ D_2(T_{n+1}-\tau) \\ D_3(T_{n+1}-\tau) \\ D_1(T_{n+1}) \\ D_2(T_{n+1}) \\ D_3(T_{n+1}) \end{bmatrix} = \left[\begin{array}{c|c} 1 & 2 \\ \hline 3 & 4 \end{array}\right] \begin{bmatrix} D_1(T_n-\tau) \\ D_2(T_n-\tau) \\ D_3(T_n-\tau) \\ D_1(T_n) \\ D_2(T_n) \\ D_3(T_n) \end{bmatrix}$$

$$\left[\begin{array}{ccc|ccc} (1-e^{-a_1(T_c-\tau)})\cdot(1-N_{pri_1}) & -(1-e^{-a_1(T_c-\tau)})\cdot N_{pri_1} & -(1-e^{-a_1(T_c-\tau)})\cdot N_{pri_1} & e^{-a_1(T_c-\tau)} & 0 & 0 \\ -(1-e^{-a_2(T_c-\tau)})\cdot N_{pri_2} & (1-e^{-a_2(T_c-\tau)})\cdot(1-N_{pri_2}) & -(1-e^{-a_2(T_c-\tau)})\cdot N_{pri_2} & 0 & e^{-a_2(T_c-\tau)} & 0 \\ -(1-e^{-a_3(T_c-\tau)})\cdot N_{pri_3} & -(1-e^{-a_3(T_c-\tau)})\cdot N_{pri_3} & (1-e^{-a_3(T_c-\tau)})\cdot(1-N_{pri_3}) & 0 & 0 & e^{-a_3(T_c-\tau)} \\ \hline (1-e^{-a_1(T_c)})\cdot(1-N_{pri_1}) & -(1-e^{-a_1(T_c)})\cdot N_{pri_1} & -(1-e^{-a_1(T_c)})\cdot N_{pri_1} & e^{-a_1(T_c)} & 0 & 0 \\ -(1-e^{-a_2(T_c)})\cdot N_{pri_2} & (1-e^{-a_2(T_c)})\cdot(1-N_{pri_2}) & -(1-e^{-a_2(T_c)})\cdot N_{pri_2} & 0 & e^{-a_2(T_c)} & 0 \\ -(1-e^{-a_3(T_c)})\cdot N_{pri_3} & -(1-e^{-a_3(T_c)})\cdot N_{pri_3} & (1-e^{-a_3(T_c)})\cdot(1-N_{pri_3}) & 0 & 0 & e^{-a_3(T_c)} \end{array}\right]$$

Figure 6.16: Matrix notation

6.11 Discrete Time Model Evaluation

In this section, the proposed discrete time model is evaluated by calculating the Eigen values of the matrix.

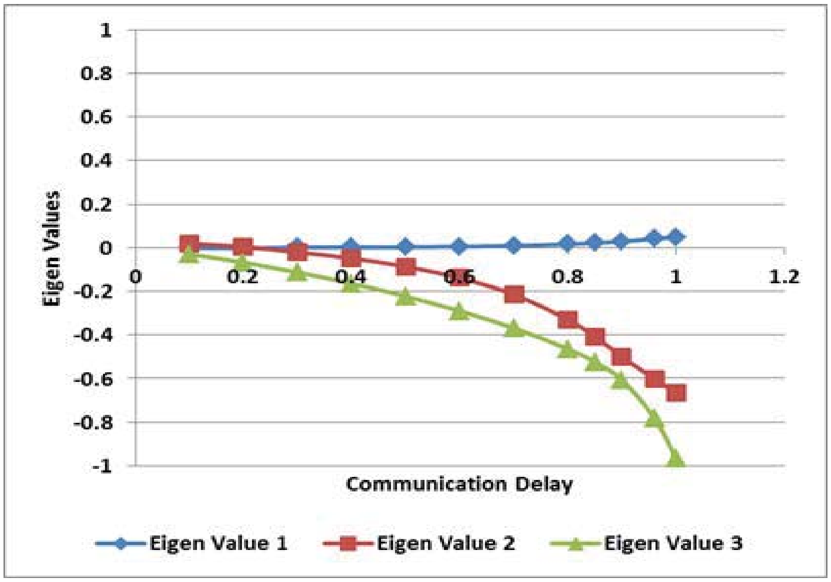


Figure 6.17: Calculation and representation of Eigen values with slow response speed and low SHA priority

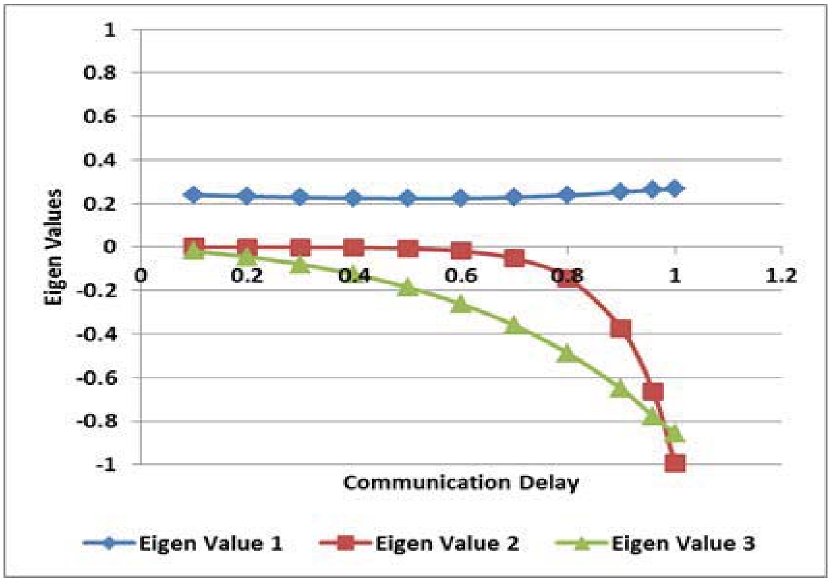


Figure 6.18: Calculation and representation of Eigen values with fast response speed and low SHA priority

From Figure 6.17, It is clear that the proposed system is stable because all Eigen values lie within the unit circle. The response speed for all three appliances are $a_i = 1, 3, 10$ and given priorities are $G_{pri_i} = 1, 5, 10$ respectively.The communication interval is fixed at 1 second and communication delay varies from $\tau = 0.1, ..., 1.0$.

From Figure 6.18, It is analyzed that the proposed system is stable because all Eigen values lie within the unit circle. The response speed for all three appliances are $a_i = 10, 3, 11$ and given priorities are $G_{pri_i} = 1, 5, 10$ respectively.The communication interval is fixed at 1 second and communication delay varies from $\tau = 0.1, ..., 1.0$.

6.12 Summary

In summary, the smart homes can be defined as a residence equipped with computing and information technology which anticipates and responds to the needs of the occupants, working to promote their comfort, convenience, security and entertainment through the management of technology within the home. The use of SES measures the instantaneous consuming power level from the SHAs. The functions of PPC are to gather ON/OFF status from each SHA, instantaneous consuming power $D_i(t)$ from SESs and calculate the remaining power for SHAs. The remaining power level is calculated based on estimation technique which is the key factor to control critical behavior of our proposed system. With this estimation, we can guarantee the maximum power consumption below the total available power limit. We also analyzed our proposed system in simulation environment. The simulation results reveal that the dependency of system parameters a_i (SHA response speed), D_i^{max} (maximum consuming power level) and G_{pri_2} (SHA given priority by user). We noticed the critical system behavior such as overshoot in total power consumption.

The main goal of this chapter is to prevent the situation when total power consumption of all SHAs in smart home exceeds the available power limit. Considering the robustness of the proposed system and the ability to maintain the maximum power, we use the worst case remaining power. With this estimation, the maximum power consumption between the power supply limit can be maintained.

Chapter 7

Implementation of Smart Home Energy Management System

7.1 Introduction

There has been a lot of interest in load modeling in the past several decades. Scale of load models can vary, ranging from the appliance level to the power grid level. In 1995, IEEE provided a load model bibliography for power flow and dynamic performance simulation. This bibliography covered almost all relevant load modeling work in late 20th century [84]. The classic load models defined load as a function of voltage and frequency, which are referred to as static load models. The dynamic load models were developed for transient studies. To better guide the load modeling work, authors in [85] provides the basic definitions and concepts. Obviously, different simulations need different load model representations. In order to study demand management, published work has focused on physical-based load models [86]-[90]. Load models for residential areas were developed in [91], [92] and tested against utility data. The models captured thermodynamic principles of building structures and the diversification was created by random distribution functions when building the distribution circuit load profile. These load models have been mostly used for direct load control (DLC) studies [93]-[95]. Other than a load behavior methodology, load models were developed based on consumers behavior [96]. Load models built from statistical survey data and historical measurements were presented in [97]-[98] with proper random functions designed for aggregation diversity. With the development of the smart grid, there is a need for load models that can facilitate the study of changes in electricity consumption in response to customer behavior and/or signals from a utility. For the load models to represent power demand activities, the following characteristics are required, which have not all been all addressed in the published literature: [99]

1. Comprehensive models should cover all major types of controllable loads so that power demand can be simulated considering consumer choices instead of simple load curtailment.
2. Physically based models should be built according to the physical and operational characteristics of the appliances to reflect the real-world situation.
3. Interactive models should allow interfaces for external signals to simulate the demand side control actions.
4. Reasonably aggregated algorithm should provide reasonable load diversification and aggregation to represent the distribution circuit load profile.

The appliance-level load models are aggregated to generate load profiles. These include conventional controllable loads and critical loads. With the proposed SHemS, the maximum power consumption of home appliances can be maintained below a certain level and allowing the home user flexibility to operate their appliances. The appliances are assigned with dynamic priority according to their different power consumption modes and their corresponding status. To maintain the maximum power limit with allocated priority, the remaining power would be calculated and reassign to the appliances. Simulation results show the effectiveness of the proposed system in managing maximum power consumption.

Due to the continuous increase of electricity demand in residential areas, power consumption and management have received more attention in recent years. To achieve efficient power consumption, intelligent power monitoring and interactive control of power consumption in smart homes are the key factors in reducing power demand peaks and activities related to avoidance of blackout effects. In this information oriented era, it is desirable to improve the crucial aspects of smart homes; reliability and stability. This should increase the competitiveness of the overall electricity market. To improve these aspects, smart homes should be operated with minimum abnormal conditions, which if occur, must be handled as soon as possible. Therefore residential circuit breaker has been playing an important role over the past 100 years, since the first oil circuit-breakers.

7.2 Motivation

Now is the rapidly changing time of tablets, smart phones, electronic tags (RFID) as well as the emerging communication advancements. The traditional power grid can not survive the challenges of everything turning into smart and interrelated [100]. The challenges of the power grid to have energy efficiency and stability are redefined. This is done by introducing intelligent innovations using information and communication technologies. The next-generation of power grid called smart grid considers real-time flow of both information and electricity. The traditional power system is only still in operation because the majority of power system loads are neither controllable nor measurable.

Power management inside households has received more consideration in recent years due to the continuous growth of residential electricity demand. To attain efficient power consumption inside smart homes, both communication technologies and energy management methods are been utilized. The emerging smart grid will provide smart homes with the flexibility of controlling its electrical consumption. Smart homes has a control system with a complete set of functions for communication, automatic control and security with various innovations. The purpose of smart homes is offering comfortable, safe, energy efficient and environment friendly life.

On the other hand, since the customer is neither an economist nor an experienced grid operator, it is impractical to request him to create an optimal household schedule to save energy, reduce cost, and help grid operation (e.g. by reducing the contribution of the consumer to the peak load). To solve this problem, automatic load scheduling methods should be provided, which can collect status and power consumption demand from home appliances and schedule them in an energy and cost efficient way by simultaneously considering comfort as well.

Because of the rapid and continuous increase in the electric power demand, the electricity distribution systems are confronted with numerous difficulties in the power grid. Developing the smart grid is embedding intelligence into the power grid and provides benefits to the customers as well as the electric power providers. It is indisputable that nowadays the number of electrical appliances in modern residences has significantly increased compared to the past. The need for immediate and simultaneous energy consumption has resulted in frequent demand peaks. The problem arising for utility companies is the fact that they are obliged to deploy expensive strategies to succeed generating enough energy to meet the demand. If the demand is not met, this could lead to a major blackout.

Excessive current demanded by appliances is referred to as overload. An overload occurs when too many devices are operated on a single circuit in other words, an electrical equipment operates beyond its rating. When an overload occurs, damage to connected equipment can occur unless the circuit is opened by an overload protection device. Slight overloads can sometimes be allowed to continue only for short periods of time but as the current magnitude increases, the circuit breaker must open faster.

The main objectives of this chapter are (i) implement a practical SHemS for Smart Homes (ii) modify the proposed system design to be more realistic (ii) a practical appliance model is introduced by setting minimum consuming power level of appliances (iv) the system architecture includes circuit breaker protection and stability (v) priority schemes should also modified according to new additional features.

7.3 Appliance Power Management Model

In existing studies, there is a lack of power assignment analysis among appliances with different power consumption modes. The appliances are categorized into two types according to their control mechanism and power consumption modes. These types of appliances are named as: smart home appliances (SHAs) and regular home appliances (HAs).

7.3.1 Implementation with Mixture of Appliances

1. **Smart Home Appliances (SHA):** SHAs of this type requires more sophisticated power consumption control while offering some flexibility. This type of SHAs have more than one state (power consumption modes) and employs custom rules for communication. This type can be seen as a flexible device when fitting its power consumption other SHAs. We can achieve SHA performance even If the maximum consuming power level of SHAs of this type reduced to a certain degree. The example

of these SHAs are simple lights, some dryers, etc [101]. For appliances belong to this type, the instantaneous consuming power level have different ranges of power level from a minimum consuming power level to a maximum consuming power level. We will refer to those as D_i^{min} and D_i^{max}, respectively (see Figure 7.1).

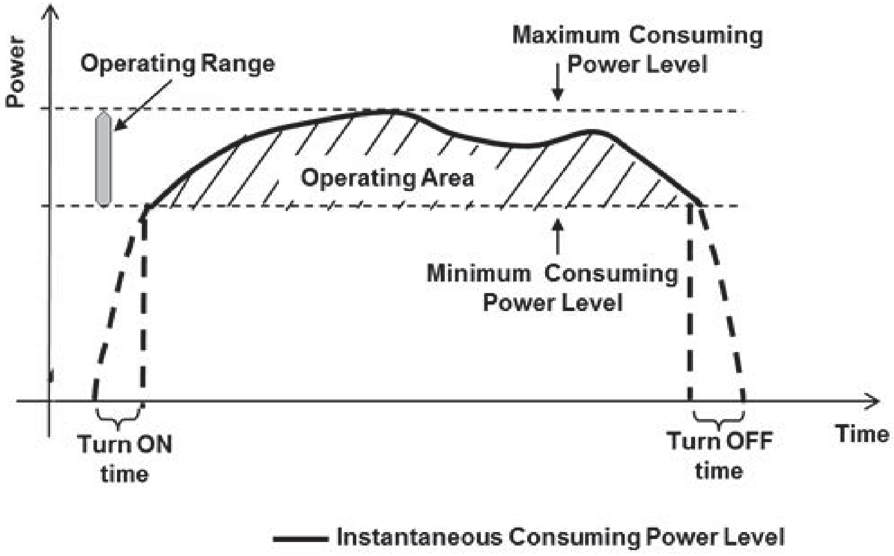


Figure 7.1: System model for power consumption modes of SHAs.

$$D_i^{min} \leq D_i(t) \leq D_i^{max} \tag{7.1}$$

When a SHA is turned ON, it will wait to perform its operation until the power available for SHA is equal to its minimum consuming power level. After that SHA can perform its operation within operation range. If the available power for SHA is less than its D_{min}, the SHA would be turned OFF.

2. **Regular Home Appliances (HAs):** For the power consumption of HAs, in this type the power consumption cannot be reduced. This means that the power consumption is constant and cannot be controlled. The main feature of this type of HAs is only on/off state. The power supply cannot be reduced otherwise the HA would not work, e.g. some washing machines, rice cookers, etc [80].

$$D_i^{min} = D_i(t) = D_i^{max} \tag{7.2}$$

7.4 Co-operative Power Sharing Algorithm

The proposed system of SHemS is based on appliance priority. Priority is used to share total available power among appliances. To satisfy the importance of appliance types, a power sharing control algorithm is proposed with the consideration of appliance different power consumption modes and priority.

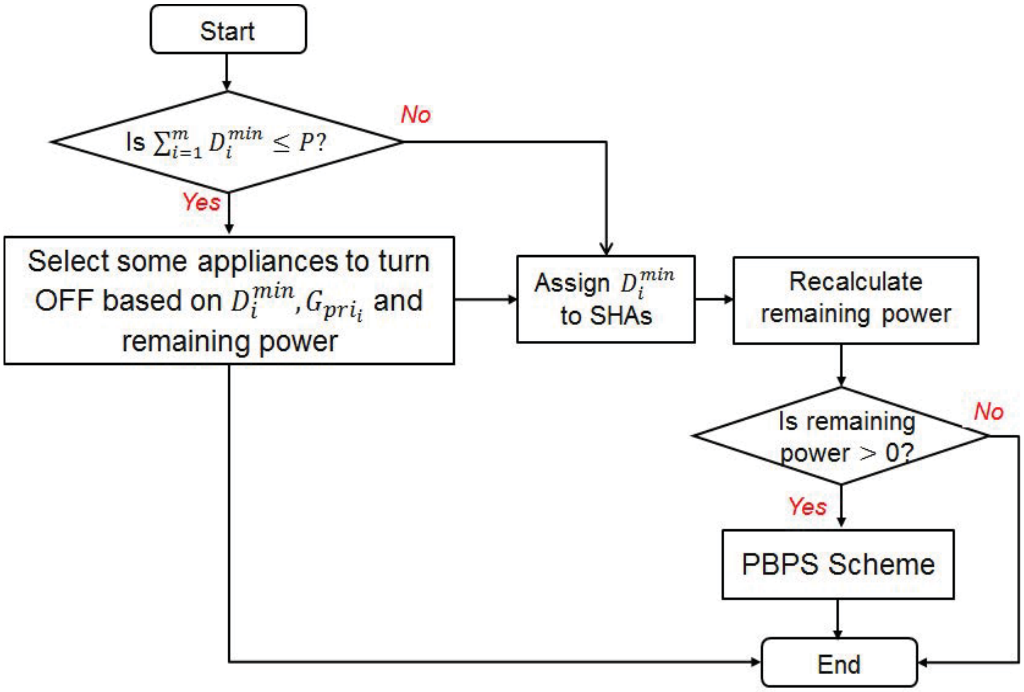


Figure 7.2: Power Sharing algorithm.

To calculate the suggested power level for all appliances including SHAs and HAs, a power sharing algorithm is proposed. This algorithm allows different types of appliances to share total available power. This mechanism will help in providing the flexibility to operate appliance in order to maximize power utilization of appliances.

Initially remaining power is equal to the total available power level, $R(t) = P$. The suggested power level for each appliance is also considered as zero in the beginning of the simulation. At first, $\sum_{i=1}^{m} D_i^{min}$ is calculated for all appliances. If $\sum_{i=1}^{m} D_i^{min} < P$, shows all appliances minimum consuming power levels are less than the total available power limit. In this case, PPC will assign minimum consuming power levels to all attached appliances and calculate the remaining power. The remaining power will assign to all appliances based on appliance priority. For the assignment of suggested power level for each appliance, priority based power sharing (PBPS) scheme is used.

In case of $\sum_{i=1}^{m} D_i^{min} = P$, PPC will assign minimum consuming power level to all appliances. After assignment of minimum consuming power levels there is no remaining power to distribute so all appliances will work with their minimum consuming power levels.

In case of $\sum_{i=1}^{m} D_i^{min} > P$, PPC needs to turn OFF some appliances based on low priority and the appliance with high D_i^{min} based on the remaining power left.

7.5 Simulation Objective and Scenario

The simulation is used to analyze the correctness of the proposed system with additional parameter of appliance. Both SHAs (smart home appliances) and HAs (regular home appliances) are considered in this simulation. All appliances (SHAs and HAs) are associated with response speed (a_i), maximum consuming power level (D_i^{max}), given priority (G_{pri_i}) and additionally each appliance have minimum consuming power level D_i^{min}.

For simulation scenario of the proposed system, three appliances (two $SHAs$ and one regular HA) are attached with their separate SES. Throughout the simulation, total available power for appliances is $P = 1.5\ kW$, given priority levels for three appliances are $G_{pri_1} = 1$, $G_{pri_2} = 5$, $G_{pri_3} = 10$ and response speed of three appliances are $a_1 = 1$, $a_2 = 3$, $a_3 = 10$ respectively.

7.5.1 Power Distribution Criteria

The main objective of this simulation is to analyze the power distribution criteria among appliances and validate the system model with different criteria. At first, appliances are analyzed with same turn ON time. Three appliances are considered from which HA_1 has $D_i^{min} = D_i^{max} = 0.5kW$. This shows that the power consumption cannot be reduced from $0.5kW$, in order to keep the appliance in working. On the other hand, appliance 2 and 3 are SHAs. This shows that power consumption of these smart appliances could vary between D_i^{min} and D_i^{max}.

For this experiment, the situation when $\sum_{i=1}^{m} D_i^{min} = P$ is analyzed at first. As the $\sum_{i=1}^{m} D_i^{min} = P$, means all appliances can work with their minimum consuming power level. In Figure 7.3, all appliances share the available power equally. The maximum and minimum consuming power levels for three appliances are given as:

1. $D_1^{min} = 0.5kW \leq D_1(t) \leq D_1^{max} = 0.5kW$
2. $D_2^{min} = 0.5kW \leq D_2(t) \leq D_2^{max} = 0.9kW$
3. $D_3^{min} = 0.5kW \leq D_3(t) \leq D_3^{max} = 1.2kW$

After assignment of minimum consuming power levels to all appliances there is no remaining power to distribute so appliances will work with their minimum consuming power levels.

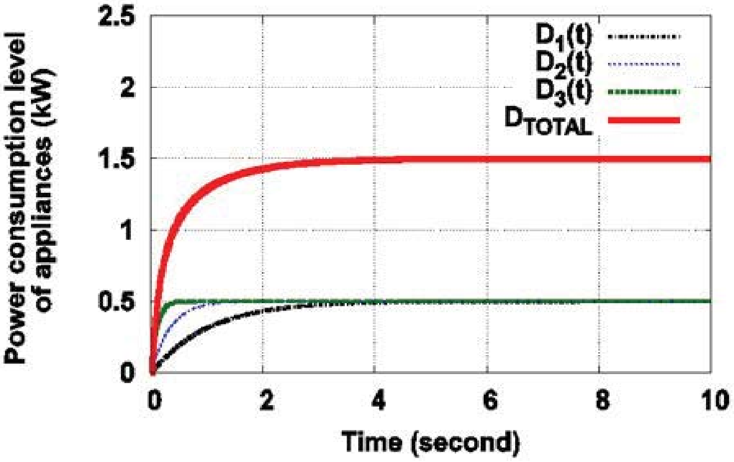


Figure 7.3: Power consumption level of appliances with $D_i^{min} = 0.5\ kW$ and same turn ON time for all appliances.

As the second experiment, appliance 1 is the regular appliance with $D_i^{min} = D_i^{max} = 0.7kW$. This shows that the power consumption cannot be reduced from $0.7kW$. For this experiment, the situation when $\sum_{i=1}^{m} D_i^{min} > P$ is analyzed with same turn ON time for all appliances. As the $\sum_{i=1}^{m} D_i^{min} < P$, means all appliances cannot even work with minimum consuming power level. PPC need to turn OFF some appliances based on appliance priority and D_i^{min}. In Figure 7.4, low priority appliance (appliance 1) is remained OFF to give power to high priority appliances. The maximum and minimum consuming power levels for three appliances are given as:

1. $D_1^{min} = 0.7kW \leq D_1(t) \leq D_1^{max} = 0.7kW$

2. $D_2^{min} = 0.7kW \leq D_2(t) \leq D_2^{max} = 0.9kW$

3. $D_3^{min} = 0.7kW \leq D_3(t) \leq D_3^{max} = 1.2kW$

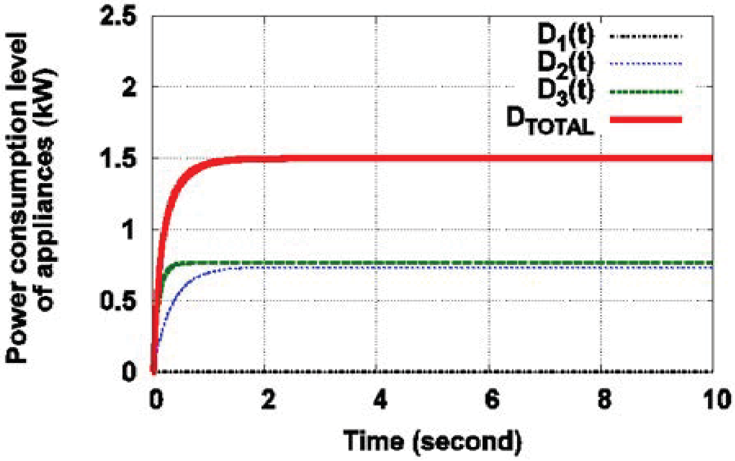


Figure 7.4: Power consumption level of appliances with $D_i^{min} = 0.7\ kW$ and same turn ON time.

7.5.2 Effects of turn ON Timing

In this experiment, effects of turn ON timings on power distribution criteria among appliances have been analyzed. In this experiment, the situation when $\sum_{i=1}^{m} D_i^{min} = P$ is tested with different turn ON timings for all three appliances. The maximum and minimum consuming power levels for three appliances are given as:

1. $D_1^{min} = 0.5kW \leq D_1(t) \leq D_1^{max} = 0.5kW$

2. $D_2^{min} = 0.5kW \leq D_2(t) \leq D_2^{max} = 0.9kW$

3. $D_3^{min} = 0.5kW \leq D_3(t) \leq D_3^{max} = 1.2kW$

From Figure 7.5, the total available power is equal to the $\sum_{i=1}^{m} D_i^{min}$. All the attached appliances with same response speeds reach to their minimum consuming power levels, there is no more power to distribute among appliances so all appliances shared the remaining power equally at their minimum consuming power levels. In Figure 7.6, with different response speeds for appliances as $a_i = 1, 3, 10$ power overshoot is observed.

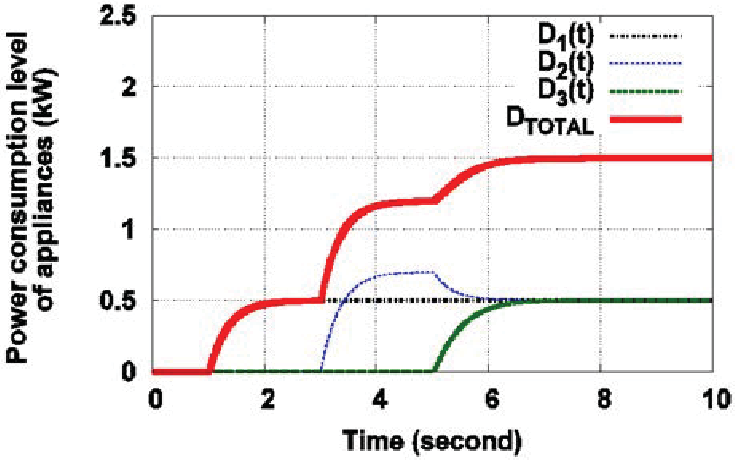


Figure 7.5: Power consumption level of appliances with same $D_i^{min} = 0.5\ kW$, $a_i = 3$ for all appliances and turn ON time for HA_1 is $t = 1$, SHA_2 turn ON time is $t = 3$ and for SHA_3 turn ON time is $t = 5$.

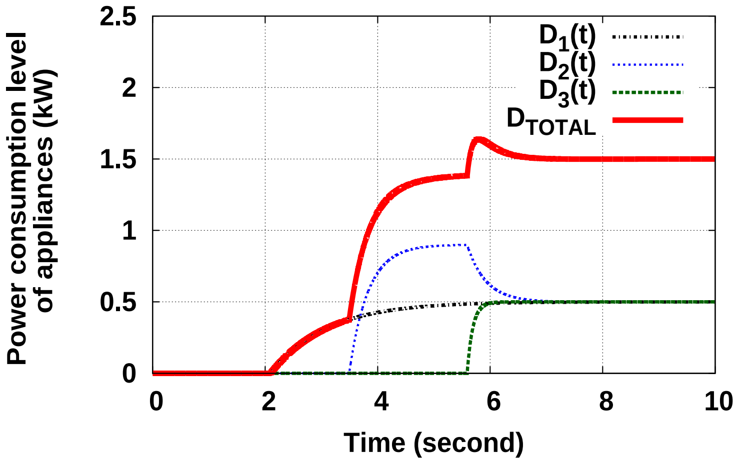


Figure 7.6: Power consumption level of appliances with same $D_i^{min} = 0.5\ kW$ and different $a_i = 1, 3, 10$for $(i = 1, 2, 3)$ appliances and turn ON time for HA_1 is $t = 1$, SHA_2 turn ON time is $t = 3$ and for SHA_3 turn ON time is $t = 5$.

In next experiment, the situation when $\sum_{i=1}^{m} D_i^{min} > P$ is tested with different turn ON timings for all three appliances. The maximum and minimum consuming power levels for three appliances are given as:

1. $D_1^{min} = 0.5kW \leq D_1(t) \leq D_1^{max} = 0.5kW$

2. $D_2^{min} = 0.7kW \leq D_2(t) \leq D_2^{max} = 0.9kW$

3. $D_3^{min} = 0.9kW \le D_3(t) \le D_3^{max} = 1.2kW$

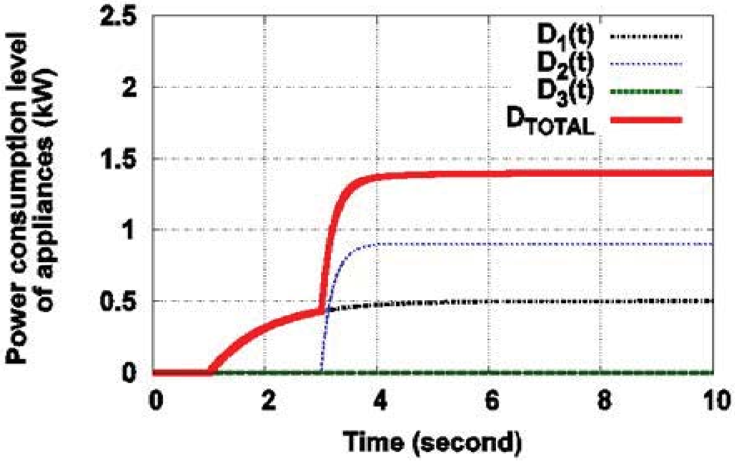


Figure 7.7: Power consumption level of appliances with $D_i^{min} = 0.5, 0.7, 0.9\ kW$ for $(i = 1, 2, 3)$, same priority level $G_{pri_i} = 5$ and different turn ON time for HA_1 is $t = 1$, for SHA_2 turn ON time is $t = 3$ and for SHA_3 turn ON time is $t = 5$.

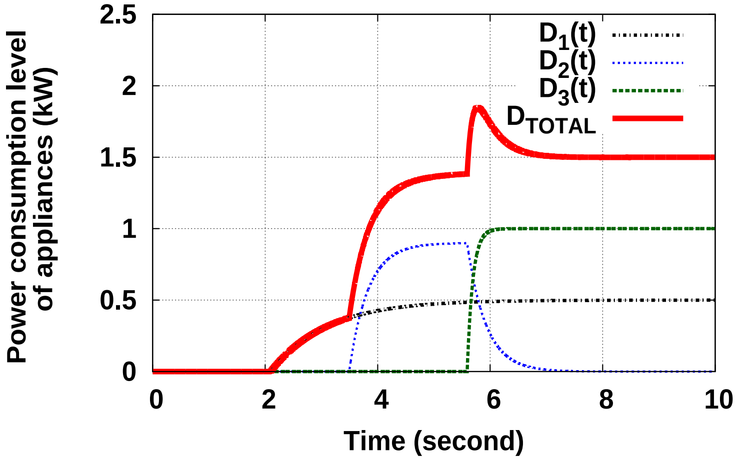


Figure 7.8: Power consumption level of appliances with $D_i^{min} = 0.5, 0.7, 0.9kW$, different priority level $G_{pri_1} = 1, G_{pri_2} = 5, G_{pri_3} = 10$ and different turn ON time for HA_1 is $t = 1$, SHA_2 turn ON time is $t = 3$ and for SHA_3 turn ON time is $t = 5$.

From Figure 7.7, the situation when $\sum_{i=1}^{m} D_i^{min} > P$ is considered. In this scenario, PPC assigns the available power to the appliances with less D_i^{min} at first to utilize available power by maximizing the no. of appliances. In Figure 7.8, appliance 2 is turned OFF by the PPC in order to give power to high priority appliance.

7.5.3 Effects of Overshoot Control

The maximum and minimum consuming power levels for three appliances are are given as:

1. $D_1^{min} = 0.5kW \leq D_1(t) \leq D_1^{max} = 0.5kW$
2. $D_2^{min} = 0.7kW \leq D_2(t) \leq D_2^{max} = 0.9kW$
3. $D_3^{min} = 0.9kW \leq D_3(t) \leq D_3^{max} = 1.2kW$

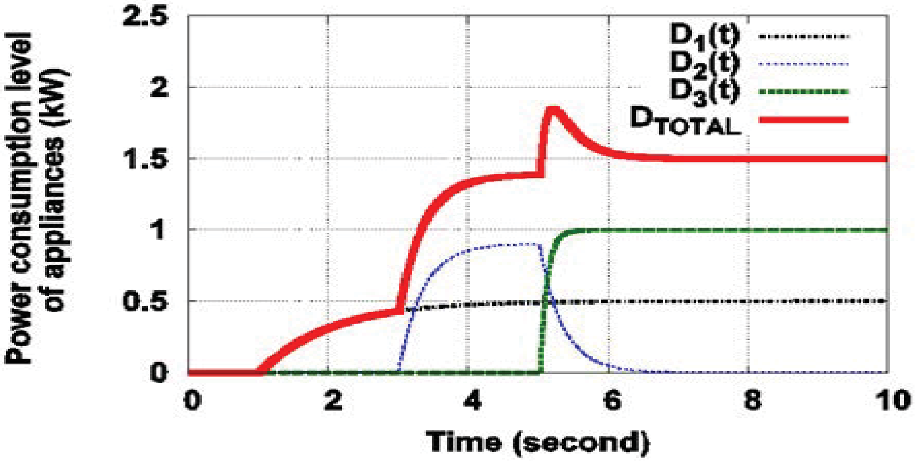


Figure 7.9: Power consumption behavior of appliances with $D_i^{min} = 0.5, 0.7, 0.9$ kW, without overshoot control.

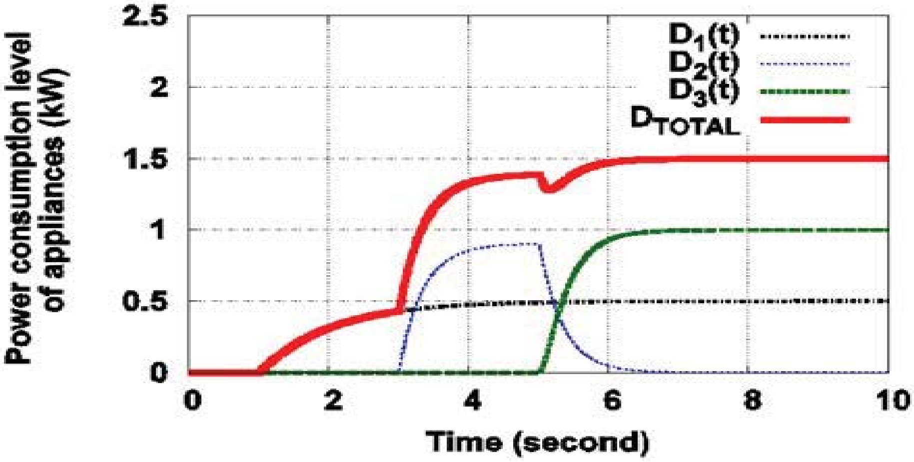


Figure 7.10: Power consumption behavior of appliances with $D_i^{min} = 0.5, 0.7, 0.9$ kW with overshoot control.

To solve the power overshoot problems observed in previous section with different appliance response speed, overshoot control is enabled. The main objective of this simulation is to control maximum consuming power limit below a certain limit. At first, the situation is applied to the proposed system which can cause power overshoot (see Figure 7.9).

In this case, last turn ON appliance with high response speed is the cause of power overshoot. In Figure 7.10, overshoot control is enabled with same situation observed in Figure 7.9. When the overshoot control is enabled, the proposed system maintained the total power limit appropriately by reducing the response speed of last turned ON appliance.

7.6 Overall System Architecture

In our system model, one sub-breaker connects to outlets, lighting and other loads. In Figure 7.11, overall system architecture is presented. At first, the scenario with only one sub-breaker attached with three smart appliances is considered. The proposed system assumed that the transfer of major power consumed level of three smart appliances from SESs to PPC, remaining power from PPC to smart appliances is considered with some time delay. It is also considered that the maximum and minimum consuming power levels of smart appliances are used to achieve maximum appliance utilization.

Circuit breaker is an important and critical component of electric power system. The circuit breaker is the basic means by which wiring is protected from both a short circuit and overload damage. The basic circuit breaker used in both residential and light commercial application. It is very important to understand the basic operation and design of the trip mechanism in a circuit breaker. The circuit breaker has a trip temperature and it is the heat generated within the breaker that causes the temperature to rise, the faster the heat rise, the faster the breaker reaches temperature and trips. A circuit breaker is designed to open (trip) before the energy passing through it creates enough heat in the branch circuit wiring to cause damage to the wiring.

In our system implementation, the tripping model of circuit breaker is considered. The details are given in next section.

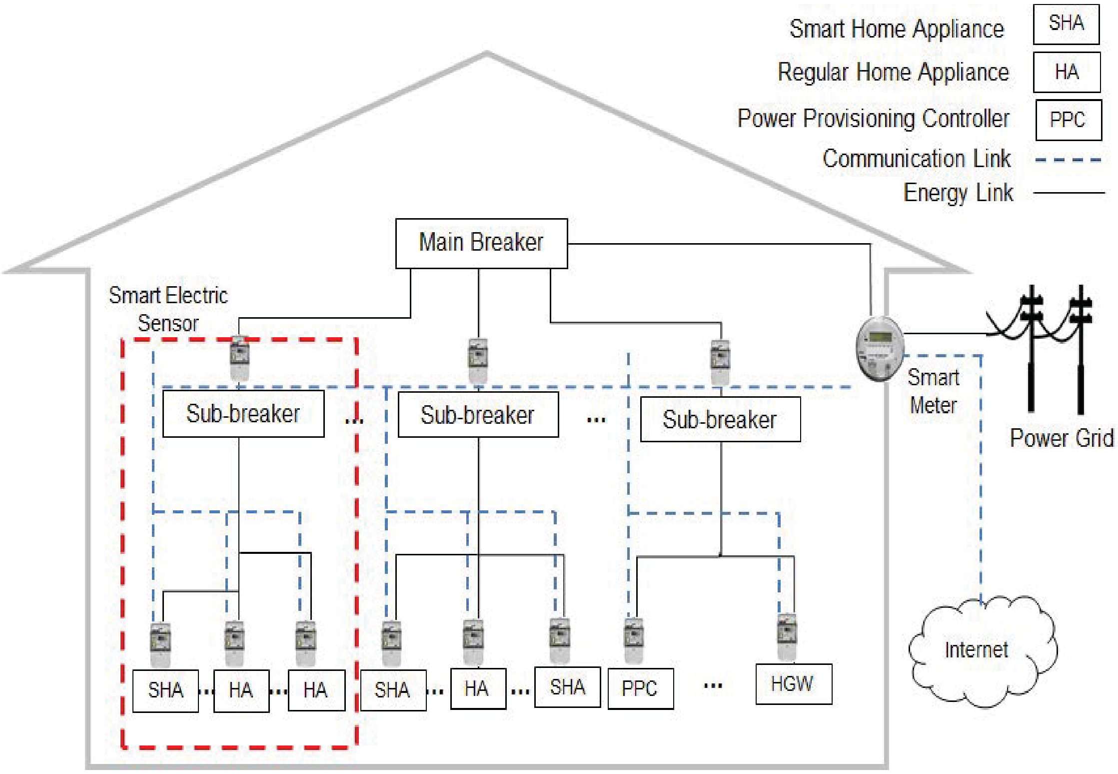


Figure 7.11: Overall system architecture.

7.7 Circuit Breaker Model

The circuit breaker is an absolutely essential device in the modern world, and one of the most important safety mechanisms in our home. Whenever electrical wiring in a building has too much current flowing through it, these simple machines cut the power until somebody can fix the problem. Without circuit breakers (or the alternative, fuses), household electricity would be impractical because of the potential for fires and other mayhem resulting from simple wiring problems and equipment failures.

Circuit breaker provides a manual approach of energizing and de-energizing a circuit and automatically on a predetermined overload condition (without damaging itself if properly applied within its rating). All circuit breakers perform the following functions:

1. Detect: When an overload current occurs.
2. Measure: The amount of overload current.
3. Act: By tripping in a timely manner to prevent damage to the circuit breaker and also the whole circuit including the appliances.

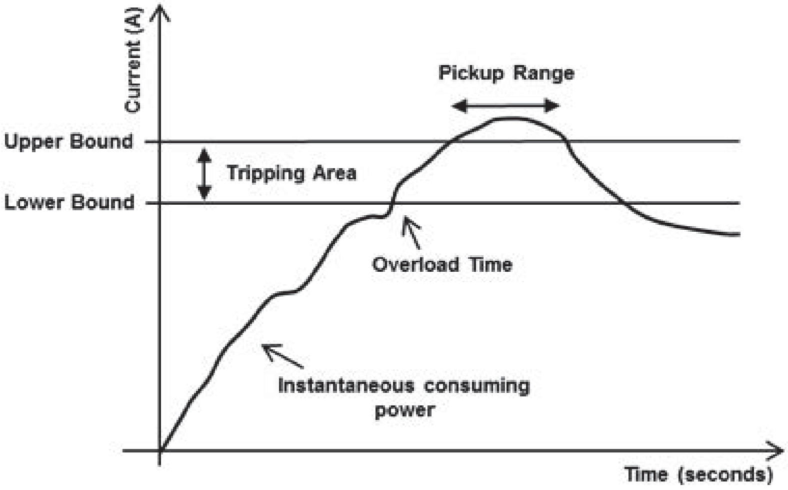


Figure 7.12: Circuit breaker tripping model.

An overloaded circuit is the primary reason for a breaker tripping. If the peak current increment is very fast the system will trip automatically as peak current exceeds the final threshold value. For critical applications that need to provide fault tolerant or fail safe operation. The rated current of a circuit breaker is called instantaneous consuming power. Lower bound is the level of instantaneous current, the circuit breaker can carry without tripping. The upper bound is the level of instantaneous current, the circuit breaker trips without an intentional time delay. Overload time is the parameter used to control the amount of time against two bound. Once the maximum instantaneous current of all smart appliances reach to lower bound, the overload time start incrementing until it reached to the specified value set by the user. Circuit breaker will remain close until overload time reached. Pickup range also controls the amount of time (from 0.05 to 0.2 second in fixed time) a breaker will remain closed until pickup range meet. Overload time prevents the circuit breaker to trip against pickup range.

7.8 Simulation Objective and Scenario

The aim of or proposed system is to analyze accuracy of the system design by enabling the circuit breaker model. Both SHAs and HAs are used in system design and analysis. In proposed system, there are two key mechanisms:

1. Sub-breaker model implementation

2. Effect of overshoot control with sub-breaker model

Simulation includes minimum consuming power level, PBPS scheme and additionally overshoot control. The main objectives of simulation are to verify the circuit breaker model functionality and test system behavior with circuit breaker tripping.

For simulation scenario of the proposed system, three smart home appliances ($SHAs$) are attached with one sub-breaker. The response speed and given priority for all three appliances are $a_i = 1, 3, 10 (i = 1, 2, 3)$ and $G_{pri_1} = 1$, $G_{pri_2} = 5$, $G_{pri_3} = 10$ respectively. The appliances turn ON timings are SHA$_1$ turn ON time is $t = 1$, HA$_2$ turn ON time is $t = 3$ and SHA$_3$ turn ON time is $t = 5$. The maximum and minimum consuming power level of $SHAs$ are $D_1^{max} = 0.5kW$, $D_2^{max} = 0.9kW$, $D_3^{max} = 1.2kW$ and $D_1^{min} = 0.5kW$, $D_2^{min} = 0.7kW$, $D_3^{min} = 0.9kW$. From maximum and minimum consuming power levels, it can be noticed that HA$_1$ is a critical appliance, SHA$_2$ and SHA_3 are controllable smart appliances. It shows that the power consumption of SHA_1 cannot be reduced. However, SHA_2, SHA_3 can change their power consumption levels between maximum and minimum consuming power levels. PPC is responsible for calculating suggested power level for all appliances. If the suggested power level for SHA is less than its D_i^{min}, the appliance would be turned OFF. The total available power for all $SHAs$ is $P = 15A$. PPC assigns available power among appliances based on their minimum consuming power levels. If there is remaining power, PPC can start sharing remaining power based on priority based power sharing scheme. If the $\sum D_i^{min}$ of all appliances is more than the available power then PPC use priority based ideal power level for power assignment (for details see chapter 5).

7.9 System Verification and Test

At first, the case when sub-breaker tripping module and power overshoot control both are disable is considered. To see the system behavior without overshoot control, system parameters are set to observe power overshoot situation (see Figure 7.9)

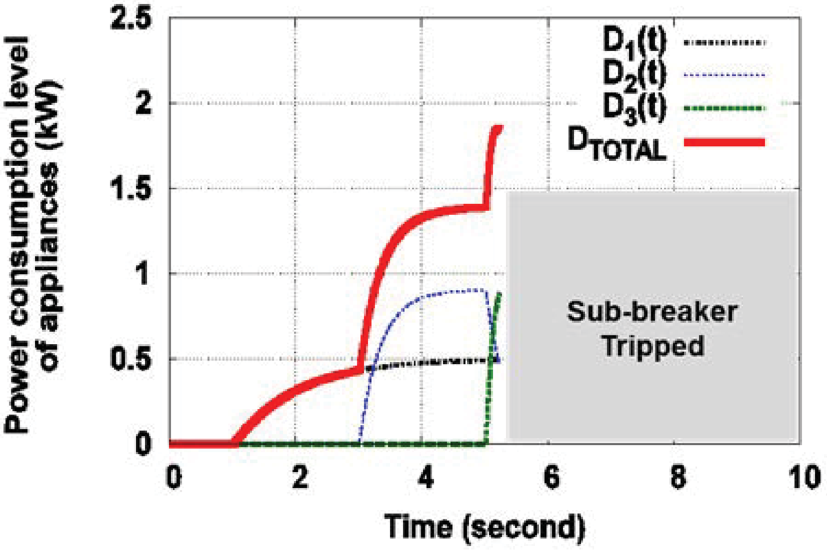


Figure 7.13: Power consumption behavior with sub-breaker tripping, overload time is 0.02.

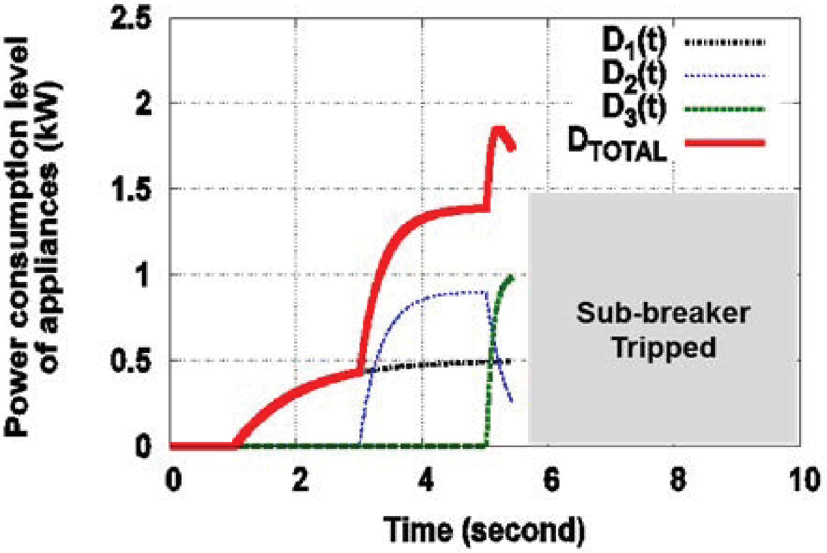


Figure 7.14: Power consumption behavior with sub-breaker tripping, overload time is 0.04.

7.9.1 Effects of Circuit Breaker Tripping

As the second experiment, sub-breaker tripping module is enabled. The upper bound, lower bound and overload time of sub-breaker are set to $19A$, $15A$ and $t = 0.2$ respectively. As observed from Figure 7.13, the total instantaneous consuming power of all $SHAs$ reach lower bound of the sub-breaker. At this point the overload time starts incrementing, the sub-breaker trips as overload time meet threshold value. The situation when overload time is $t = 0.4$ is also considered (see Figure 7.14).

7.9.2 Effects of Overshoot Control

The effects of overshoot control to the final total power consumption of sub-breaker is considered in this simulation results. The overshoot control is enabled to prevent the proposed system to reach tripping area (see Figure 7.15). This shows the robustness of our proposed overshoot control.

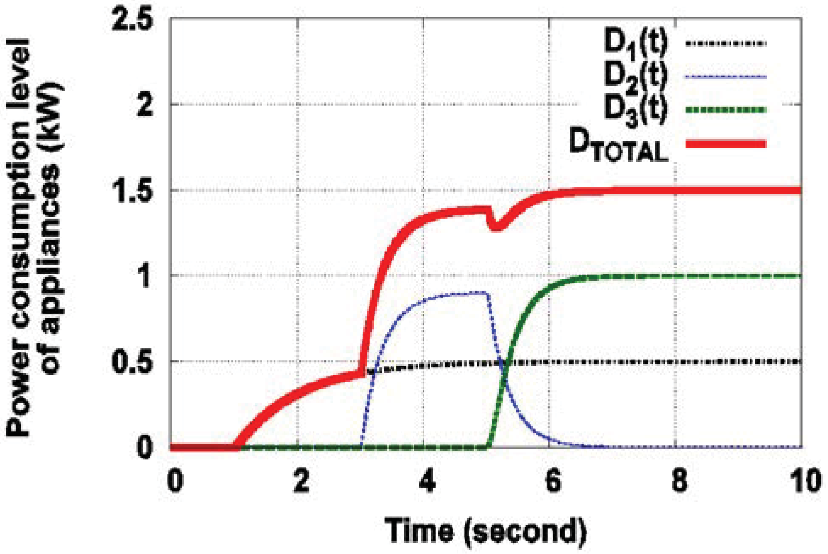


Figure 7.15: Power consumption behavior with overshoot control.

7.10 Summary

The introduction of SES has brought a paradigm shift in the analysis of system design of smart home energy management system. The main objective of this chapter is to prevent the situation of the when the total consuming power of all appliances in smart home exceeds the total available power limit. The SESs are responsible for collecting instantaneous consuming power of all smart appliances in smart home and send it to PPC. The functions of PPC are to gather ON/OFF status information from appliances and $D_i(t)$ from SES. Considering the robustness of the proposed system and the ability to control maximum consuming power, the sub-breaker tripping model is considered.

The proposed system in simulation environment is tested and verified for the maximum consuming power control. From simulation results, the overshoot control algorithm can guarantee the maximum power limit and also for preventing the system to reach in critical state of tripping. The new features are added to the proposed system to provide a more practical scenario. With the new feature of minimum consuming power level, the appliance cannot work if the available power is less than the minimum consuming power level. Co-operative power sharing scheme is modified to handle minimum consuming power level of appliances. The proposed system includes the legacy circuit breaker model as a protection mechanism to handle severe overshoot conditions in case the overshoot control is not available. The model verified and found to be working correctly.

Chapter 8

Conclusions and Recommendations

8.1 Concluding Remarks

This thesis involves a system design and implementation effort, the experiments for the system validation and control for reduction in peak power consumption for smart homes. As it is stated, the stability of actual consuming power level is primary research area that needs to be solved. The future smart homes should be dynamic and self-motivated with continual real time communication between appliances (HAs and SHAs), PPC and SESs. Embedding intelligence in the form of energy management system in smart homes to meet the challenges of improved reliability, security, efficiency and system dynamics is a challenging task. The next generation power grid also called smart grid, is a dynamic structure with continual real-time two way communication between the producers and consumers. According to the overall trends, the smart grid is an interdisciplinary technology that incorporates the fixed centralized and one-way communication organized power grid with latest developments and novelties. The essential task of electrical power network management systems is to keep the balance between power supply and demand. This thesis is progressed by the following steps:

1. Related knowledge of smart grid on consumption side, smart homes and power management strategies has been consulted. The focused areas of study are blackout prevention for the smart homes and implementation of stability test. The proposed system consists of SESs, appliances and a PPC and then analyze the proposed system for power blackout prevention by introducing the system parameters. The

use of SES will help in measuring the real-time power levels of appliances and send this information to PPC then based on this information PPC will calculates the suggested power level for the appliances, but with a communication delay.

2. The system validation and analysis is also presented for the better understanding of how proposed system design work and what is the relationship between system parameters with each other. The application of Lyapunov stability test to the proposed system to find the upper limit of the communication delay for which the proposed system is stable is also analyzed. Effects of power assignment criteria on proposed system behavior and stability have been discussed to achieve optimal system model for SHemS. Two different suggested power assignment criteria to distribute the total available power among SHAs are discussed and analyzed in simulation environment. A comparative study has been conducted which shows the change in SHA behavior by changing suggested power assignment criteria. The delay dependent stability theorem for proposed SHemS is also presented which shows that the entire system stability is dependent on communication time delay. The dynamics of the behavior of SHAs changes with the change in value of system parameters and introduces critical system events like stable/unstable and overshoot/non-overshoot. There are two main contributions (i) communication delay and (ii) comparison between two suggested power assignment criteria for SHAs. These contributions effect critical system power behavior, stable/unstable or in other words overshoot/non-overshoot. Therefore, we need to choose the system delay carefully so that the system would be stable with no power overshoot.

3. The maximum power consumption of the SHAs in the user's residence should not exceed a certain limit. Several approaches were provided and compared to reduce peak power consumption. In existing studies, there is a lack of power assignment analysis among SHAs and effects on SHA behavior. Communication between SHAs and controller is held through message exchange but there is lack of consideration of communication delay in message exchange in the overall system scenario. This is other important contribution and was found to be main factor of the system stability.

4. The detailed analysis of energy waveform is also omitted in many studies which is one of the novelties of this research. The priority is also an important consideration to reduce maximum power consumption. In proposed system, higher priority SHAs can take more power as compare to the lower priority SHAs from the available power. However the ON/OFF status of the SHAs, there is a need to reassign a part of consuming power from lower priority SHAs to the higher priority SHAs. The power assignment scheme for the SHAs are studied so that the total power is shared among SHAs. To balance the power consumed and supply of the SHAs in smart homes, two types of controlling schemes are required. The first is the priority rule for the SHAs that controls the power flows to SHAs taking into account the limitation of the SHA priority. The second is the controlling of total power consumption of the SHAs below the power limit. The main focus of study is on reducing the power consumption until the specified limit reached, that operates on a single power source.

5. As a result the transient behavior due to reassignment of power is not simple. This research offers a system to control the maximum total power consumption in detailed transient behavior considering different SHAs with different time constants. In order to guarantee the maximum power borderline, the remaining power is calculated and reassign to SHAs as their temporal target power levels.

6. In order to show, the validation of the proposed system, both simulations and experiments are conducted. The simulation results with different conditions and criteria such as effects of system parameters, border estimation for system stability, power distribution criteria and effects of turn ON timing of SHAs are also presented.

8.2 Research Discussion

For overall research discussion, a novel system design and architecture to ensure stability and power control for smart homes is proposed with EBPA criteria, RBPA criteria, PBFP scheme and PBPS scheme. All specified criteria and schemes have their own benefits such as: easier stability theorem implementation, achieve fast system response, simple implementation of SHA priority rule and achieve home user satisfaction respectively.

Further investigations and verifications of the proposed system design using Lyapunov-

Krasovskii stability theorem is also discussed. Implementation of stability test to get upper bound of delay for which proposed system is stable is also presented. Implementation of stability analysis for PBPS scheme based on discrete time model is also analyzed. Maximum power consumption with various appliances is also guaranteed to maintain user comfort for preference.

8.3 Directions and Future Research

This section discusses the future research directions for smart home energy management system in smart home environments. With the best of my knowledge, this research contributes in the issues of a system design and implementation effort for power and stability system, the experiments for the system validation and optimal control problem for large scale system. However, there have still many things to improve which are divided into short term future work and long term future work.

The short time future work are:

- Study nonlinear stability analysis
- Application of appliance submission model for better power control

The long time future work are:

- Renewable energy integration
- Smart home appliance structure with capacitor and storage
- Power consumption control for multiple household (smart community)
- Handling of fail safe problems
- Integration of storage system
- Power control from outside home with the consideration of communication delay

8.4 Improvements that needed

The implementation aspect of SHemS is the communication interval can be adaptively changeable to reduce the communication overhead. The other needed improvements are

- Proposed RBPA criteria
- SHA hardware modifications (e.g., the sensing module is built into the SHA)
- PPC control mechanism with user activity plan
- Power control with communication delay outside home and consideration of power storage and generation for HEMS.

8.4.1 Smart Home Appliance Modifications

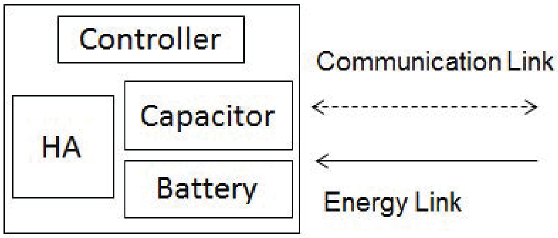


Figure 8.1: Smart Home Appliance (SHA).

Household appliances such as heating, ventilation, air conditioning, refrigerators, stove, hotplates, etc. account for a major part of the residential electricity consumption. In order to support smart grid, these appliances have to be integrated with the ability to monitor their energy usage and, possibly, to remote control their electricity usage.

It is important to define the hardware of SHA. This includes alot of parts and is depending on the employed application. In general, a SHA should have a computing unit, e.g, micro controller unit (MCU) or digital signal processor (DSP). Micro controller is a chip used to compute some simple tasks and to control electronic device. MCU allows to control inputs and outputs, to create timers and to store data in RAM, ROM, EEPROM or flash. Through this ability to control, modify and compute data is an attractive for smart appliance applications.

The simplest way to locally store data in a smart appliance is to use th EEPROM or the flash memory of an MCU. These storage opportunities are called the embedded storage and offers a relatively small storage capacity. To store measurements in the long term dedicated storage devices are beneficial. For large amounts of data, an external storage device could be connected via USB. The power consumption is directly calculated in a processing unit. With this technique it has to be considered that the MCU is constantly busy, which will add to the power consumption of the SHA itself.

This research assume that the home appliance is a smart home appliance (SHA) with communication unit and processing unit. Appliance can change its power consumption level upon receiving the "suggested power level"from the PPC, which performs intelligent computing upon receiving the information from the SESs. Considering the present research, the further research will be address not only the power and stability control but also the multiple energy resources such as solar plant, storage battery to maintain the smart home system with distributed resources. Since the system will be more complex, the stability, computation and instantaneous power supply and demand problems of the system will become the critical problems need to solve out. By solving these problems, I will consider the power and stability control for large scale system such as multiple smart homes for a smart city/community.

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Publications

International Journal

[1] S. Umer, M. Kaneko, Y. Tan, and A. O. Lim: "System Design and Analysis for Maximum Consuming Power Control in Smart House," J. of Automation and Control Eng. (JOACE), vol. 2, no. 1, pp. 43-48, (2014).

[2] S. Umer, Y. Tan, and A. O. Lim: "Priority Based Power Scheme for Power Consumption Control in Smart Homes," Int. J. of Smart Grid and Clean Energy (SGCE), vol. 3, no. 3, pp. 340-346, (2014).

[3] S. Umer, Y. Tan, and A. O. Lim: "Stability Analysis for Smart Homes Energy Management System with Delay Consideration," J. of Clean Energy Technologies, vol. 2, no. 4, pp. 340-346, (2014).

[4] S. Umer, Y. Tan, and A. O. Lim: "Integrating Stability and Power Control for Smart Homes Energy Management Systems," IEEE Trans. on Smart Grid. (*To be submitted*)

[5] S. Umer, Y. Tan, and A. O. Lim: "Implementation of Integration of Stability and Power Control Scheme for Future Smart Homes Energy Management Systems," IEICE Trans. on Fundamentals of Electronics, Communications and Computer Sciences. (*To be submitted*)

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[6] S. Umer, M. Kaneko, Y. Tan, and A. O. Lim: "System Design and Analysis for Maximum Consuming Power Control in Smart House," The Third Int. Conf. on Power and Energy Eng. (ICPEE), Phuket, Thailand, (2013).

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[8] S. Umer, Y. Tan, and A. O. Lim: "Stability Analysis for Smart Homes Energy Management System with Delay Consideration," The Second Int. Conf. on Elect. Energy and Networks (ICEEN), Phuket, Thailand, (2014).

[9] S. Umer, M. Kaneko, Y. Tan, and A. O. Lim: "Priority Based Maximum Consuming Power Control in Smart Homes," IEEE PES Conf. on Innovative Smart Grid Technologies (ISGT), Washington DC, USA, (2014).

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[10] S. Umer, Y. Tan and A. O. Lim: "Lyapunov Stability Analysis for Intelligent Home Energy Management System," IEICE Society Conference, Toyama, Japan, (2012).

[11] S. Umer, Y. Tan and A. O. Lim: "Lyapunov Stability Analysis of Energy Constraints for Intelligent Home Energy Management System," IEICE Technical Report on Ubiquitous and Sensor Networks (USN), pp. 131-135, Fukuoka, Japan, (2012).

[12] S. Umer, M. Kaneko, Y. Tan and A. O. Lim: "Energy Stability-Aware Scheme for Intelligent Home Energy Management System," 64th IPSJ SIG Mobile Computing and Ubiquitous Communications (MBL), Hokkaido, Japan, (2012).

[13] S. Umer, Y. Tan and A. O. Lim: "Study of Priority-Based Power Assignment Scheme for Smart Homes Energy Management System," 67th IPSJ SIG Mobile Computing and Ubiquitous Communications (MBL), Tokyo, Japan, (2013).

[14] S. Umer, Y. Tan and A. O. Lim: “Evaluating Power Assignment Criteria of Energy Management System for Smart Homes,” IEICE Society Conference, Fukuoka, Japan, (2013).

[15] L. S. Gin, S. Umer, Y. Tan, and A. O. Lim: “Enabling Priority-Based Power Sharing Scheme with Demand Response for Smart Homes,” , IEICE Society Conference, Niigata, Japan, (2014).