FAST DEMAND RESPONSE CONTROL STRATEGY FOR DECENTRALIZED AIR-CONDITIONING SYSTEMS IN MICROGRIDS

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Degree of Master of Science by Research

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DECLARATION

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ABSTRACT

Distributed energy systems are essential to integrate renewable energy sources to the modern electric grid. Microgrids are a distributed energy system that enables the integration of the intermittent renewable energy sources. Microgrids can operate in islanded mode without the support of the main grid in case of emergency. In this operation mode there must be a wide range of controls to operate the Microgrid until the main grid is available. A microgrid that consists of distributed air conditioning units is considered in this research. This research focuses on developing a control strategy to support the islanded operation of Microgrids using Fast Demand Response and Direct Load Control. The controller developed is a feedback controller with an Integer Linear Programming optimizer that optimizes the thermostat setpoint population of the air conditioners in the control loop. It is showed that the developed controller can be used in achieving power reserve margins, emergency load reduction and cold load pickup mitigation in an islanded Microgrid using simulations.

Keywords— Islanded Microgrid; Fast Demand Response; Direct Load Control; Distributed Air Conditioners; Inverter Air Conditioners; Thermostat Setpoint Control; Integer Linear Programming; Power Reserve Margins; Emergency Load Reduction; Cold Load Pickup;

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Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

PV: Photovoltaic

AC: Air Conditioning

Fast DR: Fast Demand Response

IoT: Internet of Things

DLC: Direct load control

FSCAC: Fixed speed compressor AC units

VSCAC: Variable speed compressor Air Conditioner

Inverter AC: Inverter Air Conditioner

DG: Distributed Generator

DSM: Demand Side Management

IPS: Isolated Power Systems

DR: Demand Response

AS: Ancillary Services

ADR: Automated Demand Response

TCL: Thermostatically Controlled Load

ACP: Autonomous Control Protocol

ACCP: Advanced Communication and Control Protocol

ADS: Automatic Dispatch System

DRAS: Demand Response Automation Server

EMCS: Energy Management and Control Systems

CDMA: Code Division Multiple Access

HAN: Home Area Network

BAN: Building Area Network

EMS: Energy Management System

DRMS: Demand Response Management System

HEMS: Home Energy Management System

WAN: Wide Area Network

MPC: Model Predictive Control

B&B: Branch and Bound

ILP: Integer Linear Programming

Introduction

Microgrids and their applications are essential for the future power system. With the concern of climate change, the world is striving to decrease the carbon footprint in every sector. In electric power generation, introducing renewable energy into the power mix and maximizing it is the solution for a low carbon sustainable solution. The renewable energy sources currently available commercially such as wind and solar photovoltaic (PV) are intermittent. This intermittency poses several challenges when integrating them with the utility grid. Microgrids can manage these renewable sources so that the negative effects on the utility grid is minimized. Also, microgrids increase the reliability of the power system by operating in the islanded mode when the main utility grid fails. This application of microgrids is quite useful for critical loads such as hospitals, security buildings, and some power plants.

In the IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems [1], in sub-clause 5.1 it states that,

“The DR island system needs to meet the load requirements. There are several considerations when dealing with the loads in an island system. The load control scheme should manage all participating loads. This functionality includes load shedding when the DR cannot serve all connected loads.”

This shows that load control in an islanded microgrid is essential for its operation. The loads in a microgrid can vary according to the type of the microgrid. If the microgrid is formed in an industrial facility, there will be more industrial loads and if it is formed in a residential building or a residential area it will have more residential electric appliances. Typically, residential apartments and sometimes office buildings use decentralized Air Conditioning (AC) units to provide air conditioning.

If building energy consumption in tropical countries is considered, the most power-consuming load type is the AC load. The load composition in a building in tropical countries is given in Figure 1 [2]. From this, the capability of using decentralized AC units for demand control programs is justified.

Occupant comfort is an essential aspect when controlling the AC loads. This research will address this issue by controlling thermostat setpoints initially and resorting to load shedding as a final resort.

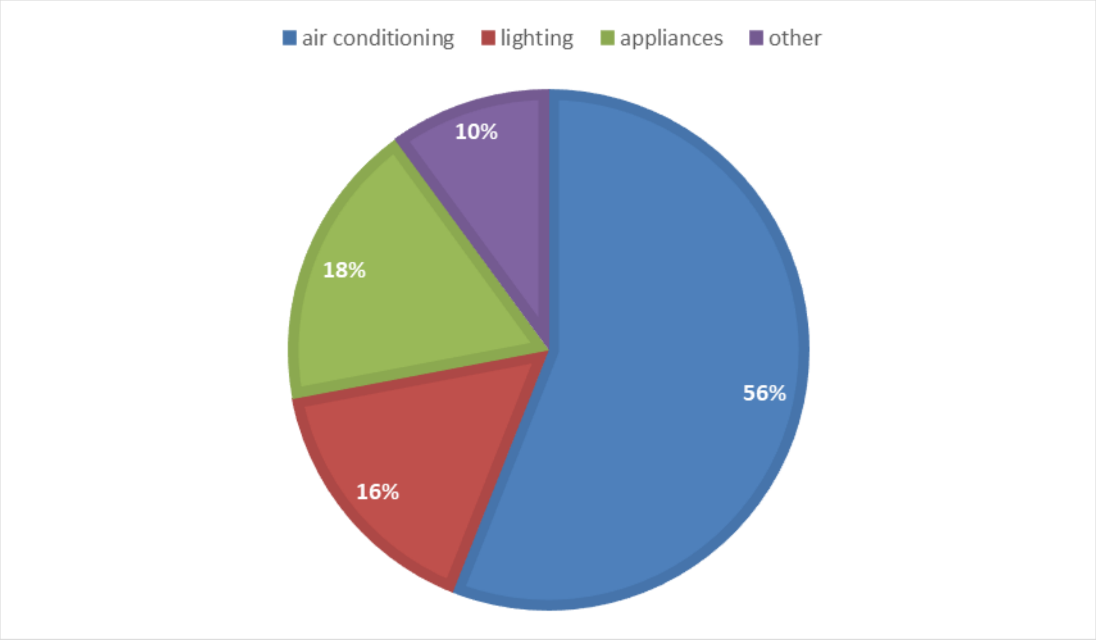

Figure 1.1. Typical Building Energy Consumption in Tropical Countries [2]

1.1. Project Objectives and Scope

The objectives of the research can be listed are

- Development of Fast Demand Response (Fast DR) strategy for decentralized ACs.
- Develop a controller for the ACs to control the thermostat using the Internet of Things (IoT) technologies.

The scope of the research can be explained by

- Emergency load control in islanded microgrids using distributed ACs is the focus of the research
- The number of ACs is reasonably low (<100)
- Direct load control (DLC) and Fast DR are used to execute emergency load control
- The control strategy is proposed to reduce the AC load in an emergency while considering the occupant comfort
- The strategy is based on thermostat setpoint control and finally resorting to load shedding only if necessary

1.2. Research Methodology

The research methodology is detailed chronologically here,

- Review the Fast DR concept and its applications
- Review islanded microgrid emergency load control
- Review on distributed ACs for demand alteration
- Develop distributed AC models
- Develop the control strategy for ACs
- Explore the applications of the strategy
- Developing an IoT based plug and play module for thermostat setpoint control for ACs

1.3. Decentralized Air Conditioning Units

There are two types of decentralized AC units.

- Fixed speed compressor AC units (FSCAC)
- Variable speed compressor AC units (Inverter ACs/VSCAC)

Both AC types are considered in this research. The difference between the two types is the working principle of the compressor. As described in the name, the Fixed speed compressor ACs, which are the early AC type has a compressor that can only run at a constant speed. These are on/off type systems. The variable-speed compressor AC has a compressor with an inverter that can operate the compressor at different speeds. The inverter AC is the more efficient AC and they are starting to be popular among the customers.

There are several types of ACs based on the construction of the AC. They are,

- Window type AC
- Split type AC
- Multi-split type AC

All these three types have the same power consumption pattern regardless of the type. The research can be applied to any of them without any modifications.

1.4. Direct Load Control and Fast Demand Response

DLC is a technology which enables the utility to control the loads in the customer premises and give certain incentive to them based on pre-agreed contracts. This is an effective way to control customer demand.

Fast DR is a Demand Response strategy that controls the customer loads in short amounts of time. The period of the control can vary from a few seconds to minutes according to the requirement. Usually, Fast DR strategies are implemented to provide ancillary services to the power system.

In all Fast DR programs that are reviewed for the project, DLC is used to control the loads.

1.5. Islanded mode operation of microgrids

In the islanded mode, microgrid frequency and voltage must be controlled [89], [90]. The minimum requirement to achieve this would be to have at least one Distributed Generator (DG) in the microgrid that can control the voltage and frequency.

With these controls, Demand Side Management (DSM) should also be implemented for emergencies where the other controls are not enough.

1.6. Thesis outline

The structure of the thesis is as follows. Chapter 2 summarizes the research on Fast DR in the conventional power grid and Isolated Power Systems (IPS). This review will be incorporated to develop the structure of the Fast DR in isolated Microgrids and identify the challenges that need to be addressed in implementation. Also, this review will identify the technology and the experimental status of Fast DR programs to justify its applicability in islanded Microgrids.

Chapter 3 is a brief review of the control of islanded Microgrids. It is focused on frequency and voltage control and summarizes the control using DSM.

In chapter 4, the models of FSCACs, and Inverter AC are developed in MATLAB/Simulink. Also, the Fast DR capability of distributed ACs is evaluated.

Chapter 5 presents the algorithm that is developed for Fast DR applications and the algorithm is implemented in Simulink using different use cases. The time consumption of the ILP, Branch and Bound algorithm is measured for an increasing number of variables is measured to imply the practical usability of the algorithm. Also, a more generalized version of the algorithm is presented in the end.

Chapter 6 presents the proposed IOT based control system hardware development.

Chapter 7 presents the simulation results of the different real-world applications of the algorithm in the context of islanded Microgrids.

Chapter 8 summarizes the conclusion and other salient achievements in the research followed by a recommendation for future improvements.

2. Fast Demand Response for Ancillary Services in Power Systems

Demand response (DR) has been identified as a viable method to provide ancillary services to power systems [2], [11]-[76]. Because of the plans of the many countries in the world to turn to a higher capacity of renewable energy soon [3]-[5], the reliability of the utility grids will be at risk due to the intermittent nature of these renewable sources [2]. The ancillary services provide the utility with several resources that can be used in an emergency or in control which in turn increases the power systems' capability to handle more renewable energy sources.

Ancillary services (AS) are services that support the power system in maintaining power quality, reliability and security. The main ancillary services are regulation, load following, spinning reserve, and non-spinning reserve. These resources are traditionally supplied by generators and with more capacity needs using DR to supply AS is studied.

DR programs are a set of programs or activities that introduce changes to the power consumption patterns of consumers as a response to the price of the electricity over time or incentives provided by the utility at certain high-cost periods or when the system reliability is at risk [6]. DR programs, DR program types, and taxonomy, DR program participants and challenges are widely reviewed in the literature [6]-[9]. Automated demand response (ADR) is identified as a type of DR program in which the DR signals of the utility are received by control equipment on the consumer side and the necessary preprogrammed control is done automatically without human assistance. Automating the DR programs is required for the advancement of the DR programs and smart grid technologies will permit the ADR programs to thrive in the future. For an overview of ADR architecture, standards, case studies, and research challenges, see [10].

Introducing DR or ADR to provide AS in the power system paved the way for a fast time scale demand response. Fast time scale demand response, fast automated demand response and Fast DR are used to describe the same concept in the literature over the years. However, Fast DR is yet to be properly defined. There are many similarities between DR for AS and Fast DR and in many cases, DR for AS can be categorized under Fast DR. in [77] Kiliccote shows that regulation services, load following, spinning reserves, and non-spinning reserves are the AS for Fast DR participation. To justify this, these AS and their features are summarized in Table 2.1 [77].

Table 2.1 Ancillary services for Fast DR participation [77]

Service	Response Speed	Duration	Market Cycle
Regulating reserves	< 1min.	30 min. (in real-time markets)	Hourly, every 15 min.
		60 min. (in day-ahead markets)	Looking ahead 2 h
Load following	~ 10 min.	10 min. to hours	5 min.
Spinning reserve	Instant response: < 10 min.	30 min.	10 min.
Non-spinning reserve	< 10 min.	30 min.	10 min.

2.1. Research Areas

The research areas are economics-related, policy-related, and technology-related [2]. Some studies may overlap in the areas they touch while others are more focused. The trend is that while economics and policy-related work are done together, and technology development is more focused. Also supporting experiments are almost always present in economics and policy-related work. There are subcategories in the technology-related literature. They are experimental studies and simulated studies. Typically, simulated studies are used for control development. There are several other notable research areas such as required communication [18], [40], [41], [52] and baseline estimation [43].

Also, there are some other approaches such as using both DR and electricity generation for AS [55], [72]. Furthermore, in [56] DR and the existing spinning reserve are used for frequency restoration. Also, in [61] primary voltage is controlled using DR. The main research areas can be summarized as in Figure. 2.1. Table 2.2 gives the classification of the literature available on Fast DR for AS.

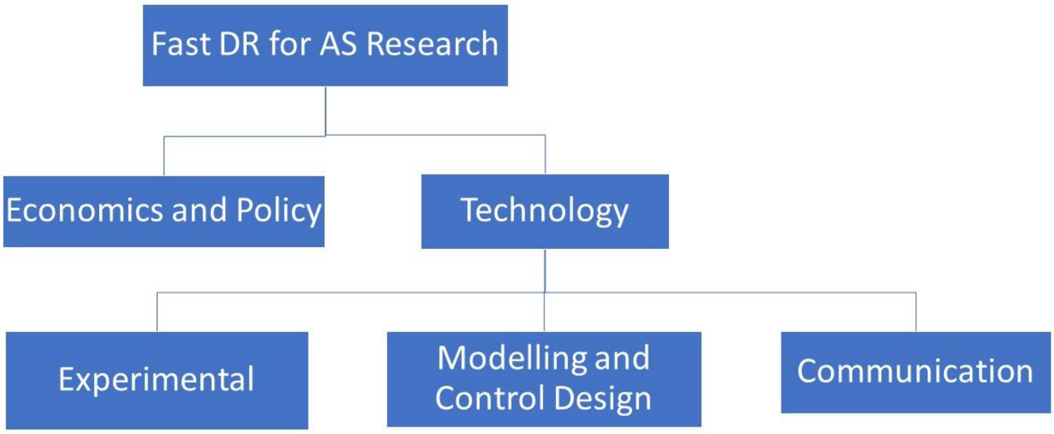

Figure 2.1. Classification of research areas on Fast DR for Ancillary Services

Table 2.2. Classification of literature on Fast DR for ancillary services

Research Type	Literature
Economics and policy related	[11]-[14], [16], [20], [23], [24], [58], [64], [66], [67, [70], [73], [75]
Technology related: experiments	[11], [15], [19], [25], [60], [62], [71], [74], [76], [78]-[80]
Technology related: control	[28]-[39], [42]-[51], [53]-[57], [59], [61], [63], [65], [67]-[70], [72]
Technology related: communication	[18], [40], [41], [52], [77]

2.2. Economics and Policy Studies

The early research addresses the economics of implementing DR for AS. The studies, [11] and [12] are the beginning of a series of research and reports to introduce the idea of AS using DR in the USA. In [12] authors have conducted a study to analyze the potential of providing ancillary services to the grid using pump loads. Their results were encouraging, and the authors have reported over $11 million in revenues annually and pointed out the policy and rule changes needed to give AS using load response. In [13] the authors argue on the costs of using generation for spinning reserve and points out that using DR for AS will reduce costs of all power system customers. Kirby answers some important questions regarding the concept and the economic value it possesses as well as rule and policy changes needed to adopt DR for AS in [14]. In [16], authors have analyzed the capability of providing DR through its manufacturing and aluminum smelting facilities. There is a market analysis done to obtain the exact financial benefits of the implementation. Also, a comparison is done to compare the different markets in the USA in [16] as well as in [24]. Similar market analysis regarding the UK, Australian, Nordic, Pennsylvania, New Jersey, Maryland Interconnection LLC (PJM) and Electricity Reliability Council of Texas (ERCOT) is conducted in [20]. Also, several international feasibility studies in Canada [66] and Italy [73], [75] is done. In [23] an interesting economic study is done to compare the costs between batteries and DR in the context of renewable energy. Also, in [58] a study is conducted to identify the mix between DR and renewable energy to minimize the cost of operating wind energy. All the studies [11]-[14], [16], [20], [23], [24], [58], [66], [73] and [75] give positive results on the economic value of implementing DR for AS. The negative results are from the authors of [64], [67] and [70]. In [64] it is concluded that immediate financial benefit to run a Fast DR type program on small domestic thermostatically controlled loads (TCLs) is negative. They also stress the fact that there are limitations of the models used and there are indirect benefits and other types of markets that are not included in the study. In [67] and [70] the researchers point out that the overall efficiency of the system is adversely affected because of the short timescale changes in the system and later compensating for them. The research areas of the economic studies can be summarized as follows,

- Preliminary feasible studies
- Studies specialized for different customers/ loads
- Studies based on different market structures
- Studies in the context of renewable energy

2.3. The Technology used in Experimental Studies

After and during the preliminary studies researchers began experimenting on the concept of providing ancillary services through Fast DR. Several notable experiments are,

- SCE experimental study
- PG&E experimental study
- LBNL experimental study
- An experimental study by Cardiff University
- An experimental study by Mitsubishi Electric Building Techno-Service and Kyushu Institute of Tech.
- LISCOOL energy project
- King Island Smart Grid project
- SYSLAB at Technical University of Denmark

Some experiments are on grid-based Fast DR programs and some are done for IPSs. The most notable experiment on Fast DR in IPS is done in [62], [80] and [81] studies. The IPS in these studies is the King Island Smart Grid. This review is focused on the technology aspect of the study.

2.3.1. SCE experimental study

In [19], [25] and [78] The Demand Response Spinning Reserve Demonstration project is presented. The authors have described the system to enable the implementation as follows. SCE is the control center that dispatches the DR signal. SCE is connected to radio towers owned by them through fiber or microwave connections. The signals are then transmitted using these radio towers to the load control switches in customer’s air conditioners. The load control switches are based on the Autonomous Control Protocol (ACP).

For load monitoring and telemetry, a combination of existing and novel means is used. For the data on the total load, existing SCE internal load monitoring is used. This system is a SCADA system [78]. It provides data on a 4s – 10s rate and this data are accessible to any external entity when given access through a secure website. The demonstration archived data from many sources for analysis. These sources are feeder level data from SCE, operator data from SCE, weather data from SCE, weather data from National Weather Service and air-conditioner load and timing data. The challenge of working with the different data sources, using existing platforms and using the internet for communication to develop a reusable, scalable and expandable solution was addressed by a multilayered implementation of the Advanced Communication and Control Protocol (ACCP) [19]. Few enhanced two-way communications enabled switches were used that could monitor the load, monitor switch closure and report and time synchronize with SCE servers. These functionalities were additional functionalities from other switches.

Few changes to the implementation were made in [78], which is phase 2 of the demonstration. The enhanced switches were integrated directly with the BPL Global data center rather than using web services. Also, the switches could be used to get data at any time. Also, a software application that directly communicated with the CAISO Automatic Dispatch System (ADS) was used. Also, the web portal used in phase 1 was enhanced [78].

2.3.2. PG&E experimental study

In [21], PG&E’s experimental study is presented. CAISO day-ahead market is considered to bid DR resources for ancillary services. The technical feasibility is studied. The non-spinning reserve is targeted in the experiment. the DR resources are deployed upon CAISO request. The Demand Response Automation Server (DRAS) is interfaced with the ADS. DRAS requests DR signals from the ADS. The OpenADR communication system is used to send DR signals to Energy Management and Control Systems (EMCS) in the participating facilities. The pre-programmed strategies are automatically executed according to these signals using the Client Logic with Integrated Relay (CLIR) box.

Each participating facility has four-second telemetry equipment to ensure accountability. This meter has a Code Division Multiple Access (CDMA) chip which uses radio signals over a cellular-based network to transmit data. These meters used Bow Networks to communicate data to CAISO.

2.3.3. LBNL experimental study

In [26], the demonstration in Lawrence Berkeley National Lab is presented. The goal of this project was to evaluate the methods used in Fast DR programs. The OpenADR Virtual Top Node (VTN) is on a cloud-based server with Ubuntu Linux. In this demonstration, it was a virtual machine housed in a data center at LBNL. Each client site has controlled loads and Open Smart Energy Gateway (OpenSEG) and a BeagleBone Black. Open source SMAP data aggregation server was used to store telemetry and DR event data. The VTN handles the direct interactions with the Virtual End Nodes (VEN). The OpenADR VEN server is running on a BeagleBone Black. The USB radio adapter, Rainforest RAVEn adapter is used to provide a wireless interface to the OpenSEG which is used to gather telemetry data. All loads on the client-side receive actuation signals from BeagleBone Black. Event notification and telemetry for the loads are done using OpenADR 2.0b. The loads used are Wi-Fi thermostat, dimmable LED bulbs, binary switches, and heat pump water heaters. In the demonstration, sites that had Home Area Networks (HANs) or Building Area Networks (BANs) were used.

Several software components in the system which enabled the operation can be identified for more clarification. OpenADR VTN Server, OpenADR VEN Server, OpenSEG Server, sMAP Data Aggregation Server and Software on the controlled end-user device are the main software components.

2.3.4. An experimental study by Cardiff University

The experiment in [53] is carried out in the UK by researchers from Cardiff University to demonstrate a load control scheme to provide primary frequency response that used local frequency measurements obtained through a smart meter. This was an experimental rig developed in the laboratory.

The main components of the rig were a smart meter, a smart load controller and smart sockets that used the HAN for communication. The smart meter measured the frequency of the power system and stored it. A Laptop PC was used to implement the smart load controller which read the frequency of the supply and decided which loads to turn off or turn on using an algorithm. Then these signals were sent to the smart sockets through the HAN. Using these signals smart sockets turned on or turned off the appliances.

The smart meter used was commercially available and the stored frequency values can be read through RS485 port using Modbus protocol [79]. The protocol convertor was used since the PC had an RS232 port. USB type Z wave Controller was used to build HAN and the data rate is 40 kbps. The smart sockets used were plugged into existing wall sockets and the appliances were plugged into the smart sockets.

2.3.5. An experimental study by Mitsubishi Electric Building Techno-Service and Kyushu Institute of Tech.

The experiment in [71] was done in Japan by researchers from Mitsubishi Electric Building Techno-Service and Kyushu Institute of Technology. It is an experimental evaluation of Fast DR.

The structure of the system is as follows. The main component is an aggregator which is consisted of DRAS, DR Control Servers, and DR Management Servers. The DRAS receives an invocation signal from the power companies using the OpenADR 2.0b protocol. The customers’ baseline consumption is calculated by DR Management Servers then DR Control Servers fix the target demand of each customer. The Energy Management System (EMS) in the customer premise controls the demand according to signals from the aggregator sent through a secured network.

2.3.6. LISCOOL energy project

One of the goals in the LISbon COOL energy project is to implement an Automated Fast Demand Response Management Solution (AFDRMS) which is a Fast DR program [74]. The program consists of two parts. One is a DER program that maximizes renewable auto-consumption on a microgrid level. Another program is a DLC program that resolves contingency situations on the network.

There are two main components in the system. They are the DR Management System (DRMS) and the AC ADR system. these two are connected through the OpenADR 2.0b protocol. The DRMS connects to industrial customers to send signals as well as using the ADR system. ADR system sends signals to VENs in the AC local controllers or Home Energy Management Systems (HEMS). VTN is the DRMS that receives DLC signals from the system operator. The end devices are connected to either ADR system or DRMS through Wide Area Networks (WANs).

2.3.7. King Island Smart Grid project

King Island Smart Grid (KISG) project has the goal of supporting high wind energy integration by providing spinning reserve and immediate fine-grained under frequency load shedding [62], [80], [81]. The system consists of DR Master Controller, communication network and slave controllers. The DR Master Controller constantly communicates available DR capacity to the Power System Controller (PSC) while checking for DR dispatch signals. The DR Master Controller was installed on a server computer in the power station control room and directly connected to PSC. Standard WiMAX antennas were used for the communication backbone. WiMAX modems are fixed in customer premises which received signals from WiMAX antennas and a slave controller box is sending signals to the smart switches in the switch box. When sending signals to the smart switches the slave controllers use ZigBee modules.

2.3.8. SYSLAB at Technical University of Denmark

In [76] researchers aim to use TCLs for DR services which focuses on secondary frequency control. Domestic refrigerators are taken as the TLC loads. The experiment was done in an islanded LV network. This experiment builds on previous research, Project INCAP. The fridges are emulated using a vanadium battery by using the real time data which were available.

The devices connected to the refrigerators are a control device, a temperature sensor, a user interface, and a communication device. The controller device is a relay unit which has power measuring capability. The cooling chamber temperature was measured by using a temperature sensor. The user interface is used to give information to the users. The communication device is a ZigBee module and it uses ZigBee wireless protocol for communication. The connection to the remote server was established using a ZigBee Ethernet gateway device. Usually, customers used an ADSL home internet connection to establish a connection with a remote server.

2.3.9. Overview

After establishing that DR can provide AS in an economical way, researchers began studying the technology needed to achieve it. There are several basic technology components of the DR for AS programs. Since these components are also available in all Fast DR programs, these technologies are identified as the technologies required for Fast DR programs.

All the controllers in experimental studies use a central controller and local load controllers. In every case considered in this review, the central controller hardware is a server computer. Many types of load controllers are used in different studies. Some of these controllers are commercial components [11], [15]. Smart switches and relays are widely used as load controllers.

Software to implement load control and telemetry is used in experimental studies. The use of OpenADR 2.0b is prominent in the experiments. Other protocols include ACCP, CDMA, Modbus and ZigBee which are used for communication. A summary of the technologies used in experimental studies is given in Table 2.3.

Table 2.3. Summary of Technology used in Experimental Studies

Study	Control		Telemetry
	Central Control	Load Control	
SCE Experimental Study [19], [25], [78]	SCE Control Center (SCADA System sends DR signal to loads through Radio Tower using VHF waves)	Load Control Switches with ACP (VHF receiver takes the signal and control loads using relays)	• Web based • ACCP
PG&E Experimental Study [21]	DRAS	EMCS controls the loads using CLIR box	• Smart Meter with CDMA chip • Network provider (Bow Networks)
LBNL Experimental Study [26]	Cloud-based server with Ubuntu Linux	• BeagleBone Black Controller • Wi-Fi Thermostat • Dimmable LED bulb With OpenADR 2.0b	• USB radio adapter (Rainforest RAVEn adapter) • OpenSEG
Experimental Load Control Scheme: UK Experiment [53]	Laptop PC	Smart sockets with HAN	• Commercially available smart meter • Modbus protocol used
Fast DR for Small Buildings in Japan [74]	DRAS	EMS with OpenADR 2.0b	EMS
LISCOOL Energy Project in Portugal [74]	DRAS in a DRMS	AC local Controllers or HEMs with OpenADR 2.0b	Not Specified
King Island Smart Grid Project [62], [80], [81]	DR Master Controller (WiMAX antennas are used to transmit the signal)	Slave controller box with smart switches (WiMAX modem takes the signal and given to smart switches using ZigBee module)	Not Used
Secondary Frequency Control based on DR [76]	Project INCAP Server	Smart relay controller (Communication using the internet)	Measurement using the same controller used for load control

2.4. Control System Studies

The simulated studies are done to develop the control logic for different loads. The control logic depends on the control load type as different loads show different power consumption characteristics.

Mainly there are three types of loads considered in previous studies and they are, TCL, distributed air-conditioners and central HVAC systems. Also, there are pool pumps [32] and data center loads [69] that are used in the studies. Finally, research on using inverter ACs and variable speed heat pumps for providing frequency response in a power system is reviewed. Classification of control logic research based on the type of load is given in Table V. Main types are used for the categorization.

Table 2.4. Classification of research on control logic based on load type

Load Type	Research
Central HVAC	[28], [29], [30], [33]-[37], [39], [42]-[51], [63], [67], [70]
Distributed air-conditioners	[57], [59]
Thermostatically Controlled Loads	[31], [54], [82], [83]
Inverter ACs & Variable speed heat pumps	[84]-[88]
Pool pumps	[32]
Data Centers	[69]

2.4.1. Central HVAC

Studies on using Central HVAC systems for Fast DR is done by several research groups. Their research focuses on building models, developing control systems and providing ancillary services without effecting the occupant comfort.

In [28], [29], [33] and [34] the researchers have gradually improved the model, control, and results. In this literature, a model based on input-output measurements is used to develop a controller. In [28], providing regulation to the grid is converted into a Linear Quadratic Regulator (LQR) problem which has a simple closed-form solution. In [29] and [35] a feedforward control architecture is proposed. In both this literature, the controlled load is a Variable Frequency Device (VFD) equipped fan in an Air Handling Unit (AHU). It was observed that 15% of fan power is used for regulation and the regulation signal can be tracked in the frequency band $f \in \left[\frac{1}{3\,min}, \frac{1}{8\,sec}\right]$ without effecting the indoor temperature. It can be derived that approximately 6.6 GW regulation capacity can be provided using all the VFD equipped fans in commercial buildings in USA. In [33] and [34], the research is expanded to include chillers. It used Variable Air Volume (VAV) HVAC system with onsite chillers. The main idea presented in these studies is the bandwidth limitation of the regulation signal. It can be derived that approximately 47 GW regulation can be provided, and the regulation signal can be tracked in the frequency band $f \in \left[\frac{1}{60\,min}, \frac{1}{3\,min}\right]$ without effecting the indoor temperature. Also, all these systems meet the ISO/RTO standards for regulation. Further studies on providing faster response is given in [36].

In [37] fine time granularity fast demand control of building HVAC system is studied. A novel scheme is proposed for building Variable Refrigerant Flow (VRF) HVAC system. an Auto Regressive (AR) model of 5-minute interval power consumption of the entire building HVAC facilities was obtained using data. The trial calculations show that the new scheme implementation will be successful. In [39] and [42] an emulation system is developed to reproduce and analyze the behavior. A neural network model is developed from actual time series data. It was found that step responses of Fast DR sometimes oscillate depending on control.

In [44] Fast DR control strategy is presented which uses shutting down chiller(s) of a HVAC system. Also, active and passive cold storage is used in this strategy to improve indoor thermal comfort and to alleviate the post DR event spike in demand. The advantages of using chillers to reduce demand is that the demand reduction is immediate and considerable. However, there are some problems such as uneven distribution of water flow and air temperature unevenness caused by shutting down essential operating chillers. These issues are addressed in [45], [46] and [48]. The paper [47] presents a control strategy based on Model Predictive Control (MPC). In [49] and [50] the control strategy for the cold storage is discussed and the complete research is presented in [51] in detail.

In [63] the researchers develop a model for commercial HVAC systems and in [67] and [70] they use it to design controllers to provide ancillary services. However, their economic study gives negative results when the overall efficiency is considered.

2.4.2. Distributed air-conditioners

In [57] load control of heterogeneous populations of ACs using a novel parametric Linear Time Invariant (LTI) model is presented. This LTI model is used to design the controller using the parameters of the AC population. The control is done by introducing offset to the user's temperature set-points. The study in [59] presents Thermostatically Controlled Appliances (TCA) which controls the Air Conditioners. A centralized load controller is developed to control TCAs for Continuous Regulation Reserves (CRRs). The logic for setting up baseline load, generating priority lists, issuing dispatch commands is given in [59]. A system consisting of 1000 HVAC units in their heating mode is modeled to provide ±1 MW CRR 24 hours a day. The TCA load controller is successful in providing robust, high quality CRRs with reduced cost for communication and load controllers. In [83] parameter section of the controller is discussed.

2.4.3. Thermostatically Controlled Loads

These studies are similar to controlling distributed ACs, but a wide range of appliances can be used with these controllers. In [31] a generalized battery model is used and in [54], bin transition modelling technique is used for the control design. In [82] regulation service is provided using DR of TCLs.

2.4.4. Inverter ACs & Variable speed heat pumps

There are number of studies on using inverter ACs and variable speed heat pumps for DR. However, they are limited to providing frequency response to power systems which can be extended to provide ancillary services. The researchers have modelled [88] and developed control systems to provide frequency regulation in a power system [84]-[88]. This research can easily be extended as a Fast DR program.

2.5. Conclusion

Many studies show that the Fast DR is economically viable with few exceptions. However, these exceptions also point out that Fast DR can be improved or that all the factors are not considered in their research scope.

Technology used in Fast DR programs is considered in the context of experimental studies and the control development. Most of the studies consider central HVAC systems, Distributed ACs and TCLs. Also, inverter ACs are considered for DR which can be directly applied to Fast DR programs. Apart from using Fast DR in main utility grid, some researchers have experimentally used it in IPSs successfully. All these findings show that Fast DR is a viable technology to provide ancillary services to main utility grids and IPSs. These technologies can easily be adopted into the islanded Microgrids.

3. Islanded Microgrid Operation and Demand Side Management

Islanded mode operation of Microgrids is crucial for the reliability enhancement of the system. In islanded mode operation frequency and the voltage of the microgrid must be controlled [89],[90]. There are several control architectures and strategies that can be used for this purpose.

3.1. Islanded Microgrid Operation

The main sources of the Microgrids are Synchronous Generators, Photovoltaic Systems, Wind Turbines and Battery banks. Coordination between these sources, specially the coordination between inertia-based sources such as Synchronous Generators and converter-based sources such as Photovoltaic systems, wind turbines and battery banks is essential for operation. These sources use droop control to control frequency and voltage in the system.

There are two control strategies that the converter-based sources operate in. They are,

- Single Master Operation
- Multi Master Operation

Apart from this, secondary load-frequency control is implemented in both cases [90].

3.2. Demand Side Management in Islanded Microgrids

The term Fast DR is not used in Islanded Microgrids in the existing research. However, with residential microgrids, Demand Response and Fast DR will be essential in many cases. There is literature on Demand Management in islanded Microgrids that are like Fast DR. These literature are mainly based on topics of under frequency load shedding, Demand Response for frequency regulation, and voltage regulation. The Table 2.4 categorize the research in each topic.

Table 3.1. Classification of research on Demand Side Management in islanded Microgrids

Application	Research
Under frequency load shedding	[103], [104]
Frequency Regulation	[90]- [94], [96]-[98], [100], [101], [104]
Voltage Regulation	[92], [93], [99]
Demand Management	[95], [102]

4. Modelling Distributed Air Conditioners and Assessing the Fast Demand Response Capability

The modelling is done using the Equivalent Thermal Parameter (ETP) Model which is used for the research. These models are based on the thermal energy transfer equations. The parameters are based on previous literature and practical values. MATLAB/Simulink is chosen as the simulation platform. The simulation is based on the house thermal simulation in MATLAB documentation [4].

For the research it is assumed that the AC is in a room defined by the following parameters. The room is consisted of four brick walls and concrete slabs as roof and the floor. This is chosen to get the parameters as close as possible to a room in a building.

Table 4.1. Parameters of the room

Parameters	Values
Height	3 m
Width × Length	4 m × 4 m
Concrete slab thickness	0.1016 m ≈ 0.1 m
Brick wall thickness	0.2032 m ≈ 0.2 m
Concrete thermal conductivity	0.8 W/mK [113]
Brick thermal conductivity	0.6 W/mK [113]

4.1. Modelling Fixed Speed Compressor Air Conditioning Units

There are several models in the literature to simulate the energy consumption of a FSCAC in a room [107], [108]. These models can be tweaked to simulate the power curve of a FSCAC. For the research the example model from the MATLAB documentation for the thermal model of a house [108] is used and it is tweaked similarly to this research [107] for simulating the energy consumption. That model is further tweaked to get the power curve of the FSCAC by feeding the compressor power as a constant (12000 Btu unit with constant EER of 3.11 W/W). For the sake of simplicity, the starting current of the compressor is neglected as a transient characteristic. Two other fans are working in the system. They are the blower fan in the room next to the evaporator and the cooling fan near the compressor. These fans add up to about 100 W which is neglected in the simulation.

The thermal characteristics of a building can be represented by a network of capacitances and resistances based on the heat transfer equations [109]. The air volume and thermal inertia of the materials can be represented as capacitances while building envelop insulation materials and heat patterns through walls can be represented as resistances. The temperatures and heat in this scenario are analogous of voltage and current in an electrical circuit. Using this understanding the following equations can be used to describe the model.

$$\left(\frac{dQ}{dt}\right)_{gain} - \left(\frac{dQ}{dt}\right)_{aircon} = (T_{in} - T_{set}).M.c$$

$$\left(\frac{dQ}{dt}\right)_{gain} = \frac{T_{out} - T_{in}}{R_{eq}}$$

Where,

$\left(\frac{dQ}{dt}\right)_{aircon}$	heat flow from air-conditioner out of a room (J/s)
$\left(\frac{dQ}{dt}\right)_{gain}$	heat flow from outside into a room (J/s)
M	air mass inside the room (kg)
c	heat capacity of air at constant pressure (J/kg.K)

T_{in}	room temperature (◦C)
T_{out}	outdoor temperature (◦C)
T_{set}	thermostat setpoint of the air-conditioner (◦C)
R_{eq}	equivalent thermal resistance of the room (K/W)

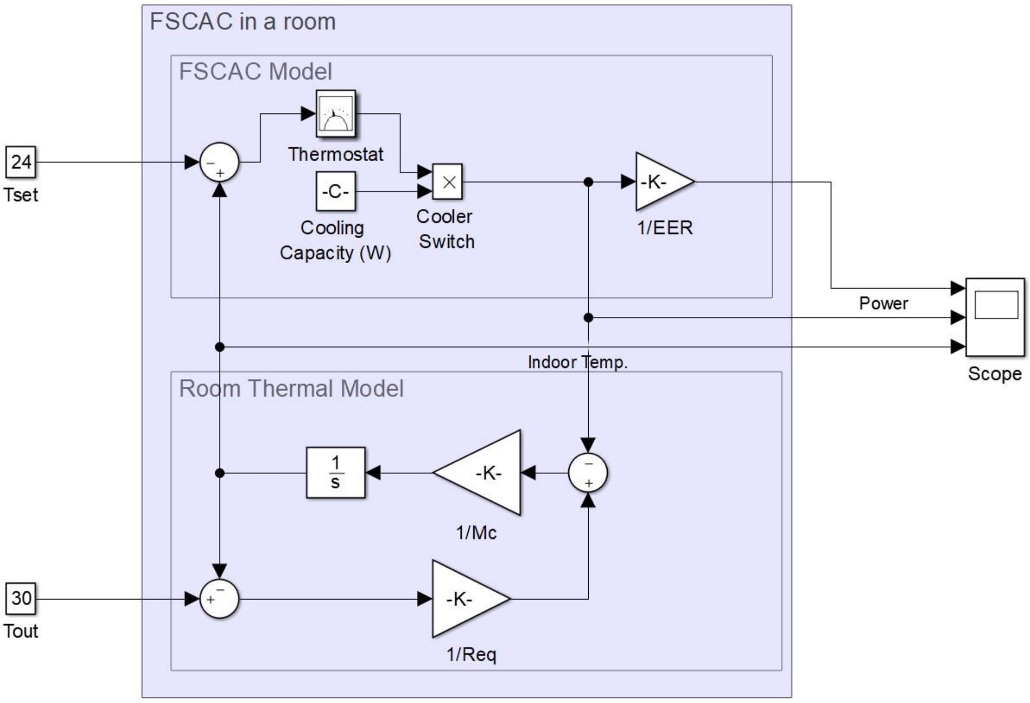

Figure 4.1. Thermal model of a room with FSCAC

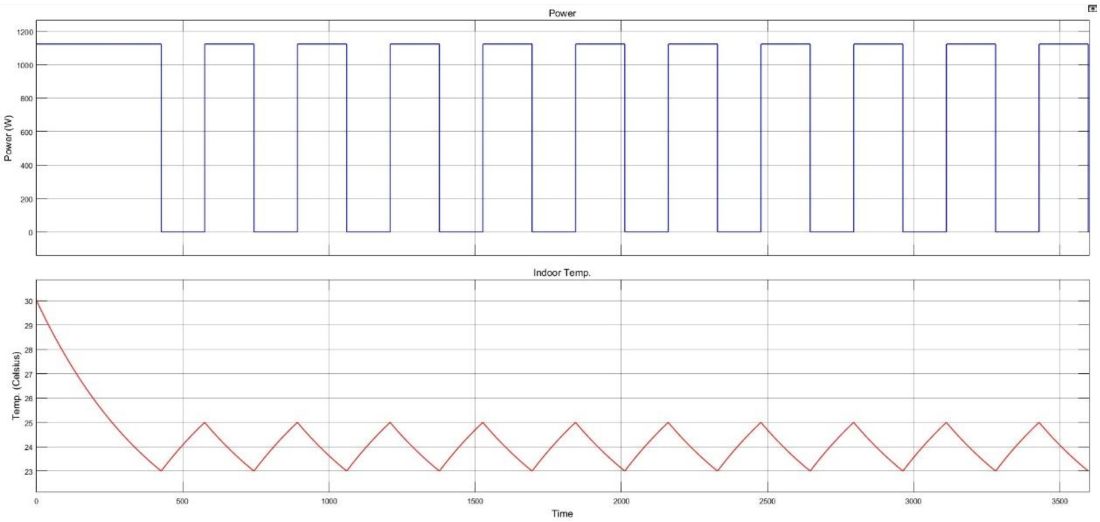

Figure 4.2. Results of the simulation

From this power consumption pattern, it is noted that emergency power reduction by using thermostat setpoint is not possible using 100 FSCACs. It may be possible for larger number of FSCACs if random operation is introduced. However, it is out of the scope of this research.

4.2. Modelling Variable Speed Compressor Air Conditioning Units

The VSCAC model is like the FSCAC model when the room thermal model is considered. The difference is that the cooling capacity of the AC is changing according to the difference between the set temperature and room temperature. The model is based on the same equations for the FSCAC model.

The same room parameters are used in this model and the AC parameters are based on the previous research [86] and specifications of commercially available inverter ACs.

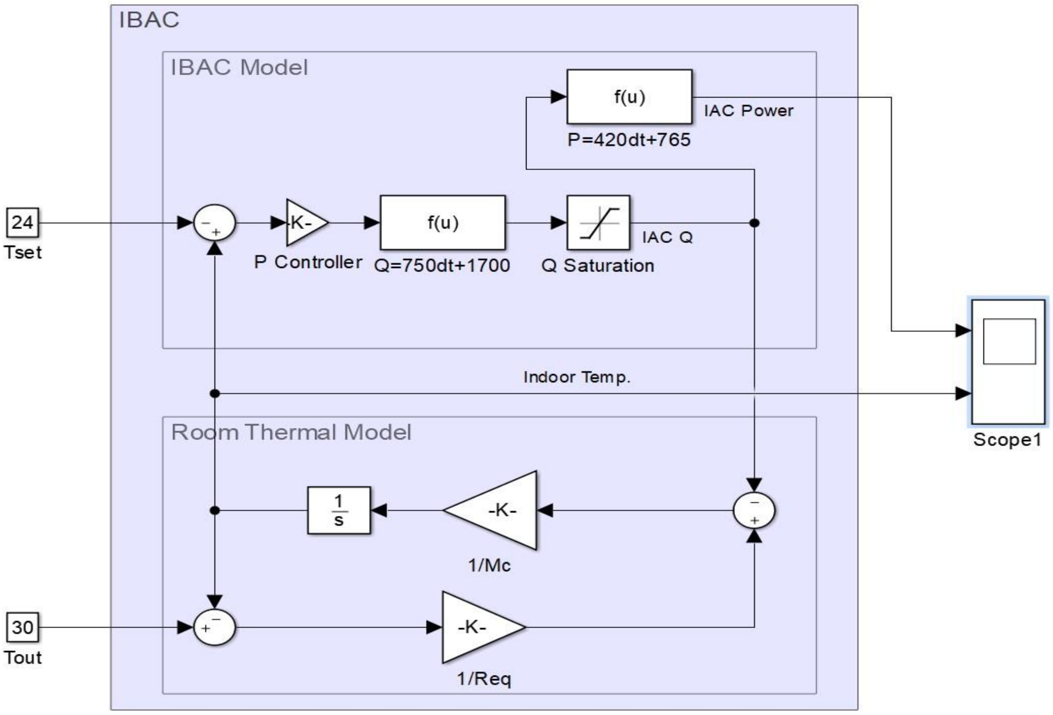

Figure 4.3. Thermal model of a room with VSCAC

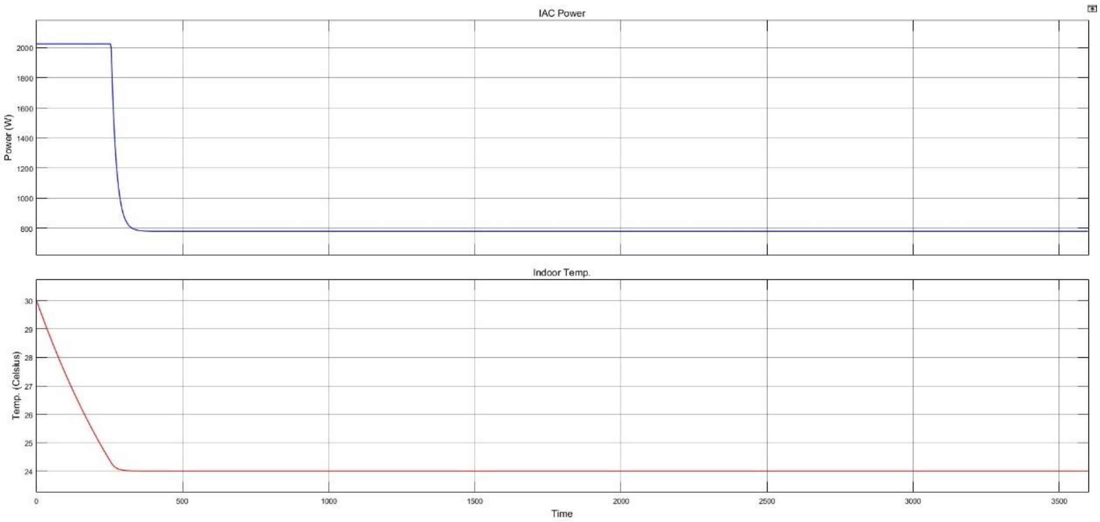

Figure 4.4. Results of the simulation

4.3. Fast Demand Response Capability of Distributed ACs

The capacity for demand alteration and the granularity of the demand are the features essential for a good demand response program.

When considering the above simulations there are key differences in the power consumption pattern of the two types of distributed ACs. The FSCACs power consumption is a square wave which changes from zero to a constant power value which is the power consumption of the compressor at the fixed speed it operates. This pattern does not change with the temperature setpoint. The time the compressor is at on state changes with the temperature setpoint, but it cannot be used to control the power consumption of the FSCAC favorably.

When considering the potential of inverter ACs for any type of demand altering program, the compressor power is the main component of the load. However, to achieve more control over the demand altering capability of inverter ACs, the power consumption of the blower fan can be considered. So, in this research, the compressor and blower fan power consumption are considered. The granularity of the inverter AC is based on the step changes that can be achieved by the load power consumption.

4.3.1. Inverter AC Compressor

The capacity of demand response is based on the highest and lowest power consumption of the load population. When considering the compressor power for demand altering, three stages must be considered as the compressor operates in a transient response, a steady state and off state. Since only the demand altering using temperature setpoints is considered in this research, off state is only used in critical conditions.

In the transient response the maximum power consumption of the compressor ($P_{max,iac}$) occurs when the operating frequency is maximum and minimum power consumption ($P_{min,iac}$) when operating frequency is lowest. These values are inherent values of the AC and can be taken from the nameplate or experimentally. For a N number of inverter AC population,

Maximum achievable power $(P_{max,t}) = N \times P_{max,iac}$

Minimum achievable power $(P_{min,t}) = N \times P_{min,iac}$

In steady state the maximum and the minimum power consumption of the compressor depends on the maximum and minimum thermostat setpoint. So, if $P_{max,set}$ is the compressor power at maximum thermostat setpoint and $P_{min,set}$ is the compressor power at minimum thermostat setpoint, for a N number of inverter AC population,

Maximum achievable power $(P_{max,s}) = N \times P_{min,set}$

Minimum achievable power $(P_{min,s}) = N \times P_{max,set}$

Granularity of an inverter AC compressor power depends on the outdoor temperature and the thermal properties of the room. It can be derived using (7). In the steady state, T_{in} is constant. So,

$$\frac{dT_{in}}{dt} = 0$$

Which gives,

$$Q = \frac{T_{out} - T_{in}}{R}$$

Now, assuming in the steady state,

Thermostat setpoint $(T_{set}) = T_{in}$.

If T_n, T_{n+1} are taken as adjacent thermostat set points, it can be derived,

$$\Delta Q = \frac{T_{out} - T_{n+1}}{R} - \frac{T_{out} - T_n}{R}$$

If the outdoor temperature is assumed to be constant,

$$\Delta Q = \frac{T_n - T_{n+1}}{R} = \frac{1}{R}$$

So,

$$\Delta P = \frac{a_2}{a_1}\left(\frac{1}{R}\right) + \frac{a_{1b_2-a_{2b_1}}}{a_1}$$

For a typical room in a building it can be shown that this value is relatively low.

4.3.2. Inverter AC Blower Fan

Permanent split capacitor or brushless direct current (BLDC) motors are mostly used in AC blower fans. Since, BLDC motors are more efficient [111] it is considered in this research. The relation between power consumption and speed is linear in BLDC motors [111] which is favorable for the control, which makes BLDC motors well suited for a blower fan of an AC in this scenario.

In the commercially available inverter ACs, there are many speed steps of the blower fan. These different speeds allow better distribution of cooled air in a room with variable conditions. For example, if the number of people in a room increase the blower fan speed should be high to achieve a better cooling effect. If the power consumption of the blower motor highest and lowest speed setting is defined as follows, the capacity for demand alteration and granularity can be derived.

P_{HI} =Power consumption of blower motor at highest speed setting

P_{LOW} =Power consumption of blower motor at lowest speed setting

Now for X number of inverter type ACs,

Maximum achievable power $(P_{max,blower}) = X \times P_{HI}$

Minimum achievable power $(P_{min,blower}) = X \times P_{LOW}$

Granularity of the blower motor load depend on the state of the blower motors. The maximum value for the granularity is $(P_{HI} - P_{LOW})$. This value is relatively low in the typical ACs. Using blower fan for the control is only used to reduce steady state error of the system.

5. Control Strategy Development

The control system implements negative feedback control. The basic structure is given in the figure 5.1.

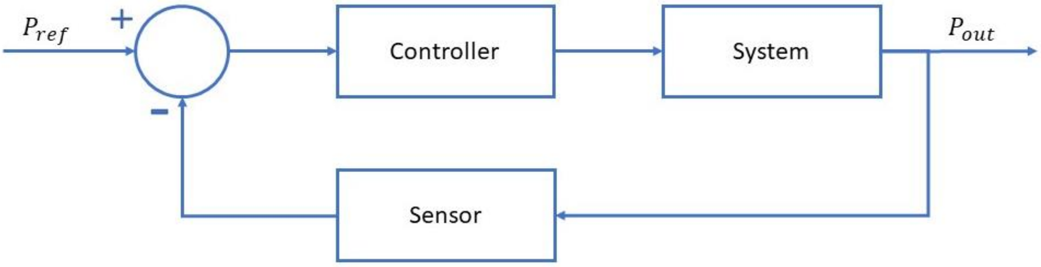

Figure 5.1. Feedback Control

In the proposed control system, the system component is the aggregated ACs. The controller consists of the control strategy and IOT based AC setpoint controllers. The sensor is an IOT based power measurement device.

Several control strategies can be used in the control system. They are,

- Steady state setpoint control
- Steady and transient state hybrid setpoint control

The blower fan control is used for reducing the steady state error in the system. The setpoint setting strategy is developed to ensure occupant satisfaction. This can be incorporated with any strategy mentioned above.

Integer Linear Programming (ILP) is used to calculate the setpoints in these control methods. The algorithm Branch and Bound (B&B) can be used for solving ILP problem.

ILP can be defined as the mathematical problem of finding a vector x that minimizes the function,

$$\min_{x}\{f^T x\}$$

Subject to the constraints,

$$Ax \leq b \text{ (inequality constraint)}$$

$$A_{eq}x = b_{eq} \text{ (equality constraint)}$$

$$lb \leq x \leq ub \text{ (bound constraint)}$$

$$x_i \in \mathbb{Z} \text{ (integer constraint)}$$

5.1. Steady state setpoint control

This control can only be executed for a step change of the reference. In such case the setpoint population is obtained using ILP to minimize the error between the reference and the aggregated power consumption of the inverter ACs. The ILP problem can be defined as,

$$\min f = n_1P_1 + \cdots + n_NP_N$$

$$n_1P_1 + \cdots + n_NP_N \leq \Delta P_{ref}$$

$$n_1 + \cdots + n_N = X$$

$$0 \leq n_1, \ldots, n_N \leq X$$

$$n_1, \ldots, n_N \in \mathbb{Z}$$

Here,

ΔP_{ref}- Error between reference and the aggregated power consumed by inverter ACs

P_i- Power consumption of compressor at ith temp. setting

n_k- Number of ACs operating at kth temp. setting

N- Number of thermostat temp. settings

X- Number of ACs

5.2. Steady and transient state hybrid setpoint control

In this control the required setpoint population is calculated using ILP like steady state setpoint control and then minimizing the error in transient state. This is done by using feedback control and ILP.

In the transient state the temperature in the rooms with inverter ACs are changing. This occurs after a temperature setpoint change. The transient time is varying with each initial and final setpoint. The power in transient state can be calculated.

If $\Delta T < u,$ $\qquad P_u = a_2 f_{min} + b_2$

If $\Delta T > v,$ $\qquad P_v = a_2 f_{max} + b_2$

If $u < \Delta T < v,$

$$P_{\Delta T} = a_2 (\frac{f_{max} - f_{min}}{v - u})\, \Delta T + a_2 (\frac{v f_{min} - u f_{max}}{v - u}) + b_2$$

When the required setpoint population is known, the transient power consumption of each AC compressor can be calculated. Now using ILP, the setpoints to change are identified with modified constraints. Also, there is a state where setpoint change is forced. The requirements for this are,

- The power consumption must be lower than the power consumption that is hoped to achieve
- $\frac{dP_{consumed}}{dt} = 0$

If these conditions are true for two timesteps of the feedback control, the remaining setpoint changes are forced one by one.

The constraints in the ILP problem are updated when the control progress through each step.

The ILP problem can be defined as,

$$min\, f = n_1 P_1 + \cdots + n_N P_N$$

$$n_1 P_1 + \cdots + n_N P_N \leq \Delta P_{ref}$$

For i = 1,…,N $\qquad 0 \leq n_i \leq X_i$

$$n_1, \dots, n_N \in \mathbb{Z}$$

Here,

ΔP_{ref}- Error between reference and the aggregated power consumed by inverter ACs

P_i- Power consumption of compressor for $\Delta T = i$

n_i- Number of ACs operating at $\Delta T = i$

X_i- Number of ACs at the required setpoint to achieve $\Delta T = i$

5.3. Blower Fan Setpoint Control

Blower fan setpoint control is used for reducing the steady-state error of the system. ILP is used in a similar process as in steady state control of thermostat setpoints to reduce the error. The ILP problem can be defined as,

$$min\, f = m_1 P_{B1} + \dots + m_M P_{BM}$$

$$m_1 P_{B1} + \dots + m_M P_{BM} \leq \Delta P_{ref}$$

$$m_1 + \dots + m_M = X$$

$$0 \leq m_1, \dots, m_M \leq X$$

$$m_1, \dots, m_3 \in \mathbb{Z}$$

Here,

ΔP_{ref}- Error between reference and the aggregated power consumed by inverter ACs

P_{Bj}- Power consumption of blower fan at jth speed setting

m_l- Number of blower fans operating at lth speed setting

M- Number of blower fan speed settings

X- Number of ACs

5.4. Case Studies

In this section several case studies are conducted to assess the control strategies. The ILP problem is solved using branch & bound method in the case studies.

5.4.1. Case Design

The step response of a population of 10 inverter ACs was simulated and studied. The required load reduction is assumed to be 2 kW. The parameters of the room and the inverter AC is given in Table 1. The 10 rooms and inverter ACs are assumed to be identical. Also, a P controller is implemented as the controller for the ACs to make their response fast and error free.

Table 5.1. Parameters of the Room and the Inverter AC

Parameter	Value
a_1(kW/Hz)	25
b_1(kW)	200
a_2(kW/Hz)	14
b_2(kW)	-75
u(C)	-1
v(C)	3
f_{max}(Hz)	150
f_{min}(Hz)	30
P controller gain	10

5.4.2. Reference Case

The reference case is given to show the problems of operating Inverter ACs without any control strategy in an islanded Microgrid. In this case all 10 inverter ACs are switched ON at once which is the worst-case scenario. The simulation shows a 20kW power spike which would stress an islanded Microgrid. For an islanded Microgrid with 100 ACs this would cause very adverse effects.

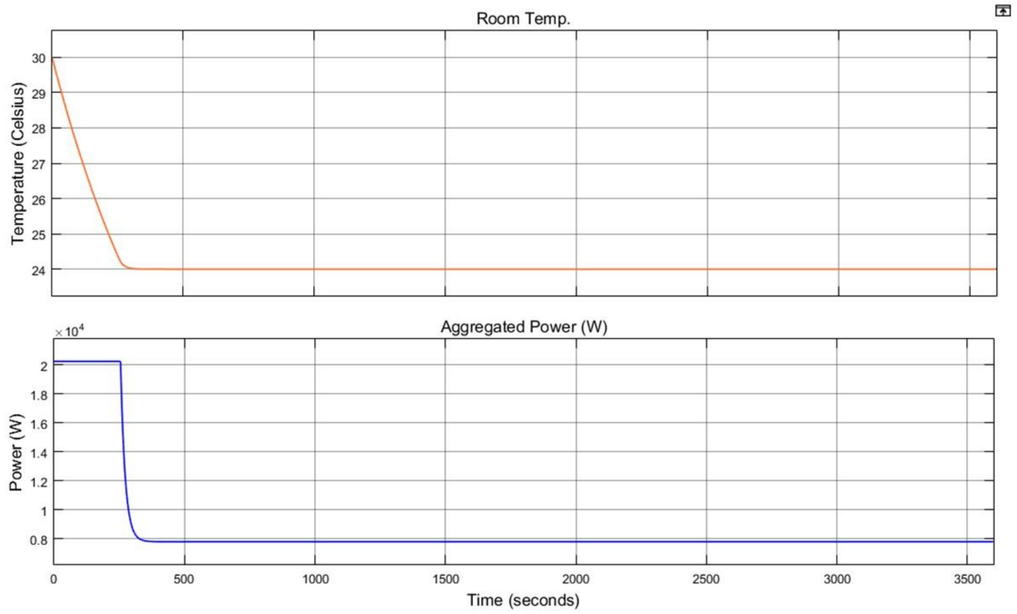

Figure 5.2. Reference Case

5.4.3. Steady State Setpoint Control

The steady state setpoint control is a straightforward strategy that consider only the steady state power consumption of the inverter ACs. When a power increase or decrease is demanded the strategy optimizes the steady state power consumption of the inverter ACs to match the required power consumption in a simple feedback control loop. The optimization is done for the thermostat setpoints and the required setpoint population is calculated in this step. Then these values are given to the inverter ACs all at once.

Since all the thermostat setpoints are given all at once, a power surge from the 10 ACs of about 10 kW occur when increasing the power which can have adverse effects. When decreasing the power consumption, there’s also a sudden drop.

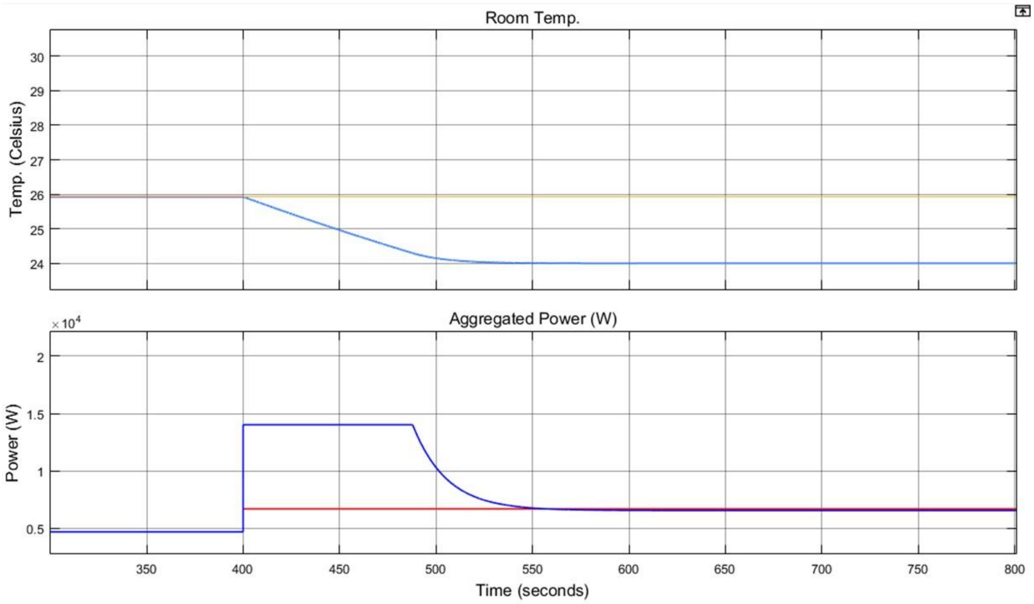

Figure 5.3. Steady State Setpoint Control

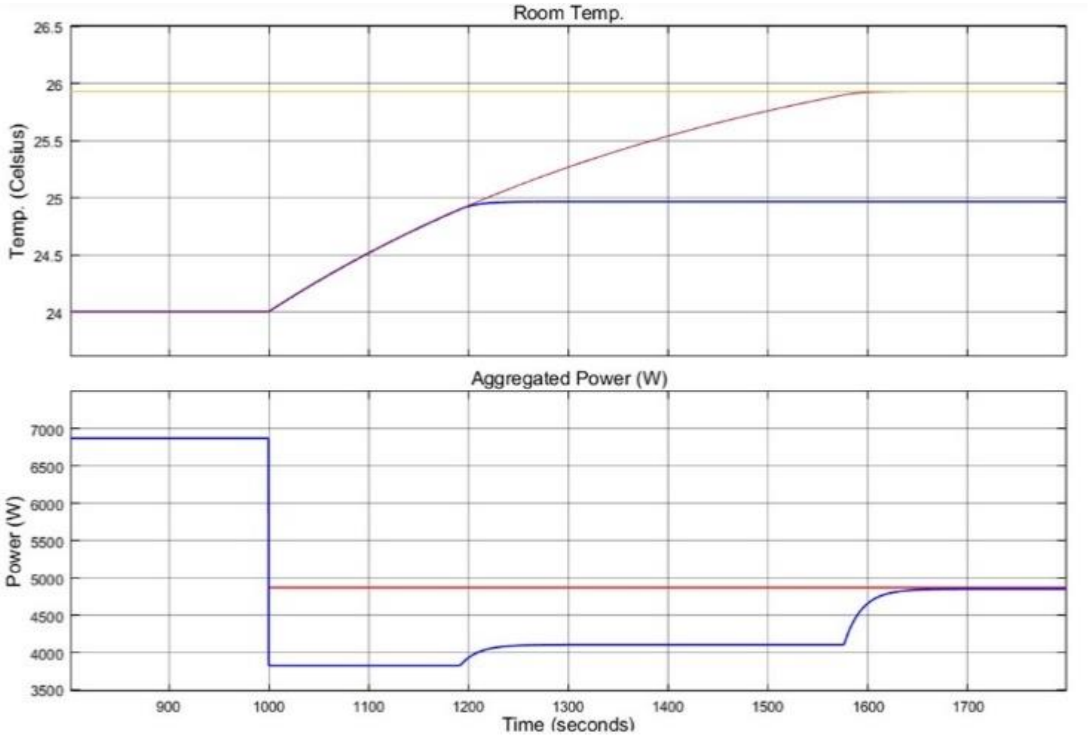

Figure 5.4. Steady State Setpoint Control

5.4.4. Steady and Transient Hybrid Control

The Steady and Transient Hybrid Control is a more advanced control strategy that considers both the steady state and transient behavior of the inverter ACs. Because of this the huge power surges can be minimized.

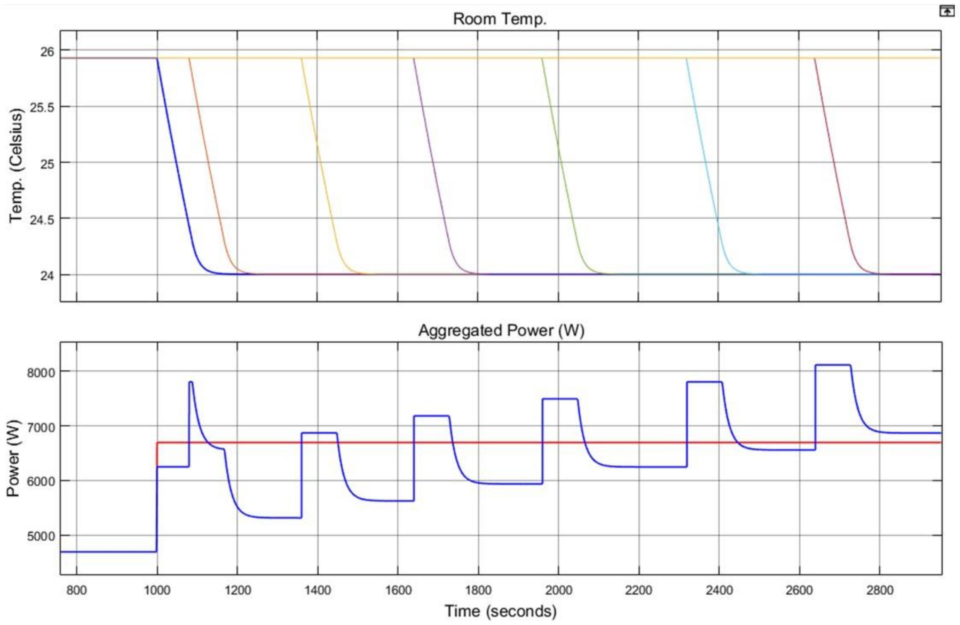

Figure 5.5. Steady and Transient Hybrid Control

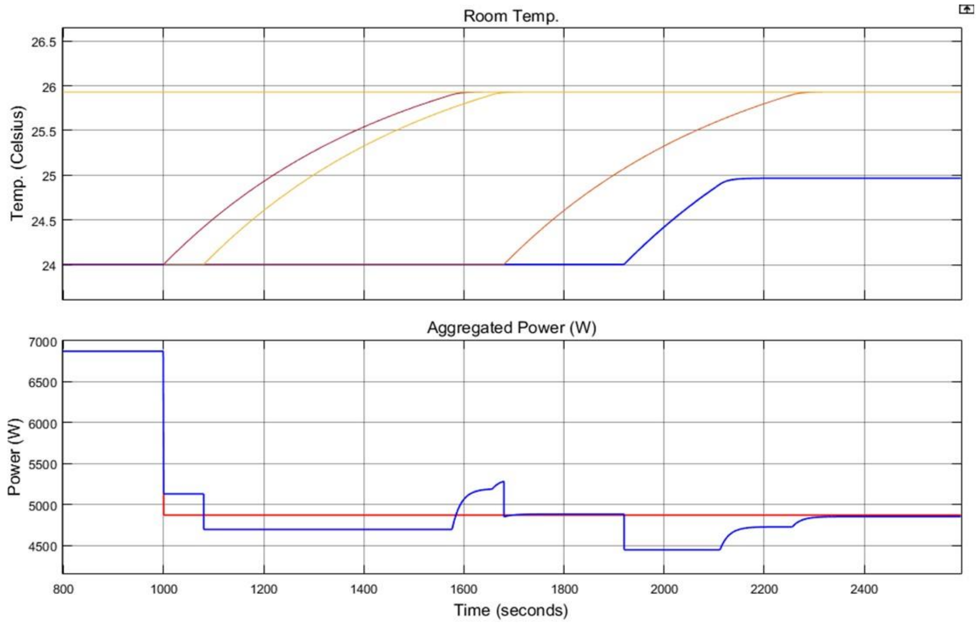

Figure 5.6. Steady and Transient Hybrid Control

5.5. Evaluation of the time consumed when using Branch & Bound Algorithm to solve the ILP problem

In this research the B&B algorithm is used to solve the ILP problem in the MATLAB environment in the strategy. The version used is 2016a and the computer is a laptop. The specification of the Central Processing Unit (CPU) is, Intel Core i5-6200U 2.3

GHz up to 2.8 GHz and the Graphical Processing Unit (GPU) which is used to run the MATLAB program is an NVIDIA GeForce 940MX with 2GB dedicated VRAM.

To find the capability of the B&B algorithm to solve an ILP problem, a general problem was formulated, and the time consumed to solve the ILP problem, when the integer variables are increased is measured. The problem can be formulated as follows,

$$\min_{x}\left\{\sum_{i=1}^{n} -100i.x_i\right\}$$

$$\sum_{i=1}^{n} 100i.x_i \leq b$$

$$\sum_{i=1}^{n} x_i = 10$$

$$0 \leq x_i \leq \infty$$

$$x_i \in \mathbb{Z}$$

Here, n is the number of variables which were changed. The ILP code was executed using timeit() [112] function which executes the code multiple times and take the mean value of them. Three of these values are taken and their mean is calculated to get a better idea about the time consumed for the code execution.

Table 5.2. Code Execution Average Time Consumption Calculation

No. of variables	Max function value	Min. function value	Chosen bound value	Time consumed in 1st try	Time consumed in 2nd try	Time consumed in 3rd try	Average time
1	1000	1000	1000	0.0165	0.0168	0.0177	0.017
2	2000	1000	1500	0.0176	0.0181	0.0184	0.018033
3	3000	1000	2000	0.0178	0.0188	0.0177	0.0181
4	4000	1000	2500	0.0189	0.0182	0.0178	0.0183
5	5000	1000	3000	0.0198	0.0194	0.0189	0.019367
10	10000	1000	5500	0.027	0.0185	0.0186	0.021367
100	100000	1000	50500	0.0253	0.0244	0.025	0.0249
1000	1000000	1000	500500	0.0802	0.0798	0.0777	0.079233
10000	10000000	1000	5000500	0.4586	0.4564	0.4506	0.4552
100000	100000000	1000	50000500	4.2656	4.2653	4.3244	4.2851

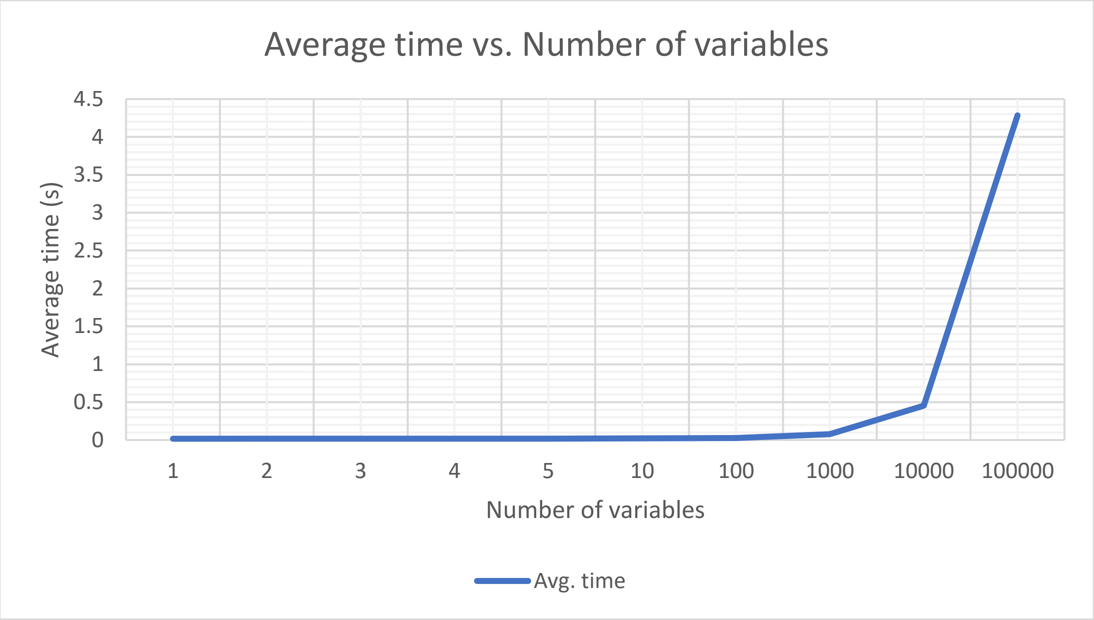

Figure 5.7. Code Execution Average Time Vs. Number of Variables

This shows that even for 10000 variables the results given are very quick. So, it is shown that the B&B algorithm can be used to solve the ILP problem quite easily.

5.6. Generalization of the Strategy for Demand Side Management

The strategy developed to control the Inverter ACs can be generalized to apply to demand control of many electrical equipment. The equipment characteristic is that they consume power in a stepwise manner in different states. Also, if the linearly changing loads can be controlled to achieve stepwise power consumption, they can be considered in the algorithm. If the ON/OFF control is considered, any equipment can be used in the algorithm. Generalization of loads is also discussed in the next paragraph.

$$\min f = n_{1,1}P_{E(1,1)} + \cdots + n_{1,N_1}P_{E(1,N_1)} + n_{2,1}P_{E(2,1)} + \cdots + n_{2,N_2}P_{E(2,N_2)} + \cdots \\ + n_{X_T,1}P_{E(X_T,1)} + \cdots + n_{1,N_1}P_{E(X_T,N_{X_T})}$$

$$n_{1,1}P_{E(1,1)} + \cdots + n_{1,N_1}P_{E(1,N_1)} + n_{2,1}P_{E(2,1)} + \cdots + n_{2,N_2}P_{E(2,N_2)} + \cdots \\ + n_{X_T,1}P_{E(X_T,1)} + \cdots + n_{X_T,N_{X_T}}P_{E(X_T,N_{X_T})} \leq \Delta P_{ref}$$

$$n_{1,1} + \cdots + n_{i,j} + n_{X_T,N_{X_T}} = Z$$

$$0 \leq n_{1,1}, \ldots n_{i,j}, \ldots n_{X_T,N_{X_T}} \leq Z$$

$$n_{1,1}, \dots n_{i,j}, \dots n_{X_T,N_{X_T}} \in \mathbb{Z}$$

Here,

ΔP_{ref}- Error between reference and the aggregated power consumed by inverter ACs

$P_{E(i,j)}$- Power consumption of ith equipment type at jth power step

$n_{i,j}$- Number of ith equipment type operating at jth power step

N_i- Number of power steps of ith equipment type

X_T- Total number of equipment types

Z- Total number of equipment

To expand the strategy, a generalization of the loads used for the strategy can be used. Several types of loads is used in industry and community. Power consumption of these loads vary in different ways. These loads can be categorized into three types.

- Constant power consuming loads

Constant power consuming loads consume a constant amount of power throughout its operation.

- Variable power consuming loads

Variable power consuming loads are loads that can be controlled to consume different amounts of power when it is switched on and this power consumption can be linear with control state or non-linear. The main requirement is that the power consumption is constant in each state.

- Varying power consuming loads

Varying power consuming loads are loads that varies the power consumption even the control state is the same. The main example of this is conventional FSCACs which use ON/OFF hysteresis control to regulate the temperature.

Both constant power consuming loads and variable power consuming loads can be used with the algorithm. Using constant power consuming loads are trivial since it is a load with a single power consuming step. Also, variable power consuming loads can be used as loads that consume power in steps. In this way a huge range of appliances can be incorporated when using the algorithm.

6. Proposed IoT based Air Conditioner Thermostat Control

The thermostat control is developed as an enabling technology to implement the strategy in a residential building. The structure of the proposed controller is given in figure 6.1. It consists of thermostat control modules, a central controller and a power measuring device.

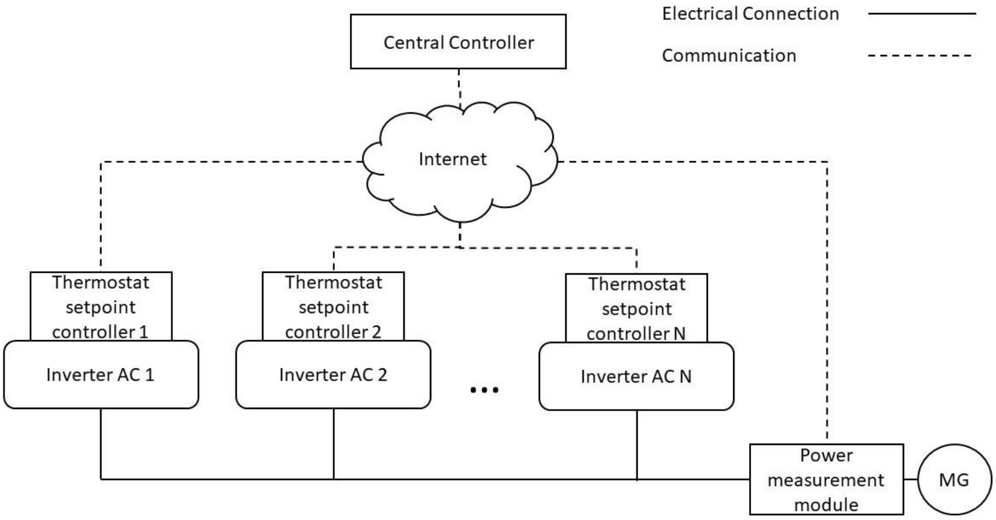

Figure 6.1. Proposed Hardware Structure for the Control Strategy

- Thermostat setpoint controller module

Thermostat setpoint controller module is based on NodeMCU IoT development board. It is an open source Lua based firmware for the ESP8266.

The first step is to develop a universal remote for ACs. It was achieved by decoding the AC remote signals using an IR sensor. Then these signals are stored in central controller memory and sent to the NodeMCU using a web server to transmit through an IR transmitter.

- Power measurement module

This is a typical three phase/ single phase power measurement circuit with a NodeMCU. The NodeMCU connects to the internet and sends power measurement data to the central controller using web services.

- Central controller

This is a webserver which runs the algorithm in real time. The output signals are calculated using the strategy in this server.

7. Application of the Control Strategy

Three applications have been considered in this research. All these applications are used for the islanded operation of microgrids and based on the IEEE guide [1].

The three applications are,

- Achieving power reserve margins in islanded mode microgrids

Power reserve margins are managed in the islanded microgrid to ensure a steady operation. These margins act as a buffer when an emergency occur. This margin acts as the maximum power consumption of the load in normal operation.

- Emergency load reduction

Emergency load reduction ensures the safe continuous operation of the islanded microgrid in an emergency where frequency drops because the generation is lower than the consumption. In such cases generation and consumption balance is reestablished using emergency load reduction.

- To mitigate cold load pickup

Cold load pickup is the sudden load surge in the feeders after restoring the power in a microgrid. The diversity of load is low in these cases because of the TCLs. These cases can be managed by using staged steps to start the system.

The applications are simulated in MATLAB/Simulink 2016a environment. A modified version of the model [110] is used for the simulation. The model is shown in the Figure 7.1. The simulated islanded microgrid consist of a Diesel Generator rated at 150 kW, a fixed base load of 80 kW, A variable step load of 20 kW and 100 inverter ACs. The inverter ACs are the same as the ones discussed in previous sections.

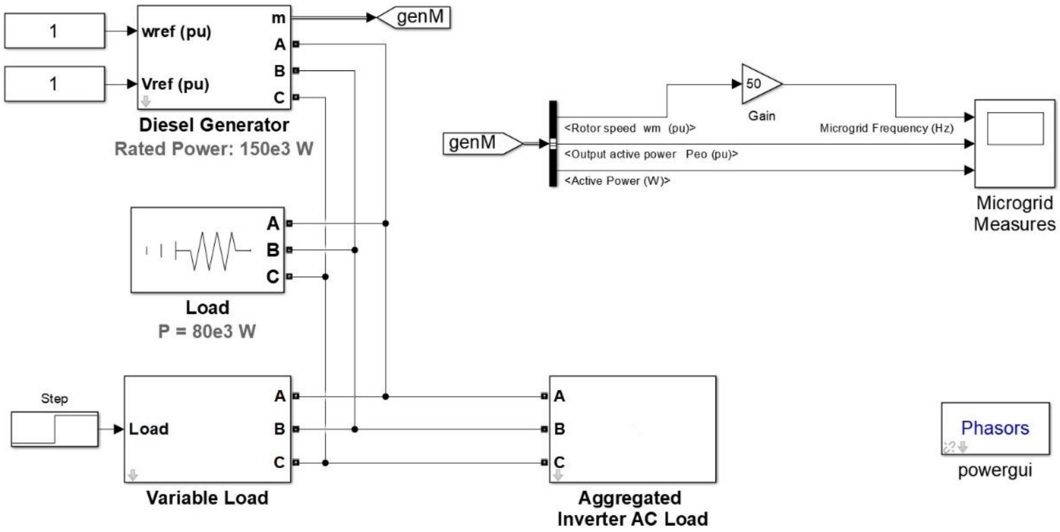

Figure 7.1. MATLAB/Simulink Model of the Microgrid for Demonstrating the Applications

7.1. Achieving Power Reserve Margins in Islanded Mode Microgrids

Power reserve margin of the simulated Diesel Generator is taken as 10% of the rated power. So, the maximum power usable without exceeding the power reserve margin is 135kW. When the power consumption increases above this value, inverter AC power consumption is reduced using the control strategy.

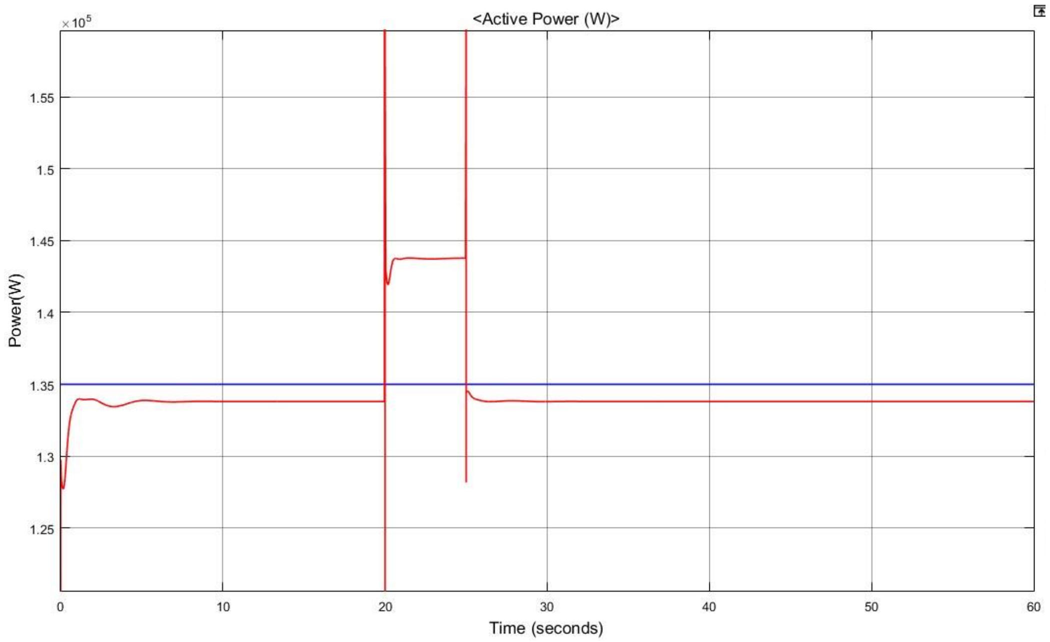

Figure 7.2. Application: Achieving Power Reserve Margins

7.2. Emergency Load Reduction

The emergency load reduction is required when the load exceeds the generated power. In this case, the base load and the inverter AC load add up nearly to the full capacity of the Diesel Generator. Then in 20s, another 20 kW load switches on which disturbs the demand generation balance.

- Without emergency load shedding

The effect to the microgrid without emergency load shedding is shown in the Figure 7.2. The frequency of the Diesel Generator decreases, and it generate power impulses. This is an undesirable result which adversely affect the microgrid.

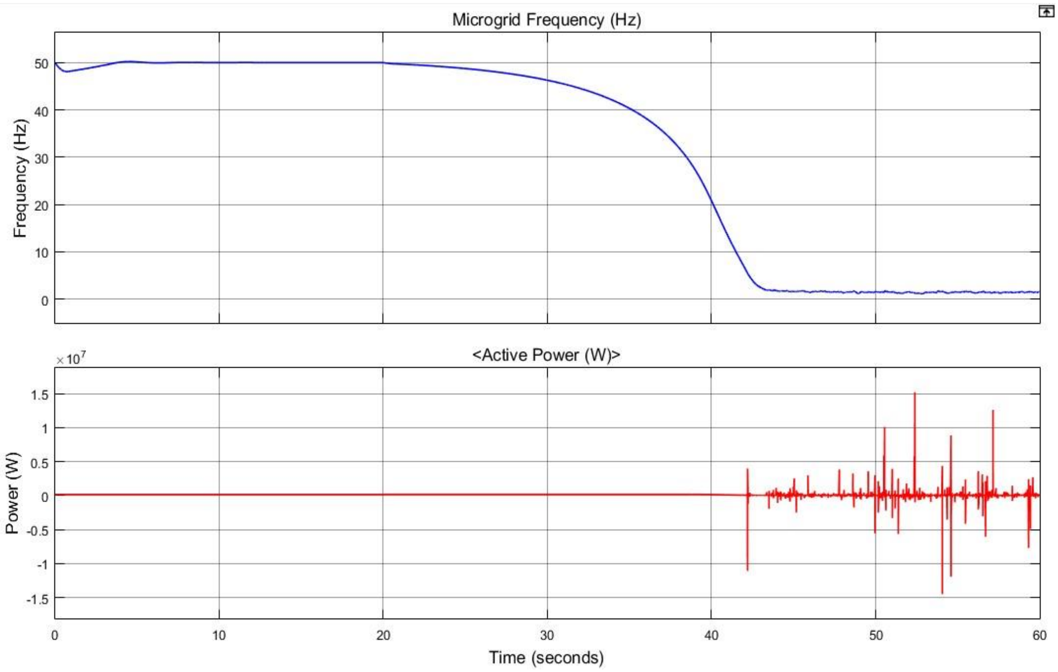

Figure 7.3. Without Emergency Load Shedding

- With emergency load shedding

The variable step load occurs at 20s and in 5s (Which is achievable according to the literature review on Fast DR, Chapter 2) the load control strategy is implemented. The results are shown in Figure 7.3.

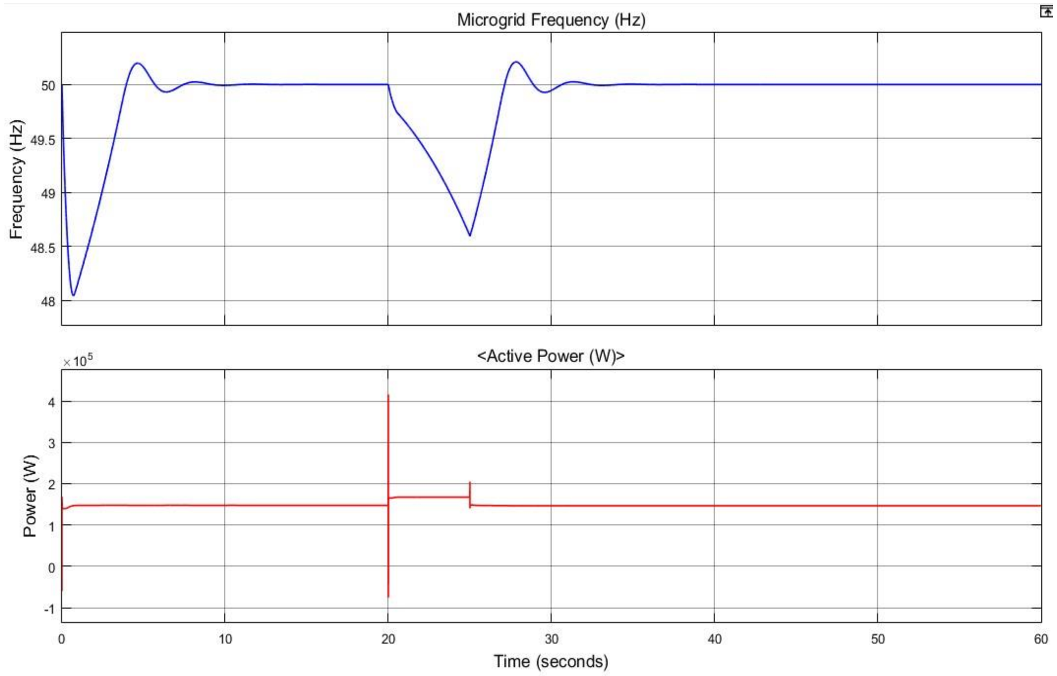

Figure 7.4. With Emergency Load Shedding

7.3. To Mitigate Cold Load Pickup

The sudden power surge due to restoring the power in a power system and turning the loads all at once is Cold Load Pickup. This can be mitigated for the inverter ACs using the developed algorithm.

The simulation is done using the 10 inverter AC model which shows that the power consumption can be controlled near a required amount. For the simulation the value was taken as 80 kW. It was shown that 100 inverter ACs can be switched ON without surpassing the 80 kW value from huge amounts.

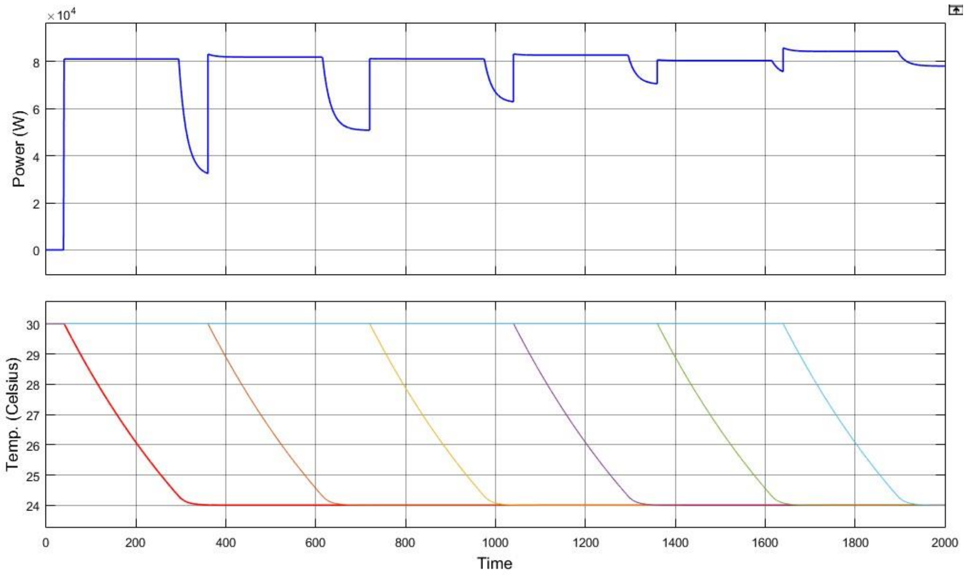

Figure 7.5 Mitigating Cold Load Pickup using the Strategy

7.4. Possibility of Using the Control Strategy in Smart Grids

The control strategy developed in this study can easily be used to implement a Fast DR program in a smart grid. The difference will be that the control signal will originate from the utility and there must be telemetry to know how much Fast DR capacity is used by each customer. Also, having a central controller for each premise is probably a good decision to increase the reliability.

8. Conclusion

Demand side management is essential for the islanded operation of Microgrids. Fast Demand Response is a critical demand side management strategy to reduce the power consumption in a Microgrid in an emergency. Buildings can be considered as Microgrids. The residential buildings which are situated in urban areas can work as Microgrids with the addition of distributed energy sources such as diesel generators and solar photovoltaic systems and the necessary controls. The air conditioning systems consume the most power in such buildings. Usually the air conditioning systems of the residential buildings are distributed air conditioning units. These units are controlled using remote controllers which alter the thermostat setpoint of the air conditioner. Since air conditioning units are consuming most power it is sensible to utilize them for demand management.

There are two main types of distributed air conditioners. They are the conventional fixed speed compressor type and the variable speed compressor which is usually called the inverter type. By analyzing the power consumption pattern of these two types it was concluded that inverter type air conditioner is the suitable for a stable system. Since inverter type air conditioners are used increasingly in the industry, this decision is justified.

This thesis presented a control system that utilize the thermostat setpoint control of inverter air conditioners to control the power consumption effectively. In particular,

1) A control strategy of the thermostat setpoints to control the power consumption of the inverter air conditioners is developed.
2) The control strategy is generalized to apply for any type of load.
3) A feedback control system to control the power consumption of the inverter air conditioners is proposed.
4) IOT based power measuring device and air conditioner thermostat controller is proposed.
5) The capability of the setpoint control strategy and feedback control to be used in practical applications is simulated. The applications are,
    a. Achieving power reserve margins
    b. Emergency load reduction
    c. Cold load pickup

For future works, a novel idea that can be researched is the possibility of using multiagent systems for the operation of this control system.

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