2021

Analysis of Power Quality Constrained Consumer-Friendly Demand Response in Low Voltage Distributions Network

Chittesh Veni Chandran
Technological University Dublin, chittesh.venichandran@tudublin.ie

Recommended Citation

Veni Chandran, C. (2021). Analysis of Power Quality Constrained Consumer-Friendly Demand Response in Low Voltage Distributions Network. Technological University Dublin. DOI: 10.21427/5CV8-VJ47

Funder: Technological University Dublin

Analysis of Power Quality Constrained Consumer-Friendly Demand Response in Low Voltage Distributions Network

Chittesh Veni Chandran

OLLSCOIL TEICNEOLAÍOCHTA
BHAILE ÁTHA CLIATH
DUBLIN
TECHNOLOGICAL
UNIVERSITY DUBLIN

A thesis submitted in fulfilment of the requirements for the
degree of Doctor of Philosophy

School of Electrical and Electronic Engineering
Technological University Dublin

2021

Under the Supervision of
Dr. Malabika Basu and Dr. Keith Sunderland

Abstract

Load management using demand response (DR) in a low voltage distribution network (LVDN) offers an economically profitable business platform with peak load management. However, the inconvenience caused to the consumer in depriving their devices and the low levels of associated incentive have contributed to lower consumer acceptance for DR programs in the community. However, with the increasing number of controllable consumer loads, a residential-level DR program is highly plausible in the short to medium term. Further, additional DR capabilities (including ancillary services) are likely to improve the remuneration potential for participants in DR. Considering the perspective of a distribution network operator (DNO), any service useful for maintaining the stable and secure operation of an LVDN will always be appreciated. Thus, in addition to DR's peak load management potential, any further contribution in maintaining power quality (PQ) in the network considered as an ancillary service to DNO will create a profitable business opportunity.

Firstly, primary PQ management tasks in an LVDN are maintaining voltage profile and reducing harmonics. With the advancement in the consumer electronics market, increased penetration of non-linear low carbon technologies (LCTs) based loads at the consumer-side, will increases the harmonic content in the LVDN. While consumer devices may have non-threatening levels of harmonic components, they can still cause issues by accumulating at the main feeder when the additive nature of harmonics are considered. Further, and in respect to harmonics, total harmonic distortion (THD), as a universal indicator, may not be a deterministic measure of the impact of harmonics due to THD’s dependency on the magnitude of fundamental current.

Moving to the voltage issue, in an electrical network, it is required to maintain the voltage level of all nodes in the network between regulated tolerance levels. However, during peak load hours, the voltage at the end of a radial feeder may drop below the tolerance level. The corollary is also an issue. A light loading scenario on the same feeder with a higher penetration of solar photovoltaic distributed generators (SPVDG) injecting active power can create a voltage rise scenario.

While consumer loads/loading are responsible for these PQ issues in the network, there is no direct obligation on residential level consumers to manage them as long as they are individually operating within the regulation limits. However, a DR option can utilize PQ’s dependency on loads to provide additional service to DNO to mitigate any PQ violations. The DR program's success is critically dependent on consumer participation. It also becomes essential to operate the program with a minimum level of consumer inconvenience. Therefore, a proposal for micromanaging consumer load on an LVDN while considering consumer inconvenience and attaining PQ objectives is thus the theme of this thesis.

This research proposes a PQ constrained consumer-friendly DR (PQ-C-DR) program that can provide additional ancillary PQ management services along with conventional DR capabilities. Due consideration is given to minimize consumer inconvenience while operating DR to ensure social acceptability and equity. Harmonic levels in the network are essentially integrated as harmonic heating constraints to maintain stable levels of harmonics in LVDN. A DR in conjunction with a co-ordinated incremental and ‘fair’ curtailment algorithm is introduced to manage the voltage levels in the radial LVDN. A sensitivity study of the proposed algorithm is performed on an urban distribution network model under different operating scenarios.

This thesis introduces a new algorithmic dimension in applications for load management to ancillary services (PQ management) using DR. The PQ-C-DR will favour consumer comfort while profiting all stakeholders involved, which essentially creates a win-win scenario for all network participants – essential in DNO/consumer negotiations to achieve wider DR engagement. Improving the profitability of DR by providing additional service(s) is beneficial to both customers and retailers. Furthermore, the DNO benefits from delaying additional peak and PQ management related investments, which could essentially improve the utilization factor of the network.

Declaration

I hereby certify that this thesis which I now submit for examination for the award of Doctor of Philosophy is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Technological University Dublin and has not been submitted in whole or in part for another award in any Institute.

The work reported in this thesis conforms to the principles and requirements of the Technological University Dublin's guidelines for ethics in research.

Technological University Dublin has permission to keep, lend or copy this thesis in whole or in part, on condition that any such use of the material of the thesis is duly acknowledged.

Acknowledgement

I am deeply thankful to God Almighty for all blessings that has guided and supported me during all times.

I would like to express my sincere gratitude to my supervisors, Dr. Malabika Basu, and Dr. Keith Sunderlnd. They were always motivating, encouraging and supportive to the best and had their doors always open for a chat. Their meticulous guidance, constructive and valuable suggestions, timely discussions, and clarifications of my doubts increased my cognitive awareness and helped me make a deeper analysis of the research. Their guidance helped me all the time of research journey and while writing of this thesis.

I would like to thank the Technological University Dublin for providing me the opportunity of doctoral research here. I also thank the Fiosraigh Scholarship Programme, Graduate Research School and the School of Electrical and Electronic Engineering for providing funding and resources for my research.

I am thankful to all my colleagues from the School of Electrical and Electronic Engineering. To name a few, Sandipan Patra, Paul Leamy, Aitor, Liam, Shahab Sajedi, Zeeshan Ahemad, Arsalan Zaidi, Kevin, Padraic, Claudia, Dan, Shuo, Sreedhar, Hicham, Shivananda and Roberto, I cherished your camaraderie.

I whole heartedly appreciate and thank Andrew Dillon and Finbarr O Meara for their kind support in the laboratory. Especially Andrew (Andy) who is the best IT expert I have ever seen in my life. I am also thankful for the interesting discussions and insights provided by Dr. Damon Berry and Dr. John McGrory.

I am indebted to Dr. Tibin Joseph and Dr. Sasidharan Sreedharan for their continuous guidance and support throughout. Especially Tibin, who has been in a role of a teacher, mentor, friend, and an invaluable advisor for all my silly questions. Adding to this, I would also like to thank Sebin, Anand, and Vipin for their support for this research. For Sebin, who has one of the most pleasant and helping character to always have as a friend.

To my parents Krishna Veni, and Chandrasekharan and my sister Chahna, for their encouragement, support, and unconditional love. To my dear wife Remya, I am so thankful to you for your tremendous support, understanding and motivation. I would also like to thank all my family members for your support and encouragement during this period. And I want to thank my furry good boy Blue who had his ways to make me to rejoice my lively moments.

Abbreviations List

AC	Alternating current
C-DR	Community-based Demand response
DC	Direct current
DG	Distributed generator/Generation
DLC	Direct load control
DR	Demand response
DR-VC	Demand response based voltage control
DSO	Distribution system operator
DT	Distribution transformer
EU	European union
FIS	*Fuzzy* inference systems
GTI	Grid tied inverter
HC-C-DR	Harmonic constraint consumer friendly demand response
ICA	Incremental curtailment algorithm
LP	Linear programming
LVDN	Low voltage distribution network
MILP	Mixed integer linear programming
PQ	Power quality
PV	Photo voltaic
PVDG	Photo voltaic distributed generation
RE	Renewable energy
REG	Renewable energy generators
RER	Renewable energy Resources
RMS	Root mean square
SPV	Solar photovoltaic
SPVDG	Solar Photo voltaic distributed generation
THD	Total harmonic distortion
TSO	Transmission system operator
α	Consumer inconvenience factor
β	Device inconvenience factor

Table of Content

Contents

Table of Figures

Table of Tables

Chapter 1 Introduction

1.1 Problem Statement and Research Motivation

During the last two decades, there has been an unprecedented growth in demand for electricity and associated consumer electronics. With high penetration of smart domestic loads, the low voltage electrical distribution network (LVDN) has now become far more controllable than any time in the past. The accumulation of these controllable loads introduces a remarkable opportunity for load management techniques to harvest the flexibility available in LVDN. However, load management algorithms like demand response (DR) are not well appreciated in the consumer community due to their impact on consumer comfort [1] along with low incentive for the inconvenience. The concept of DR is considered very intrusive to many consumers. The modern DR approaches in literature are exploring additional service opportunity of DR apart from conventional load management. Such ancillary services that enhance safe and secure operation of distribution network (DN) are well appreciated by a distribution network operator (DNO) and can generate additional revenue for a DR program. Further, focussing on consumer acceptance by minimizing the impact on consumer convenience will improve participation.

Keeping LVDN in context, the issues concerning a DNO include, peak load management, harmonics management, maintaining voltage profile, and ensuring security of supply. A DR program can directly intervene the peak load scenario for the operator. However, with an increasing number of smart loads and active distributed generators (DG), the network power quality (voltage and harmonics) issues have raised the LVDN operational inconvenience. The power electronic switch-based consumer loads have contributed to the non-linear current demand in the network and thus, increase the presence of harmonic content. In fact, the low levels of harmonics from a domestic environment will propagate upwards to the main feeder and accumulate there, potentially forming unfavourable operating conditions [2][3][4].

With policies like “Domestic Solar power scheme” in Ireland, high levels of solar photovoltaic generators (PVDG’s) are installed in the distribution sector [5]. Even though they are considered as beneficial to the electricity sector by reducing its carbon footprints, their intermittent nature is contributing to the power quality issue [6]. In a radial network with high levels of PVDG installed, the voltage at the end of the feeder would greatly depend on the generation and loading in the feeder. At light load and high generation (typical mid-day), the voltage may be much higher than the regulations tolerate. On the other hand, with a heavy loaded feeder (low generation), the voltage profile may fall below the regulated value [7].

In short, an increased number of non-linear consumer loads increases harmonic content of the network, whereas volatile loading and generation create under/over voltage issues. The LVDN connection of loads and generators contribute to these power quality issues, so an active power management algorithm like DR can effectively manage these issues providing PQ control service for DNO. However, a successful DR program needs to ensure a choice for consumers to decide on the level of inconvenience that they can tolerate for participating. Hence, this thesis proposes a consumer-friendly DR capable of constraining power quality issues of the network by micromanaging consumer loads.

1.2 Research Objective

In general, operational issues with active management of grid operation deals with load-generation balance, power flow control, reserve management, frequency regulation, voltage and other power quality management. [8][9]. Advanced technologies in the power system network have undoubtedly enhanced the system's controllability, which has a positive impact on increasing RER penetration and electrical load efficiency. However, these advanced technologies, that are based on power electronic switches, can have a negative impact on the power quality in the system. The non-linear consumer loads distort the current waveform, i.e., they generate harmonics. Further, increased intermittent DG penetration and high demand could create voltage issues in an LVDN. This means that there exists a trade-off between the negative and positive impacts of adopting advanced technology and which generally forms the bottleneck for further increases in improvement (efficiency, RER penetration, and reliability). These impacts can adversely affect the system security and stability. There is an irony however; PQ depends on consumer loads operating as well.

Managing the PQ of supply in the DN is an obligation of the DNO. As complex as the problem may seem, the PQ of the distribution network has a direct correlation with loads in the network. Managing consumer devices/loads that influence the PQ of DN can contribute to the safe and reliable operation of an LVDN and can effectively be a valuable tool for a DNO. Further, the flexibility offered by enabling consumer device operation control is an attractive feature for an electricity supplier to increase the use of cheaper RER when the price in the market is high.

However, any acts of energy management that deprive the utilization of consumer devices of their interest would introduce an inconvenience to the consumer and would lead to social unacceptance of such procedures. With monetary benefit from direct load displacement being slim, an additional service provided by DR has to be explored to benefit stakeholders involved economically.

Since the PQ in a system is contribution of load operating in the network, a load management technique like DR has the potential to provide ancillary service (PQ management) to manage safe operation of LVDN which could provide additional benefits.

In conclusion, the research question in this thesis is formulated as,

> *How to manage power quality issues in a LVDN through a consumer-friendly demand response?*

The potential of DR in peak load management is thoroughly researched and established with large loads. However, with the residential sector contributing one-third of the total network load, utilities are reluctant to employ DR due to its dependency on consumer participation. Creating a consumer-friendly DR is thus a critical task of this thesis. Integrating, harmonic and voltage quality as a constraint to the DR algorithm is a novel idea to enhance the application of a DR program. Developing and testing each of these constraints on a DR offers a validation of the possibility of such application of DR program to ensure maximum utilization of our system without compromising the system quality or integrity.

To answer the primary question, the following sub questions are formulated:

1. *What are the major applications and development in the area of demand response?*
2. *Can DR provide additional ancillary services while being consumer friendly?*
3. *How to formulate a harmonic PQ restricting mechanism?*
4. *Is THD an accurate representation of the severity of harmonics, as the main PQ concern in the distribution network?*
5. *How to include a voltage quality constraint using a DR program?*
6. *How to synergise the PQ management and DR program to achieve safe PQ limits?*

Answering each of these sub-questions opens a distinct individual pathway that has to be thoroughly studied. To answer the research questions, the thesis is organised with following sub objectives:

1. *To propose a consumer engagement plan suitable for encouraging the consumer to participate in DR program (Chapter 3).*
2. *To develop a detailed DR model which minimizes consumer inconvenience to schedule the consumer individual loads (Chapter 3).*
3. *To develop a harmonic analysis and identify suitable constraint to incorporate with load management program (Chapter 4).*
4. *To develop a voltage constraint algorithm to manage voltage profile in the LVDN (Chapter 4).*
5. *Extending the DR model to incorporate harmonic constraint to limit the harmonic accumulation at PCC (Chapter 5).*
6. *To incorporate a voltage management algorithm to the DR program (Chapter 5).*

The relationship between consumer load management and consumer inconvenience is direct. This thesis initially establishes the consumer inconvenience relationship with DR program while providing engagement plan options for the consumers while testing the algorithm in different scenarios involving 74 consumers within an urban distribution network. The engagement plan gives the consumer a sense of control over their participation. To incorporate the power quality aspect, initial attention is focused on harmonic power quality, leading to the development of harmonic heating constraint. The voltage quality is explored later to envisage the possibility of the application of DR to manage voltage profile in a radial DN. These analyses are implanted on the representative urban distribution network with solar PVDGs. Marrying the power quality issue with an energy management program is a critical contribution of this thesis. An approach that manages the energy balance issue and can contain issues with the quality of supply and security of the system is hence the theme of this research. The findings of this work could also help to formulate a safe practice in the domestic environment to minimize or nullify the hazardous effect of harmonics. A schematic structure of the thesis is given in Figure 1.1.

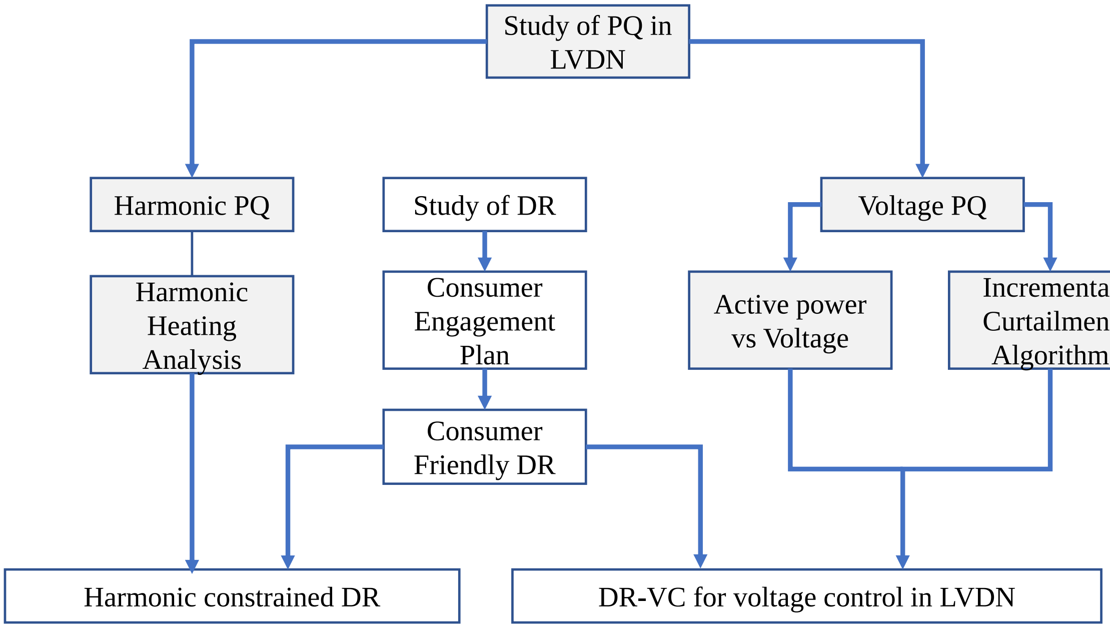


Figure 1.1 Schematic of thesis structure

1.3 Thesis Outline

To address the research questions, the thesis is structured into 6 chapters.

- **Chapter 2.** This chapter sets the stage for this research by providing contextual knowledge on different topics. The application of DR program and associate technique is deeply evaluated. The power quality issues are explored, especially in the context of harmonics and voltage issues. The chapter also outlines the current scenario in distribution networks with RER and nonlinear loads to identify the implications to PQ and the need for a load management algorithm.
- **Chapter 3.** The chapter focuses on developing a consumer-friendly DR program algorithm. The algorithm schedules consumer appliances based on the inconvenience related to the device and the participation of the consumer. The developed algorithm is utilized for incorporating harmonics and voltage constraints in chapter 5. Also, the performance of the algorithm is evaluated on an urban distribution network consumers with different load profiles.
- **Chapter 4.** This chapter presents independent modelling techniques utilized to perform preliminary studies to understand the effects of harmonics. The chapter

also develops an understanding to utilize harmonic heating constraints. Later a relationship between voltage and active power is developed to propose a voltage management algorithm. The methodologies developed form the bases of constraints for limiting harmonics/voltage in an LVDN. The algorithm is tested on an urban distribution network. Solar PVDG integration as an active power source on harmonics in the system is also evaluated in this chapter.

- **Chapter 5.** The subsequent chapter details the findings of the analysis performed using the models developed in the previous chapter. The chapter utilizes the evidence and justification drawn of earlier chapters to propose and formulate an intelligent consumer-friendly PQ constraint DR algorithm. The algorithm uses load management to constrain harmonics in the system with minimal consumer inconvenience. The application of load and generation management for voltage management is also implemented in this chapter. The overvoltage is addressed using an incremental curtailment algorithm, and DR manages undervoltage.
- **Chapter 6.** This chapter revisits the research objectives and provides an overall conclusion and contribution of the thesis along with suggestions for future work.

Chapter 2 Literature Review

2.1 Overview – The Energy Transition

When the Paris agreement was signed by 196 countries on 12th December 2015, the global energy trend for the next three decade was unambiguously defined [10]. The focus on low carbon and zero carbon technology has steadily increased throughout the world, focusing on achieving the proposed targets. With the EU leading the way with member states showing remarkable efforts to comply towards zero carbon by 2050, the opportunity for employing the latest green technology is well appreciated [11]. Adaptation of renewable energy source-electricity (RES-E) targets has paved the way for high penetration of intermittent generation technologies, such as wind and solar energy harvesting opportunities throughout the electricity network. Beside resource depletion, the impact on carbon reduction, and the climate change, increase in number of RE generators is also driven by a decrease in its technology cost. For many countries, with increased dependencies on clean energy for domestic heating and transportation, the electricity demand is expected to rise by 50% in the next decade [12].

The European Union (EU) has set forth targets of 32% of energy requirement be fulfilled by the RE by year 2030 [13]. Individual targets and policies frameworks are initiated in the member state to fulfil towards EU commitment. The climate action plan in Ireland intends to have 80% of the electricity demand met by RE (electricity) in year 2030 [14]. To meet the growing demand while ensuring a 80% RE electricity target is achieved by 2030 requires substantial amount of renewable generators at all levels in the power network. Further, facilitating decarbonisation in transport and heating would burden the electricity sector with their additional demand [12].

The ambitious plan requires contributions from different levels. Increased levels of distributed RE resources are integral part of achieving 2030 and 2050 targets. Government policies promoting investment in low carbon technologies (LCT) based generators are already on the way. The domestic solar power scheme promoted by Sustainable Energy Authority Ireland (SEAI) have incentivised PVDG installation in a domestic dwelling increasing the penetration of these intermittent resources[5]. The Renewable Energy Feed-in-Tariff (RE-FIT) provided by different EU states would further support the installation of RE generators [15]. However, these intermittent generators have created a new paradigm for unforeseen distribution network management issues, especially voltage quality issues. Yet, a higher level of controllability of converters and reliable communication channels, DGs are entering the realm of dispatchable energy sources. Now, the availability of small scale distributed generators (DG's) as dispatchable resources can potentially transform the electrical power industry to micro-manage the available resources within the hands of a system operator [16][17].

The intended clean energy target has also demanded maximum utilization of available energy or improvement in energy efficiency of consumer loads. Along with the increased number of consumer loads, the energy efficiency revamp has increased the number of non-linear loads in the DN. The impact of harmonics due to non-linear loads are well understood, and further, their mitigation methods are usually very expensive. It is hence essential to develop a methodology to manage the level of harmonics in the DN economically. Since these PQ issues (harmonics and voltage) are derivatives of consumer loads, it is a logical idea to utilize load management algorithms to regulate PQ issues. However, any program denying the operation of consumer devices when in demand causes inconvenience, which is a disincentive for a consumer. Further, at times, being a part of the DR program can be perceived as an obligation for consumers participating in the program. Hence, it is essential for the DR program's success to provide consumers with a choice and acknowledge consumer inconvenience by keeping it to a minimum.

With increasing non-linear loads (demand) and increased number of RE generators (with intermittent contributions) in a LVDN can potentially create power quality violations (namely, harmonic and voltage quality). With a transforming energy sector that accommodates energy transition, it is important to account for the plausible grid operational issues and also enable an operator to handle them when they arise or better to avoid them before they occur. Thus, an optimized energy management/scheduling tool can potentially alleviate any power quality issues in the system even before they occur. This chapter sets up the context while briefly elaborating on each topic to essentially achieve contextual knowledge to perceive a power quality constraint consumer-friendly DR (PQ-C-DR).

Initially, this chapter explores power quality, especially the harmonic and voltage quality within the Distribution Network. Later, the idea of DR and recent techniques used to employ DR are explored. A brief conclusion from the surveyed literature is presented at the end.

2.2 What is Power Quality?

The problems concerning the quality or condition of the power supply in an electrical network are generally termed as power quality (PQ) problems. It encompasses all aspects associated with amplitude, phase and frequency of voltage and current waveforms. The PQ deviations may result from a disturbance (transient and steady-state) in the power circuit. The disturbance causes current or voltage waveform to deviate from the normal operation level resulting in other PQ issues. Different classifications of PQ (issues) are available in literature based on different categorising properties [18][19]. With respect to voltage based PQ, issues include under/over voltage issue, voltage flicker, and voltage sag/swell. A non-linearity in the system can cause sinusoidal supply waveform (voltage and/or current) to deviate from its wave shape and is called harmonics PQ issue. A large system event (active power change) can also cause the system frequency PQ issue causing system frequency to deviate from 50/60Hz. Finally, a complete loss of supply (interruption) is also a PQ issue that impacts the system's reliability.

Previously PQ issues were mainly confined to the public utilities. However, with advancement in electronic technology, the number of PQ sensitive customer loads has increased. The direct implication of deviations in PQ from the standard operating limits may cause equipment not to operate, malfunction or premature failure. Thus, the PQ issues can cause loss of asset or loss of service, which can be correlated with cost. A report from Electric Infrastructure to Support a Digital Society (CIEDS) estimates a \$15-\$24 billion loss per year for the United States (US) economy due to PQ issues [20]. Good PQ is essential for customer load to function correctly. Yet, almost 70% of the PQ disturbances are caused due to customer loads [21]. Further, a study conducted by Massive InteGRATion of power Electronic Devices (MIGRATE) on utilities in Europe states that 35% of total PQ issues are related to harmonic and further 35% on voltage issues [19]. At times, the voltage issue is caused by power sag/swell in the network. It can be unarguably said that a good PQ of the power supply is essential for the power system's normal and safe operation. Contextually with the thesis, the harmonic PQ and under/overvoltage PQ issues are explored in detail.

2.3 Power Quality in Distribution Network

The distribution network (DN) which is conventionally radial in nature would supply individual consumer loads through distribution lines. A typical structure of radial distribution network is represented in the Figure 2.1. The modern electrical power network is designed and operated to ensure high quality of supply, and a high level of security of supply, without facing excessive generation and distribution costs. Typically, an operator is not just responsible for maintaining a continuous supply but maintaining the quality of the supply is also in the operators' remit. The distribution code defines limits for operating the system while maintaining these PQ parameters for a DSO [22]. The limit essentially stipulates maintaining within tolerance limits the magnitude of voltage with a pure sinusoidal waveshape. The DSO would operate its asset within these regulated limits, but the PQ parameters in the network are contributions from both the supply side as well as the demand side. This means that the quality of supply is influenced by the loads demanding the supply. Thus, a set of such PQ standards (BS EN 50160, IEC 61000-3-4) and EU directives are also defined for consumer side (demand side) equipment to operate [23], [24],[25]. However, the cumulative effect on PQ by operating the consumer equipment are not directly controllable to a normal DSO operator unless a secondary PQ enhancing devices are employed [26], [27]. This is not the usual case until an associated equipment failure or serious operational issues are observed as the economics behind such [PQ enhancing] devices are not economical. However, the causes of a serious event may have progressively built up over a period of time due to small issues usually considered tolerable. For example, low levels of thermal overloading of a power line may not trigger a fault immediately but can contribute to faster deterioration leading to eventual failure [28]. Voltage stress applied on capacitor due to under and overvoltage can cause its premature failure. It may be thus required for the operator to be aware of situations that create unfavourable operating conditions and be equipped to manage them.

Normally, the power flow from distribution transformer (DT), through the feeder lines to the consumers feeding their loads. The power converters modules in smart consumer loads are composed of electronic switches which makes the converter draw non-linear current while operation. These non-linear devices drawing nonlinear current (represented by harmonic current) will distort the supply voltage waveform causing PQ issues in the network. Strict government policies and restrictions has motivated higher compliance from many of the manufactures to adhere to high PQ standards restricting harmonic injections by individual devices to a certain extend [25]. That being said, harmonic currents are cumulative in nature and can accumulate at the point of common coupling (PCC) [29]. With higher numbers of such non-linear devices operating simultaneously in the network can results in higher levels of harmonic current, which causes higher distortion of voltage at PCC. With high rating non-linear load like EV and heat pumps in promotion, the harmonic PQ of distribution network is expected to have move to severe levels in a LVDN. Increased amount of harmonic content in the system may not always give any direct hazardous situation to the operators, however, the accelerated deterioration of equipment and cables in the system would provide a clear implication of existence of high amount of harmonics and its notorious nature [30]–[33]. Further, the adverse effects can be also observed in the nuisance tripping of circuit breakers, saturation of distribution transformers, premature failure of consumer equipment, and overloading of motors [34]–[36]. Such adversity in the operation of the grid can be managed by carefully analysing the operation and foreseeing (pre-empting) such conditions. Revisions of network related PQ standards with changing time has proposed safe levels of harmonic current in a DN [23], [25]. Also, harmonic mitigating devices (Harmonic Filters), when connected in a network, manages the harmonic emission is a potential solution. However, with harmonics being contributed by consumers and only being dangerous at high levels of non-linear loads operating simultaneously does not always justify employing these expensive PQ equipment. As consumer devices are the culprit in the harmonic issue (in LVDN), micro-managing the consumer demand in a DN can create an opportunity to manage harmonics without much investment.

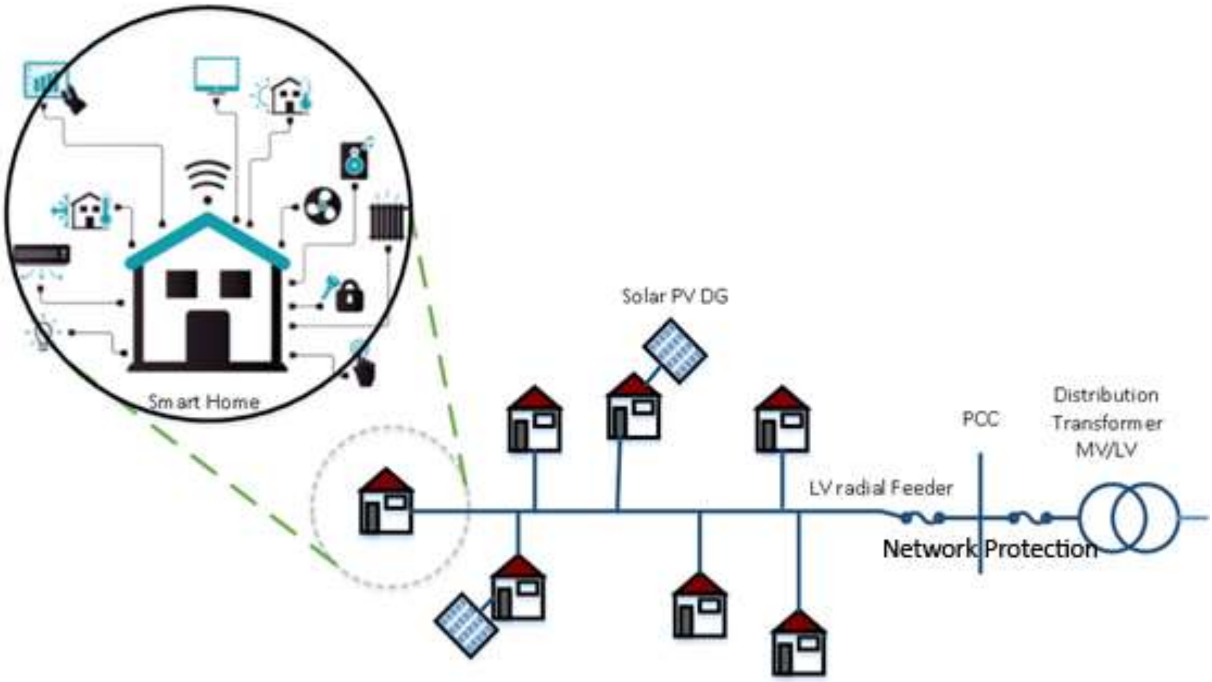


Figure 2.1 A typical radial distribution network

With improved technology, affordable grid-tied renewable generators are increasing their presence in LVDNs. With promotion driven by low carbon policies and increasing demand, the penetration of DGs in a DN will inevitably increase. In a radial distribution network like in Figure 2.1, with increase/decrease in loading level, the voltage profile drops/rises across the feeder length as shown in Figure 2.2. Nowadays, advancement in technology has also enabled consumers to be an active component of a DN while being capable of producing energy to serve demand across the network, and even causing power to flow towards the DT. The voltage drop in the LVDN feeder is proportional to the impedance (also in LVDN R>>X) and the current (loading). According to IEC 60038 standard, a voltage level of 230/400V ± 10% is recommended for a standard 3-phase 4 wire system of DN. The tolerance of maximum 10% (V_{max} and V_{min}) is expected to be maintained throughout the DN under all operating conditions. With heavy loading scenario, such as daily peak load, the voltage at the end of the feeder may not be within the tolerable limit impacting the supply quality. Also, with high DG penetration and low loading (typically a mid-day) there is more generation in the network than the load and hence power (current) flow towards the DT which in effect keeps the sending end (end of feeder) voltage higher than at DT or can go beyond the recommended upper limit. A radial LVDN is vulnerable towards both these undervoltage and over-voltage scenarios. Since these issues are due to the level of loading/generation in the network, a carefully designed active power management system can be a simpler solution to these complex dynamic issues.

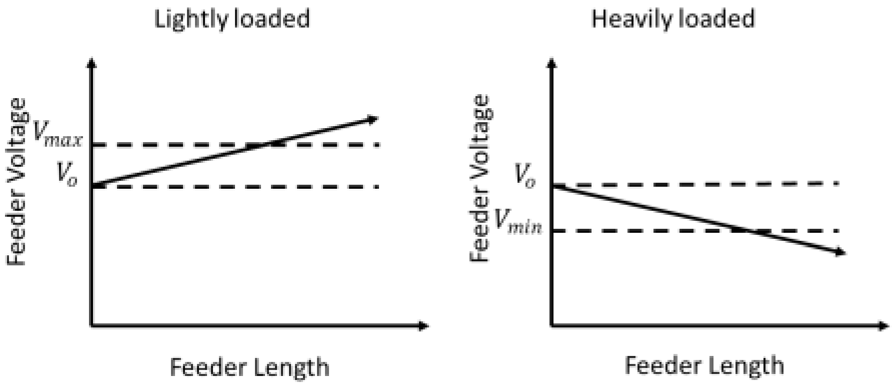


Figure 2.2 Radial feeder voltage profile figure

2.4 Harmonics and its Basics

Harmonics are considered one of the major power quality problems as they distort the standard voltage and current profiles that are sinusoidal in nature. Generally, the source supplies a distortion-less sinusoid voltage and current. Still, due to the non-linearity of the system components and the loads connected, the source is forced to supply a distorted voltage/current. A Fourier decomposition of the distorted waveform can represent harmonics by sinusoids with frequency as an integer multiple of the distorted waves fundamental frequency. The complete representation of harmonic content to represent a wave is called as its harmonic spectrum. Ideally, with a linear device operating and ideal supply, the harmonic component will be zero except the one with the fundamental frequency. Technically, harmonics can be viewed as individual sinusoidal sources of electricity operating at integer multiple of fundamental frequency pushing power through the same line. When they add up, they form a distorted waveform rather than sinusoids. The current harmonics for a symmetric waveform can be represented by,

$$I(t) = \sum_{h=1}^{n} I_{(h)}(t) * \sin\left(2\pi h f t + \emptyset_{(h)}(t)\right) \tag{2.1}$$

Where, $I(t)$ is the actual current waveform with respect to time, A is the harmonic magnitude, f is the fundamental frequency, $\emptyset$ is the phase angle, and h is the harmonic order ($h = 1,2 \ldots . n$). Each of the decomposed left-hand side of equation 2.1 gives a harmonic component of the order h. Figure 2.3 presents the impact of the harmonics component on the sinusoidal supply waveform. In a practical case, the impact is cumulative of the individual effect of each harmonic component.

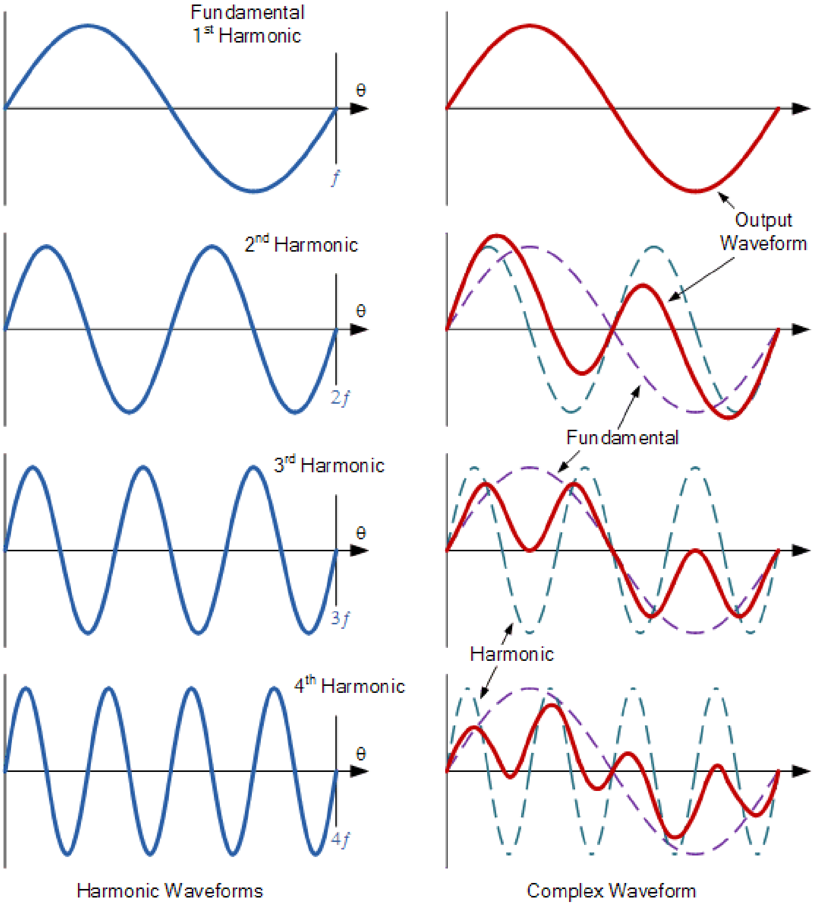


Figure 2.3 Harmonic waveforms and its impact on sinusoidal source. Source: https://www.electronics-tutorials.ws/accircuits/harmonics.html

2.5 Types and Sources of Harmonics in an Electric Power System

Harmonics are expected in a power system network due to the non-linearity throughout. The non-linearity due to the reactance component of the network element itself will generate harmonics in the system but at very low levels. The major source of harmonics in the network are non-linear loads connected by the consumers. These individual loads demand non-linear (or harmonic) current from the network to operate. Due to the additive nature of harmonics, they accumulate at the point of common coupling (PCC) [18]. The point of common coupling (PCC) is defined as the point at which a transition of supply in the power system structure happens in the power network perspective. In a residential environment, the PCC is the supply input point. In a DN, the PCC is usually considered at the network DT.

Harmonic sources are devices that draw harmonic current from the supply to operate. The typical non-linear loads include devices with inductance/capacitance, which draw lagging/leading current from the source. The non-linearity distorts the sinusoid form of current and voltage from the source and impacts other devices that expect non-distorted supply. Apart from these conventional non-linear loads, modern electronic switching device based loads consume intermittent current and are supported by an inductor/capacitor to improve the device's efficiency. These modern smart efficient devices are overhauling the consumer electronics market and have contributed to a steady increase in non-linear loads in the DN.

The nature of harmonics produced by each type of load is distinct and has very distinguishable signatures that can also be used for identifying a particular load using their harmonic profile. Different methods are suggested in the literature to estimate the source of harmonics [37], [38].

Harmonics are classified based on the frequency at which they occur. For example, odd harmonics, even harmonics, triple-n (multiples of three) harmonics being a few. If they occur at non-integer multiple of frequency, they are called interharmonics [39] and sub-harmonics[40]. Interharmonics are components whose frequency is not an integer multiple, and sub-harmonic are whose frequency is greater than zero but less than the fundamental frequency. Harmonics are also categorized with sequence components representation depending on their frequency. Each type of harmonics is prominent with different sources, and thus, they can be connected together forming loads with a particular harmonic signature. The general type of harmonic signature and the loads producing it are given in Table 2.1. The sources of harmonics (non-linear loads) are increasing in the network, especially the DN due to the proliferation of smart loads. The future of DN suggests higher penetration of power electronic switches and electronics based non-linear loads causing severe distortion to current and voltage waveform [34].

Table 2.1: Types of harmonics and their corresponding sources [41]

Type of Harmonic	Sources of Harmonic
DC	Electronic switching devices, half-wave rectifiers, arc furnaces (with random arcs), geomagnetic induced currents (GICs)
Odd harmonics	Non-linear loads and devices
Even harmonics	Half wave rectifiers, geomagnetic induced currents (GICs)
Triple-n harmonics	Unbalanced three-phase load, electronic switching devices
Positive sequence harmonics; Negative sequence harmonics; Zero sequence	Operation of power system with non-linear loads. Unbalanced operation of power system or a balanced 3-phase 4-wire system with a single phase non-linear load connected phase to neutral.
Time harmonics	Voltage and current source inverters, pulse-width modulated rectifiers, switch-mode rectifiers, and inverters
Spatial harmonics	Induction machines
Inter-harmonics	Static frequency converters, cycloconverters, induction machines, arcing devices, computers
Subharmonics	Fast control of power supplies, sub-synchronous resonances, large capacitor banks in highly inductive systems, induction machines
Characteristic harmonics	Rectifiers, inverters
Uncharacteristic	Weak and unsymmetrical AC systems

2.6 Harmonics and Their Impacts

Individual non-linear loads produce harmonics throughout the network. Yet, the significant impact of harmonics is analysed at the PCC as they would accumulate to the maximum value at the PCC providing insight into the worst-case scenario. The negative impact of harmonics depends on the devices that are flowing through and could lead to reduced performance and eventually premature failure. For example, the high frequency component of harmonics at the transformer core can increase the core loss and create overheating of the transformer core and its insulation causing faster ageing and failure [43]. In the case of a relay trigger or circuit breaker, the harmonics can interfere with the electronics and cause nuisance tripping causing loss of supply [44]. It can also interfere with protection equipment by overheating their magnetic core or the current flowing component itself [34]. The operation of electronic devices is impacted by harmonics, especially devices that rely on supply voltage zero-crossing detection. With distorted voltage and current, the zero-crossing of current and voltage waves won’t coincide causing undesirable current flows to damage equipment. Sensitive equipment is more vulnerable to electromagnetic interference due to high-frequency current. Telephone interference due to high-frequency current flow has a significant impact on telecommunications. At times of harmonic resonance, a low impedance path for harmonic current through the equipment circuit can facilitate a short circuit. The impact of harmonics on different equipment and levels are well researched and quantified to a large extent. Table 2.2 gives a generic list of devices, the issues related to the operation as created by harmonics, their mitigation methods, and their drawbacks. This thesis acknowledges the different impact of harmonics and their mitigation methods proposed in the literature. However, most of the methods proposed in the literature are cost incurring and with associated increases in complexity. For a DN, it might not always justify the economics related to employing mitigation devices and hence would benefit from a simple asset oriented micromanagement to manage harmonics and its impacts.

Table 2.2: Impact of harmonics on equipment

Device	Issue	Mitigation	Drawbacks
Transformer [45][46][43]	• Increased core loss • Faster ageing and insulation failure • Overheating • Core saturation • Reduced efficiency	• Use K-factor derating • Use DSTATCOM • Use UPQC • Tuned harmonics filters • Passive/active filters • Guidelines of derating are given in ANSI/IEEE standard C57.110	• Underutilization of assets • The derating may not always be sufficient with high harmonic heavy loading scenario. • Additional expense on infrastructure. • Can lead to power factor issues
Relay and circuit breaker [44][34][47]	• Nuisance tripping or sympathetic tripping • Maloperation or loss of coordination of relay • Magnetic core overheating • Tripping of thermal relay due to overheating	• Continuous monitoring of health of relay • Enhanced filter circuit • Derating calibration to account for harmonic impacts	• Additional man hours • Additional cost • Calibration may not be accurate
Telecommunication [48]	• Interference • Noise • Issues with right of way	• Filter circuits in the communication link • Avoid construction near the telecommunication lines • Use compensation using cable sheath	• Additional cost • Added complexity
Harmonic Resonance [49], [50][51]	• Equipment failure • Short circuit • Over heating	• Fine-tuned passive filter • Series/shunt active filter • Virtual impedance control • Harmonic compensator	• Expensive • Complex technique and algorithms

Electronic equipment [52]**[57] [58]**	• Increases losses • Circulating current • Zero-crossing detection error • Reduced performance • Interleaving current • Faster ageing and premature failure	• Passive filter • Low pass filter • Active filter	• Incur additional cost • Non-flexible • Low pass filter may pass lower order harmonics
Induction motor and VFD [51] [52][32]	• Overheating • Unbalanced loading • Torque ripple and vibrations • VFD irregular operation • Premature failure	• K-factor transformer • Passive shunt filter • Fine-tuned passive filter • Active filter • Detuned capacitor	• Non-flexible • Sensitive to voltage unbalance • Hard to retrofit in future • Incur additional cost
Transmission lines and cables [30] [57][31]	• Increased thermal loading • Faster ageing • Increased corona loss and thermal loss. • Resonance with cable capacitance	• Derating conductors • Harmonic resonance filter • Series harmonic filter • Use UPQC	• Underutilization of assets • The derating may not always be sufficient with high harmonic heavy loading scenario. • Additional expense on infrastructure. • Can lead to power factor issues
Measuring Instruments [58], [59]	• Incorrect measurement • Core saturation of magnetic material • Heating	• Harmonic filter • Enhanced measuring algorithms. • Utilizing high sampling rates • Secondary coil designed for harmonic filter	• Expensive. • Additional complexity to implement. • Filters may not be designed for all harmonic frequencies.

2.7 Harmonics Power Quality Standards and Indices

Generally, the large load customers are responsible for ensuring that their systems operate in compliance with the Grid Code or distribution code standards according to [4]. Both Grid Code (CC10.13) [60] and Distribution Code (DCC9.5.1) [61] stress upon the consumers to ensure that their plants are operating without resulting in any voltage fluctuation or distortion. However, the utilities are still responsible for maintaining the quality of supply to an acceptable standard. Even with operating the consumer facility within the boundary specified by standards, the cumulative impact on the harmonics in the network may violate the operating limits specified by these standards. Moreover, domestic consumers are not normally regulated by PQ standards while using their appliance as it is indeed extremely difficult to monitor the individual consumers. Yet, with a weak source grid, the low levels of harmonics can distort the supply waveform to create sever impact to other devices.

Standards and recommended practices are defined by various authorities to limit the PQ issue in the distribution network. A few of the standards are listed below, and as a sample limits imposed by few of them are given in Table 2.3.

- IEC 61000-2-4 – Electromagnetic compatibility (EMC) - Part 2-4: Environment – Compatibility levels in industrial plants for low-frequency conducted disturbances (2002)
- IEC 61000-2-12 – Electromagnetic compatibility (EMC) - Part 2-12: Environment – Compatibility levels for low-frequency conducted disturbances and signalling in public medium-voltage power supply systems (2003)
- IEC 61000-3-3 – Electromagnetic compatibility (EMC) - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤16 A per phase and not subject to conditional connection (2013)
- IEC 61000-4-30 – Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods (2015)
- IEC TR 61000-2-1 – Electromagnetic compatibility (EMC) - Part 2: Environment - Section 1: Description of the environment - Electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems.

- IEEE 519 – IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems (2014)
- EN 50160 – European Standards: defines the main characteristics of the voltage at a network user's supply terminals in public low voltage and medium voltage electricity distribution systems under normal operating conditions.
- CIGRE TB 261 – Power Quality Indices and Objectives (JWG C4.07, 2004) ER G5/4 Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom (2011)

Table 2.3: Standards and their associated harmonic order (h) limits

Standard	EN 50160	IEEE 519 (up to 69kV)	IEC 61000-2-2, IEC 61000-2-12	IEC 61000-3-6
Purpose	limits	limits	compatibility levels	indicative planning levels
Voltage level	LV, MV	LV, MV	LV, MV	MV
h	Harmonic voltages as percentage of fundamentals			
3	5	3	5	4
5	6	3	6	5
7	5	3	5	4
9	1.5	3	1.5	1.2
11	3.5	3	3.5	3
13	3	3	3	2.5
15	0.5	3	0.4	0.3
17	2	3	2	1.7
19	1.5	3	1.76	1.5
21	0.5	3	0.3	0.2
23	1.5	3	1.41	1.2
25	1.5	3	1.27	1.09
23<h<40		3	2.27 x (17/h) - 0.27	1.9 x(17/h) - 0.2
THD, %	8	5	8	6.5

Apart from the table given above (Table 2.3), IEEE Standard C57.110–1986 describes recommended practice for establishing transformer capability when supplying non-sinusoidal load currents. The distortion limits are detailed in IEC/TR3 61000-3-6, limiting total distortion permitted at PCC. IEEE Standard 519, IEEE recommended practices and Requirements for Harmonic Control in Electrical power system, provide procedures for controlling harmonics on the power system and also state respective limits for harmonics. It states, for most systems (below 69 kV), the Total Harmonic Distortion (THD) should be less than 5%. The standard IEC/TR3 61000-3-6 also further elaborate on the procedures to calculate the harmonics in the system at PCC. European standard EN 50160 [62] recommends that under normal operating conditions, the total harmonic distortion of the supply voltage (including all harmonics up to the order 40) shall be less than or equal to 8%.

Harmonic indices can represent the level of harmonics. A list (and brief description) of a few indices used for representation of harmonics are provided below.

(a) Total harmonic distortion (THD) percentage (Current): It is the most common harmonic index used to indicate the harmonic content of a distorted waveform. Harmonic content is represented by its root mean square (rms) value. THD % is given by,

$$THD\% = \frac{\sqrt{\sum_{h=2}^{\infty}(I^h)^2}}{I^1} \; X \; 100 \tag{2.2}$$

Here, I^h is the current magnitude of harmonic order h and I^1 is the fundamental component of the current harmonic spectrum. Commonly, harmonic limits are represented by the THD value. The main advantages of using THD is, easy to compute with quick measurement. However, the information from spectrum and amplitude is lost. Also, the impact of harmonics are not directly evident from THD. THD can be calculated for either voltage or current.

(b) Total demand distortion (TDD): With current THD, the fundamental current is related to total rms current and can vary with respect to loading. This can show high THD % when the load is operating at low power, e.g., idling. With TDD, the harmonic current is represented with respect to the rated demand current and will be a constant.

$$TDD\% = \frac{\sqrt{\sum_{h=2}^{\infty}(I^h)^2}}{I^{rated}} \; X \; 100 \tag{2.3}$$

Where I^{rated} is the rated current of the load.

(c) Telephone Influence Factor (TIF): was proposed by Bell Telephone Systems (BTS) and Edison Electric Institute (EEI) to determine the influence of power system harmonics on the telecommunication system. It is similar to THD with a weight factor (w_h)that reflects the response to human ear. It's given by,

$$TIF = \frac{\sqrt{\sum_{h=1}^{\infty}(w_h V^h)^2}}{\sqrt{\sum_{h=1}^{\infty}(V^h)^2}} \qquad 2.4$$

Where, V^h is given by harmonic component of voltage.

(d) Individual Harmonic Factor (IDH): is a measure of individual harmonic component contribution to fundamental and is given by,

$$IDH = \frac{I_{rms}^{h}}{I_{rms}^{1}} \qquad 2.5$$

(e) Distortion Index (DIN): it is the ratio of total harmonic power to total power, and is given by,

$$DIN = \frac{\sqrt{\sum_{h=2}^{\infty}(I^h V^h)^2}}{\sqrt{\sum_{h=1}^{\infty}(I^h V^h)^2}} = \frac{THD}{\sqrt{1+THD}} \qquad 2.6$$

Where, V^h and I^h are harmonic voltage and current respectively.

Harmonic indices are used according to the application. Generally, THD is accepted as a good representative of harmonics and standards are defined on THD% limits. The current harmonics represented as magnitude of harmonic component are different for different loads. Hence it is essential to model harmonic loads to represent the distortion it can induce in the current waveform.

2.7.1 Non-Linear Device Modelling and Harmonic Power Flow

In general, the power system rarely consists of purely resistive devices and usually has an inductive or capacitive component associated with the device. However, while modelling, they are weighted on their impact on the observed results to quantify an approximation that could reduce the model's complexity. This method at times neglects non-linear component and create an approximate model, especially in the case on an LVDN with low reactance component.

A harmonic study can be performed at the device level or system level. The approach considered in this thesis has touched both these areas while the overall focus kept in a LVDN system context.

Further, the modelling of harmonic inducing equipment depends on the equipment being considered and the details of interest in the study. Developing an accurate model to represent harmonic distortion by smart devices will be a major research area. The granular approach to represent harmonics has to be modelled in sufficient detail to capture the impact of harmonics while keeping the overall process manageable.

There are two common methodologies to obtain stochastic harmonic load models of aggregated users, namely, component-based, and measurement-based approaches (Figure 2.4). The component-based approach uses a bottom-up technique that models each individual device (household appliances) based on the circuit schematic or the measurement parameters. The benefit of this approach is in representing the diverse consumer loads. However, as each household needs to be modelled separately as an individual household, appliances cannot be generalised in this methodology. This is therefore, a cumbersome method. The associated complexity is further increased if the harmonic angle is considered, which may constantly vary in terms of the operating condition. Moreover, depending on the individual component manufactures, the performance, and characteristics of individual devices of the same type would also vary. Most of the presently available models were developed with the component-based methodology (e.g.[63]–[65]).

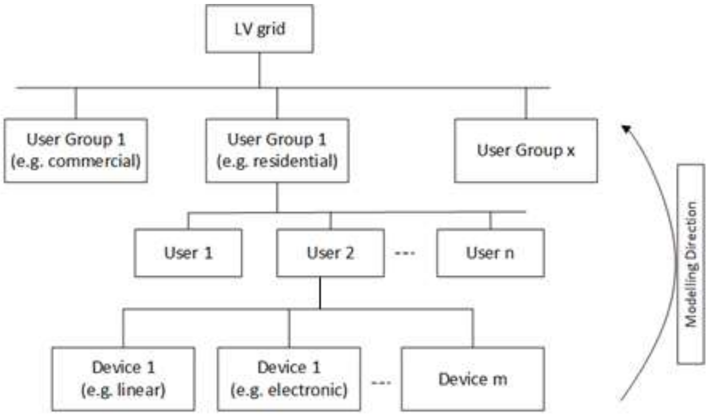


Figure 2.4a Component based modelling

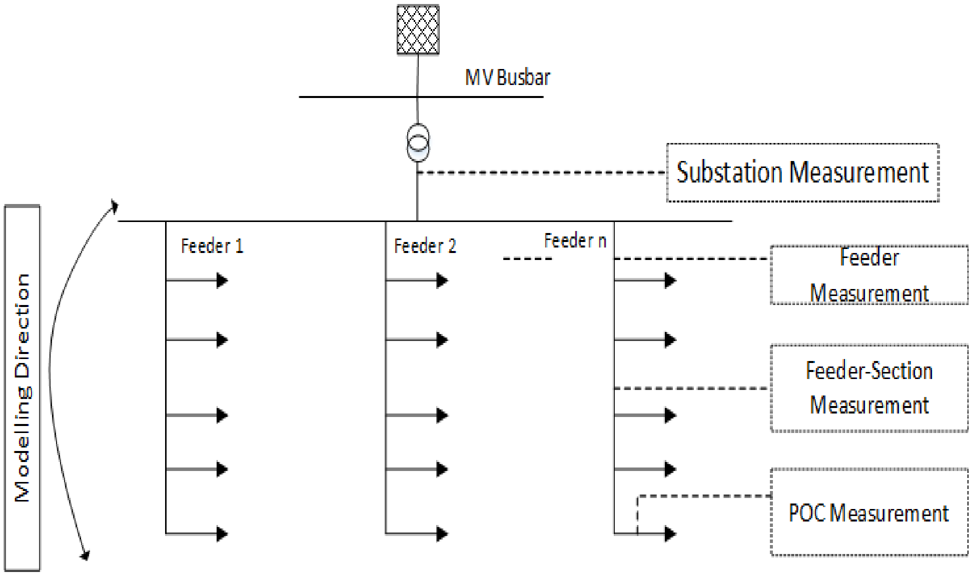


Figure 2.4b Measurement based modelling

The measurement-based approach, as the name suggests, uses measurements. Measurements at different sites in a network are recorded, including the aggregated effect of devices connected to the respective measurement site. The main bottleneck of the measurement based approach is the lack of measured data from the network [66]. However, with the increasing number of advanced measurement instruments and new smart meter technologies incorporating an integrated harmonic measurement unit, the measurement-based modelling approach is expected to improve. This will result in an accurate and reliable representation of particular domestic environment models in the future. A bottom-up residential harmonic load modelling technique that uses the measurements based approach and stochastic approaches is presented in [67]. The harmonic spectra of various appliances are established based on measurements. The same approach is again described by authors in another paper [68].

The authors in [69] model a constant load model to represent LCD TV, refrigerator and washer with harmonics and perform experimental validation of the model. The load is modelled as a voltage controlled current source along with a filter in the MATLAB® Simulink environment. A conventional load modelling approach using constant current source modelling is generally utilised throughout the literature for harmonic load modelling. However, [70] suggests that the model is not accurate enough with large voltage distortions and balanced network conditions. The paper proposes a Norton equivalent model, which can adjust the parameters with changes in operating conditions. The authors claim that the proposed model is suitable to model a large number of appliances in the residential grid. It utilises measurements acquired at different operating conditions for driving Norton parameters. The model is given in Figure 2.5. The authors [70] provide a set of verified harmonic profiles for a number of domestic appliances.

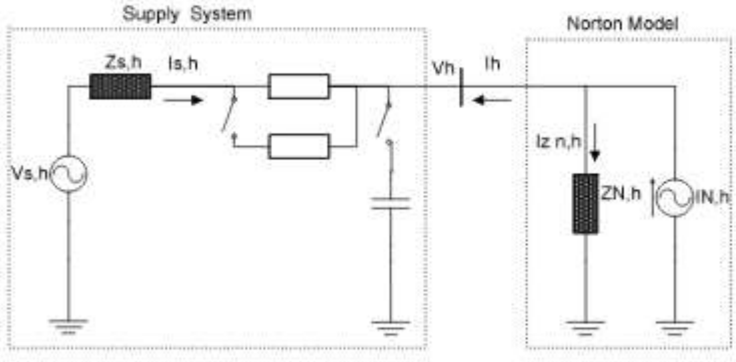


Figure 2.5: Norton equivalent model (load side) and thevenin equivalent model for supply system [70]

Machine learning, using parametric estimation and linear regressing models, are presented in the recent literature. For example, [71] uses multivariate multiple regression to predict the harmonic current produced at the point of measurement. The paper validates the generated outputs with a MATLAB® Simulink based model and also with a real system model. Linear regression modelling or parametric regression modelling is utilized in [72] to find the harmonic current and voltage contribution at the point of measurement. A prediction-based approach is presented in [85], which predicts a non-linear load's magnitude, phase, and THD. Authors of [73] use an admittance matrix that combines the traditional ZIP model of load and utilises the least square method for parametric estimation. Authors of [74] use autoregressive neural networks to predict the harmonic content of the load. These (prediction/machine learning-based) approaches are useful for quantifying harmonics produced in a network with low source impedance or with low short circuit capacity. However, the major limitation of the machine learning-based method is the availability of data and the influence of data resolution [75].

The Norton based approach is useful for systems with large short circuit capacity or in other words, in systems where (significant) non-linear load connections will not distort the supply (source) voltage. Also, these methods can be applied in non-iterative harmonic power flow algorithms, which is also an added advantage when computation power is limited.

To investigate the impact of harmonic load on the network level, the measurement-based approach is more suitable. The measurement can be done at any location and be aggregated at the PCC. Also, the range of harmonics around the operating region of the equipment/device can be modelled as a distribution function. The distribution will represent devices from different manufactures to a reasonable approximation. This can also be used to form an aggregated harmonic profile from multiple devices.

2.7.2 Harmonic Heating Impact

This significant increase in harmonics in the LVDN has not always been considered serious as the cumulative effect at the point of common coupling (PCC) was low compared to the fundamental component. With the increased penetration of non-linear devices in the LVDN, the accumulation of harmonics at the PCC increases. Section 2.6 discusses the impact of harmonics on different equipment. This section investigates the harmonic heating impact explicitly.

Harmonic heating effects due to the accumulation of harmonics in a conductor can cause a dramatic increase in the thermal loading of the conductor. These effects are examined by Palmer *et al.* [76] where pipe type cable modelling is employed through finite element analysis that utilizes the Nehars McGrath harmonic heating model. Cable heating effects in the presence of harmonic distortion are analysed and experimentally verified by Blackledge *et al.* [33]. The authors briefly explain a cable heat transfer method and discuss the harmonic rating factor introduced in BS 7671 [91] the national standard for electrical installations in the United Kingdom. Fundamentally, the ampacity of power cables is limited or determined by the maximum operating temperature within which the insulation can maintain its optimal performance. For example, the cables constructed with a cross-linked polyethylene (XLPE) dielectric are typically restricted to a maximum temperature of 90°C [77]. An increase in temperature will lead to faster deterioration of the conductor and significantly lower the operating life apart from fire risk. Harmonics cause increased heating of the conductor while the current carried may be less than the rated current. A recent report published by the National Fire Protection Association (NFPA) points out the growing number of states in the United States that are not able to follow the current edition of National Electric Code (NEC). In the report, titled “Falling Behind on Electrical Safety: Wide Variations in State Adoptions of the NEC Reveal Neglect of Electrical Safety” [78], NFPA indicates the risk of fire and safety issues which can be caused due to the non-adherence of consumers to the NEC which is updated every three years. This issue is further exasperated as the harmonic content and the heating produced by it are increasing while the regulations in this regard are inconsistent. More locally, ET 101:2008, the Irish electrical installation standard (for installations <1kV) [79] recommends a neutral overcurrent relay connection to protect against excessive harmonics in a 3 phase system. Such a relay facilitates automatic disconnection when excess current contributed by harmonics is detected in the neutral. However, this method only accounts for triple-*n* harmonics and does not sufficiently address the other orders of harmonics that can arise in such environments.

2.8 Cumulative Impact as a Consequence of Harmonics

Poor Power Quality (PQ) might cause technical inconveniences that lead to significant financial losses due to direct and indirect costs. Specifically, harmonics has a direct impact on utility companies’ costs and revenues [80]. Estimating the extent of losses incurred and the economic consequences of a PQ event or disturbance in different sectors of daily life is considered quite difficult [81].

Researchers have suggested using energy efficient converter-based equipment that consumes low energy as a solution to reduce demand [82], but such ‘energy efficiency enhancements’ corrupt electrical systems with the introduction of harmonics [83]. So, what are the impacts of our new energy efficient loads on the system? Analysing the load profile, the average daily demand is most of the time low and sometimes less than 50% of total capacity[84]. It is only during a few specific times of a day that we need energy more than normal generation capacity – if ever [84]. During this period the use of energy efficient devices could adversely impact the network as the harmonic content increases.

Furthermore, THD cannot solely be considered as the measure of harmonic impact in the system. This is due to its dependency on fundamental current. During standby operation of devices THD may be very high without being harmful to the grid.

So how can distribution network management economically and efficiently address this problem of increasing harmonic device penetration? Previously, there has not been much interest, primarily as the harmonic content of the system was considered very low. However, in recent years, the trend in using power efficient devices has increased dramatically and along with the expectation that the penetration of electric Vehicles (EV's) is also increasing [85], significant impacts from harmonics in the LVDN are inevitable.

2.9 Voltage Quality in Distribution Network with DG

With the intention of achieving EU 2020 targets and other national and global climate change policies, there has been a widespread promotion to install grid connected distributed generators, such as, rooftop solar photo voltaic generators (SPVG) in low voltage distribution network (LVDN) [5]. This higher penetration of distributed generators (DG) in LVDN has led to numerous advantages such as, reduced electricity bills for consumers, reduced line losses, increased reliability, and reduced emissions [86]. However, along with such advantages, the DG has also introduced some technical issues for LVDN, including overproduction, voltage rise, reverse power flow, harmonic issues, and metering issues. Significantly, the impact on voltage profile in a radial LVDN can be either, positive or negative [87],[88], [89]. The positive impacts include reduced line losses, better voltage profile during heavy load, lower emission cost, and higher system capacity. These generators are not usually utility owned, and hence, the positive impacts are not always guaranteed. The negative impacts such as overvoltage/voltage swell issues are site (location or distance from DT) dependent in a LVDN radial feeder. Hence a regulatory evaluation must be conducted to decide on maximum connection capacity at any given nodes in the radial feeder. One such effort is presented by the Commission Regulation

(EU) 2016/631 in the 'Requirement for Generators' (RFG) code [90]. It categorises DGs and defines maximum export capacity for each class. The RFG also accounts for the voltage stability and propose the upper and lower voltage levels at points of connection (PoC). However, the maximum export capacity could violate the voltage boundaries depending on the length of the radial feeder and the loading.

Further, such limitation on maximum connection capacity can in effect, create a bias for consumers based on their location on the feeder. Ignoring such a limitation could potentially create overvoltage issues under lightly loaded conditions with high concentrations of SPVG (typical mid-day in residential community). Though such scenarios would be rare, considering the safety of the network they have to be avoided.

On the other hand, the increased amount of consumer demand in the domestic sector includes domestic heating and transport transformation. The peak loading through the feeder is bound to create undervoltage issues due to high line voltage drop. The issue will be more significant to the low voltage radial feeder, which, under normal operation has lowest voltage at the end of the feeder. The straightforward solution being reinforcing the feeder may not always be the most economical solution.

2.9.1 Active and Reactive Power Control for Voltage Regulation

The European standard EN 50160 dictates, the voltage magnitude variation in an LVDN (3.3kV or less) to be less than 10% of the mean 10 minutes root mean square (RMS) value and the rapid voltage change should be less than 5% [62]. Also, the supply voltage unbalance must be less than 2% for a 10 minutes RMS. Adhering to these operational constraints are generally considered the duty of a distribution system operator (DSO), and traditionally on-load tap change (OLTC) transformers, line voltage regulators, capacitor switch banks, and line drop compensator. are employed [91]. However, with modern advancements in communication and control technology, sophisticated control can be implemented readily. In literature, active and reactive power injection/absorption control is proposed through a grid tied inverters (GTI) control to regulate voltage profile in LVDN[92][93]. A secondary active method to control voltage in LVDN is by utilizing the converter of a DG connected. The German grid code [94], proposes the use of DG’s GTI control to manage LVDN voltage violations. A novel droop control using active and reactive power control (PVDG’s GTI) based approach is discussed in [95]. Also in [96], the authors propose a local and central controller in a hybrid DG system with battery energy storage (BES) to maintain the voltage at point of common coupling (PCC). The paper utilizes active and reactive power injection control of DG’s and BES to maintain voltage level within limits. In [97], a positive, negative and zero sequence based current controller with reactive power compensation (filter capacitor) is proposed to maintain the voltage at the connection point.

A GTI control based approach is an effective methodology to regulate active and reactive power injection/absorption (in effect, voltage control) but the complexity of control may induce increased computational burden for the controller. Further, methods involving the droop characteristics of the GTI require manufacturers to assure a consistent operational characteristic as well. Reactive power control methods primarily depend on the (DG) GTI VAR rating and upstream transformer loading. Active power curtailment method can be exploited at both generator (limited again by VA rating) and consumer load to manage the voltage violations. As mentioned in [108], the German grid code advocates for DG-based GTI to manage LVDN voltage violations. Through single phase system reactive power control, unbalances are also created which could lead to neutral current at transformer neutral. Further, the operation of a GTI with active and reactive power control can create dynamic stability issues as discussed in [98][99]. A voltage sensitivity matrix calculation based on active and reactive power control is proposed in [100][101]. However, this method relies on complex calculation and system information.

The over voltage and under voltage issues in the LVDN can be effectively managed using active power regulation involving curtailment of load/generation. Load curtailment is managed by a DR program, whereas the DG output curtailment would require separate consideration.

2.9.2 Curtailment of DG power output

Irrespective of the monetary benefits of utilizing renewable energy to the maximum, at times it is not possible to accommodate all available generation capacity due to the restrictions imposed for the safe and secure operation of power system. In 2018, the system operator in Ireland could not utilize 6% of the power generated, accounting to 707 GWh [102]. The curtailment may be however due to system constraints which creates difficulty matching power to load demand. The constraints imposed by the system may be, line loading limit, minimum generation limit, operational constraints and voltage limits [103]. During over voltage conditions, the most efficient method thus employed is active power curtailment from an operator's perspective.

An active power management algorithm as described in [104] [92] uses active power injection set point to regulate the voltage at the point of connection. To manage the overvoltage scenario an active power curtailment is executed by controlling the set point based on droop control or sensitivity matrix calculation. The loss of useable energy is considered inevitable in such a scenario [105]. However, in a radial feeder, the maximum impact of the voltage related curtailment is observed at the end of the feeder. In this regard, the highest sensitivity is towards the voltage rise at the end node [106][100]. The feed in tariff (FIT) revenue is thus severely affected for consumers connected at the end feeder resulting in an unfavourable bias in the community. Considering a fair curtailment strategy is thus essential for promoting DG in an LVDN.

2.10 Demand Response

In 2013, the European Commission pointed out that the "'*potential of the demand side response at the Union scale is enormous: peak demand could be reduced by 60 GW, approximately 10 % of EU's peak demand".* This highlights explicitly the energy and cost saving and indirectly points at the possible CO_2 reduction in the energy production sector [107]. The peak demand occurs during a short period during a day and could be controlled by careful load management techniques. This technique will also improve the system operation reliability and further improve the possible penetration limit of renewable energy sources (RESs). A decentralized power sector is more conductive for it is now more friendly towards small scale generations. Integration and management of economic operation of RERs along with maintaining generation demand balance is a non-trivial issue for system operators. Measures to address these challenges can be classified into three categories: *supply-side management*, which regulates the uncertainties in the renewable production using conventional generations or by managing the renewable output directly using curtailment methods; *supply-demand management*, which utilizes the energy storage capacity in the grid to balance between the supply and demand.

Finally, *demand-side management* (DSM) conducts the demand adjustment or load management according to the actual electricity price at any given point in time. This thesis explores the opportunity provided by demand-side management while responding to consumer demand. The availability of technology to micromanage demand is currently underutilized due to its few drawbacks. The following sections will present the fundamentals of DR, their main classifications, techniques, and their implementation bottlenecks.

2.10.1 Background and Definition

Under the name of load management, the IEEE PES working group started to disseminate technical knowledge and coordinate activities [108]. DSM was first introduced by the Electric Power Research Institute (EPRI) in the 1980s as a series of activities that utilities undertake to change their load shape or energy consumption pattern for benefit maximization, investment delay, and reliability improvement [109]. Demand Response (DR) can be considered as a subsidiary of DSM and essentially is a consumer economics based program, which in turn will be economical for producers/utilities. The US Department of Energy (DOE) defines demand response as: changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to afford incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [110]. DR directly interacts with consumers while adjusting their individual consumption pattern in a superficial way according to the time of use or based on the price.

2.10.2 Classification of DR

The basic methodologies involved in DR are relatively similar, and hence DR can be classified primarily based on three categories as provided in Table 2.4. While DR actions typically involve either shifting electricity use from peak times to off-peak times or simply using less at peak times, demand response can also mean increasing electricity use (during off-peak).

Based on the decision making criteria the demand response program can be broadly classified into; an *Incentive based program* and *Time based Program* [111]. Incentive based program, generally employed by industry, uses pre-approved contracts to manage consumer loads using different decision-making criteria. A simple DR program uses direct control of consumer loads, and the benefit provided depends on the load managed. While market based DR utilizes market signals as trigger mechanism, price based DR depends on the price of electricity as its trigger. The demand would be reduced during high price period and increased during low price period. With fixed pricing, the DR is prescheduled as a typical load curve peak and for a valley that is already known. Alternatively, the DR is activated only during a fixed period in a day for Time based Program. It can also use price received during a critical peak in a term or consider price in an ‘extreme day’ within a term to decide the pricing scheme. However, the dynamic pricing scheme uses real-time price signals to calculate the demand reduction.

Technology wise, DR can be categorised by three options; manual, semi-automated, and automated. The manual DR is enacted by the consumer based on the input signal from the utility or price signal. The semi-automated DR is when the consumer pre-sets the operations of devices based on the trigger signal. The device automatically optimizes the consumption based on user programming. Contrary to this, an automated DR (ADR) is completely self-sufficient in decision making and operating consumer devices. It uses a trigger signal to initiate and dictates consumer loads based on the most optimized consumption pattern. With smart appliances, ADR is the most attractive form of DR with the potential of additional capabilities. The Demand Response Research Center, funded by the California Energy Commission, has published a technical report on the OpenADR project. The project intends to provide interoperable signals to buildings and industrial control systems that are pre-programmed to take action based on a demand response signal, enabling a demand response event to be fully automated, with no manual intervention [112].

Further, test implementation in the European sector on ADR are discussed in [113]. The level of implementation of ADR varies with application, and hence the complexities also vary. The small microgrid based centralized algorithms are presented in [114] to find the best scheduling of home appliances in the domestic environment. However, their application in large distribution networks would prove challenging. In [115], more advanced decentralised control technologies are discussed.

A DR program has to be approached with different decision-making levels and can form a separate long list of classification. However, in Table 2.4, an overview category is shown based on user approach, optimization technique and time scale. The DR program depends greatly on the knowledge of consumer demand, which can provide an option for day ahead scheduling when available ahead of time. Real-time DR helps in congestion management, DR can also be implemented by an aggregator combining loads from multiple users or a single independent user can apply it. The aggregator approach gives higher load shifts, which enables market participation. The optimization approach mainly depends on the problem type (mathematical model), objective, solution type and user skills.

This thesis evolves into proposing an automated, incentive based, single user day ahead DR solved by a stochastic optimization technique.

Table 2.4: Classification of DR

	Methodology	**Technique**	
DR Control Strategies [111]	Incentive based DR	Simple DR	Direct load Control
			Curtailment program
		Market based DR	Ancillary service market
			Demand Bidding
			Emergency DR
			Capacity Market
	Price Based DR	Dynamic Pricing	Real time pricing
		Fixed Pricing	Critical peak pricing
			Time of Use
			Extreme Day Pricing
Approaches	User Participation	Single user	
		Aggregated user	
	Optimization approach	Classical	
		Metaheuristic	
	Time scale	Day-ahead	
		Real time	
Technologies	Manual		
	Semi-automated		
	Automated [116] [112] [113] [114]		

2.10.3 Methodologies/Algorithms used for DR

Demand response has been implemented as manual, semi-automatic and fully automatic systems optimizing different objectives realised through various algorithms. In developing a robust, reliable, and flexible DR program, it is critical to employ a suitable algorithm. Hence, it is important to appreciate the different algorithms in literature before choosing one for any application.

A DR program can be formulated as a constraint optimization problem. The optimization program can be solved using linear/non-linear optimization or metaheuristic optimization techniques. Apart from this, in literature, other techniques are also applied to achieve DR, such as direct load control [117], model predictive control [118], agent based modelling [119], and machine learning based demand response [120]. Table 2.5 shows a representative example of each type and its associated application parameters. The choice of algorithm depends on various factors including, type of problem, number of dependent and independent variables, application level, and programmer choice. Yet, most optimization techniques can potentially solve most DR problems depending on how the problem is modelled. The advantage arising by efficient modelling is with execution time, scalability, and ease of application.

The choice between non-linear programming (NLP) or linear programming (LP) depends on the objective function (also known as cost function) and the type of constraints. A non-linear cost function (and/or non-linear constraint) is solved using an NLP method [121]. Whereas the linear problem is solved using LP techniques. As the DR program in most cases will have an ON-OFF signal as output for a particular time interval, hence an integer output is mostly favourable. So, in most cases with LP or NLP a mixed-integer LP (MILP) or NLP (MINLP) version is preferred [122]. The problem formulation itself is an intricate step for a DR implementation. Most of the DR programs are optimized for cost saving (either for customer or for utility). Other objectives include load peak management, resource optimal utilization, flexibility optimization, and increasing renewable utilization. Often efficient modelling can potentially achieve multiple objectives. For example, in [123], the utility profit is maximized while making sure the consumer bill is reduced. In [124], a MILP is used to schedule consumer appliances to reduce the peak hourly load of a household. With a linear problem for domestic appliance scheduling, MILP is an effective optimization algorithm.

Metaheuristic optimization techniques are based on the random search method. This kind of optimization is useful when the problem variables and solution space is large [125]. Compared to classical optimization, heuristic optimization can find the global optimal solution with less computation effort. However, compared to a MILP DR program, heuristic programs can be potentially cumbersome to model and execute. Further, with the increased number of variables, the convergence time can increase depending on tolerance settings. With advanced computing availability, the machine learning (ML) based approach is also a useful technique for implementing a DR program. However, the inherent drawback of dependency on the amount of data can cripple robust largescale implementation of ML based DR.

When compared to all techniques, only *fuzzy* logic based technique shows potential to model consumer comfort or inconvenience as it can articulate linguistic values effectively [117]. However, the scalability of such program is increasingly difficult with a large number of variables. In literature, there are techniques by which consumer thermal comfort is considered while operating thermal devices using LP, NLP, or heuristic optimizations. However, consumer inconvenience associated with non-thermal devices operation restriction is seldom considered while formulating a DR program. Optimizing a problem over consumer inconvenience to schedule domestic appliances to meet required reduction requests will be a technique to simultaneously achieve two objectives: minimum consumer inconvenience and DR.

Table 2.5: Examples for different optimization technique applied for DR

Optimization Algorithm	Level	Objective function	Decision variable	Main Constraints	Comments
NLP and MINLP [122]	General	Participating node and daily payment for energy loss.	Load factor for different DR buses for different hours.	Maximum curtailment rate. Voltage limit. Power flow equations	Use direct load control. DNO is the decision maker and consumer comfort is not considered
NLP [121]	General. A system with 10 consumers	Minimize cost of generation	Consumption of each consumer at each time slot	Min and max consumption limits. Generation demand balance.	Consumers' preferences and their energy consumption patterns have been modelled in the form of convenience function.
MINLP[126]	General. With 3 energy hubs (CHP, Gas, Storage)	Minimize total cost of generation	Consumption of each load at each time slot	Constraints of converters and storage. Ramp up/down limit.	Considers real time pricing and load/generation uncertainties. Multiple energy resource scheduling.
MINLP and MILP [127]	Modified IEEE 6-bus system	System flexibility	Value of wind uncertainty variable	Ramp up/down of units. Energy balance. Storage levels.	Presents unified flexibility formulation with multiple resources with DR. Converts an MINLP problem to MILP. Considers wind uncertainty level in model.
MILP [124]	Residential	Peak hour load reduction	Peak load	Operation of appliances at each time slot.	The appliances are time shifted based on peak load. Can be applied in conjunction with load reduction request.
Bi level PSO [123]	Residential with appliances.	Maximisation of retailers'	Price and start time.	Power balance. Appliance operation cycle.	Considers price signals and comfort requirements. Two level optimizations

		payoff and minimisation of household's bill			using EV and PSO. Compares GA and PSO.
GA[128]	Smart grid with residential, commercial, and industrial load	Minimize square of error between demand and proposed demand.	ON-OFF status of different shiftable loads	Number of devices shifted from time slot.	With large number of controllable devices, a DR program is very efficient and effective. Beneficial for all class of consumers.
SA [129]	Residential microgrid with 100 users	Maximize payoff for utility, retailers, and consumers	On-OFF status of appliances	Energy consumption by appliances at different time slots	Beneficial for utility, consumer, and retailers. Implemented for large consumer sets. Use real time pricing
Machine learning [130]	General residential	Minimize electricity cost (expenditure)	Peak price	Thermal comfort	Environmental impact was also used as a metric. A combination of optimization and machine learning was used. Tested on real data
Model predictive control [131]	Residential	Minimize electricity cost	Wholesale electricity price	Start-up and shut down time. Operational time. Thermal dynamic equations.	Uses real time pricing. Use flexibility of thermal and non-thermal devices. Thermal comfort level is considered.
Fuzzy logic [117]	Residential	Peak load management	Peak period	*Fuzzy* rules	Consumer thermal comfort is considered.

2.11 Benefits of DR Program

A high degree of social and environmental benefits can be achieved through efficient DSM or DR strategies. A study of 3 different DSM implementation scenarios is studied in [132] and results show a decrease of 8.3-16% of summertime regional electricity demand. A strategic DR/DSM can effectively reduce the impact on supply-side issues as well as reduce the non-renewable generation and thus lower associated unfavourable impacts [133]. Such positive environmental impacts include improved ecosystem reducing carbon emission and negating climate change and improve health benefits.

The DR program can be considered as an effective solution for compensating the intermittency of the renewable energy system, further improving flexibility of the system which in effect increases the penetration of RER's. Although the energy cost of renewable resources is typically low (for example, wind generation), the associated system costs can be substantial. As with high penetration, it becomes essential to maintain a higher system reserve to manage the intermittency of RER generations. The cost of maintaining the spinning reserve and quick start reserve (standing reserve) can be minimized using effective modelling of DR/DSM. In [134][109], DR has been considered as a prime resource to facilitate higher penetration. A model studied on active demand response in Great Britain is presented in [135]. The authors show that the investment on gas-fired peak load plants can be reduced significantly by using DR. This would have a much more significant impact on CO2 reduction.

A DR program inherently promotes benefits to the consumer by generating direct saving for consumers. The load curtailment in DR can provide ancillary service to system operator recovering additional income to the participants. Sufficiently large flexibility can be utilized in the electricity market to generate additional income by bidding as a virtual power plant with quick start up that can also provide reserve capability.

From literature, compared with storage technologies, DR programs can effectively achieve all those performance enhancements that storage can provide (except voltage regulation) without the heavy investment cost. The potential services that a DR program can provide are provided in Figure 2.6. The objective of this research program will be to add another layer to the Figure 2.6 to accommodate power quality issues within the DR program.

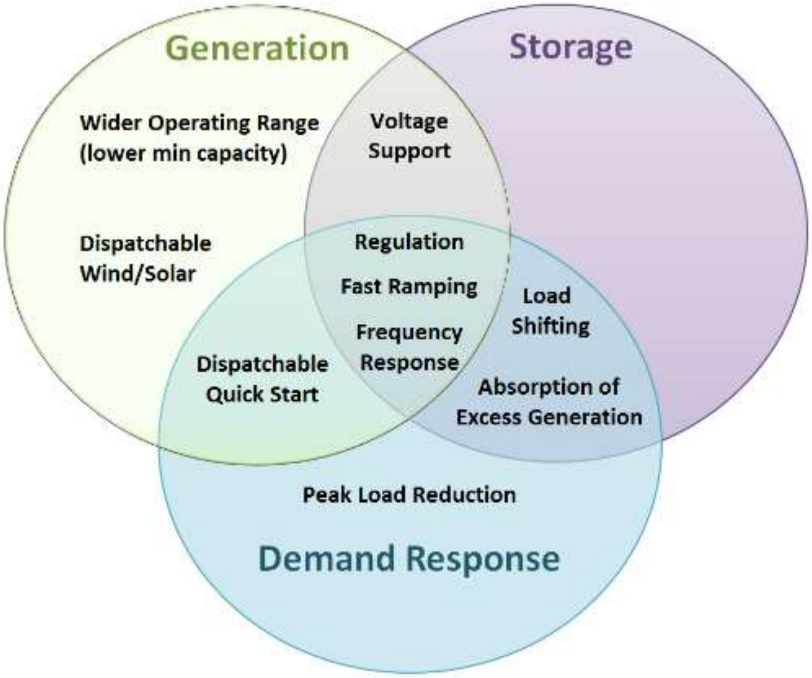


Figure 2.6:Services provided by demand response[136]

2.12 Challenges in DR

The first set back faced since its theoretical formulation (1970's) is the technological hurdles that limited a reliable communication channel for administering DR signals. It was not until the 2nd decade of the 20th century that industries started utilizing DR technology to increase their profit margin with little or no inconvenience by managing peak load. While technological hurdles were previously considered as one of the main challenges for DR and DSM implementation, this has changed due to technological advances in smart grids [137]. The advancement of technologies such as grid-wide bilateral communication, communication powered smart appliances, powerful controllers, cloud-based aggregation mechanisms and economically viable energy storage resources can be named in this regard. Yet, with a proven technology and many successful pilot studies, there are very few dominant suppliers that may be interested in facilitating a residential-level DR program all over the world. Adding to that, domestic or lower load level DR programs are still not used much. A few main factors affecting the implementation of DR can be listed as:

a. Consumer awareness for benefits of DR [138], [139], [140]
b. Consumer participation [141]
c. Energy policies and Market [111]
d. Cost benifit of DR program [142]
e. Dynamic electricty pricing scheme availablity [142][110]
f. Availability of smart controllable appliances and home automation technology.
g. Energy market balancing with increase intermittent RER’s [109]

In recent times, one of the major bottlenecks is consumer acceptance due to the inconvenience and the low magnitude of profit in the lower (distribution network) level consumer[117]. This is because the deviation of the end-user’s normal consumption will lead to consumer discomfort or inconvenience. Generally, incentives for bearing this inconvenience are not acknowledged as attractive, and hence the load management programs are not appreciated in the consumer market. Naeem *et al.* [143] investigate the dependencies of DR programs on social and economic factors. In [138], Hassan *et al.* indicate a relationship between consumer inconvenience and DR and how the inconvenience to consumers increases with the magnitude of load decrease. This influences the participation of consumers in a DR program as consumer inconvenience can be considered as the direct measure of consumer comfort.

Further, the importance of consumer awareness and clarity of the information to consumers are discussed in [141]. The same paper proposes a consumer engagement DR plan to control a central heating thermostat. The consumer behaviour based model presented in [139] again identifies the importance of consumer satisfaction on the success of a DR program. The paper also points out that the incentive based DR program has a greater influence on consumers (than the price based) in achieving consumer engagement. The Electric Power Research Institute (EPRI), states, “The industry is only at the beginning of learning to understand their customers and figuring out what people want to do”[144]. The requirements of people are so diverse; dependent on social and demographic parameters leading to extreme difficulties in generalising an engagement plan/DR program. The European Commission [145], points out that, consumers should be given the right incentives to encourage more active engagement and contribution to system performance and stability. For instance, a survey conducted by Opower [140], shows the consumers feels it is important for suppliers to notify them about the critical periods and the associated tariff structure/implications. The issues with the consumers also include: a consumer's ability to react (meters, tariff structure and knowledge) and market design and regulation (access rules and incentives).

Another significant barrier to implementing DR technology is the lack of appropriate market mechanisms in current market structures [146]. Current implementation mainly focuses on emergency contingency support and ancillary services, with limited participation in the day-ahead market. This mechanism requires direct market bidding and contracts between the participating parties. The restrictive model of these markets limits effective participation of DR programs in the power market as it requires advance notice for changing demand for emergency scenarios[147]. System operators also recognize that DR is a valuable resource, but that consumers may withdraw from it if the inconvenience of participating becomes too great. The requirement of advance planning of demand response causes uncertainty in the response that can be achieved in real-time. Hence, in [146], the authors conclude that even though DR is capable of providing flexibility to the system, under current market conditions effective flexibility of DR is less than the conventional peak load plants.

The energy policies and the current tariff structure, especially the residential customer tariff, negatively affect the success of a DR program. The tariff structure consists of various parts and is not straight forward for a consumer to understand. For the success of the DR program a consumer must have a clear idea about each part which will have a positive impact on DR acceptance. The market should also be price responsive to demand change. However, this will indirectly shift the responsibility of maintaining the system security to the end users from the system operators. This is a major deviation from the current regime where consumers have no regard for the real time price of electricity or any concern for maintaining the reliability of the power system. With DR regimes, consumers are active participants in energy balance and system security. Any regulatory or market redesign must consider that the market needs to be stable, thus providing efficient signals for generation capacity and network upgrades, while maintaining reasonable rates for consumers. In [148], the authors suggest an end user tariff system that could be restricted to a predefined range. The consumers would not be overburdened due to excessive price volatility and the burden of maintaining system stability and security.

These underlying factors, implying a current failure of DR are mainly motivated by the risk involved in such programs to succeed with respect to customer participation, the low monetary benefits, and lack of supportive government policies. However, these issues notwithstanding, an automated DR algorithm optimised for consumer inconvenience could be an acceptable evolution of DR, thus motivating higher participation and leading to better profit margin.

Even with consumer consent, the amount of controllable load is another important factor dictating the success of a demand response program. Peak levelling (discussed later) is a benefit of DR, where there should be enough controllable load corresponding to the peak to effectively minimize the peak at that point of time. For instance, if we consider lighting load, it may not be controlled during the period of 6 pm to 7 am during which the lighting is an essential need. This is a major issue of DSM or DR integration which was identified from the beginning [3].

2.13 Smart Loads and Consumer Comfort

Advanced technologies have improved the efficiency of consumer loads and has made them “smart”, hence enabling smart home environment. They can now be configured to adapt to consumers' needs, environmental conditions, to anticipate consumer demand and coordinate between other devices. The smart home consists of a home management unit that forms a central controller or supervisor dictating instructions based on a master algorithm [149]. The smart loads can also be remotely operated by consumers or by other smart operating devices based on the control configurations. The remote operation facility on smart devices provides high potential for any DR program to exploit, and increases the potential benefit for DR. However, they were mainly concentrated with large load customers. Demand response program is seldom used with the residential sector due to drawback in technology and communication channels along with low levels of controllable resources. With revolutionary technological advancement and large loads like EV, the system operators and utilities are considering the potential of DR in the residential sector to provide flexibility in system operation [150][151]. The residential demand being close to one third of total electrical demand [73], a DR program could now displace a higher load percentage in the power system thanks to smart loads. The potential of DR to offer flexibility to the system is an attractive response to manage system contingency/congestion similar to a solution provided by distributed battery units (an expensive solution).

Micro-managing consumer resources even in a domestic environment can enable higher utilization of LVDN infrastructure, delaying investment on network up-gradation to handle peak load or even power quality issues.

The DR program's performance is also strongly dependent on understanding consumer demand behaviour [142][152]. Further, motivating consumers to participate in a DR is also critical for a successful DR [116]. The essence of DR being displacing (denying when needed) consumer loads creates inconvenience to the consumer, which is rewarded by income generated by displacing the load. Predetermining consumer demand and adjusting consumer devices' operation yielding minimum inconvenience to consumers can enhance the tolerance of consumers towards the DR program. Further, a sense of control over participation or involvement is essential for a consumer's confidence in any DR program. This essentially points to the characteristic DR program to respond to consumer participation while minimizing their inconvenience when engaging in DR. Further, enhancing the economic benefits acquired not only from peak load management but also from providing ancillary services can pay higher dividend to a consumer attracting high consumer engagement.

2.14 Consumer Device Transition

Decarbonizing the electricity sector is significantly dependent on decarbonizing the electrical generation. However, achieving the 2030 and 2050 EU targets of decarbonization requires to maximize utilization of generated electricity. The EU sets forth a target of improvement of 32.5% in energy efficiency by year 2030 [13]. To achieve this, energy labelling and ecodesign rules were promoted to help consumer to obtain energy efficient products from the EU market [153]. A set of labelling frameworks were developed categorizing consumer products depending on their product group highly promoting energy efficient devices into the consumer market and creating manufacturer obligation to produce the same. Ireland’s climate action plan also indicates the objective on achieving an energy efficiency target to 32.5% by year 2030. The focus on energy efficient equipment design drove power electronic based smart equipment market to flourish.

Additionally, smart consumer product became more controllable owing to modern electronics inside. The transition of consumer electronics from static to semi-automatic to automatic and finally to smart devices has progressively dependent on evolution of electronic components, controller design and communication infrastructure. For example, the electric heater, which was a fixed heating device initially, has transformed into multi setting heating device and timer-based thermostat heating and finally to a remote-controlled thermostat that can also use real time information to set a room temperature. Undisputedly, every step of this transition has focussed on consumer comfort and ease, but still manage to be energy efficient and profitable.

The ability to remote control these consumer equipment allows micro-managing electricity consumption and can reframe the conventional electricity market by providing demand side management options [154]. However, this also instils a new set of issues due to the non-linear nature of these smart devices resulting in non-linear current flow accounted as harmonic currents [155][52]. The nonlinearity of these devices induces very high total harmonic distortion (THD) with low levels of linear loads in the system. Accumulation of these harmonic currents at the point of common coupling (PCC) has the potential of causing a devastating impact. Combined with steady growth of consumer load demand, the future is set forth to have a major chunk of generation being utilized by the residential sector and by non-liner loads. The emission target set by EU is demanding a drastic reduction in internal combustion based engines and promote electric vehicles. Anticipating the future with higher number of electric vehicle (EV) and electric heat pump, the amount of non-linear load in the system will become a real threat.

2.14.1 Domestic Consumer Loads

To completely appreciate the domestic demand response effectiveness, it is important to understand the characteristics of individual domestic loads. These domestic loads include all the general-purpose electric equipment available in a domestic dwelling and may/may not be used at any given time of the day. For a DR application, the domestic loads in a household environment can be broadly classified into Dispatchable/Non-Critical appliances and Non-Dispatchable/Critical Appliances.

2.14.1.1 Dispatchable/Non-Critical Appliances

This class includes loads which can be switched off or rescheduled by the DR algorithm to alter the demand. In other words, these are the appliances whose start time can be shifted across the day in response to the price change. Usually, the consumer has the autonomy to decide which appliances are to be included in this category. To be specific, they are non-critical devices which when turned off will not cause much inconvenience to the consumer. Furthermore, this category can be broken down into four groups based on their operation and technology used,

a. **Fixed power pattern devices:** These devices have a predefined power profile, i.e., once the device is switched ON the power consumption profile cannot be altered until the operation is completed. A washing machine is an example of such loads as the machine operates for a specific time when set to a particular mode consuming power based on its load profile.

b. **Flexible power pattern devices:** Contrary to the first group of devices, the power consumption pattern or power profile can be altered during the operation for these devices. For example, the plugged-in electric vehicle (PEV) charging pattern can be varied using a flexible charging control; thus reducing/increasing the energy consumption at a particular time.

c. **Thermal Devices:** this includes devices used for controlling the ambient temperature in a dwelling and water heaters. They are high power devices and are usually readily available to switch ON and OFF for a DR program. For space heating, a well modelled DR programme considers the consumer inconvenience due to temperature change along with atmospheric temperature to set a tolerance temperature range. This allows the DR to schedule and alter the space heater operation in order to manage demand.

d. **Curtailable loads:** These are loads which can be turned OFF without needing them to be turned ON at later stage. Usually, the number of these kinds of loads in the dispatchable category is very low. However, consumers can list devices in this category and assigning priorities.

2.14.1.2 Non- Dispatchable/Critical Appliances

These include loads that cannot be altered. In other words, they are critical loads which when demanded are to be facilitated without any intervention.

2.15 Conclusion

From a consumer perspective, various utilities have introduced dynamic tariff systems which have a normal tariff and peak load tariff [84]. Allowing the management and operation of loads in response to the price/peak load will generate additional income for consumer while sacrificing their comfort. The applicability of DR to provide additional services can increase the monetary benefit for participation. With increased non-linear loads and variable generation in the distribution network can potentially incubate PQ issues leading to asset/financial loss additional to security risk. Since harmonic and voltage issues are due to the level of loading/generation in the network, a carefully designed DR system can be a simpler solution to these complex dynamic issues. With the rising demand for more green and clean energy, the concept of demand-side management is gaining importance as it has the potential to provide ancillary services for the operator. Further observations from the literatures can be summarized as follows:

1. Power quality issue is a major concern in the distribution network with high penetration of harmonic loads and generators.
2. The number of non-linear loads in the distribution networks are increasing. This will rise the harmonic content of a typical distribution network.
3. The impact of harmonics is evident on almost all equipment connected to the network. However, the severity depends on the type of equipment.
4. Harmonic standards are defined for different voltage levels. The restrictions are different with different standard. With low voltage distribution network, the restrictions could be violated with increased non-linear load and cumulative nature of harmonics.
5. Harmonic heating effects, due to the accumulation of harmonics in a conductor can cause a dramatic increase in the thermal loading of the conductor.
6. Estimating harmonic voltage and current levels remains a challenge when there is a limited amount of network or component data available.

7. A reduction in efficiency of end-user equipment is possible in cases with high voltage distortion and can be studied further. If it is seen that this reduction in efficiency is significant, it could form the basis for new voltage-distortion limits.

8. There is a need for methods to automatically analyse large amounts of power quality data, including mapping existing harmonic voltage and current distortion levels.

9. Poor Power Quality (PQ) might cause technical inconveniences that lead to large financial losses due to direct and indirect costs.

10. Combined effect of all the domestic harmonic inducing devices is a significant concern in the management of a distribution network.

11. Harmonics are increasing with respect to the number of PV systems penetrations.

12. The distortion levels increase with the multiple harmonics inducing devices installations at the same node.

13. Increase Electric Vehicle penetration is going to further increase harmonic emission in LVDN.

14. The voltage profile on the radial distribution network depends on the loading in the feeder.

15. The generation level in the radial feeder has a direct co-relation with voltage in the feeder.

16. The maximum export capacity of a DG in the radial feeder can be impacted by the location of DG on the feeder.

17. Demand Response is a feasible solution for managing the demand in the network.

18. Demand Response has the potential to reduce the peak load in the load curve. Demand Response can in effect reduce the CO2 emission by limiting peak plant operation.

19. The success of a DR program depends on various factors, consumer comfort (acceptance), government policies, dynamic tariff system, the algorithm employed and on the level of implementation.

20. The success of DR program depends greatly on consumer acceptance.

21. Numerous methodologies are available for the implementation of DR, and the choice depends on application and developer.

22. Demand Response can create monetary benefits to the stakeholders.

23. The benefit from participation in DR is low. However, additional gird service opportunity can improve the overall benefit to participants and stakeholders.

24. Application of DR to manage harmonics and voltage PQ is not presented in the any literature.

These conclusions from the literatures are the bases of following research arguments:

1. An efficient and intelligent home energy management system (EMS) can be formulated to address distribution level load management issues promoting higher consumer participation.
2. The EMS can use DR to regulate the load during peak times or high tariff times to reduce the overall load.
3. The EMS can monitor and regulate the harmonic emission in a distribution network to safe operation limits.
4. A well modelled active power management based EMS can also be utilized to regulate the voltage profile in the distribution network.
5. The consumer acceptance/consumer comfort is one of the major influencing factors in the success of a DR program and hence needs to be carefully modelled and incorporated in the DR algorithm.
6. Harmonic content in the distribution grid represented as THD%, may not be sufficient to represent the severity of harmonics in the system and additional limiting conditions are to be applied.

Chapter 3 Energy Management Using Consumer-friendly Demand Response (C-DR)

3.1 Overview

Developing an easily scalable consumer-friendly demand response program to micromanage consumer demand is the focus of this chapter. The importance of consumer acceptance discussed as one of the main challenges in chapter 2 is represented as the prime variable for demand response (DR) control. A DR program in a conceptual scale is initially required as a skeleton to understand the functioning of a load management program. In appendix A, a simple direct load control (DLC) DR program is built and presented.

Initially, a fuzzy-based DR program is utilised to establish the relationship of consumer comfort with changing thermal load in a domestic environment (or inconvenience due to load denial). The fuzzy logic is used as a simple representative technique to account for linguistic consumer comfort variable. Thereafter, a consumer engagement plan is defined to promote consumer participation, which instils a sense of control to consumers regarding their energy management program. The linear programming (LP) based DR model developed later utilises the consumer engagement plan parameter to regulate the energy consumption in the house, such that, the inconvenience caused to the consumer is in accordance with their engagement plan choice. Compared to the fuzzy model, an LP based model is easily scalable and is simpler to model. The performance analysis of the algorithm is evaluated using different base case analysis in this chapter.

3.2 Consumer Comfort and *Fuzzy* DR

To appreciate the dependency of a DR program towards consumer inconvenience, a *fuzzy* logic-based DR is implemented. The fuzzy logic was first proposed by Lotfi Zadeh [156]. *Fuzzy* systems are considered as universal approximates that quantify non-precise inputs to obtain solutions that are based on rules. Essentially, *fuzzy* logic facilitates (fuzzy) controllers to take into account of complex inputs such as human comfort, which maybe based purely on human reasoning and perception. This enables *fuzzy* based control algorithms to model non-deterministic inputs using non-numeric linguistic values. Human characteristics, behaviour and response are easily represented by linguistic values rather than using crisp Boolean logic [156]. Furthermore, *fuzzy* logic can represent intermediate values similar to human decision making.

Fuzzy inference systems (FIS) help to model human knowledge into linguistic ‘if-then’ conditional statements; without using precise quantitative analysis. These ‘if-then’ statements are called upon as rules in the *fuzzy* system. Inputs and outputs, which are modelled as linguistic variables, are characterised by their appropriate membership function with attributes defined as linguistic values. Typical membership functions are representations of the input characteristics and vary smoothly without sharp boundaries between 0.1 and 1. Inputs are combined using logical AND, OR, and NOT operations. In general, first input values are ‘fuzzified’ or mapped to their respective membership functions and the degree of membership is assigned. Then statements of rule assign these partial memberships to the associated output membership functions after the logical operation of inputs. The outputs are weighted according to the strength of each rule. The final output is calculated using respective defuzzification techniques [156].

As a representative of consumer comfort, thermal comfort is considered in this study. As the thermal comfort is subjective while depending on people, their activity level, and the ambient temperature, the modelling approach will consider only ambient temperature. The consumer comfort is thus mapped to the ambient temperature which translates to consumer inconvenience when temperature control is not available. These conditions are replicated using the *fuzzy* modelling technique. The *fuzzy* DR model is realised through the *fuzzy* toolbox in MATLAB. The schematic structure of model is given in Figure 3.1. The inputs of the *fuzzy* DR controller are consumer profile, smart meter data and environment condition data. Outputs are the signal(s) of allowed load along with the ‘on’ or ‘off’ signal for the air conditioning system. The input and output are modelled using only two types of membership function: triangular and trapezoidal membership functions. The output of the controller is defined using around 450 rules which are mainly different possible combinations of input vs outputs. They are defined based on the experience and intuition of input output relationships. To implement a *fuzzy* based controller a basic household data selected is given in Table 3.1.

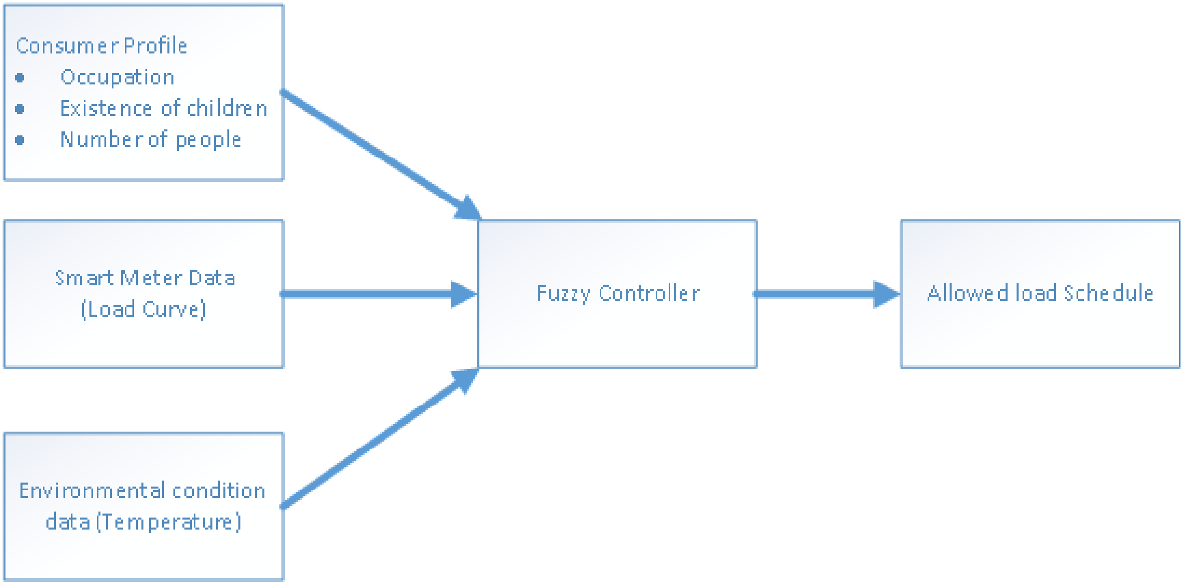


Figure 3.1 *Fuzzy* logic based Demand Response model

Table 3.1 static input data of household

Assumed basic data of individual household	
Number of people in house	3
Existence of children	Yes
Occupation	Full time
Total Load	5kW Peak

A house for 3 people with maximum demand of 5kW is utilised to implement *fuzzy* controller. A typical domestic load demand curve for such dwelling is given in Figure 3.2. The load curve shows that the demand is high during the morning 6 am to 9 am and evening 6 pm to 10 pm. The DR is designed to regulate the load during this period to reduce peak of load demand. Since customer comfort is considered, the switching ‘on’ and ‘off’ of the air-conditioning load is dependent on ambient temperature (Figure 3.3). The temperature data for the location of house located in Dublin is obtained from the meteorological data centre [157]. The temperature associated with a normal day, a warm day and cold day is defined so that the variation of DR will also depend on customer comfort for the same load demand. These temperature data are plotted together in Figure 3.3. The load curve after DR execution for these temperatures is shown in Figure 3.2.

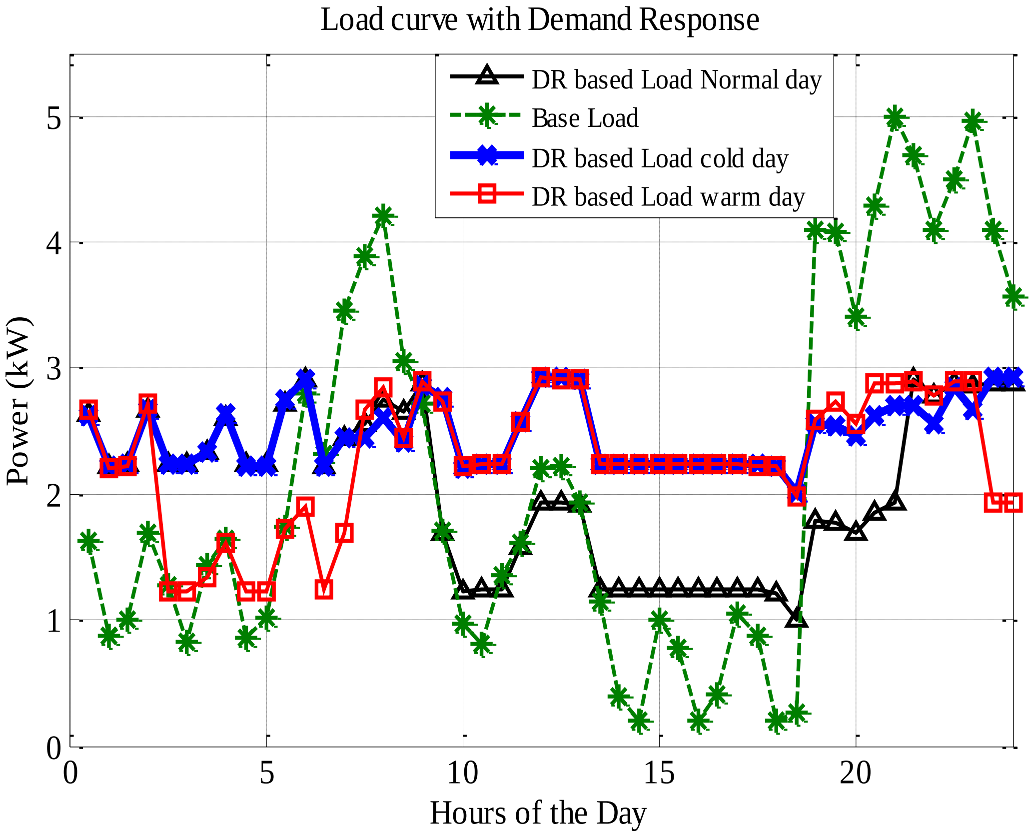


Figure 3.2 DR for different temperature

It can be observed that with ambient temperature change the DR based load also changes for the same load demand. In other words, with all other parameters constant, the control of heating/air conditioning depends on the ambient temperature and not just a DR requirement. Also, the comfortable temperature range can be gradually offset. That is, when the cut in temperature is reached the controller may decide not to turn on for a short while within the tolerance. This decision override is achieved by the *fuzzy* controller which is working on the linguistic rules which state that the air-conditioner should be 'on' if the temperature is high, or the associated heater should be 'on' if temperature is low and irrespective of the load peak. This is under the assumption that, use of temperature regulators depends solely on consumer comfort. Even then, the load during the peak demand is reduced and DR load management is achieved by controlling other available loads in the house. With a 'normal' temperature profile, a higher amount of load reduction is possible. Such decreased amount of reduction may affect the performance of a DR program. However, the consumer acceptance would increase and hence, when it is implemented, an increased participation would constitute to an impressive difference in load demand.

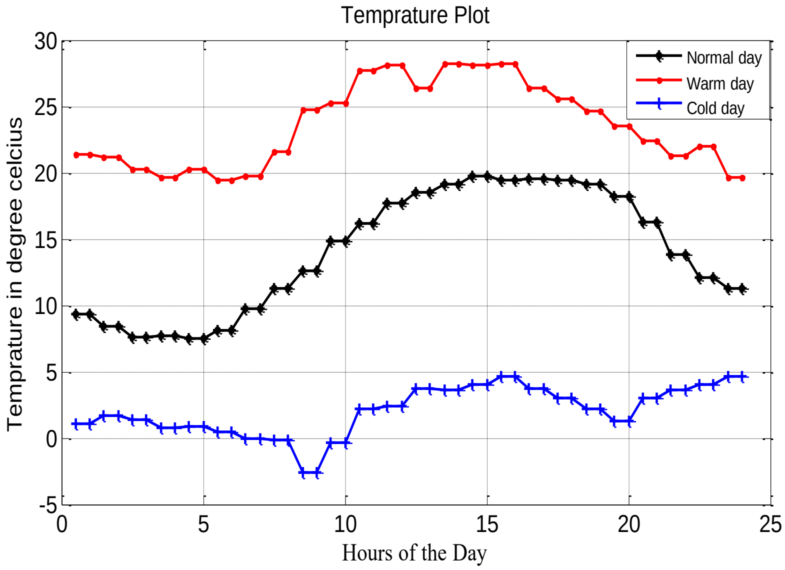


Figure 3.3 Temperature curve for warm, cold, and normal day (Data from http://www.met.ie)

3.2.1 Consumer Comfort vs DR

Mapping of consumer comfort and load management is relatively straight forward. However, ensuring consumer participation into a DR scheme is relatively difficult. As a basic human nature, consumers want to feel the control over their decisions or their level of engagement in a DR program. Hence, this work, proposes a set of consumer engagement plans to instil consumer with a sense of control over their participation in a DR program based on the amount of inconvenience they are ready to tolerate.

The correlation between consumer comfort and the load management program is very evident, and a fuzzy based DR can effectively model it. While using consumer thermal comfort as the reference for consumer comfort the ambient temperature tolerance is defined. With change in atmospheric temperature and depending on the occupancy in the house, the thermostat setting is regulated. However, with the increased size of system and system parameters, the fuzzy rule set becomes very difficult to model and execute. Hence, a more robust technique is required to incorporate the concept in a more realistic manner. A linear programming based two level optimisation technique will be presented (in a later section) which can contextualise consumer inconvenience in a load management algorithm.

3.3 Consumer Inconvenience and Consumer Engagement Plan

From fuzzy based DR (Section 3.2) finding, the relation between the consumer comfort and load management was evident. The finding from thermal comfort based fuzzy model can be extrapolated to all other device related comfort changes. However, when consumer comfort is defined explicitly on every device usage, it requires intensive modelling consideration. Rather, a consumer can represent the inconvenience related to each device by a value called as device level inconvenience factor (β). Now, this (β) can be defined by consumer depending on their reasoning. In this thesis two levels of inconvenience are defined; consumer inconvenience (α) and device inconvenience (β). Where consumer inconvenience relates to inconvenience due to total demand change and device inconvenience is related to each device.

Also, from Chapter 2 the consumer participation has been considered as a major bottleneck when proposing a DR program [117] [143]. Keeping this in mind, it is important to consider consumer convenience as the limiting factor for DR based load management while enabling consumer to have a choice with respect to ratio of their participation. The sense of control is in fact an important factor in consumerism driven market model. The participation plan is defined based on ‘α’.

This thesis proposes a consumer engagement plan at different levels so as to recruit the consumer to take part in the energy management opportunities provided by DR. The engagement plan can be devised considering various factors, however, to simplify the concept, here only one major factor is considered; consumer inconvenience (α).

Further, the engagement of a domestic consumer in the load reduction plans is not very well motivated by the monetary benefits offered by it. From literature it has been observed that a persistent motivation for the DR schemes can be reaped by correlating the benefits to environmental factors. From these understandings, four types of consumers are identified:

i. Super Green Savvy: users that tolerate higher amount of inconvenience as they are aware of the social benefits of DR program and are also motivated by the higher amount of incentive and the relative impact on environment.

ii. Green Savvy: users who are motivated to join the program due to its benefits but are only moderately tolerant on the load change.
iii. Green aware: users who are willing to participate with the DR program but, would not tolerate high inconvenience and obviously are given less incentives.
iv. Reluctant: users who are sceptical and are not willing to participate in the program and thus will not contribute to the load reduction desired by the grid operator.

Furthermore, to make the program attractive, a fixed incentive plan per month can also be initiated for the consumer willing to participate in the DR program as an availability charge. This concept is also ignored in the presented study as the government policies (promoting green energy or reducing peak demand) would greatly affect the magnitude of this incentive, and if included, may draw incorrect conclusion with demographics such as Urban and Rural plans. This thesis does not explore the DR based incentive, however, would propose it as a future possible work in regards.

For each type of consumers an inconvenience factor is defined (α). The value of inconvenience will update with the participation of a consumer in an interval depending on the activity in the interval. This ensures that consumer having high tolerance to inconvenience will not be chosen repeatedly to manage the load reduction. This inconvenience change associated with the consumer will be updated for each load change.

3.4 Consumer-friendly Mixed Integer Linear Programming Based Demand Response (C-MILP-DR): Problem Definition

Drawing conclusions from the findings and discussions in the previous sections and from Chapter 2 a set of characteristics of demand response program to be developed is given as:

1. The DR program should be simple enough to model, easily scalable, and fast enough to compute in a 15-minute interval.
2. The proposed algorithm should be flexible to incorporate a new set of constraints when and where developed.
3. The program needs to be capable of obtaining the community level objectives while ensuring minimum inconvenience to consumers.
4. The program should be able to schedule individual devices in the domestic environment

5. The algorithm should consider engagement plan chosen by consumers to micromanage their devices.
6. The proposed algorithm should be sensitive towards the participation of consumers and respond to the dynamic inconvenience.

Ensuring all these characteristics features are available in a DR algorithm needs careful modelling. Again, considering the observations from Chapter 2 a linear programming (LP) technique is chosen to implement DR program. Also, with careful observation of the characteristics of DR program and the associated objectives from Chapter 2, it can be concluded that, the algorithm can be separated to have two distinct levels; Community level and Domestic level. The stage 1 (Community level) would decide on the amount of load reduction proposed for each consumer which would be based on their engagement plan. The objective of stage 2 (Domestic level) would be to implement device operation rescheduling (based on device priority) to ensure the reduction proposed by stage 1 is achieved. However, our major focus is towards the community level DR as they would be incorporated with additional network level constraints later.

3.4.1 Assumptions

The wide variety of applications and implementation of DR warrants a set of assumption boundaries to be defined, creating an explicit case relevant to this thesis. So, while developing these stages and the algorithm, certain assumptions are taken into consideration, given by;

1. The algorithm assumes the individual device requirement/demand is known. It’s essential to determine the prescheduling of loads according to DR restrictions.
2. The algorithm assumes the load reduction request is available ahead of time. As algorithm calculate device schedule for future, it requires future demand reduction requirement available.
3. Each consumer is assumed to have the same devices and their rated power consumption is also assumed to be available. To have a consistent, unbiased result, it is essential to keep all variables except decision making variables constant.
4. Only the active power consumption is considered, and reactive/harmonic power consumption is ignored. However, if required, the algorithm can be extrapolated to

include them. While the DR is implemented for active power consumption it could affect the reactive/harmonic power consumption of the network.

With these assumptions we can now formulate the stage 1 of the DR algorithm which would distribute the reduction among the participating consumers

3.5 Stage 1: Problem Formulation

As mentioned previously in 2.14.1, the loads are categorised broadly as Dispatchable and non-dispatchable loads. Let, there be ‘n’ number of consumers. So, the total power consumed at a given time ‘t’ is given by

$$P_{Total}(t) = \sum_{j=1}^{n} P_j(t) \qquad 3.1$$

Where, P_j is the power consumed by the jth consumer. The time dependency factor is dropped from here on as it would not impact the analysis once the time interval is defined. Further, each consumer may have ‘m’ number of devices in their dwelling. Now the total power consumed is given by at a given time ‘t’ is given by

$$P_{Total} = \sum_{j=1}^{n} \sum_{i=1}^{m} P_{ij} \qquad 3.2$$

Where, $i \in \{1, 2, 3, \dots\dots m\}$, $j \in \{1, 2, 3, \dots\dots n\}$ and P_{ij} is the power consumed by the ith device from the jth consumer. The total power of demand of the house at a given time is contributed by the non-critical and critical devices. So, the total power consumed can be re-written as,

$$P_{Total} = \sum_{j=1}^{n} \left(\sum_{i=1}^{m} \left({P_{ij}}^{NC} + {P_{ij}}^{C} \right) \right) \qquad 3.3$$

${P_{ij}}^{NC}$is a vector of power consumed by the individual non-critical devices and ${P_{ij}}^{C}$ represents the vector of power consumed by the individual critical devices. For instance, the demand of a particular consumer can be given by a demand vector representing the status of the devices. It is given by,

$$A_{ij} = \begin{Bmatrix} A_1 \\ A_2 \\ A_3 \\ \vdots \\ A_n \end{Bmatrix} \quad 3.4$$

$$A_j = \{D_1 \quad D_2 \quad D_3 \quad \dots \quad \dots \quad D_m\} \quad 3.5$$

Where, $D \in \{0, 1\}$, which is the status of the devices 'D' at the house and indicate 'ON' if it is '1' and 'OFF' if it is '0'. Thus, the dimension of demand vector (A) will be n x m. In effect, A_{ij} gives the status of the ith device of the j^th consumer. Now, the total power consumed equation can be re-written as

$$P_{Total} = \sum_{j=1}^{n} \left(\sum_{i=1}^{m} A_{ij} \left(P_{ij}{}^{NC} + P_{ij}{}^{C} \right) \right) \quad 3.6$$

The demand status vector is time dependent and changes with each time interval, thus gives the operator the demand requirement of a consumer at a particular time. To perform DR or energy management, the grid operator issues a load reduction request or may define a peak load (P_{Peak}). In either case the DR management scheme is supposed to perform load reduction (for the current scenario we are only considering load reduction) which is given by

$$\Delta P = P_{Total} - P_{Peak} \quad 3.7$$

The first stage of DR scheme is to distribute this load reduction to different consumers throughout the grid based on the consumer inconvenience factor. For instance, '$\propto_j$' be the inconvenience of 'j^th' consumer. The value of '$\propto_j$' can be anywhere from 0 to 1 being a fraction. Consequently, the objective is to

$$minimize \left(\sum_{j=1}^{n} \alpha_j \Delta P_j \right) \quad 3.8$$

Where, ΔP_j is the individual power reduction demanded from the consumers. The power component and the inconvenience component when combined to form the objective function will form a correlation with each other. This objective is subject to constraints,

$$\Delta P = P_{Total} - P_{Peak} \qquad 3.9$$

$$\sum_{j=1}^{n} (\Delta P_j) \leq 0.5 \sum_{j=1}^{n} (P_j) \qquad 3.10$$

$$\Delta P \leq \sum_{j=1}^{n} \Delta P_j \qquad 3.11$$

$$0 \leq \propto_{ij} \leq 1 \qquad 3.12$$

This forms the first stage of optimisation where the load reduction required is distributed to the consumers based on their inconvenience tolerance limit. However, while this objective is achieved in subsequent time intervals the algorithm needs to account for the fairness of choosing consumers for DR management and hence would require considering the following factor,

- The same consumer should not be given the burden of reducing demand in all consecutive intervals.
- There should be fairness between consumers choosing same engagement plans.

The inconvenience associate with each consumer is by default set to the same value by choosing a particular consumer engagement program. But, during the day if the particular consumer is chosen for load reduction, the inconvenience value increases for the next iteration/interval and thus makes sure that the same consumer having lowest inconvenience value won’t be given the burden to reduce the demand in the next immediate interval or the amount of reduction requested would at least be reduced. The increase in inconvenience per participation is set to a fixed increment value of 0.05 per customer in this study. This can also set to be a function of load reduction and duration of reduction. Further, the maximum reduction per consumer should also be restricted to 50% of total demand to ensure that a particular consumer will not be penalised for having higher tolerance or lower value of inconvenience.

3.6 Stage 2: Problem Formulation

The second stage of optimisation has the objective of deciding the devices that need to alter its state of operation for each consumer to achieve the demand reduction proposed by the previous stage. The output of second stage would produce a device operation status vector 'B_j' which provides the information of list of devices operating after DR engagement.

$$B_{ij} = \begin{Bmatrix} B_1 \\ B_2 \\ B_3 \\ \vdots \\ B_n \end{Bmatrix} \qquad 3.13$$

$$B_j = \{D_1 \quad D_2 \quad D_3 \quad \dots \quad \dots \quad D_m\}$$

Where again, $D \in \{0, 1\}$, which is the status of the devices 'D' at the house and indicate 'ON' if it is '1' and 'OFF' if it is '0'. In effect, B_{ij} gives the status of ith device of jth consumer. The devices deprived of operation can be given by device denied vector R_{ij},

$$R_{ij} = (A_{ij} - B_{ij}) \qquad 3.14$$

The amount of load reduction is achieved can be given by,

$$\Delta P_r = \sum_{j=1}^{n}\left(\sum_{i=1}^{m} R_{ij} {P_{ij}}^{NC}\right) \qquad 3.15$$

Corresponding to the consumer inconvenience there is an inconvenience associated with each device. If a consumer is deprived of operating a washing machine will have a different inconvenience if the same consumer is deprived of using a television. Thus, different devices will have different inconvenience factor associated and given by β_{ij}, which is the inconvenience associated with altering the operation of ith device of jth consumer. This value forms a priority list of devices in a domestic environment. Further, the consumer will always have an option to set different priorities for the devices in their household. A weight updating algorithm could also be employed to ensure fairness between the devices in consideration. This makes it obvious to choose the inconvenience value as the objective function for second stage MILP-DR. The flow diagram for both stages is given in the Figure 3.4.Thus, the objective function is to

$$minimize\left(\sum_{j=1}^{n} \beta_j R_j\right) \qquad 3.16$$

Subject to,

$$\Delta P_j \leq \sum_{i,j=1}^{n,m} R_{ij} P_{ij} \tag{3.17}$$

$$0 \leq \beta_{ij} \leq 1 \tag{3.18}$$

$$\Delta P \leq \sum_{j=1}^{m} \Delta P_j \tag{3.19}$$

The status vectors will have values 1 and 0 corresponding to ‘ON’ and ‘OFF’ status respectively inside them corresponding to each device. The vector A gives the demand status of all devices in the house and hence the critical devices will have a status 1 when demanded and would not be changed by the DR management algorithm.

The sum of load reduction by individual houses would be equal to or less than the total reduction required by the operator. Cases would occur where total reduction may not be achieved due to limitation imposed by constraints. The algorithmic flow diagram is given in Figure 3.4.

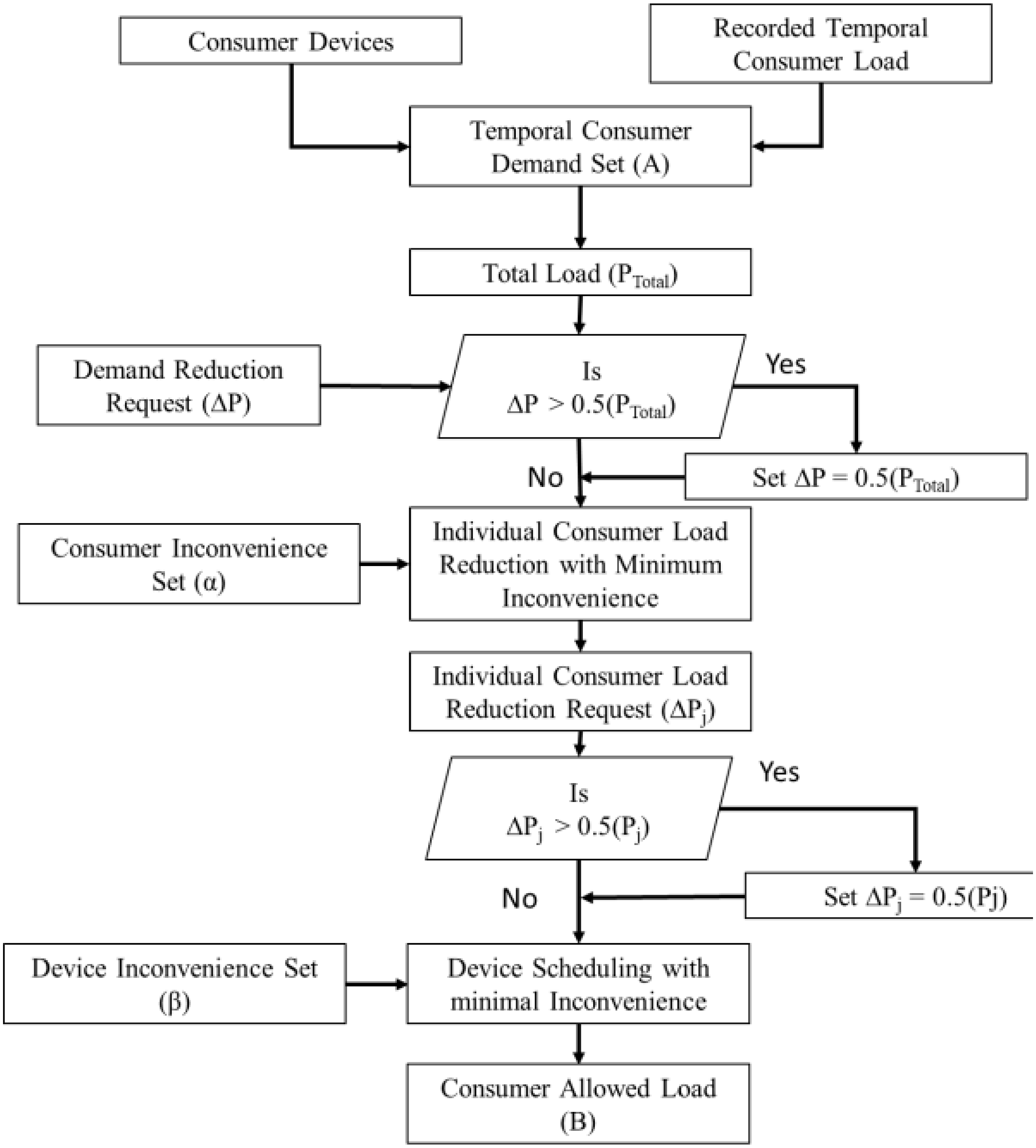


Figure 3.4 Two stage C-MILP DR

3.7 Test System and Load Model

In order to test the proposed algorithm, a community-based test network model is required. A suburban low voltage distribution network (LVDN) from Dublin city, Ireland is considered in this thesis to implement the algorithm and any future developments (Figure 3.5). The network has 74 consumers connected to the 3 phases fed through a distribution transformer. Since the detailed network model is not warranted currently for the algorithm, the detailed description of the network is given in the next chapter relating to its significance. The loads are modelled as active power (P) consuming elements and are depending on the rating of the device.

All optimization problems are modelled in MATLAB® scripting environment using CVX toolbox. The mixed-integer programming and linear programming problem is solved using Gurobi solver. The solution was cross verified in MOSEK solver as well. The computer was on Windows 7 powered by two intel® Xeon® E5410 processors (2.33GHz & 2.33GHz) with 20GB RAM.

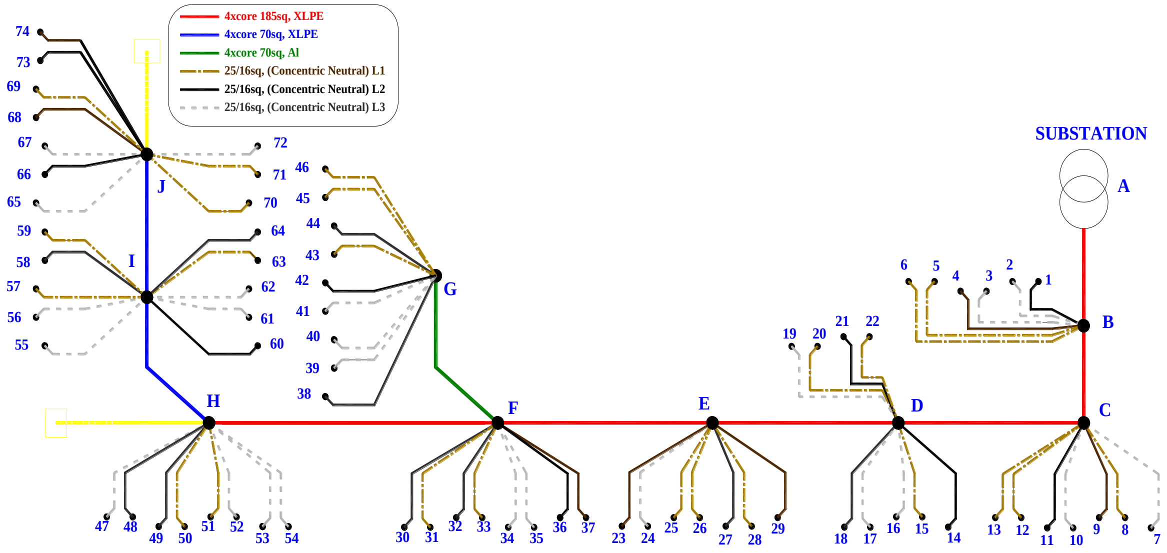


Figure 3.5 Urban distribution network with 74 consumers (Dublin, Ireland)

3.8 Data Set

The sensitivity study of the presented algorithm is performed using two separate data set. Dataset 1 has an individual power consumption of different devices (12 devices) in the domestic environment with a resolution of 1sec [158](DRED Data Set). The dataset is processed to form instances of operation for each 15 minutes time interval. Further, a residential load data and consumer profile data (dataset 2) are obtained from the household electricity survey conducted by Department of Energy & Climate Change, UK [159]. The data has a resolution of 10 minutes and contains the power consumption profile for each household devices as well. The data set also consist of different consumer profile categories and the corresponding consumptions. The extracted data is processed to obtain the instances of operation and the rating of device is considered as the maximum power consumed. The data set is used for evaluating the sensitivity of the algorithm towards different types of consumers. Dataset 1 has only device level energy consumption recorded from single consumer. Whereas dataset 2 has averaged consumer energy consumption profiles of consumers of different socio-demographic category. The different consumers in dataset 2 is classified based on, the number of people living, type of house, and existence of children. More details on the data are given in the following individual case studies.

3.9 Case Studies on Residential Domestic Network

To evaluate the performance of the proposed DR algorithm 2 different cases are evaluated. The case 1 is evaluated based on the performance of the algorithm towards managing loads depending on the engagement plan of the consumer. Whereas, in case 2, the sensitivity is evaluated against the diversity of consumers with different socio-demographic profiles.

Case 1: Performance evaluation of C-MILP-DR towards the consumer engagement plan

The C-MILP-DR algorithm (Section3.4) along with the proposed engagement plans (Section 3.3) is first tested on the 74 consumer urban distribution network (Figure 3.5). The objective is to characterise the performance of C-MILP-DR towards the engagement plans and to the dynamic consumer inconvenience. Hence, same data set (Dataset 1) is repeated for 74 domestic houses which would then serve same load. In effect, the demand profile for each individual consumer for the day is same. This would provide an accurate view of sensitivity of the algorithm towards the consumer inconvenience (and Engagement plan) which is the only varying factor. The 74 consumers are distributed to the proposed four engagement plans and their associated range of tolerable inconvenience value (α) is given in Table 3.2. The inconvenience value in a practical case needs to be calculated based on the maximum available controllable (dispatchable) load of the consumer. However, this study would begin with a set of random inconvenience value as all consumers are assumed to have same load profiles and demand profiles.

Table 3.2: Distribution of consumers based on engagement plans

Consumer Engagement Plans	**Inconvenience (α) Range**	**Percentage of Consumers**
Super Green Savvy	[0.2 – 0.5)	30%
Green Savvy	[0.5 – 0.7)	27%
Green aware	[0.7 – 1)	35%
Reluctant	1	8%

To begin with, the DR program is expecting a reduction request from the operator at any given time for which a random reduction request was generated. Stage 1 of the program dictates the individual reduction demanded from each consumer based on the inconvenience value. The inconvenience level 'α' of the consumers are initiated as per their engagement plans and later updated. This stage also calculates the total demand in the network and checks the feasibility of the demand reduction request. For instance, if the overall demand reduction request is more than 50% of the total demand, the algorithm fails to find an optimal solution and thus would return an infeasibility error. This limit is influenced by the total load, number of consumers, demand of each consumer, the engagement plan, and the amount of dispatchable load (given in equation 3.10). Hence, this limit is variable depending on the scenario. The input to the second part of DR optimisation is the load reduction request for individual consumers generated from first stage.

Stage 2 generates device operation schedule. This optimises the device operation in the house based on the inconvenience level (β) defined for each device. This inconvenience parameter is for each device whereas the engagement plan is on over all inconvenience relating to per kW load change. This inconvenience level (β) can be defined by the consumers for their device separately. Also, it must be acknowledged that individual device level inconvenience may be different for each consumer. However, in the presented research, this value is assumed based on a general idea about the device and is kept same for all consumers. This eliminates the any possibility of skewing of results due to difference in β for different consumers. Yet, inclusion of β is critical to showcase the ability of algorithm to distribute demand reduction correlating consumer convenience. As certain devices are categorised as non-dispatchable devices, they would not be altered during the optimisation. The list of devices considered in a domestic environment are given in Table 3.3 along with their corresponding assumed inconvenience factor. The list is in accordance with the domestic load dataset 1.

From the Table 3.3, the inconvenience factor is 1 (highest inconvenience) for non-dispatchable devices and different values ($0 \leq \beta \leq 1$) for dispatchable devices; representing the inconvenience of the consumer if the device is not allowed to operate during a demand for the same.

Table 3.3: Device List, their Inconvenience and Ratings

	Device	**Inconvenience (β)**	**Ratings (W)**
1	Television	0.9	200
2	Fan	0.2	100
3	Fridge	0.4	150
4	Laptop Computer	0.45	45
5	Electric Heating Element	0.1	2000
6	Oven	0.45	1500
7	Computer	1	200
8	Washing Machine	0.2	800
9	Microwave	0.75	600
10	Toaster	0.8	600
11	Sockets	0.35	50
12	Cooker	1	1700

The simulation is performed for every 15 minutes forming 96 intervals representing 24-hour period of a day. The demand for each period is updated using previous allowed load and the new requirement. However, the major focus is set forth for algorithms capability to allocate consumer load reduction between consumers while causing minimal impact to consumer convenience. Hence, if the demanded load reduction is not achievable the algorithm steps down (relax the constraint) the demand reduction to a lower value and keeps on doing so until a feasible solution is obtained. Further, if a device is denied operation, it is recorded and would be requested back to operate by the algorithm during the off-peak time which forms the time shifting of device operation. This ensures the consumer requirements are met during the day. However, certain devices like heater and fridge are not brought back for total intervals for which it was denied operation as they are able to retain its stable operation for 2-3 intervals without compromising its performance. This in effect reduces the load consumption improving the all-around energy utilisation.

The DR is performed only during the peak period which is isolated to be Morning (7AM to 9:30AM), mid-day (12PM to 01:30PM) and evening (6PM to 9:30PM). These timings are selected based on intuition and can be altered whenever required, but they represent peak demand periods with respect to a general demand profile considered.

The aggregated load and load after DR are presented in the Table 3.4 and is plotted in Figure 3.6. As stated before, all 74 consumers are having same load demand which would give a better understanding of DR programs sensitivity towards the consumer engagement plans. From the Figure 3.6, it can be observed that during the off-peak intervals the total load is increased than the actual demand depicting the load rebound which makes sure that all the necessary loads of the consumer are time shifted and not deprived. From Table 3.4, it can be observed that the MILP-DR without considering consumer inconvenience was programmed to reduce load as requested and was able to reduce 8.4% of over-all load for the day compared to 7% when consumer inconvenience was considered. However, as observed in various literature [138], the success of DR greatly depends on consumer acceptance, which directly correlates to the load rejection/deprivation. The presented algorithm not only considers the load reduction at peak times but also accounts for consumer inconvenience or in-effect consumer comfort. The necessary loads which are turned off during the peak are also returned which enhances the consumer conviction towards the program.

Table 3.4: Total Load and DR Load with and without C-MILP-DR for a day

Method **Load 74 House for a Day**	**MILP-DR with ‘α’**	**MILP-DR not considering ‘α’**
Total load demand	5090kWh	5090kWh
Total Load Allowed using DR	4871kWh	4797kWh
Load Reduction during DR	356kWh	431kWh
Load reduction after time shifting Loads	219kWh	293kWh

From Table 3.4, it can be observed that the total reduction for the day in this scenario was only 7%. However, during operation the algorithm was able to reduce up to 25% of total load for an interval (at 9:15 PM). As discussed earlier this value depends greatly on number of factors. The reduction achieved while considering consumer inconvenience is lower, yet the algorithm can attract more consumers, which would increase consumer participation leading to higher reduction possibilities.

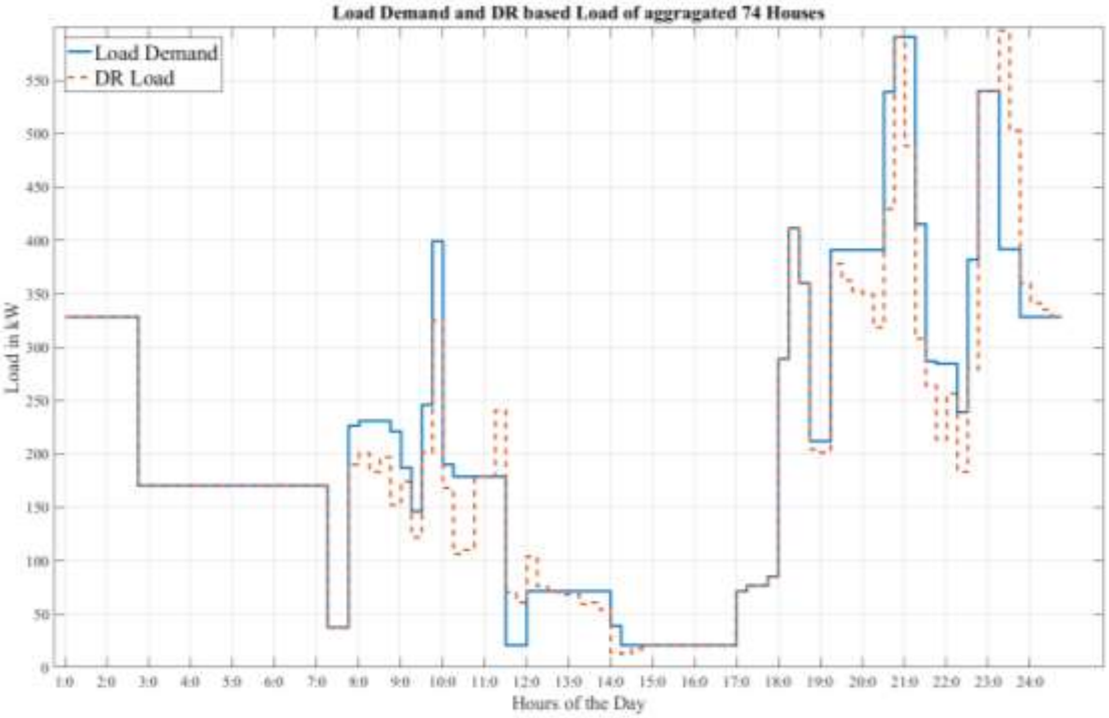


Figure 3.6: Total Load and DR load change for 74 consumer aggregate

Four representative consumers engaged in four different consumer engagement plans are chosen as examples. The Figure 3.7 represents a Super Green Savvy consumer according to Section 3.3 and is willing to endeavour in high amount of load reduction if demanded, and hence starts with a very low value of α, indicating high tolerance to load reduction (tolerance $\alpha \in [0,1]$). Essentially the lowest value α can have is 0, however considering a practical point of view, this works assumes the lowest value possible to be 0.2. This was also supported by testing of algorithm with various value and 0.2 provided a better result. Observing the time interval from 8:00AM to 11:00AM, the value of α for consumer in Figure 3.7 who choose Super Green Savvy engagement plan increases for the next interval when they participate in the load reduction in the current interval. When consumer is not participating in the reduction the value of α decreases in fixed step for each iteration until it reaches the default value set by the engagement plan. Compared to consumer in Figure 3.7 in the same interval (8AM to 11 AM), consumer in Figure 3.8 who has chosen a Green Savvy engagement plan would have lower tolerance to load change and would participate less in load reduction. Similarly, consumer (Figure 3.9) using Green aware engagement plan would participate less than Green Savvy consumer and would cause lesser load reduction. Figure 3.10 represents a consumer who is not interested to participate in any sort of program in the set of 74 consumers. Form these figures the capability of the algorithm to choose consumers based on their engagement plan can be observed. The MILP-DR can thus introduce fairness between consumers engaged with different engagement plans and also establish fairness to consumers by not choosing consumers with low α repeatedly. The algorithm can be further modified in the similar way to include fairness between different consumer devices.

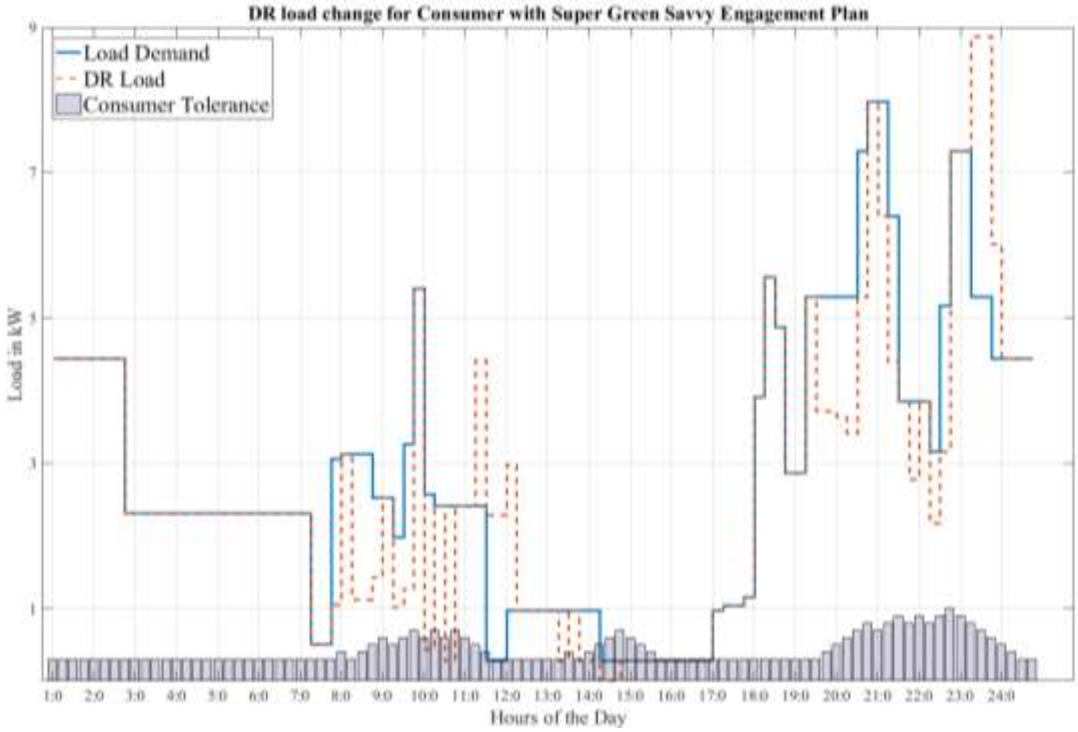


Figure 3.7: MILP-DR for consumer with Super Green Savvy engagement plans

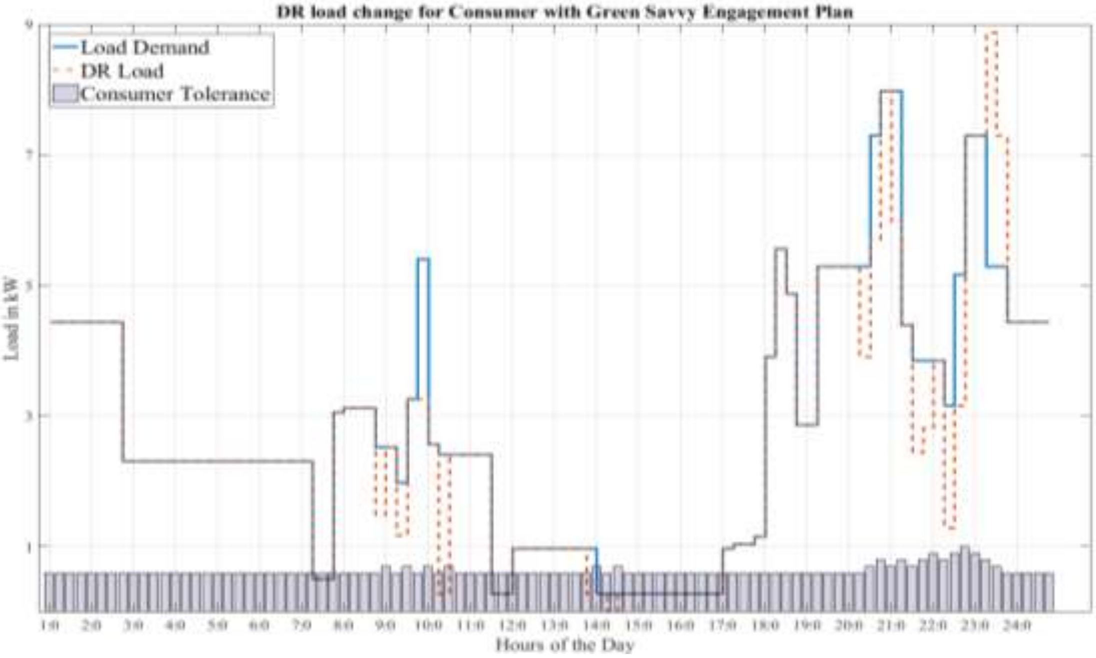


Figure 3.8: MILP-DR for consumer with Green Savy engagement plan

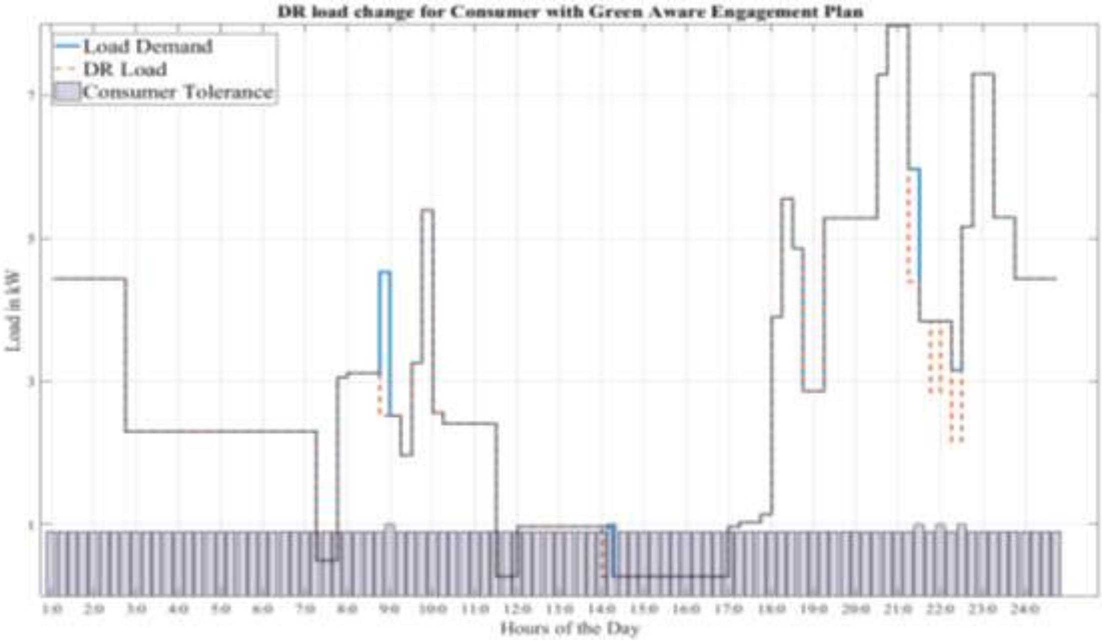


Figure 3.9: MILP-DR for consumer with Green Aware engagement plan

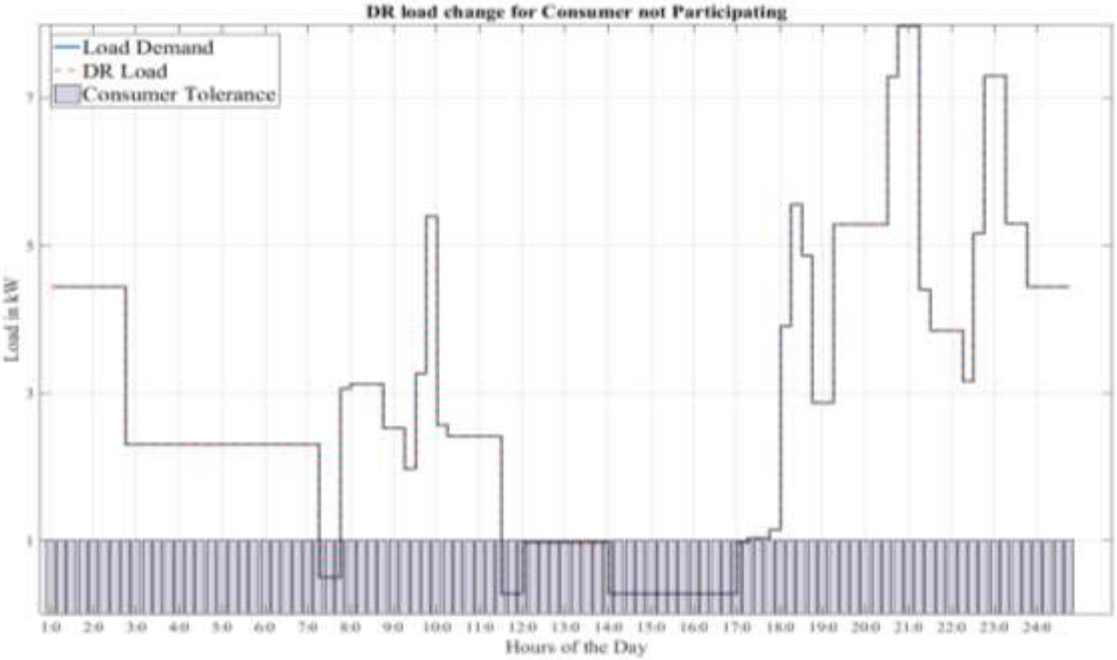


Figure 3.10: MILP-DR for consumer with Reluctant engagement plan

Case 2: Performance evaluation of C-MILP-DR towards the diversity of consumers with different socio demographic profiles

In the previous scenario, while interpreting the results, it is evident that, the proposed C-MILP-DR is sensitive towards the change in consumer inconvenience value (engagement plan) and hence would always try to choose consumers with minimum inconvenience. However, as for the common understanding from the literature in section 2.12, the amount of load rescheduling would depend on various factors like, type house, number of people living, season, day of week, and number of children. It would also depend on the demographics of an area. Hence, to propose a robust DR program which can be applied under all socio-demographics scenarios, we needed to evaluate the performance of proposed algorithm (C-MILP-DR) with different consumer profiles representing different socio-demographics identifiers (Data set 2). With different consumer categories, the power consumption pattern (appliance usage pattern) is different and can impact the capability of DR in load reduction (while minimising consumer inconvenience). The impact is assessed in terms of the load reduction accommodated by each class of consumers while engaged in different engagement plans as described in the section 3.3.

The socio-demographic classification utilised in this work is provided below along with the parameters used in the classification (Table 3.5). Each of these categories represent a change in electricity consumption pattern. The representative sets of profiles corresponding to Table 3.5 are illustrated in Figure 3.11. The same household on a working day and holiday would display different consumption patterns as illustrated in Figure 3.12. The difference between the working day and holiday load consumption profile is its spread. On a holiday, the loads are comparatively spread throughout the day, however, in a working day it has high demand during peak time.

Table 3.5.Representative consumer profiles

Consumer Profile	**House type**	**Number of People**	**Children**	**Type of Day**
Profile 1	Detached	2	No	Workday
Profile 2	Semi Detached	3	Yes	Workday
Profile 3	Semi Detached	4	No	Workday
Profile 4	Semi Detached	4	No	holiday
Profile 5	Flat	2	No	Workday
Profile 6	Flat	2	No	Holiday
Profile 7	Terrace	4	yes	Workday
Profile 8	Terrace	4	yes	Holiday

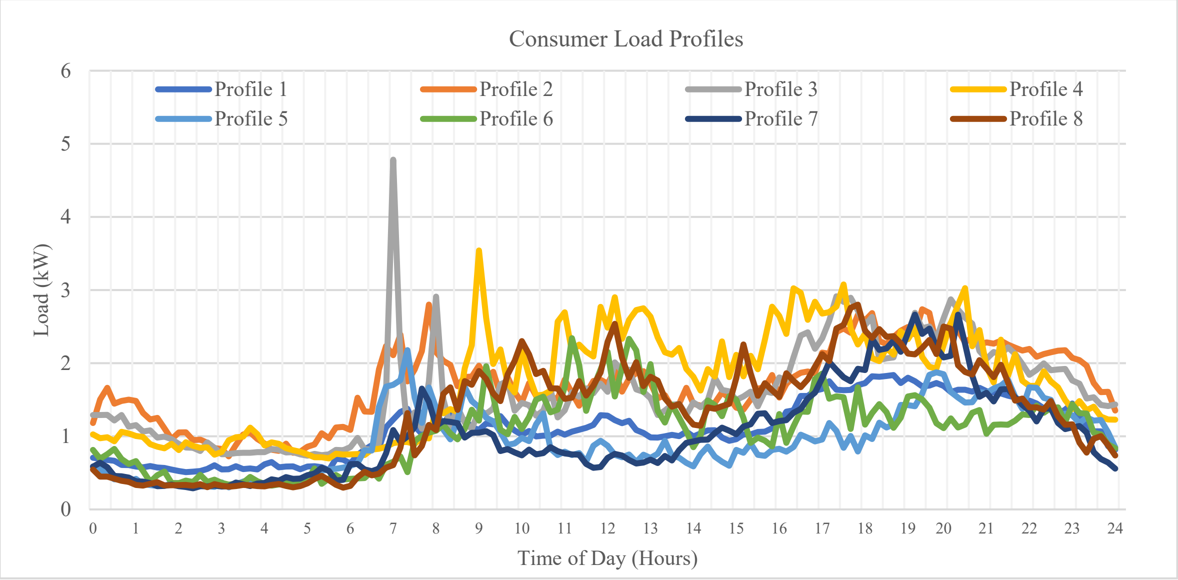


Figure 3.11. Load profiles of 8 categories of consumers

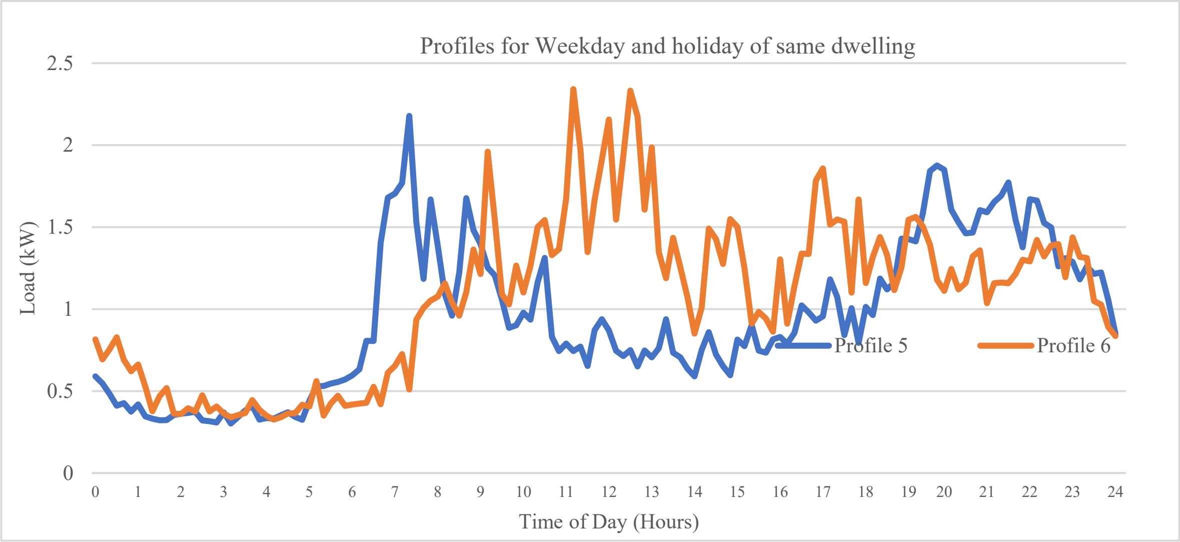


Figure 3.12. Load profiles for weekday and holiday for a flat dwelling

The loads considered in the domestic environment in the present case and their corresponding inconvenience value are provided in Table 3.6. The values of device level inconveniences is populated based on the understanding of a domestic environment and is exemplar. Higher the value of β, higher is the inconvenience if it is refused operation. The algorithm is implemented in the 74 consumer suburban LVDN utilised in the previous section (Figure 3.5) and consumers are categorised into these 8 profiles while assigned to different engagement plans corresponding to Section 3.3 and Table 3.2.

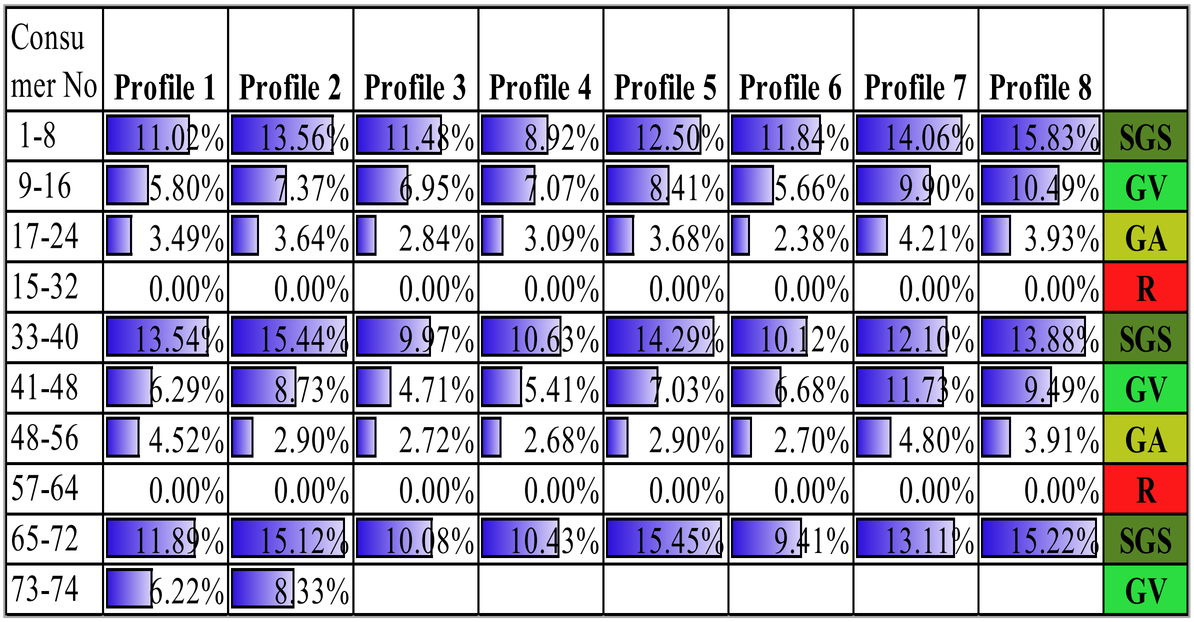
Table 3.6. Domestic loads and their inconvenience

Domestic Loads	**Inconvenience (β)**
Fridge	0.2
Cooker	0.8
Lighting	0.8
TV	0.8
ICT	1
Dishwasher	0.35
Water heating	0.2
Heating	0.35
Power Plug 1	0.5
Power Plug 2	0.5
Showers	1
Washing	0.25
Drying	0.2

The C-MILP-DR is initiated when a reduction request is provided. In this study peak periods are assumed and corresponding to the peak period, a random reduction request is generated. The assumed peak periods are (7AM to 9:30AM), mid-day (12PM to 01:30PM) and evening (6PM to 9:30PM). These timings have been selected based on intuition and can be altered whenever required, but they represent peak demand periods in respect to a general demand profile under consideration. The simulation is performed for every 10 minutes w.r.t the resolution of data constituting 144 intervals for a day. The consumers with different profiles are distributed into the different engagement plans. The amount of reduction contributed by each consumer is based on the engagement plan, thus providing consumer choices to participate according to their convenience rather than committing fully to load reduction. Similar to previous case, the first stage of algorithm (Figure 3.4) generates individual house load reduction request which would be the input for the second stage. The second stage of the MILP-DR produces a device operating schedule based on the device operation demand. All other constraints on the algorithm are kept same as the previous scenario.

The 74 consumers representing 8 different consumer categories and their contribution on overall load reduction is presented as percentages in Table 3.7. The table is colour coded for different engagement plans. The primary observations are, the load reduction contribution of each consumer is based on the engagement plan chosen. The Reluctant class of consumer isn't contributing any reduction as expected. The green aware category is least participating while the super green savvy is the largest participant Figure 3.13, represents the load profile and corresponding DR for a consumer with super green savvy engagement plan. The variation of their tolerance while engaging in the DR shows the capability of algorithm to account for fairness in consumers participating which would regulate the contribution of a consumer through time. This along with efficient communication would be an attractive feature of the program compelling consumers to utilise the benefits of DR.

Table 3.7. Percentage load reduction for consumers with different load profiles and different engagement plans



Consumer No	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7	Profile 8	
1-8	11.02%	13.56%	11.48%	8.92%	12.50%	11.84%	14.06%	15.83%	SGS
9-16	5.80%	7.37%	6.95%	7.07%	8.41%	5.66%	9.90%	10.49%	GV
17-24	3.49%	3.64%	2.84%	3.09%	3.68%	2.38%	4.21%	3.93%	GA
15-32	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	R
33-40	13.54%	15.44%	9.97%	10.63%	14.29%	10.12%	12.10%	13.88%	SGS
41-48	6.29%	8.73%	4.71%	5.41%	7.03%	6.68%	11.73%	9.49%	GV
48-56	4.52%	2.90%	2.72%	2.68%	2.90%	2.70%	4.80%	3.91%	GA
57-64	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	R
65-72	11.89%	15.12%	10.08%	10.43%	15.45%	9.41%	13.11%	15.22%	SGS
73-74	6.22%	8.33%							GV

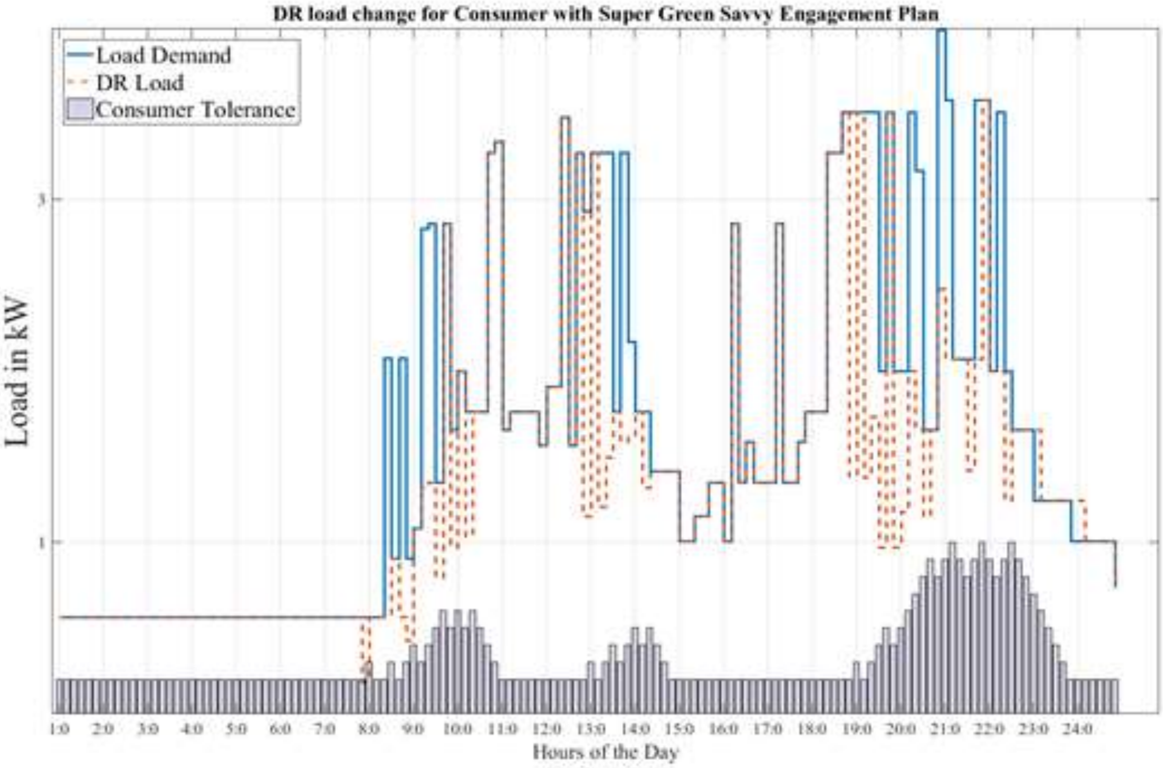


Figure 3.13. DR load change for consumer with Super Green Savvy engagement plan

Considering the objective to analyse the impact of social profiling on performance of DR, observations from Table 3.8 show that with higher number of residents results (Profile 3 and Profile 4) has a minor impact on DR as the shiftable loads generally are not allocated based on the number of occupants. With increasing numbers of people (occupants), an increase in the overall load in the house is evident and, in this regard, this is indicative of critical loads that are associated to people. The shiftable loads such as, the washing machine, dishwasher, and heating. remains the same. Analysis for a longer period (week), could provide additional usage of non-critical load that may be shiftable. However, in a day-to-day DR, increase in number of occupants may not be very useful right away. Further, children appear to increase the total loads as well as shiftable loads (Profile 7, and Profile 8) when compared to other profile with same number of people (Profile 3 and Profile 4) The assumption for such an inference is in respect to increasing cleaning and maintenance requirements being associated with children present in the house, which give a clear implication of dependency of performance of DR with respect to social status. Another interesting observation from Figure 3.12 and Table 3.8 is that, even though the load for same social profiles is relatively higher for holiday periods compared to the workday, the DR load reduction achieved is higher on a workday compared to a holiday. The assumption for such an observation is that the load is spread along the day than concentrated at the peak time. In such instances, the house has a lower load demand (in peaks period) in holiday periods compared to workdays. Thus, proposed DR algorithm can respond to load profiles and does not force a reduction always. Which would promote the acceptability of the DR program.

Figure 3.14, shows the aggregated load demand and the associated load reduction. The total overall reduction in load achieved for the day is 6.6%. However, instantaneous reduction has peak reduction of up to 36% at certain times, with peak rebound of 12%. The amount of reduction possible, as discussed earlier, can depend on various factors. A careful modelling, along with efficient consumer profiling, can enable an aggregator to micromanage the demand in the network while improving the economics related and improving the utilization of electrical devices.

Table 3.8 Load reduction in kWh for consumers of different category based on engagement plans

Consumer No	**Profile 1**	**Profile 2**	**Profile 3**	**Profile 4**	**Profile 5**	**Profile 6**	**Profile 7**	**Profile 8**	
1-8	3.82	5.16	3.46	2.76	4.58	4.55	4.29	6.03	**SGS**
9-16	2.01	2.62	2.12	2.01	2.89	2.05	2.96	3.96	**GV**
17-24	1.22	1.28	0.82	0.88	1.25	0.86	1.39	1.51	**GA**
15-32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**R**
33-40	4.96	5.41	2.90	3.03	4.88	3.66	3.57	5.24	**SGS**
41-48	2.12	3.06	1.37	1.63	2.57	2.42	3.86	3.62	**GV**
48-56	1.72	1.05	0.79	0.76	0.99	0.98	1.42	1.48	**GA**
57-64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**R**
65-72	4.01	5.29	2.92	2.97	5.27	3.41	3.87	5.75	**SGS**
73-74	2.10	2.92	0.00	0.00	0.00	0.00	0.00	0.00	**GV**

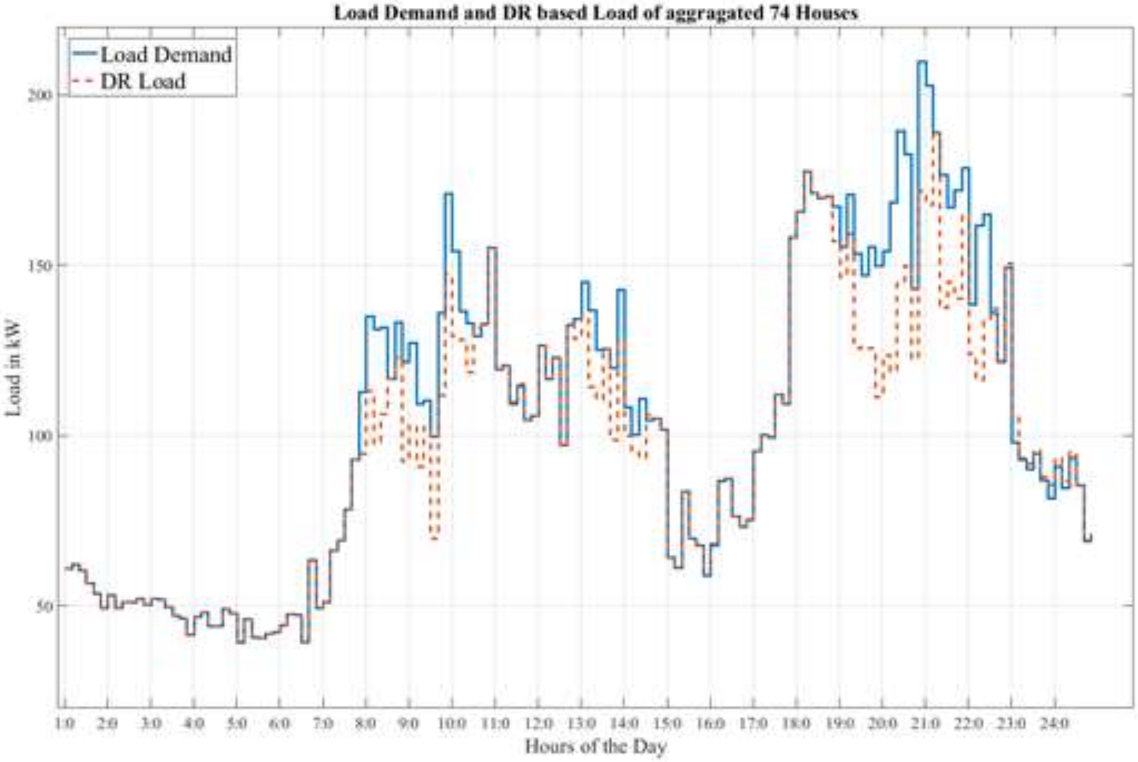


Figure 3.14: Total load and DR load of 74 consumers

3.10 Conclusion

By utilising the non-deterministic characteristics of fuzzy control algorithms, a DR controller is implemented to account for customer comfort and hence schedules the temperature control equipment in conjunction with DR. The correlation between consumer inconvenience and load reduction is utilised to propose a set of consumer engagement plan. The C-MILP-DR model presented in this work and its associated performance investigation (attempting to enhance the acceptability of DR to consumers), has highlighted its capability in considering the consumer load, inconvenience, and social parameters. The DR was effectively able to distribute the load reduction based on the engagement plans allocated to each consumer. The C-MILP-DR was also able to establish fairness between the consumers chosen to load reduction without penalising them for being available. The capability of the algorithm to shift the load to an off-peak period, was also observed along with its contribution to improving the energy utilization. The social profile-based data was used to account for consumer demand. The observations suggest that the DR is not very sensitive to the number of people in the house, rather it has higher co-relation to the size and type of house. Further, it also shows that the presence of children in the house increases the size of shiftable load enabling the DR to achieve higher reduction. The DR has higher operability when the load profile has higher concentration during the peak time rather than a more spread-out load profile. The proposed algorithm with better consumer profiling combined with a fast and efficient communication channel, and consumer notification interface will have a higher conviction for consumers to participate in the energy management program like DR.

A well modelled consumer-friendly DR program can have further applications than just peak load management, for example, can function as virtual power plant. However, its application on providing ancillary service to manage power quality of the network has not been explored yet in literature. The next chapter derives a relationship between consumer load and PQ. It also develops a set of PQ constraints to incorporate to the C-DR.

Chapter 4 Ancillary Service by C-DR – Power Quality

4.1 Overview

The issues concerning the quality or condition of the power supply in an electrical network are generally termed as power quality (PQ) issues. These include harmonics related issues, undervoltage and over voltage issues, flicker, resonance, and frequency related problems. Even though these issues are considered as network based, they are induced mainly by the connected loads; either directly or indirectly. Thus, managing the operation of these connected electrical loads are a reasonable solution technique to address these issues. This chapter intends to establish two facts: the impact of power quality problems and load - power quality relation. As this thesis contemplates the formulation of a consumer-friendly DR technique, it is advantageous to explore additional capabilities of DR to increase potential benefit to all stakeholders involved. With PQ issues contributed by load, a load management program like DR can manage the PQ in the network by changing operation of loads that aid secure operation of the network. This requires carefully modelling and integration of such PQ constraints to the DR program. Two main power quality issues are considered: harmonic, and voltage PQ. The chapter initially dives into a harmonic analysis to quantify the impact of harmonics instead of only depending on THD percentage. This analysis methodology is fully explored in a domestic environment as well as on a network level. Later, a voltage quality issue due to high loading and high DG penetration is contextualised. The chapter will establish a means to incorporate these PQ issues as a driving constraint for the PQ constraint DR program developed in next chapter.

The chapter initially details an analysis on harmonics in the domestic environment using domestic loads. This is later extrapolated at LVDN level. Further, a harmonic heating methodology is developed and applied over a representative urban distribution network. Later part of chapter presents a relationship between voltage and power and their application on under and over voltage management. The methodological structure of the chapter is given in Figure 4.1

Assumptions

The assumptions considered while formulating, executing, and analysing the work proposed in this chapter are:

1. The harmonic phase angle is ignored in most of the cases which implies that harmonic phase cancellation is ignored. This provides the most severe accumulation harmonic current in the context.
2. The continuous operation of the system is not considered, instead, instantaneous operational analysis is performed.

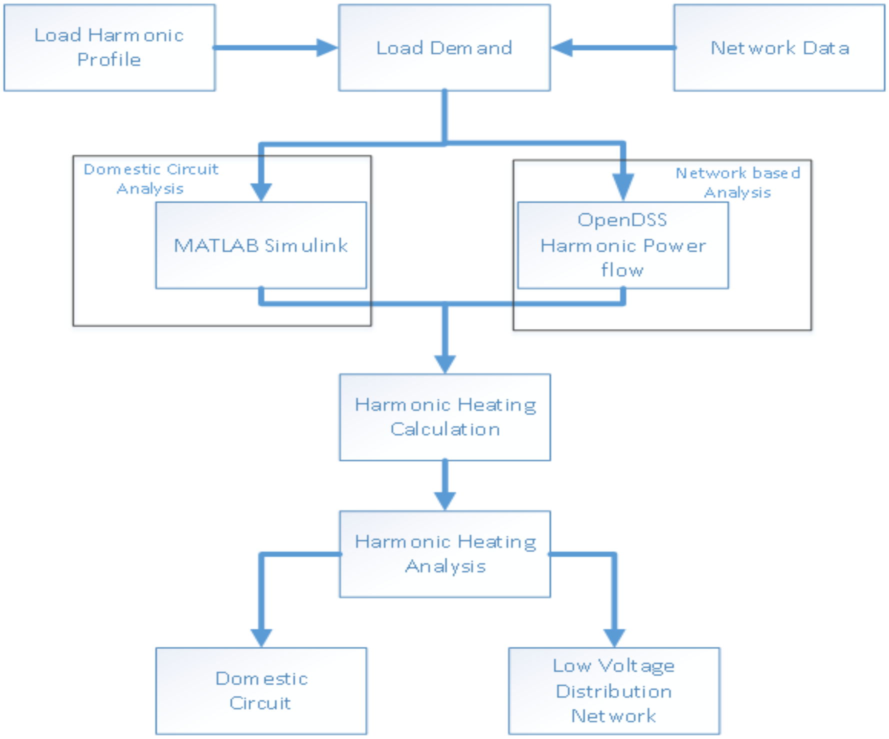


Figure 4.1 Chapter structure

4.2 Harmonic Analysis

The power quality in a distribution network starts at the load. The characteristics of power required by the loads becomes the characteristics of power supplied by the source. The first step in analysing harmonics in a distribution network is to quantify the harmonics in a domestic environment. A household network cabling system is considered in accordance with the British wiring standards, BS7671 (IEE/BSI. 2018)[160]. Power is distributed through radial circuits, with cables of different current carrying capacities (I_z). In a domestic context, lighting circuits are facilitated through a 1.5 mm^2 (I_z ≈16A capacity) wiring system, while general services (socket) circuits are facilitated through a 2.5 mm^2 wiring system (Iz ≈ 26A capacity). The daily power consumption of lighting/general service load may vary depending on various factors (including occupancy, demographics, and socio-economic factors). In this study, the power quality analysis of the appliances during their operation mode is considered and hence does not rely on the manufacture pre-specified values of power quality. The simulation of the domestic environment is carried out in MATLAB Simulink environment. The linear and non-linear harmonic load models have been developed using controlled current sources in Simulink power system (SPS), based on available harmonic information (% of THD, harmonic current spectrum) of domestic load data. The data was collected based on measurements from appliances in a residential building [161]. In most readings considered, the magnitude of the harmonic current order above 21st order is found to be less than 5% of the fundamental. The measurements were performed using an instrument power quality analyser C.A.8230 Ampflex, from Chauvin Arnoux [162]. The setup structure is given in Figure 4.2. The measured power consumption values obtained from the power analyser is in Table 4.1. The domestic loads cumulatively had a THD% of 17.7% while all (8.6kW) load working simultaneously. The power required by the dynamic devices vary depending on the operation.

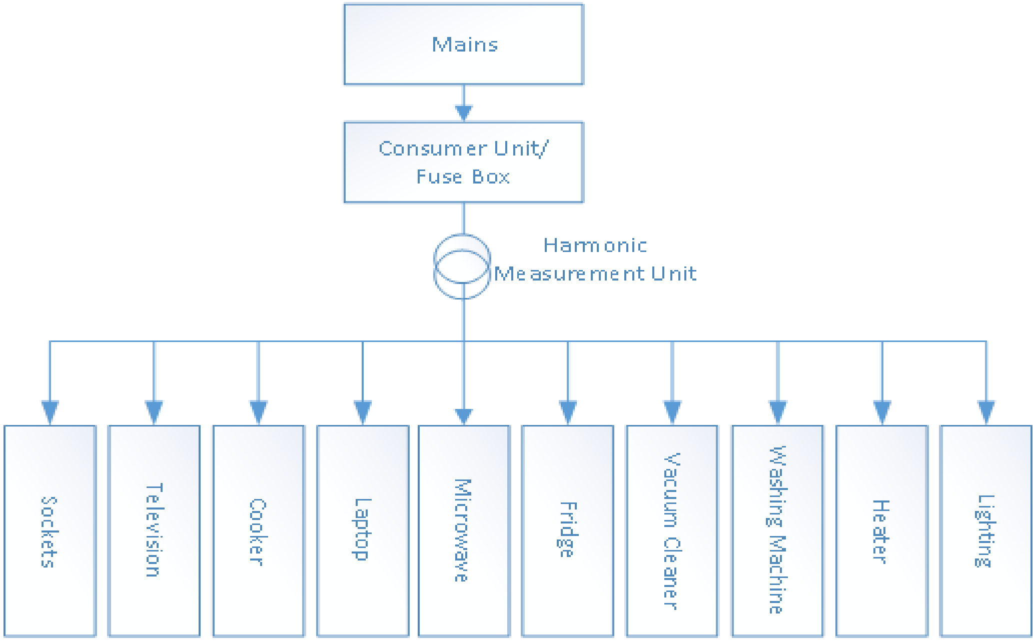


Figure 4.2 Domestic power circuit diagram

Table 4.1: Power consumption of the electrical appliances measured in a building in Dublin (Measured)

Electrical Appliances		Active Power (P) (W)	Reactive Power (Q) (VAR)	Harmonic Power (H) (VAR)	Apparent Power (S) (VA)
Non-Linear Harmonic Load					
Static	Compact Fluorescent Lamp (CFL)	14	5.5	19	25
	Microwave oven	1250	220	300	1304
	Refrigerator	110	120	15	163
Dynamic	Washing Machine	600 - 2000	410	200	1983
	Vacuum Cleaner	335 - 1100	100 – 500	170 - 510	730 -1120
	Laptop	55-110	38	190	212
Linear Load					
Static	Heater (bedroom)	2000	0	0	0
	Electric Cooker (Oven)	1200	0	0	0

The worst-case scenarios in the context of harmonic magnitude in a domestic environment occurs when multiple harmonic loads are connected to a single sub circuit as the harmonics are generally cumulative in nature. Hence to understand this environment, various probable combinations of harmonic loads are combined to form different case studies. The impact of harmonics is analysed at the measuring point in Figure 4.2. A total of six harmonic loads were considered along with two linear heating loads forming 255 combinations. The details of these loads are given in Table 4.1. Exemplar cases are provided in Table 4.2 with their corresponding current total harmonic distortion (THDi) calculated. Where,

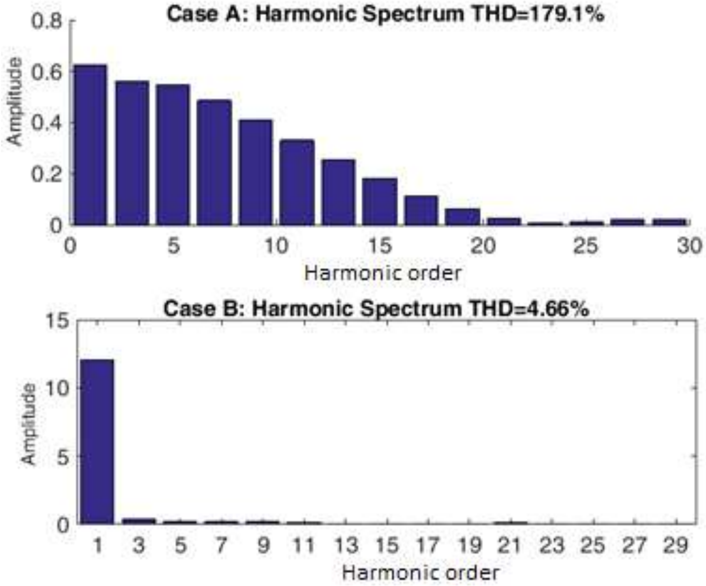
$$THD\,\% = \left[\frac{\sqrt{\sum_{i=2}^{n}(I_n^2)}}{I_1}\right] X\, 100 \qquad 4.1$$

Where, I_n is the harmonic current and I_1 is the fundamental current. The linear loads (heater and cooker) are turned OFF for the results presented in Table 4.2 as the effect of non-linear loads are being evaluated. Harmonics are cumulative in nature and adds up at PCC. The maximum load in the house was 8.6 kW when all loads operate simultaneously. This gave a total THD % of 17%. Now, to understand the worst possible scenario in a domestic environment, five combinations that accumulated the highest THD percentage are considered and presented in Table 4.2. The level of THD% is used to sort the cases. Each case has different combination of loads and in effect contributes to the difference in aggregate THD %.

Table 4.2: Harmonic devices different combinations and their resultant THD percentage

	Light	**Microwave Oven**	**Fridge**	**Vacuum Cleaner**	**Washing Machine**	**Laptop**	**Current THD (%)**
Ratings (in Watt)	40	1350	160	1400	1200	250	
CASE 1	ON	ON	OFF	OFF	ON	ON	44.64
CASE 2	ON	ON	ON	OFF	ON	ON	42.12
CASE 3	ON	ON	ON	OFF	ON	OFF	41.31
CASE 4	OFF	ON	ON	OFF	ON	ON	40.73
CASE 5	OFF	ON	ON	OFF	ON	OFF	39.74

The existing THD of most of the cases were relatively very high when compared with IEC and IEEE 519 6100-3 standards. An interesting observation while performing different simulation cases were with the combination of harmonic load and resistive load (linear load). Figure 4.3 illustrates that, when the harmonic profile associated with CFL (Case A), and CFL and resistive load (Case B) is considered, THD% is not always the optimal measure of the severity of harmonic content in the system. This emphasises the fact that THD% does not always help a system operator to even understand the harmonic pollution in a system. From Equation 4.1, the THD is a ratio of the fundamental to the vector sum of harmonic components. When a purely resistive load like a heater is connected to a circuit containing harmonic load, the fundamental current component increases without change in the harmonic current content. Now, THD may appear to be lower; even though the harmonic profile did not change. Hence the harmonic pollution will still be observed in the system, which is evident from the harmonic spectra illustrated in Case A and Case B of Figure 4.3. This scenario could be intolerable for many sensitive consumer equipment and could eventually lead to premature failure of such devices. This is because sensitive nature of consumer equipment containing electronic circuitry could form a lower impedance in the context of certain harmonic frequencies.


Case A: Harmonic Spectrum THD=179.1%

Case B: Harmonic Spectrum THD=4.66%

Figure 4.3 Harmonic spectrum with and without resistive load

With these observations, two things are now evident;

1. Harmonics in the domestic environment depend on the combination of load operations and can be higher than allowed values by the standards/regulations.
2. The impact of harmonics cannot be exactly represented by only THD value and in that regard, requires a better quantification technique.

The next section develops a harmonic heating quantification method which can indicate the severity of harmonics in a circuit using thermal impact of harmonics on cable system.

4.3 Losses Due to Harmonics

In any conductor when sinusoidal currents are introduced, the geometry associated with the conductors introduces a complex electromagnetics problem. The sinusoidal varying magnetic flux induces a time varying magnetic flux density which induces eddy currents and the skin effect. With higher frequencies this results in higher losses relatively, in comparison to a DC context. The ratio of AC to DC resistance is the parameter that varies for each harmonic frequency. The inductive element of the cable is not considered here as the associated value is sufficiently small and it does not cause an active power loss contribution to heat. However, the same is not true if the voltage waveform is considered. The difference in resistances sheds light on the difference in power losses induced [76][33]. The ratio of AC to DC resistance is described generally by [76],

$$\frac{R_{AC}}{R_{DC}} = \frac{\int \frac{(i(x,y))^2}{\sigma} ds}{I^2 r_{DC}} \tag{4.2}$$

The integral relates to the cross-sectional area of all conductors in the system (cognisant of conductivity, σ). The i(x,y) is the RMS current density which is a function of position ((x,y) is position). The inclusion of i(x,y) helps to account for the conductor geometry and how it affects current propagation. I represents the RMS current flowing through the conductor irrespective of the (geometric) position. The effective resistance ratio is the weighted sum of resistance ratios calculated at each frequency, as provided in [76]

$$\left(\frac{r_{AC}}{r_{DC}}\right)_{eff} = \sum_{n=1}^{\infty} \gamma_n^2 \left(\frac{r_{AC}}{r_{DC}}\right)_n \tag{4.3}$$

where γ_n is the ratio of nth harmonic current to the magnitude of total harmonic current. Considering only non-sinusoidal load current, and in consideration of a Fourier transform application, multiples of fundamental frequency, which themselves are sinusoidal, can be determined. The total heating caused by each component and in the context of a low voltage distribution network, the ratio of AC/DC resistance is approximately equal to 1.02 [163]. The total power loss can be obtained as follows:

$$P_L = I^2 r_{AC} \tag{4.4}$$

$$P_L = 1.02. r_{DC}. I_1^2 (1 + THD_i^2) \qquad 4.5$$

where I is the total current consumed by the harmonic load. Including the THDi (i.e., the total harmonic distortion pertaining to the current) factor in the equation to quantify the harmonics as

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \qquad 4.6$$

where, I_1 is the fundamental current, I_n is the harmonic current component for each harmonic order and n is the order of harmonics. Power loss without harmonics or AC resistance considered is:

$$P_{L\_normal} = I^2 r_{DC} \qquad 4.7$$

The equation 4.5 would give the loss produced in the conductor considering the impact of harmonics and would be higher with higher harmonic content. The equation 4.5 also takes account of fundamental current and the THD together in the equation. The difference between the loss calculated by equation 4.5 and equation 4.7 is interesting to observe with increasing harmonics. It offers a comparison of the mismatch between the normal power loss and the loss incurred through THD (considering harmonics) to understand the harmonic rating factor that may be required for derating the sub-circuit cable. The quadratic relationship between the power loss and THD that will incur an inconceivable deviation in heating with higher harmonics content is apparent from equation 4.5.

With $THDi = 0$,

$$P_L \approx P_{L\_normal}$$

And when $THDi = 100$, under assumption $i^2 \approx I^2$

$$P_L \approx 2.04 \times P_{L\_normal}$$

As the harmonic pollution increases in an electrical network, the heating in the cable increases and may eventually be higher than the rated value for a particular conductor. This situation may not be recognised by standard protection equipment as it relies on the root mean square (RMS) value of current. However, modern protection circuits with thermal overcurrent protection may detect if the increase in temperature is in the same circuit as of the protection unit. The temperature rise on the conductor due to the increased heat depends on various factors such as the installation method, ambient temperature, and rate of cooling. The modelling of temperature rise would be dependent on various dynamic factors and hence not considered here. Therefore, the relative error of loss (W) as effected (proportionally) by the temperature rise is the preferred consideration in this analysis.

4.4 Harmonic Heating Analysis: Domestic Network

In the same domestic network given in Figure 4.2, the harmonic heating calculation developed in the previous section can be applied. In the household network wiring, the main circuit, where the harmonic measuring unit is located, is considered for the thermal analysis. However, the methodology can also be applied to the sub circuit and to the cable of an extension cord through which multiple consumer devices may be simultaneously connected. Equation 4.7 calculates the loss without considering the harmonics and equation 4.5, loss taking harmonics into account.

Now considering the domestic wiring given in Figure 4.2, the loss in line connecting mains circuit is calculated using equation 4.5 and equation 4.7 respectively for different cases (combination of devices operating). The cases presented in the Table 4.2 is chosen to calculate the loss with and without harmonic consideration and is represented in Figure 4.4. The calculation presented is considering a 1-meter wire of 4 sq mm with maximum current carrying capacity of 20 A. The wire resistance is considered as 5 mΩ/m. The maximum rated power loss is 20W for the entire length of cable.

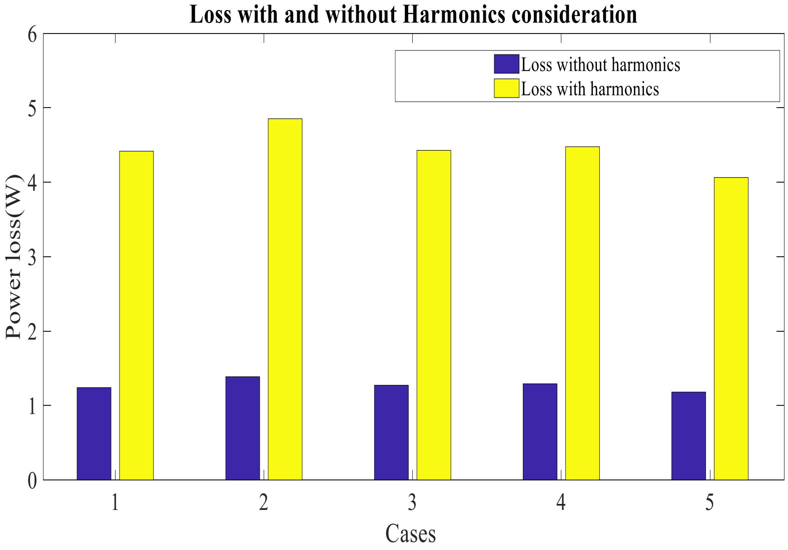


Figure 4.4: Loss with and without harmonic consideration

A large deviation is observed in each case between the loss calculated with and without harmonics shown in Figure 4.4. In most of the case, there is more than 200% increase in loss with case 2 having the highest of 270%. With rated current of 26A, the cable can have a maximum heating of 5 Watts/m. Even though, these values (Figure 4.4) are still within the maximum loss in the line. Yet, under a scenario where the system is operating at rated current with same levels of harmonics may severely deteriorate the cable and thus impacting its lifetime and performance or the worst case – fire hazard.

To calculate the loss incurred by harmonics in a LVDN, a harmonic power flow needs to be executed. This provides individual harmonic current for each cable which can later be utilised to compute harmonic loss. For this study OpenDSS toolbox with MATLAB COM interface is used to compute harmonic power flow.

4.5 Harmonic Power Flow: OpenDSS

OpenDSS is an open source electrical power system analysis software designed by the Electric Power Research Institute (EPRI), which can simulate the operation of balanced/unbalanced distribution network operation. The user-friendly tool is designed to operate as a stand-alone software as well as in-process COM interface with various scripting platforms like MATLAB, python, C#, R, and other languages. The software is designed to accommodate the commonly unbalanced distribution network operation and offers various types of analytical techniques by default. The software utilises a current injection technique for realising network components and hence facilitates almost all RMS steady state analysis (i.e., frequency domain). This feature enables the software to perform harmonics current flow/harmonic power flow analysis to facilitate harmonic analysis. The software can also perform fault study, Monte Carlo Fault study, Dynamic analysis, along with yearly and daily power flow analysis. The application of OpenDSS thus is restricted only by the modelling of a problem by user. The capability and credibility of the software is well acknowledged in the research domain with various publications in reputed journals. A well elaborated and resourceful documentation [164] is also published along with active discussion forum.

The formulation of an analysis methodology for the proposed research requires a robust but powerful tool to conduct harmonic current/power flow analysis that is sufficiently flexible to integrate with other platform (MATLAB for instance). OpenDSS fulfils all of these requirements and hence has been used to model the network and conduct harmonic power flow. OpenDSS provides two power flow methods built into its engine: 1) Iterative power flow and 2) Direct power flow solutions. For Iterative power flow the loads and distributed generators are treated as injection sources (current injection model). Whereas the Direct method is based on a rather straightforward application of the nodal admittance (Y matrix) method to represent networks and network components in system admittance matrix. The power delivery elements in the circuit are linear and wholly described in the Y matrix. Two different algorithms are used in Iterative power flow: Normal current injection mode and Newton mode. The Normal mode which is a faster method utilises a simple fixed–point iterative method to solve the distribution network. It works well with stiff bulk power sources and unbalanced networks. The Newton mode, however, achieves higher convergence capabilities even though it is a bit slower. It is generally preferred for yearly-mode simulations. Typically, iterative power flow is used for calculations with nonlinear loads (for Harmonic Power Flow).

In Harmonic analysis, the nonlinear loads are modelled as a Norton equivalent or current injection model. OpenDSS provides several load/component models with its V-I characteristics (constant power, constant Z, and various combinations). The user defines various harmonic spectra which may be recorded associated to the load or generation. The spectra contains magnitude and harmonic phase angle. OpenDSS solves this set of nonlinear equations iteratively using a fixed-point iteration as described earlier. The engine solves the network equations for each frequency for harmonic producing elements defined by the user.

4.6 Low Voltage Distribution Network

Extending the harmonic loss deviation analysis to a distribution network requires the LVDN network to be modelled in the OpenDSS environment. The network utilised for this study is the same as the network utilised in the previous chapter (Chapter 3) The network, illustrated in Figure 4.5, urban distribution network, is representative of an actual suburban low voltage distribution network in Dublin city, Ireland and contains a supply transformer and a radial distribution system. It was modelled using OpenDSS software, which has harmonic analysis capability. The network contains nine 3 phase radial distribution lines delivering power to 74 household loads through the associated distribution lines. The rating of the loads varies depending on the dwelling size, demographic, and number of occupants. The network lines are modelled as overhead lines and the sub-feeder cables are 185 mm2 and 70mm2, with copper and/or aluminium conductors and cross-linked polyethylene (XLPE) and/or polyvinyl chloride (PVC) insulation material. The consumer distribution conductors are 25mm2 concentric neutral cable. The network configuration model is consistent with that presented in [165]. It has 9 sections connecting 10 nodes (mini pillars) of distribution 3 phase feeders starting from the distribution transformer (20/0.4kV) and denoted in red and blue colour as AB, BC, CD and so on. It consists of 74 households (numbered 1 to 74) supplied by these 10 mini-pillar connections. Each household is connected by single phase supply provided by the closest mini pillar. Further detailed modelling aspects of the network are discussed in [22]. The OpenDSS network model incorporates the harmonic profile for the individual loads as defined using the recorded data and simulation in previous section (Section 4.2). The loads are modelled as the lumped constant PQ load i.e. constant active and reactive power consumption and represented by current injection model to incorporate harmonics [166]. Random distribution of solar PV is considered across the network with the individual PV power ratings of 5.25kW. That is the maximum power that can be delivered by a single solar PV system is 5.25kW. The domestic loads and PV generators utilised in the network harmonic analyses are based on the allocations employed in [95]. The network model utilised is modelled in OpenDSS using [165] and the hosting capacity of the network and the PV connection position/location is based on [95]. The connected node and rating of solar PV, and maximum hosting capacity is adopted from [95]. The hosting capacity is defined as the ratio of total amount of PV power generated in the network to the KVA rating of transformer connected to the feeder. In this analysis it is 36.9%. The structure of network and the location of PV modules are given in Figure 4.5.

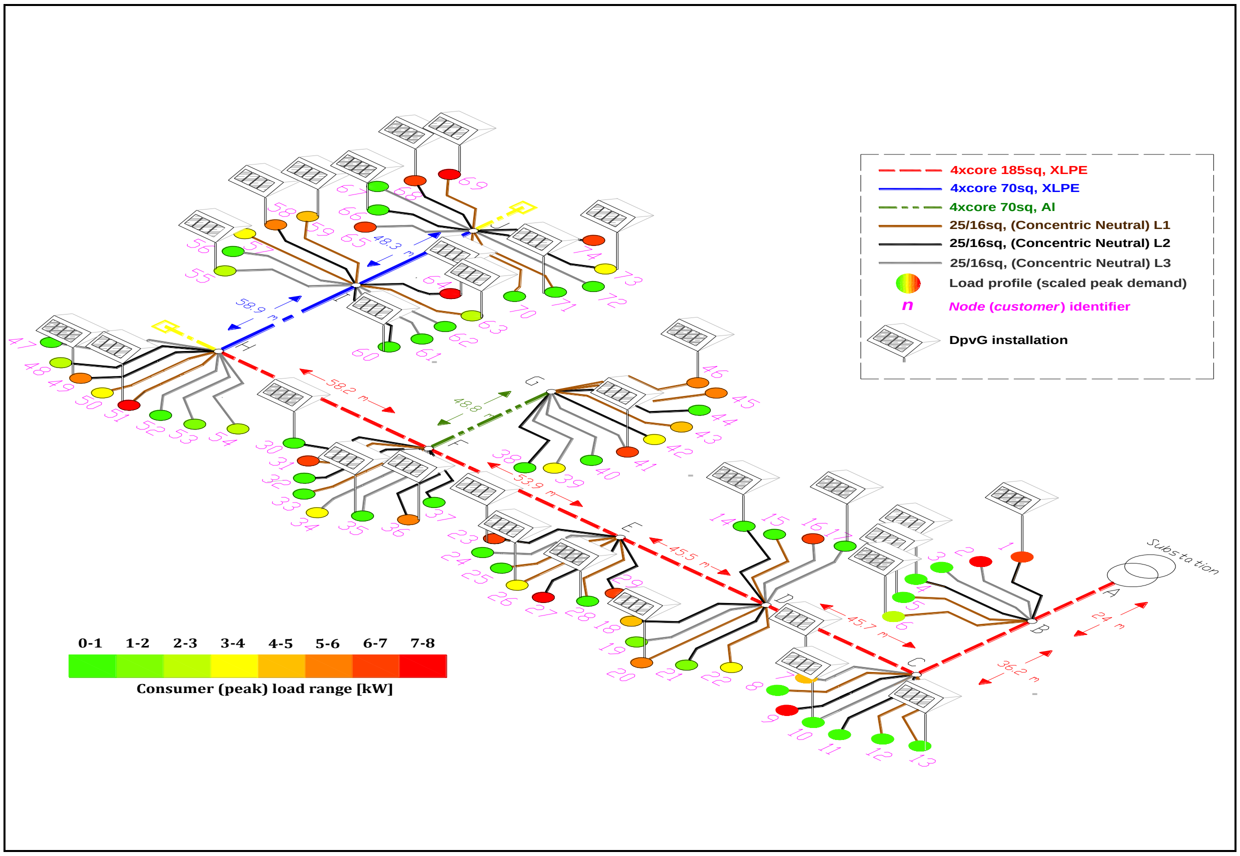


Figure 4.5: Urban Distribution Network model [165] incorporating the domestic load/PV profiles in [95].

4.7 Harmonic Heating Analysis: Low Voltage Distribution Network with and without DG

The harmonic heat loss deviation calculation and the associated analysis is performed for the LVDN provided in Figure 4.5. The analysis is performed under two cases: with solar PV generator and without solar PV generator. The total load on the distribution network is 196.9 kW from 74 individual household load distributed at different sections of the network as illustrated in Figure 4.5. The analysis considers each household with same number of devices (loads) as that of section 4.2 (Figure 4.6). However, the actual loading (devices that are ‘ON’) may differs according to the load data acquired from ISSDA [167] data set. Hence, the devices ‘ON’ – ‘OFF’ parameter is dropped and a fixed THD% is assumed with all customers. The load profile adopted for this study is a domestic load recorded by the Irish Social Science Data Archive (ISSDA) [167]. The harmonic profile of each load is synthesised from the domestic load harmonic profiles by using harmonic scaling factor. The domestic loads cumulatively had a THD% of 23.7% while all (8.6kW) load working simultaneously. With each load combination, the THD% will change. However, for the simplicity of the analysis, the THD% emitted by all 74 household is maintained at same 23.7% by scaling the harmonic current with respect to scaling of load or fundamental current. The scaling factor was linear, which was a reasonable assumption as individual household THD% was assumed to be same in order to have consistent and comparable results. This is also due to the additive nature of harmonic current[168]. The mathematical justification of linear scaling is presented below.

Let $I_1, I_2, I_3 \dots I_n$ be the harmonic current spectrum for a load of ‘X’ kW. The current THD is given by equation,

$$THD = \frac{\sum_{i=2}^{n} \sqrt{I_i^2}}{I_1} \tag{4.8}$$

Here, I_n is the individual harmonic current and I_1 is the fundamental current.

When the load is reduced to half and the current spectrum is scaled by half we get, the load as ‘X/2’ kW and current spectrum as $\frac{I_1}{2}, \frac{I_2}{2}, \frac{I_3}{2} \dots \frac{I_n}{2}$. Now the THD for this current spectrum, is given by

$$THD = \frac{\sum_{i=2}^{n} \sqrt{\left(\frac{I_i}{2}\right)^2}}{\frac{I_1}{2}} \tag{4.9}$$

$$= \frac{\sum_{i=2}^{n} \sqrt{I_i^2}}{I_1} \tag{4.10}$$

Which is same as initial THD value given in equation 4.8. Thus, a linear scaling factor for harmonic spectrum is a justifiable method to keep a constant THD value for all loads. The analysis is performed on the cable section AB (near to DT) which has maximum current drawn from transformer and hence would be worst affected. The cable has a per unit length resistance of 0.25mΩ/m with a maximum current rating of 360A. This would account for a maximum heating loss of 32.5Watts/m.

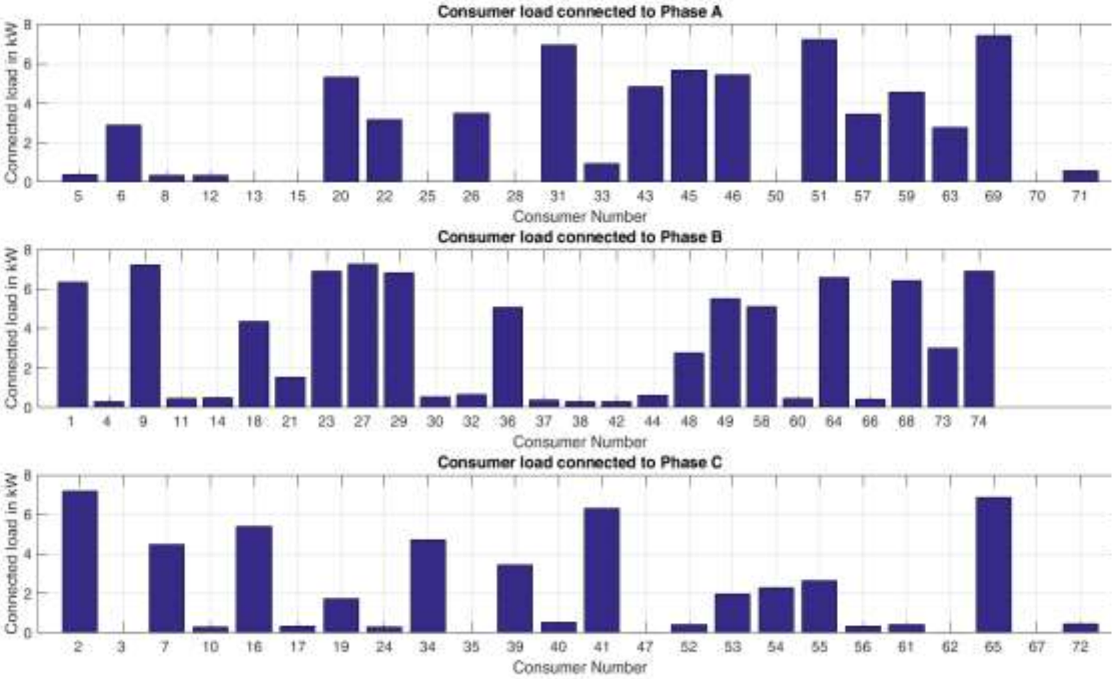


Figure 4.6 Loads connected to network by each consumer

CASE I: Without Solar PVDG

Despite having fixed THD%, the current magnitudes (including harmonic) will vary according to load (scaling – equation 3.9). The loading levels are assumed to be according to Figure 4.6. In this case (case I), harmonic power flow analysis is conducted without any PV generation. From here on, the loads are referred to the consumer total loads rather than individual devices. All houses in the network are assumed to be operating at a power factor of 0.9 lagging which is reasonable owing to the relatively low number of inductive loads in the domestic environment. The values for individual harmonic current components are obtained for each main feeder line connecting nodes given by A, B, C etc. in Figure 4.5. The section numbering in the proceeding results and figures is consistently labelled with Figure 4.5. The harmonic heating on each phase conductor is calculated along with the heating caused due to the RMS component of the (phase) current and the error is depicted in the loss deviation plot in Figure 4.7. The normal loss and the harmonic heating loss are calculated by equations 4.7 and 4.5 respectively. The first observation from Figure 4.7 is that harmonic heating is much more in line 2 (L2) which is the result of high loading in L2 and a high THD (Figure 4.8) in L2. Furthermore, it can be observed that the harmonic heating increases as it moves from last section to first due to cumulative effect of harmonic propagation at the main feeder. The difference in error at certain sections is almost twice the RMS heat calculated which justifies the problem that there is a major harmonic heating effect on conductors. Interestingly, distribution systems seldom operate at maximum loading limits and hence the effects may not be obvious. However, power system engineers are increasingly challenged to push system loading to higher levels day by day and hence the effects may soon become readily visible in the system.

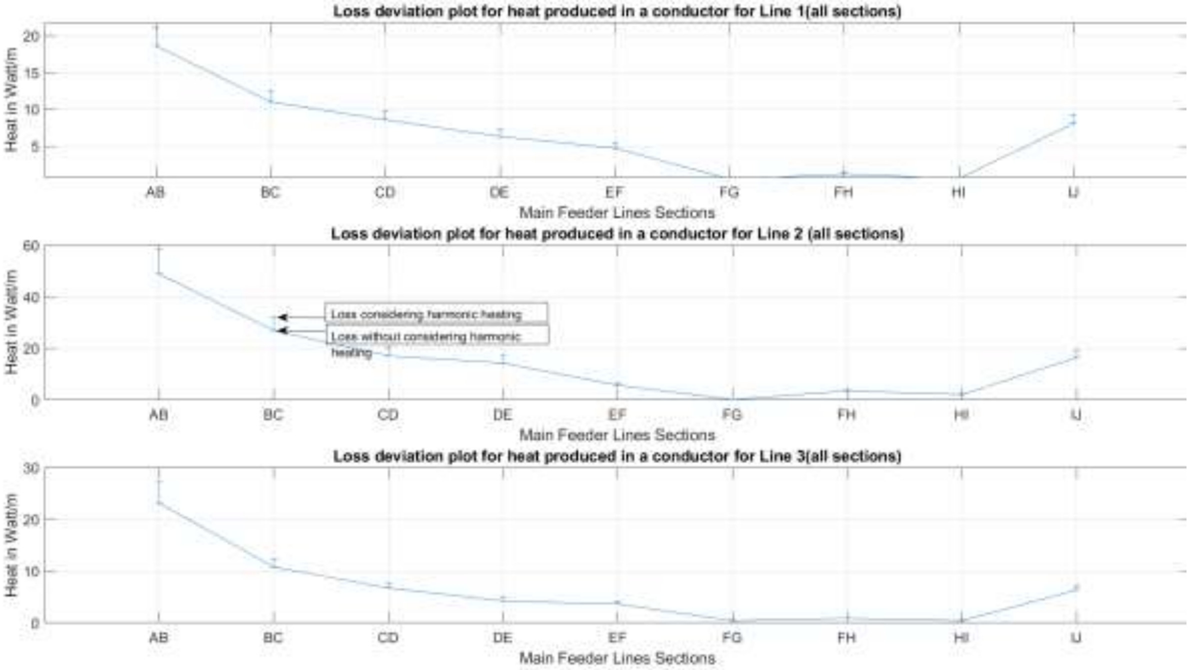


Figure 4.7: Loss deviation plot for harmonic heating in individual phase without solar PV

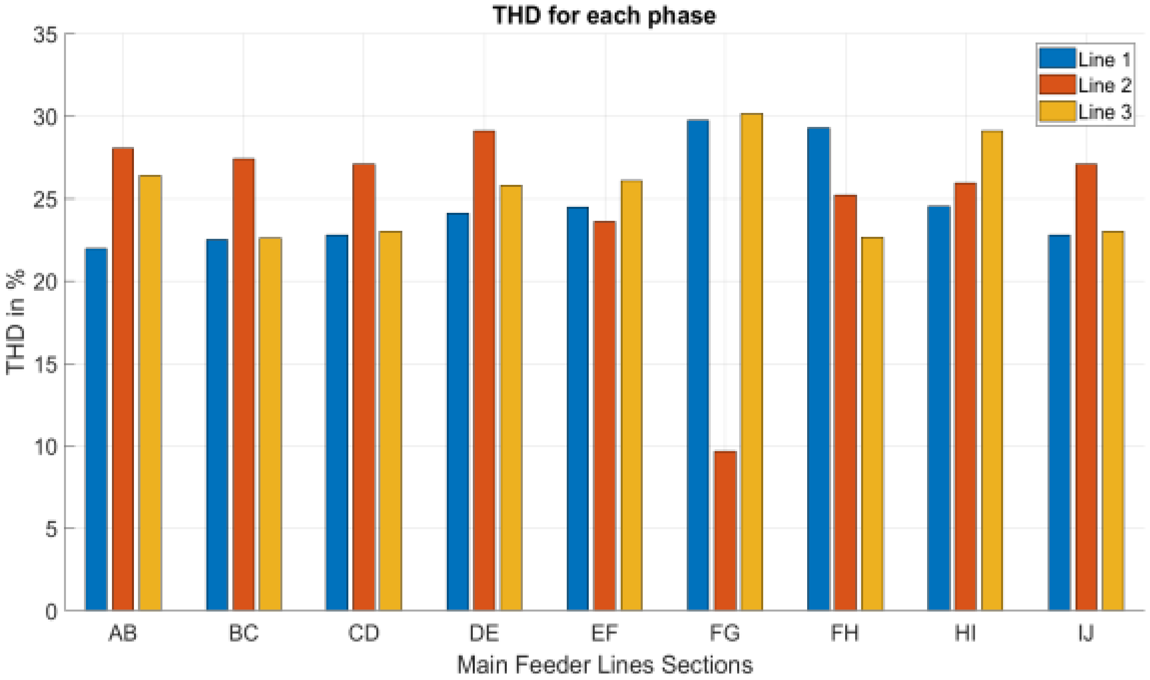


Figure 4.8: THD in each phase for every section without PV

CASE II: With Solar PVDG

The second part of analysis presented in this work considers the inclusion of solar PV generators. In this regard, the distribution network model supports a hosting capacity of 36.7%. This is in accordance with the work presented in [95] where the authors suggest the 36.7 % as an optimal hosting capacity for the network if network control mechanisms are to be avoided. The hosting capacity is defined as the maximum PV power that can be accommodated on the feeder without causing any adverse impact and is given to the ration of distribution transformer KVA rating [169]. Even though, solar PV generator is non-linear equipment and would induce harmonics, the case presented here considers PV generators as a linear power source. If PVDG are to supply the non-linear current, it would undermine the impact of worst-case scenario. Also, with better regulation intact for DG installation, that harmonic THD of a DG system is less than 5% if connected [170]. Solar PV generator systems are arbitrarily placed throughout the network in such a way that the nodal voltage will not raise above the regulations (1.10 pu). Now, harmonic power flow is executed, and harmonic heating calculations are conducted. Considering Figure 4.9 and Figure 4.10 suggests that the heat produced in the individual sections of main feeder has reduced considerably owing to the fact, at each node the majority of load is supplied by the local PV and hence the power transmitted through the main feeder is very small. However, it is apparent that while sufficiently smaller in magnitude, the associated loss deviation plot shows a considerable loss ratio when the loss due to harmonics are compared to the normal (RMS) heating loss. These facts conclude that, even though the PV is a harmonic source it helps to reduce the heat loss by reducing the line loading and in effect reduces the total harmonic heating as well. However, Figure 4.10 shows significant THD values and especially at section F-G. This occurs as the PV supplies all the fundamental component of loads and hence all harmonic current requirements are met by main grid, which leads to low value of fundamental current in main feeder section and high value of THD in the same. Figure 4.11 shows a scatter plot of fundamental current both cases (Case I and Case II).

The Case II may not seem to be an issue as the heating in the cable is much less, but the power factor at the substation transformer would be so low to have economic operation as most of the active power is supplied by PVDG. This may further cause saturation of transformer cores. This points to the need for a balance in PV penetration from a harmonic perspective to have a safe stable and economic operation of the distribution network. Different combinations of PV hosting capacity, loads and harmonic profiles could be considered for analysis. For example, preliminary analysis considering non-linear loads with varying THD% at the end of this network (pillar J) indicated significant implications for percentage THDv manifestation at that part of the network. However, in the context of serving as a reference, the emphasis in this work is to present extreme (practical) scenarios across the entirety of the network.

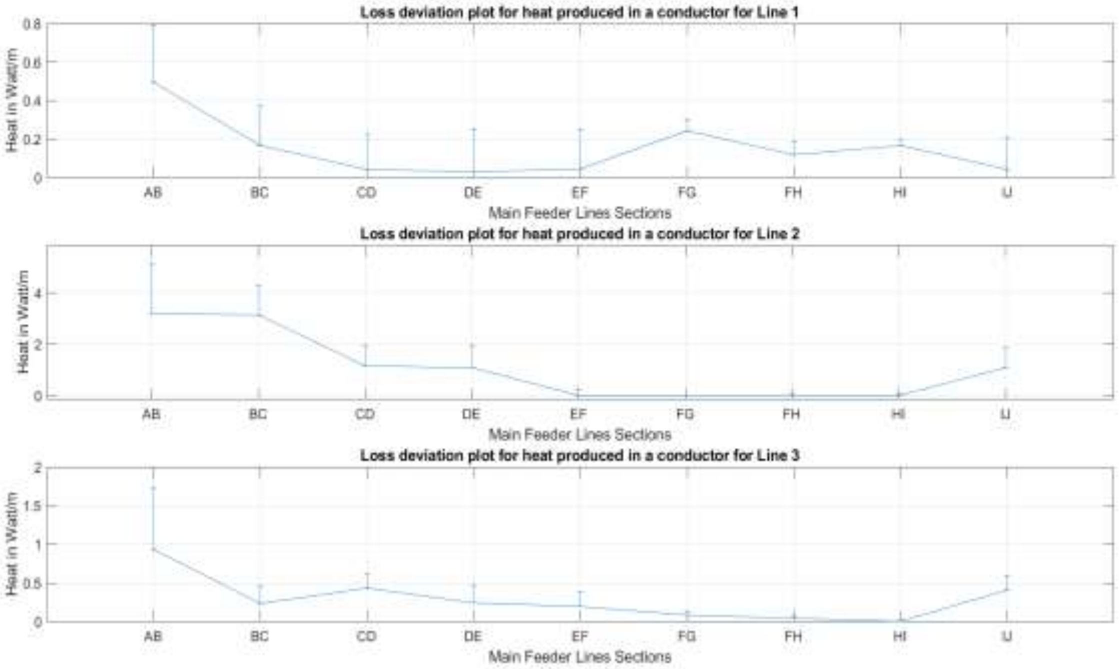


Figure 4.9: Error plot for harmonic heating in individual phase with solar PV

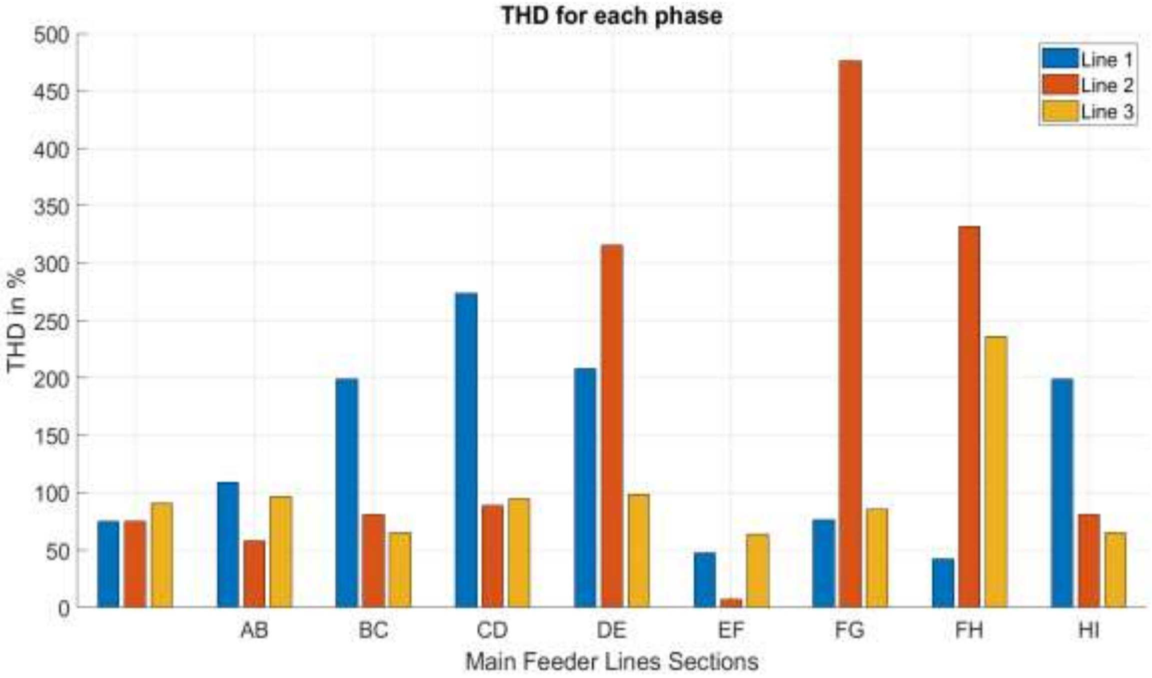


Figure 4.10: THD in each phase for every section with PV

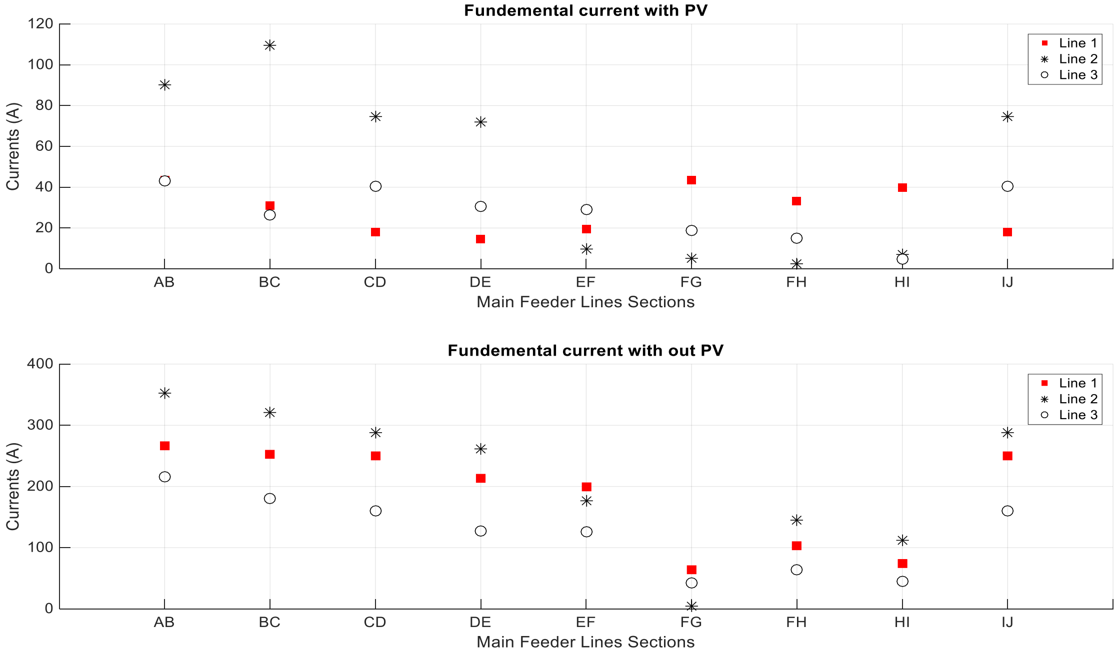


Figure 4.11: Scatter plot of fundamental current at all phase at each node with and without PV

4.8 Harmonic Loss Constraint

The harmonic loss analysis points to a simple fact, that is, THD% may not always give a straight answer to the impact of harmonics. Further, it also shows the cumulative impact of harmonics in the system. The solution may consist of strict regulations which can still be violated with additive nature of harmonics, or harmonic filters which are expensive. A direct observation in this context states, managing load operations can manipulate harmonic emission in the network. However, each of these loads demand different levels of harmonic currents and the source supplies them. The impact of non-linear loads of each consumer in the network accumulates in the main feeder as harmonic currents. This indirectly points out the fact that, controlling the operation of devices connected to the network can influence the harmonic power quality. By micromanaging consumer loads producing harmonics, a safe operating network environment can be ensured for the operator. A single harmonic measuring unit located near the start of the feeder can be utilised to monitor the harmonic content in the radial network.

Utilising the harmonic heating loss as the limiting factor to quantify impact of harmonics in the cable indirectly accounts for THD as well. Hence harmonic heat loss factor is used as a constraint for harmonic constraint consumer-friendly DR (HC-C-DR). The constraint is modelled as a limit violation given by,

$$P_L < max(P_{Lconductor}) \tag{4.11}$$

Where, $P_{Lconductor}$ is the power loss in the cable under maximum current carrying capacity. The complexity and associated operational constraints will be discussed in the chapter 5. This could be utilised to maintain the harmonic heating value below the maximum cable heating and ensure safe operation of the radial network in the context of harmonics.

4.9 Voltage PQ

Apart from harmonic PQ, voltage quality of electrical supply system is an essential PQ parameter in maintaining safe operation of power system. The supply voltage drives the power flow around the network and hence is critical to maintain smooth operation of power system. In a distribution system context, maintaining the voltage quality within the safe operation limit throughout the network is a tricky endeavour. With voltage drop in the line proportional to impedance and current, a radial distribution system voltage profile largely depends on its loading. This provides an opportunity for load management program like DR to participate in managing voltage profile in the network to safeguard the system operation.

Traditionally active power curtailment (load shedding) method has been used to control the voltage drop in the LVDN for a long time [171]. A DSO may also maintain the voltage within the standard by regulating the operation of on-load tap changer (OLTC) transformers, line voltage regulators, capacitor switch banks, and line drop compensators. [91], which are generally expensive resolutions depending on the size of feeder. Also in literature, an intrinsic method based converter operation control of grid-tied inverter is proposed, which utilises the active or reactive power control to reduce overvoltage [98][99]. However, with advanced computing capability, the DSO control centre can potentially have demand, and generation predicted to reasonable accuracy which can now give way to distributed dynamic cost-effective voltage control mechanism. A load management algorithm thus can enable the DSO operator to manage network voltage level by curtailing load/generation to manage under/over voltage issues. The following section establishes a theoretical relationship between the active/reactive power with voltage under DG scenario. This follows integration of a voltage management technique to the consumer-friendly DR program presented in Chapter 3

4.10 Relationship Between Active and Reactive Power to Voltage

This section presents the theoretical background for voltage regulation with active and reactive power control followed by modelling approach for demand response-voltage control (DR-VC) algorithm utilising the active and reactive power management in a DG integrated LVDN.

Consider a two-bus distribution system with embedded DG as given in Figure 4.12. Under normal condition, the power flow from bus 1 with voltage V_1 to bus 2 with voltage V_2V$_2$though the connected transmission line having 'R' and 'X' as resistance and reactance to feed the load connected at bus 2.

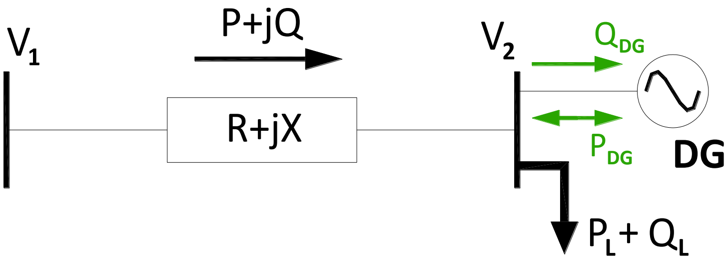


Figure 4.12 Two bus power system with integrated DG

Initially when DG is not injecting any power, active and reactive power flowing through the line connecting the bus 1 and 2 is given by $P + jQ$, which is the same as the active and reactive power demanded by the load$P_L + jQ_L$ (ignoring transmission loss). The voltage drop at bus 2 is given by [171],

$$V_1 - V_2 = \Delta V = \frac{PR + QX}{V_2} \tag{4.12}$$

Differentiating the above equation with respect to P and Q respectively gives,

$$\frac{d\Delta V}{dP} = \frac{R}{V_2} \quad , \quad \frac{d\Delta V}{dQ} = \frac{X}{V_2} \tag{4.13}$$

It can be observed that, the change in the voltage with respect to change in active power is proportional to the line resistance and reactive power is proportional to the line reactance. The hardcore dependency found between the reactive power and voltage in a transmission and sub transmission level [172] system is not found in the distribution system as the LVDN's are generally of very short distance with high resistive component than reactive component. Also, the maximum loading capacity of the LVDN system unlike transmission system is not bound by the voltage drop as the low X/R ratio results in violation of thermal loading limit much before the voltage violation while increasing load. Now, with the DG connected and injecting power, the equation (4.12) can be written as,

$$V_1 - V_2 = \Delta V = \frac{(P_L - P_{DG})R + (Q_L - Q_{DG})X}{V_2} \tag{4.14}$$

With active power being the dominant factor in controlling the voltage at bus 2 (X/R << 1), an increase in DG active power (P_{DG}) causes the value of ΔV to decrease. Considering a purely linear load and zero reactive power injection by the DG, the value of V_2 becomes greater than V_1 when $P_{DG} > P_L$ (reverse power flow). This in effect can cause an overvoltage if $P_{DG} >> P_L$ or during light loaded condition. As the number of buses increases, the furthest bus will incur maximum voltage violation and could thus be violating the upper boundary of voltage (generally 1.1p.u). The probability of such a scenario to occur in an LVDN increases with increased penetration of PVDG's (especially at lightly loaded condition, e.g., mid-day). From equation (4.14), there is a relationship between reactive power and voltage drop (however small it may be) and hence, reactive power management can be utilised for voltage regulation as it is usually relatively inexpensive. Generally, the renewable energy based DG seldom operates at fully rated capacity (rated kVA) and could easily be used for reactive power support by regulating the operation of GTIs connected to it [173][94]. The rated power of DG can be given by,

$$S_{DG} = \sqrt{(P_{DG}^2 + Q_{DG}^2)} \tag{4.15}$$

The maximum reactive power support which can be provided by DG is given by (while satisfying equation (4.15)),

$$Q_{DGmax} = \sqrt{\frac{1}{(cos^2\,\theta)} - 1} \tag{4.16}$$

Where 'cosθ' is the operating power factor. However, with a practical consideration in a DSO point of view, it is generally not advisable to reduce the power factor of DG below 0.9.

Distribution code also stipulates the consumers to maintain the DG power factor between 0.95 lagging and unity (DCC6.9.1) [22]. Hence, the study uses a fixed power factor correction of 0.9 lagging as a first step towards voltage regulation during overvoltage. Controlling the reactive power at the node and in the network can therefore be utilised to regulate voltage up to a certain level (depending on the economics involved).

The exact amount of active/reactive power change required to regulate the voltage at a certain node can be calculated from equation (4.14). Also, the literature [101] utilises computation of voltage sensitivity matrix to calculate active/reactive power required for necessary voltage regulation. However, unlike many transmission and sub-transmission system, the unbalanced nature of the distribution network may pose difficulty in expressing and solving system equation to compute the sensitivity matrix. Another well explored method available in the literature is utilising droop control which can provide the value of active/reactive power required based on the droop characteristics of grid tied inverter (GTI) of DG [95]. This method even if simple to utilise, would depend on accurate representation of droop characteristics of GTI manufactured by different manufacturers. Further, it has to assume that the droop characteristics would not change during the operation lifetime of GTI. The proposed methodology in this thesis utilises an incremental reduction method to curtail the power injected by DG surrounding the overvoltage node without heavily penalising nearest DG.

4.11 Overvoltage Management - The Technique

Overvoltage is generally associated with higher DG power injection at light load conditions, which cause a reverse power flow. With the reverse power flow, from [95] it can be observed that the voltage rise is highest at the end of the feeder. Now as an initial measure the operation of DG can be set at 0.9 leading power factor and absorb the reactive power (equation (4.14)) and reduces the over voltage. If the voltage rise persists, the straightforward remedy is to isolate the DG connected to the overvoltage node. However, this introduces a dilemma as the overvoltage at the end of the feeder is contributed by all consumers connected to the feeder all along. In this thesis, instead of applying DR, a direct generation response is incorporated as an incremental curtailment algorithm (ICA) which commences an iterative curtailment loop with the active power (P) injection of DG connected at the end of feeder reduced by 5%. If overvoltage persists, successive iterations not only decrement the P injection by 5%

(cumulatively) for DG connected to the end feeder but DG connected to previous node are also included for a 5% reduction from their active power generation. This process continues, reducing P injections by DGs connected on the feeder until the voltage falls back to the nominal upper bound. The mathematical representation of this process is given by,

$$\Delta P_i^{DG} = 0.05P_i^{DG} \times C_2 \; \forall i \in \{1,2,\ldots,p\} \quad \forall\, p \notin \{p - C_2\} \tag{4.17}$$

$$P_i^{DG} = P_i^{DG} - \Delta P_i^{DG} \tag{4.18}$$

where $P_i^{DG}$is the power injected by the DG connected at ith node, 'p' is the total number of PVDG in the feeder and C_2 is the iteration number. The incremental reduction imposes a fairness towards curtailment of DG power injection especially that of DG connected to the end of the feeder by requiring a participation where most of the DG's share the curtailment. However, there is no guarantee that all DGs connected to the feeder will participate in this algorithm, but the approach reduces the burden inflicted on prosumers (DGs) at the end of the feeder. Further, the DG connected near the DT has less sensitivity towards voltage increase at end of feeder when compared to DG connected there. The proposed algorithm is represented as a flow chart in Figure 4.13.

4.12 Undervoltage Management - The Technique

For the under-voltage management, a C-DR program proposed in Chapter 3 is utilised. The C-DR reduces the consumer load based on their engagement plan for an undervoltage scenario. The engagement plan distribution is the same as given in Table 3.2. The network parameter for the urban distribution network is the same as in section 3.9 and as used in previous scenarios in this chapter. The simplified flow chart is given in Figure 4.13. Considering equation (4.14), any change in P_L can change the voltage at node 2. With the C-DR algorithm, the consumer loads are varied to match the required loading level that maintain the voltage at most sensitive node (pillar 9) within 0.9 pu. The level of demand reduction required is iterated successively increasing 5% at a time for each interval. The loop checks for voltage violation and moves forward to the next interval once the voltage is within the limits. Like previously, load management is performed based on the engagement plan of each consumer. Unlike, the generation curtailment the demand reduction is not focused on the undervoltage node, rather, the whole network keeping the consumer inconvenience to the minimum.

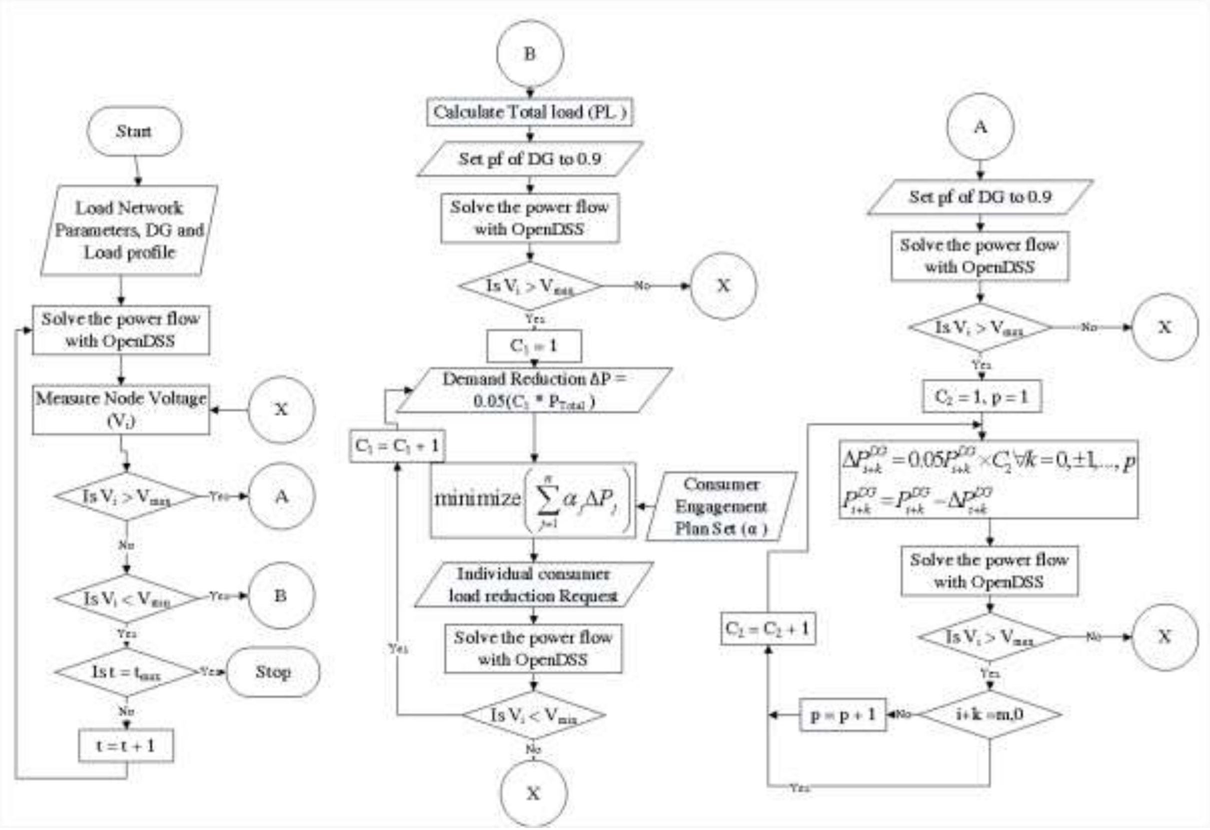


Figure 4.13 Flow chart

4.13 Conclusion

The PQ issues with the distribution network are usually dependent on the load connected, and the length of the feeder. Which indicates to the option of load regulation to manage them.

Harmonic distortion and its associated problems are not new concepts. However, the issue has heretofore not been afforded sufficient importance within the domestic/distribution network environment. The analysis presented in this chapter indicates the need to consider their effects in a building/network system to preserve and maintain the stable long-term operation of electrical services in the context of modern smart environments.

The initial analysis of a domestic wiring circuit indicated that there is a significant deviation in respect to expected power loss and actual power loss in cables as a consequence of harmonic distortion. The impact of such deviation can pose a threat when accumulation of harmonics occurs at main circuits. However, with increased penetration of non-linear loads can end up with scenarios which threaten the safety of consumer and equipment.

The harmonic heating analysis conducted on the distribution network reveals a serious situation in the context of cable loss (heat loss) deviation. While such a ‘worst case scenario’ is highly unlikely, it offers better insight towards the future with high penetration of non-linear loads e.g., electric vehicles.

The results of the analyses presented with the renewable energy source integration (solar PV) suggest that with increases in PV penetration, the active element of power may be reduced. However, the THD can increase even though the harmonic content in the network may not have varied significantly. The increased THD may not cause dangerous levels of heating, but the essence of this analysis is on the fact that THD may not be used as an only implication of harmonic pollution in the network. Taking account of this finding, harmonic heating loss is used as an indicator for severity of harmonics in the distribution network.

Since, the harmonic pollution is contributed by harmonic loads connected, managing the operation of these loads will in effect enable managing harmonics in the connected network. Thus, utilising a load management algorithm constraint by harmonic heating loss would be ideal for an operator to manage safe operation of the network without investing on filter devices.

In case of voltage quality, with increased loading, the network voltage levels are lowered with distance from the DT, but with DG active power injection the voltage profile is regulated much better. Yet again, with low loading the high active power injection of DG causes the voltage profile to breach the upper bound. As load/generation has a direct impact on voltage profile of the feeder, a load/generation management algorithm can be used to regulate voltage profile. For overvoltage scenario, a generation response algorithm is proposed, and for undervoltage a load management (DR-VC) algorithm is proposed.

The next chapter will present different case study to validate the algorithm proposed to constraint harmonics and manage voltage of profile in an LVDN.

Chapter 5 Power Quality Constraint Consumer-Friendly DR - Modelling and Case Study

5.1 Overview

The performance evaluation of the consumer-friendly DR (C-DR) model (in Chapter 3) showcases its capability to respond to the consumer inconvenience and the consumer's socio-demographic status. The C-DR model is also able to accommodate the reduction in demand without overburdening consumers. The flexibility thus achieved can be utilized to shift loads in time. Therefore, various smartgrid projects can use this algorithm to manage power demand supply mismatch, improve flexibility in the system, participate in the market as a virtual power plant, all with improved customer satisfaction. This chapter probes and evaluates the idea of utilizing an improvised C-DR algorithm to manage power quality in the distribution network. Namely, harmonic power quality and under/over voltage.

The DR implemented as a service for DNO usually employs an aggregator/agent who compiles the need of the hour and initiate the algorithm. The roles of aggregator is not explored in this thesis and hence for all reference of initiating a DR can be assumed to be done by an aggregator.

Initially, the harmonic heating constraint is incorporated to form a harmonic constraint consumer-friendly DR (HC-C-DR) algorithm. The algorithm is implemented under three different scenarios. Later, the C-DR algorithm and incremental curtailment are applied to manage under/over voltage scenarios in a 74 consumer-connected radial feeder.

5.2 The Simulation, Network Design, and General Parameters

The 74-consumer urban distribution network (Figure 3.5) is utilized to implement the power quality constraint consumer-friendly DR (HC-C-DR) algorithm. Two different consumer load profiles/configurations are used. A randomly distributed set of single-phase PVDG’s are considered in the network connected to different consumers (consistent with Section 4.7). The PV profile (scaled) was obtained from measured data for a typical summer day in August for a 1.7 kW Saynno PV panel setup. The profile is scaled to form different penetration levels depending on the penetration scenarios. All the simulations are performed for every 10 minutes totalling 144 simulation intervals for a day. The power flow is served by the OpenDSS simulation platform [174].

The consumers are connected to a single phase supply, and hence 74 consumers are connected to different phases, as given in Table 5.2. The consumer number is consistent with the number shown in Figure 3.5. The consumers are sorted to each engagement plan (Section 3.3) and are given in Table 5.3. The sorting of consumers has been consistent in all the following scenarios and will not impact the correlation between the scenarios. The devices considered in the household and their associated ratings are given in

Table 5.1. The cumulative harmonic spectrum of these devices are represented in Figure 5.1. The THD % is calculated based on the spectrum and the spectrum is contributed by consumer devices operation. That is, with different combination of device operation, the spectrum will be different and thus, the THD % will be different. The devices considered in each household are consistent for all flowing scenarios.

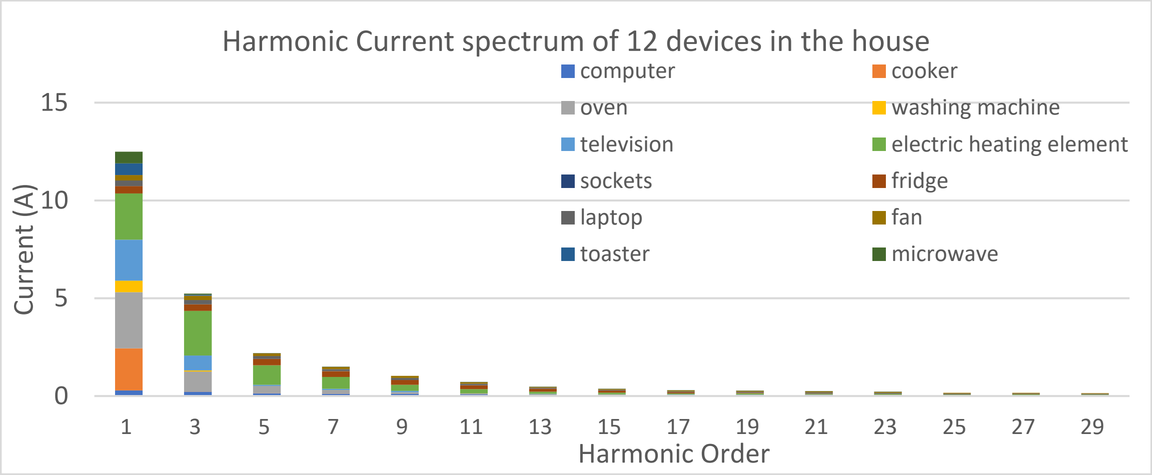


Figure 5.1 Harmonic spectrum of a single consumer with all loads active

Table 5.1. Device list, their inconvenience and ratings

Device	**Inconvenience (β)**	**Rating (W)**
Computer	1	140
Cooker	1	800
Oven	0.45	800
Washing Machine	0.2	600
Television	0.9	200
Electric Heating Element	0.1	1000
Sockets	0.35	50
Fridge	0.4	150
Laptop	0.45	45
Fan	0.2	150
Toaster	0.8	400
Microwave	0.75	400

Table 5.2.Consumers per phase

Phase A	**Phase B**	**Phase C**
5	1	2
6	4	3
8	9	7
12	11	10
13	14	16
15	18	17
20	21	19
22	23	24
25	27	34
26	29	35
28	30	39
31	32	40
33	36	41
43	37	47
45	38	52
46	42	53
50	44	54
51	48	55
57	49	56
59	58	61
63	60	62
69	64	65

Table 5.3.Consumer per engagement plan

SGS	**GS**	**GA**	**R**
1	9	17	25
2	10	18	26
3	11	19	27
4	12	20	28
5	13	21	29
6	14	22	30
7	15	23	31
8	16	24	32
33	41	49	57
34	42	50	58
35	43	51	59
36	44	52	60
37	45	53	61
38	46	54	62
39	47	55	63
40	48	56	64
65	73		
66	74		
67			
68			
69			
70			

70	66	67
71	68	72
	73	
	74	

71			
72			

5.3 Harmonic Constraint Consumer Friendly DR (HC-C-DR)

Three scenarios are evaluated employing harmonic constraint DR with different load and generation profiles. Scenario 1 is with all load demand active, while scenario 2 is the same as scenario 1 loading but with different PVDG generation profiles. Scenario 3 has 8 different consumer load profile classified based on their socio-demographic characteristics.

5.3.1 Scenario 1: All Load Active

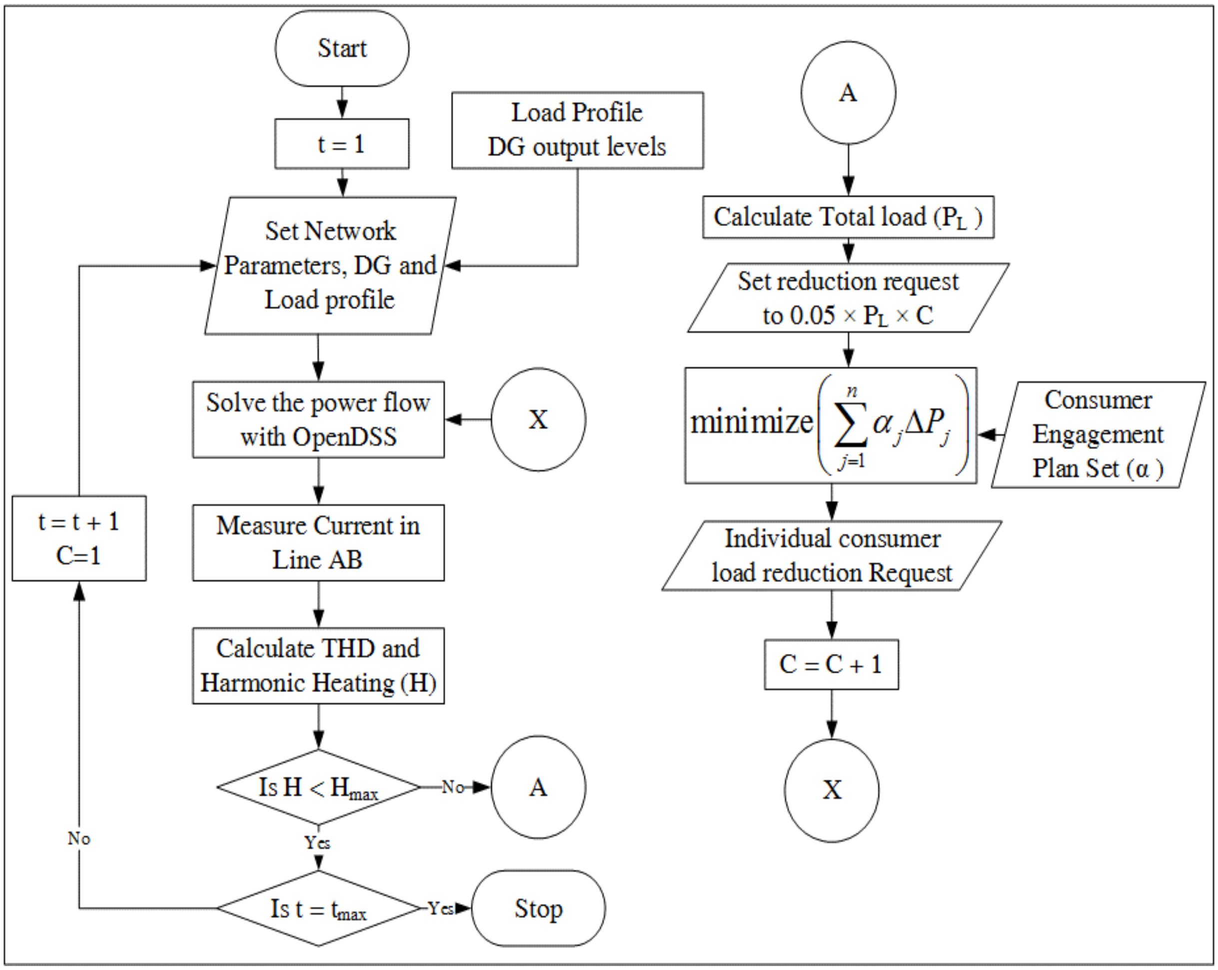
This scenario is intended to showcase the worst-case performance consideration of the presented (HC-C-DR) algorithm. All 12 consumer loads are set to be active/in-demand for all 74 connected consumers throughout the day. While consumers are participating through different engagement plans, the algorithm will attempt to regulate consumer loads, consistent with the specifics of the four engagement plans (Section 3.3) to ensure harmonic heating arising in the network is below the maximum continuous operating value. The overall impact on consumer inconvenience will be a minimum while these operations are performed. The total peak load demand for a single consumer is 4.7kW.

Even though the current spectrum throughout the network is measured, the critical point for analysis in this study is the section (AB) of the line after the transformer. As this section will support the maximum current that flow in the network. Harmonic heating is calculated in this section (AB) of the line using the current (ampere) harmonic spectrum and the line's resistance.

The DR program is initiated when the harmonic heating is more than the nominal heating. Where nominal heating is defined as the maximum heating (in watts) calculated using equation 4.7, when the maximum rated current passes through the cable. The maximum rated current for the cable in section AB (185 sq mm XLPE) is 360A. However, with all loads connected, this particular scenario we have assumed a 130% loading of cable which gives a fundamental current to be close to 470A for Phase A and C. While Phase B is the most loaded phase in the network hence 135% overloading capability is assumed. Under normal operation, i.e., with linear current flowing in the cable, the heating loss in the cable (equation 4.7) is 55, 60 and 55 watts per unit length (resistance of the cable is 0.25mΩ per meter length) for phases A, B and C. Since reactance doesn’t cause heating, it is not considered here.

With the non-linear current flowing in the cable, the ohmic heating loss induced in the cable is given by equation 4.5. This heating loss due to non-linear current is also called harmonic heating loss. With higher harmonic currents, the harmonic heating increases exponentially. The heating depends on fundamental current values and THD %. Hence, the THD% may be much higher at certain times, but the harmonic heating may still be within the limit due to low fundamental current. If the heating loss is higher, HC-C-DR will detect the increased heating in the cable and initiate a DR program to reduce consumer loads. The reduction in consumer load would reduce fundamental current and harmonic emission in the network associated with the load. This procedure will reduce heating in the cable and hence ensures the safe operation of the system. The consumer-friendly algorithm ensures that the inconvenience faced by the consumers in the network is proportional to their engagement plan and is also a minimum.

The HC-C-DR manages consumer load reduction at individual consumer by turning OFF consumer devices based on their priority/device inconvenience level (given in Table 3.3). The consumer usually would have the ability to choose the priority levels his/her devices in the house. However, the presented analysis is not focussed on the granular level of details on the consumer device priority list and the priority of devices are not updated in any iterations. Also, the priority list of all devices for all consumers are kept the same for all following scenarios. This eliminates the need to showcase device operation cycles in results as they are only to be considered as harmonic emission sources. A flow chart depicting the proposed HC-C-DR is given in Figure 5.2. The load reduction request is initiated at 5% per phase with increased harmonic heating loss and is updated 5% for each subsequent iteration. For example, if cable section AB of phase A is violating the maximum loss, the algorithm will initiate a 5% load reduction in phase A. The THD% and heating loss is calculated again after the load reduction. If heating loss is still more than the rated value, the algorithm reduces 10% of the total initial load in phase A and checks the heating loss again. This continues as long as the heating loss is less than the rated value for each phase. The load reduction in each iteration is distributed to customers based on their engagement plan.



$$\text{minimize}\left(\sum_{j=1}^{n}\alpha_j \Delta P_j\right)$$

Figure 5.2 HC-C-DR algorithm flow chart

Further, it has to be noted that the device switch OFF is chosen explicitly on device inconvenience value and not on the harmonic spectrum. This drawback of the algorithm can be overcome by collaborating the inconvenience factor with harmonic impact to form the priority list. However, in light of consumer-friendly focus of DR in this thesis, it could potentially contradict the minimum inconvenience objective. Thus, such an approach is not considered.

The all load scenario can also be considered as a boundary locator for operating the system. They provide the maximum load and harmonics at which the system can operate safely. Table 5.4 shows the system parameters before and after implementation of HC-C-DR at 8:40 PM of the day under scenario 1. This particular time is chosen arbitrarily. The percentage change in the cumulative value of each parameter considered here in the network is also given in Table 5.4.

The heating induced before DR operation in the cable section AB is 64, 75 and 61 Watts in phase A, B and C, respectively. The HC-C-DR reduces the load by approx. 11% in the network in total, thus reduce heating loss in cable to 52, 60 and 53 Watts in phase A, B and C with corresponding load reduction of 13%, 13% and 8 % in each phase. The maximum heating loss allowed in each phase under normal operating condition is 55, 60 and 55 Watts for Phase A, B, and C (with a line overload of 130-135%). Thus, the HC-C-DR successfully reduced the heating loss in the cable to less than the normal operating value. The current THD % was reduced during this load reduction as the HC-C-DR has also turned off harmonics injecting load in the network. The reduction in current demand also contributes to the reduction in heating. The current flow before DR operation was very close to the maximum operating limit and would be considered safe to operate if a bit lower. However, harmonic heating loss considered is substantially higher (approx. 20%) than the normal operating limit of the cable at this time instance. The presented analysis methodology and HC-C-DR identified the potential threat arising from overheating and was able to reduce load to manage this issue. The change in inconvenience (α or Tolerance value) along the network is also given in Table 5.4.

Table 5.4.System parameters before and after DR at 20:10 hours for Scenario 1

	Before DR	**After DR**	**% Change**
Total Network Load (kW)	284.99	253.26	11.1%
Total Load Phase A (kW)	91.04	79.37	12.8%
Total Load Phase B (kW)	98.91	86.46	12.6%
Total Load Phase C (kW)	95.04	87.44	8.0%
THDi % Phase A	18.74	18.04	3.7%
THDi % Phase B	18.99	18.05	4.9%
THDi % Phase C	18.22	17.71	2.8%
Iab Phase A (A)	481.57	433.23	10.0%
Iab Phase B (A)	520.35	470.84	9.5%
Iab Phase C (A)	472.06	438.99	7.0%
Heating line-ab Phase A(W)	63.99	51.66	19.3%
Heating line-ab Phase B (W)	74.78	60.00	19.5%
Heating line-ab Phase C (W)	61.38	52.98	13.7%
Total Network Inconvenience	41.48	45.81	10.4%
Inconvenience in phase A	14.35	16.39	14.2%
Inconvenience in phase B	15.38	17.55	14.1%
Inconvenience in phase C	11.25	11.87	5.5%

The following figures show network-level cumulative changes in certain parameters throughout the day (with and without HC-C-DR). Figure 5.3 shows the change in consumer inconvenience parameter in each of the 3 phases throughout the day. The inconvenience level steadily increases for consumers in each phase as the load reduction is implemented to reduce the cable heating loss. The cumulative value is higher in phase B as it has more consumer connections than in the other two as given in Table 5.2. The cumulative inconvenience value in each phase varies throughout. The same consumer is not chosen to engage in DR due to increased inconvenience while engaging in DR for the previous interval. The cumulative value of inconvenience change in phase C is lower as phase C has a higher number of customers in the Green Aware and Reluctant engagement plan. Hence phase C contributes to lower engagement. Moreover, phase C also has lower number of consumers than phase A. A pre-run of the HC-C-DR algorithm on the network with a step increase in load reduction request would provide a correlation between possible demand reduction and network-level inconvenience mapping possible reduction [in demand] along with network inconvenience at any given time. This can form a look-up table for an operator on possible flexibility in the network. However, this study [scenario 1], focuses more on the capability of HC-C-DR to alleviate power quality problems and hence considers the aforementioned study as possible future work.

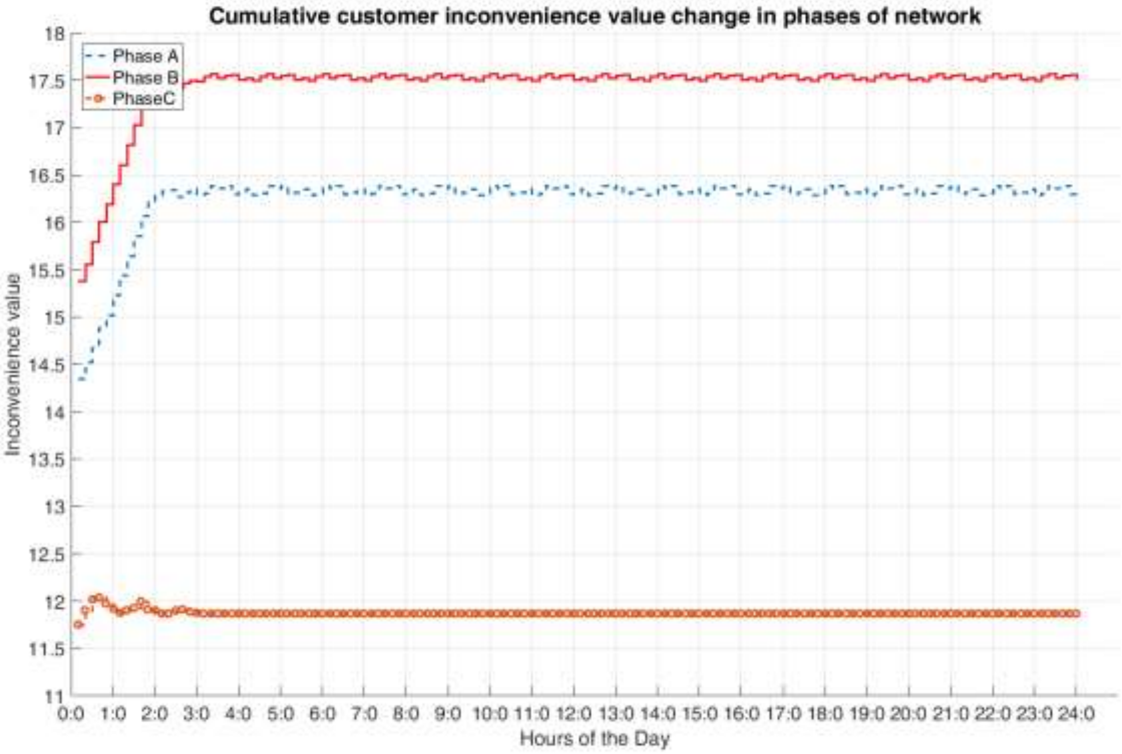


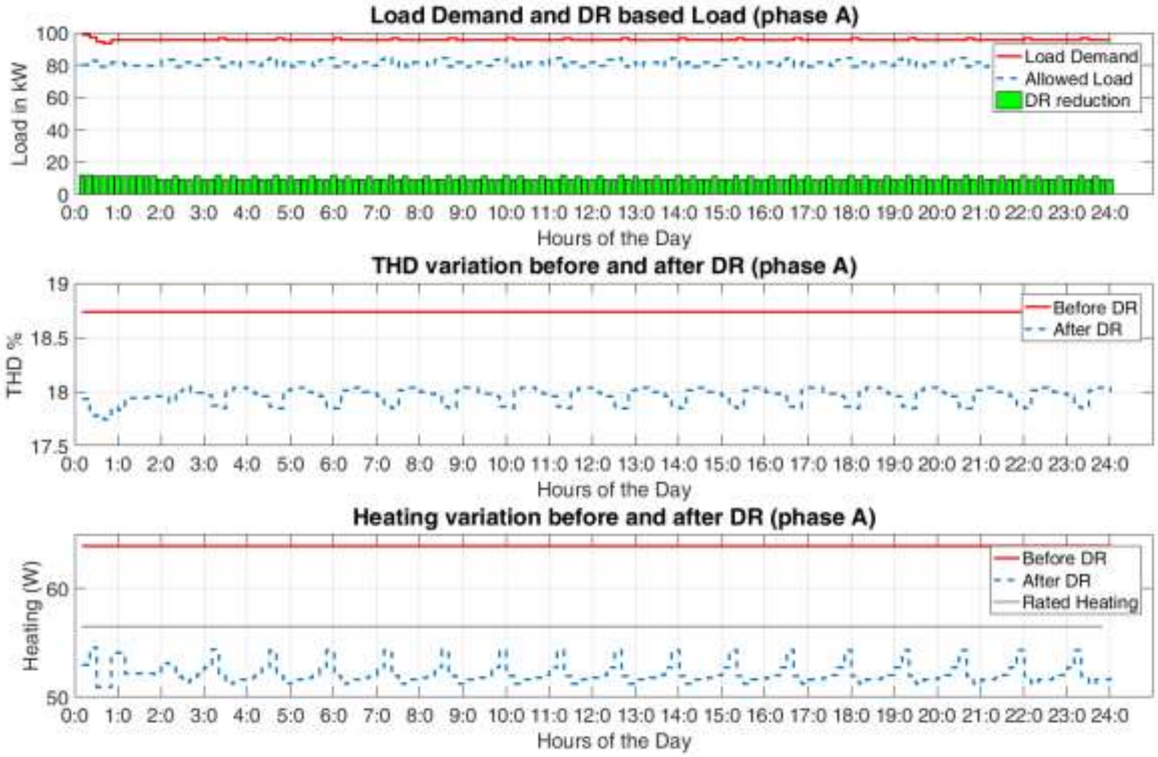
Figure 5.3 Cumulative consumer tolerance per phase for a day

The per phase cumulative load demand and reduction along with the variation of THD and cable heating for the entire day is given in Figure 5.4 - Figure 5.6. The figure shows the load demand and the cable heating loss associated with it before and after HC-C-DR employed. The algorithm is successfully able to bring the cable heating loss within the appropriate limit as shown in Figure 5.4 - Figure 5.6. Since this scenario considered all load requirement active throughout the day, the demand, THD%, and heating loss associated are constant lines with the same load. These figures also demonstrate the algorithm's ability to align the reduction of load based on requirement imposed by additional heat loss generated in each cable phase rather than applying a constant reduction throughout the network. An algorithm that strictly adheres to the PQ standards to the cable parameters in an extensive network would be highly beneficial to networks operators.

The total load on the network for the day was 7584kWh when each consumer was demanding 4.27kW. The demand reduction per phase is given in Table 5.5. As expected, a higher reduction is observed in Super Green Savvy Engagement plan customers. The Green Aware Engagement plan customers are not chosen even though they are available. This set of consumers may come in when aggressive demand reduction is warranted in some instances. Representative consumer load demand and demand reduction per phase are given in Appendix B.

Table 5.5.Demand reduction per phase for different engagement plan in kWh

All values in kWh	**SGS**	**GS**	**GA**	**R**	**Total**
Phase A	163	85	-	-	248
Phase B	171	131	-	-	302
Phase C	186	-	-	-	186
Total	519	216	-	-	735



.

Figure 5.4 Load, THD and heating variation for a day in phase A

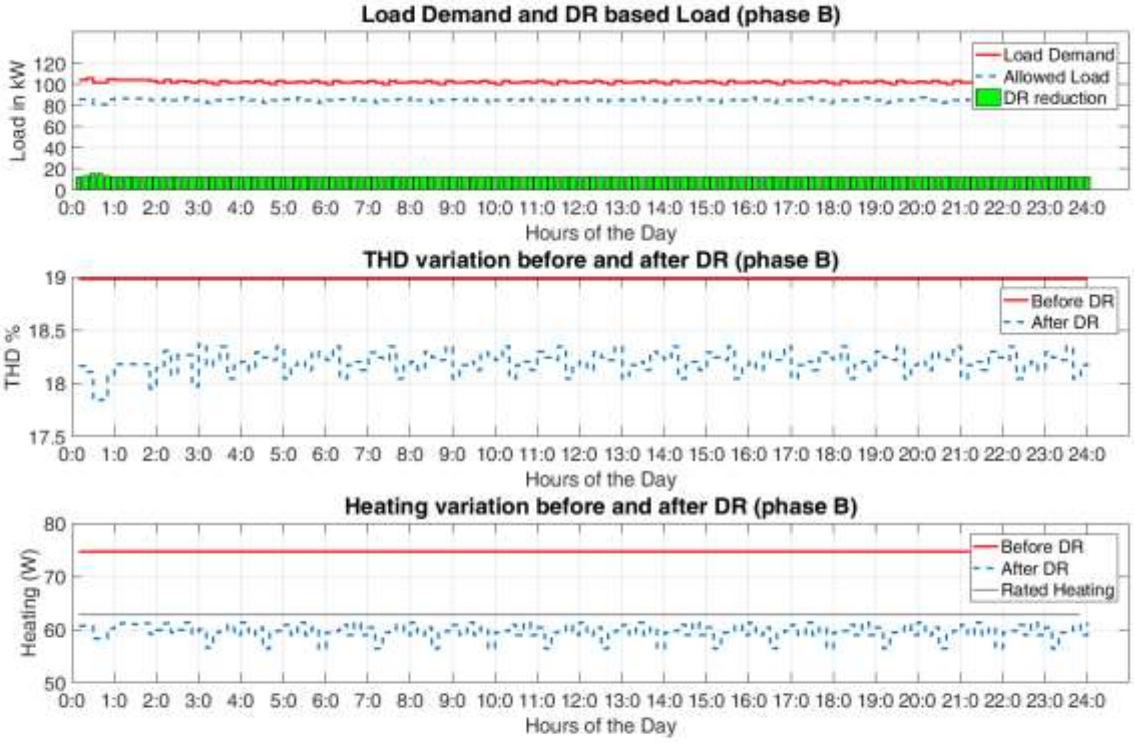


Figure 5.5 Load, THD and heating variation for a day in phase B

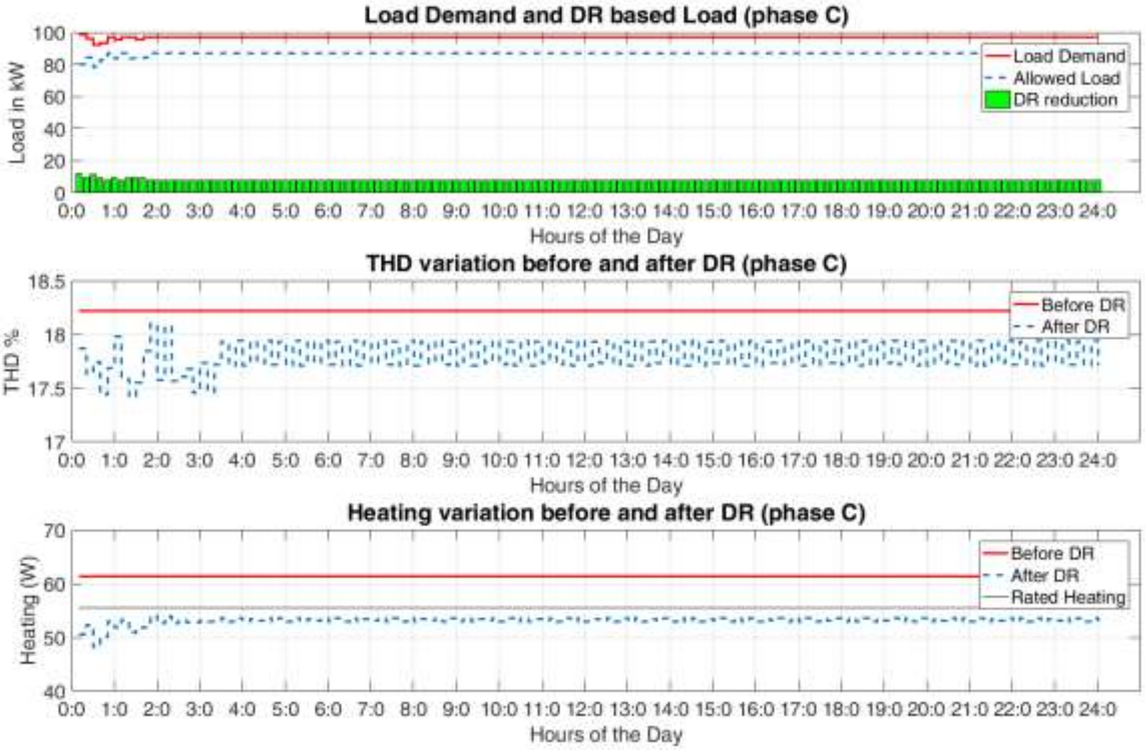


Figure 5.6 Load, THD and heating variation for a day in phase C

5.3.2 Scenario 2: With Different Levels of DG Penetration

This scenario uses the full load active condition from scenario 1 and adds solar PVDG to the network. Throughout the day, all 32 SPVDG power injection profiles are kept the same and follow a recorded pattern as given in Figure 5.7. The connected nodes of PVDG are given in Figure 4.5 and in Table 5.6. The level of penetration of PVDG is varied to have two levels of penetration. The high penetration scenario with a hosting capacity of 36% (maximum for the network[95]) and a low penetration scenario with 18% hosting capacity. Here hosting capacity refers to the level of total rated SPVDG in the network to the rating of distribution transformer (DT)(500kVA). The maximum peak output from the connected SPVDG is 5.75kW.

Further, the SPVDG is modelled as a pure sinusoid generator with 0.9 pf and no harmonic emission. This is employed considering the current strict regulation for grid-connected generators [175] [90]. PVDG being a purely linear source eliminates any harmonic cancellation which could undermine the study objective. A sensitivity with DG as a harmonic source is proposed as future work. The DT provides the non-linear current requirement of the load. Thus, with increased penetration, a higher level of THD% can be observed in section AB due to the reduced fundamental current requirement (already discussed in Chapter 4). However, the harmonic current flowing through the section remains the same. This scenario, along with different penetration levels, emphasizes the discussion in Section 4.4, using only the THD% not reliable metrics to sufficiently represent the harmonic severity in the distribution network.

The HC-C-DR will only activate during an increased heating loss in the cable and not just with a high THD percentage. The consumers in the network are participating in the DR program through an engagement plan (given in Table 5.3). The DR program manages the load to reduce harmonic heating in the cable while ensuring inconvenience caused to the consumer is minimum.

Table 5.6.Consumers with PVDG in each phase

Consumer in Phase A	Consumer in Phase B	Consumer in Phase C
5	1	3
13	4	7
20	14	10
26	23	17
28	36	34
31	49	39
43	58	55
51	64	65
57	68	
59	73	
63	74	
69		
71		

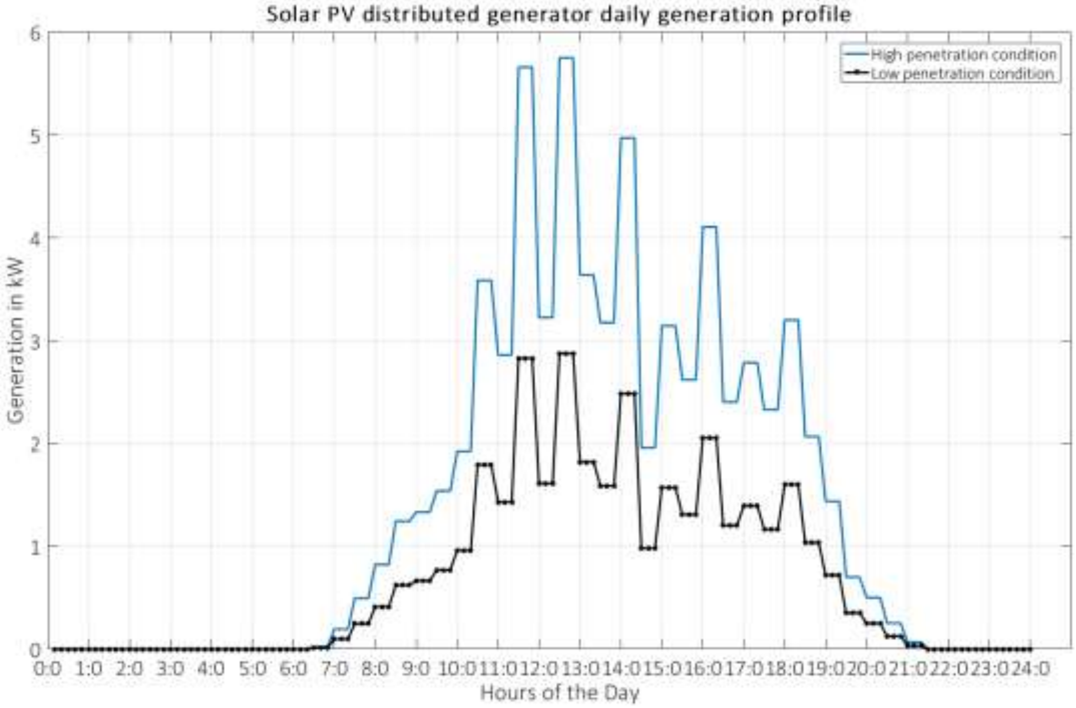


Figure 5.7 SPVDG generation profile for 24 hours

5.3.2.1 High Penetration Condition

With high penetration scenario, all 32 PVDG's are set to operate at full rating to have a maximum rating of 5.75kW. All 12 loads (Table 3.3) of 74 consumers are set to active demand. The consumers are participating according to their specific engagement plans. Compared to scenario 1, the cumulative consumer tolerance in Figure 5.8 corresponds to the change in generation in the network. This is not due to the lowering of consumer demand. Instead, the demand is met by the SPVDG generation during its generation period. This is evident from Figure 5.9, where the current flowing in the section AB is lowered with respect to the PVDG generation profile (comparing shapes in Figure 5.7 and Figure 5.9). Hence, the demand reduction required during this period is significantly lower than in other periods. However, this is not always the case as the DT still provides the non-linear current needed for the load to operate.

Figure 5.8 Cumulative consumer tolerance per phase for a day

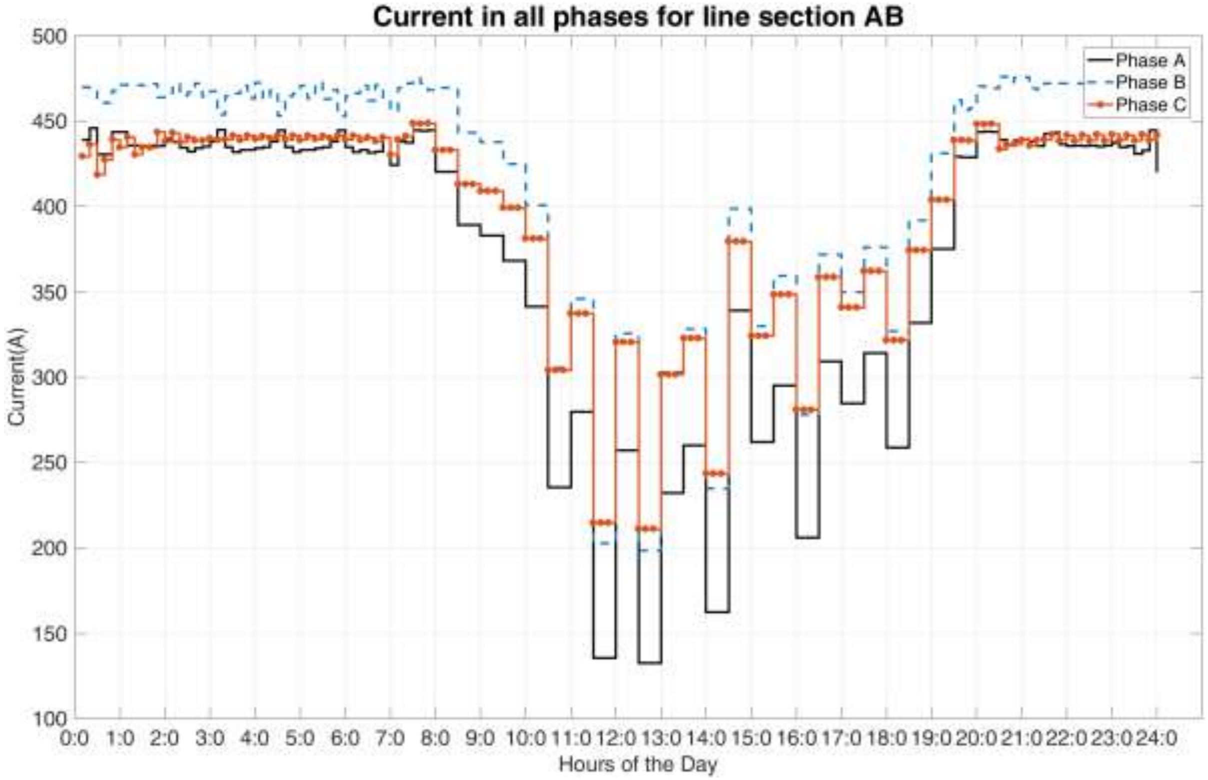
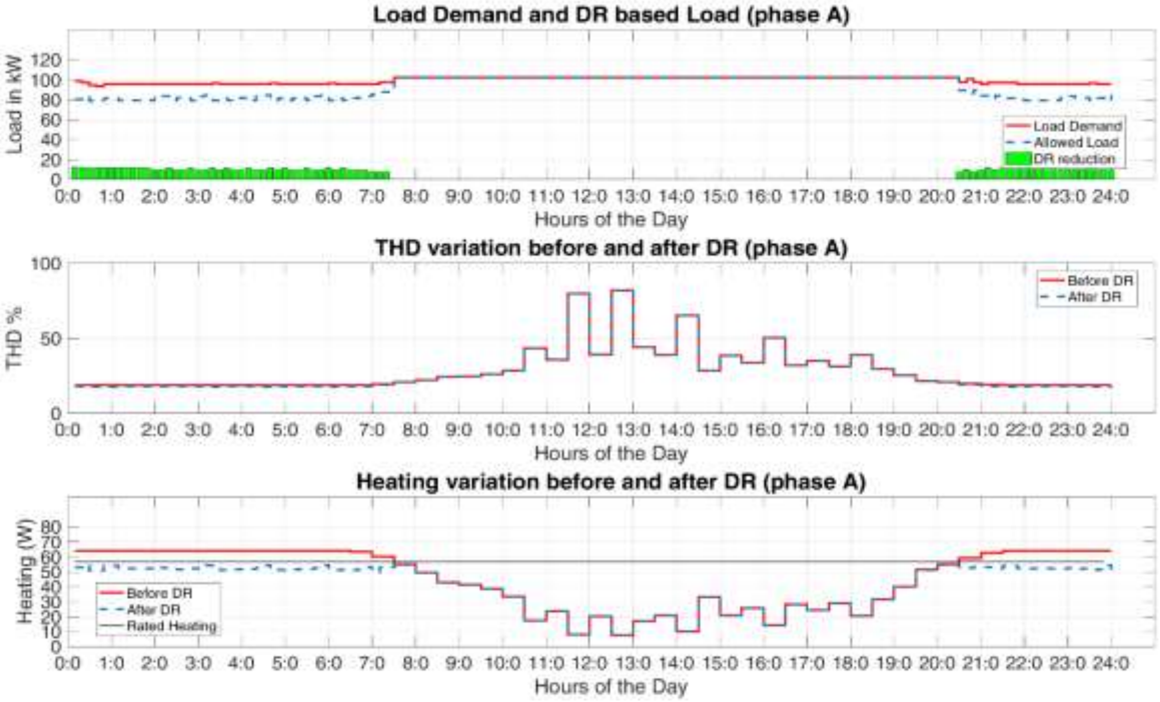


Figure 5.9 Current flow per phase for a day in section AB

From Figure 5.10 - Figure 5.12, the THD % in these phases are increasing during the high penetration scenario which would increase the heating in the cable. Hence, the potential advantage of having a PVDG to minimize the loading in the system may not always solve the cable heating issue. Without considering harmonic heating, the heating in the cable may be under the safe operation limit, which is not the case owing to the harmonic heating component. The THD% and heating loss in Figure 5.10 - Figure 5.12 show a pattern regarding the PVDG power output(Figure 5.7). A closer comparison between scenario 1 (Figure 5.4 - Figure 5.6) and scenario 2 (Figure 5.10 - Figure 5.12) shows that the total demand reduction required with PVDG in the system is lower. This is also evident from the lower levels of cumulative consumer tolerance in Figure 5.8. This is owing to a portion of local load during the daytime being supplied by PV. This reduces the current in the cable section AB. Meanwhile, all harmonic currents are supplied through AB and hence the THD% during the daytime is much higher than any acceptable limit. Yet, in the LVDN perspective, the system is safe as cable heating is lower than the maximum rated value. This may beg the question of distortion of voltage in the network. However, this low level of harmonic current will not distort the supply voltage to dangerous levels considering the nature of a large transmission power grid to have a stiff reactance (due to inductance).


Load Demand and DR based Load (phase A)

THD variation before and after DR (phase A)

Heating variation before and after DR (phase A)

Figure 5.10 Load, THD and heating variation for a day in phase A

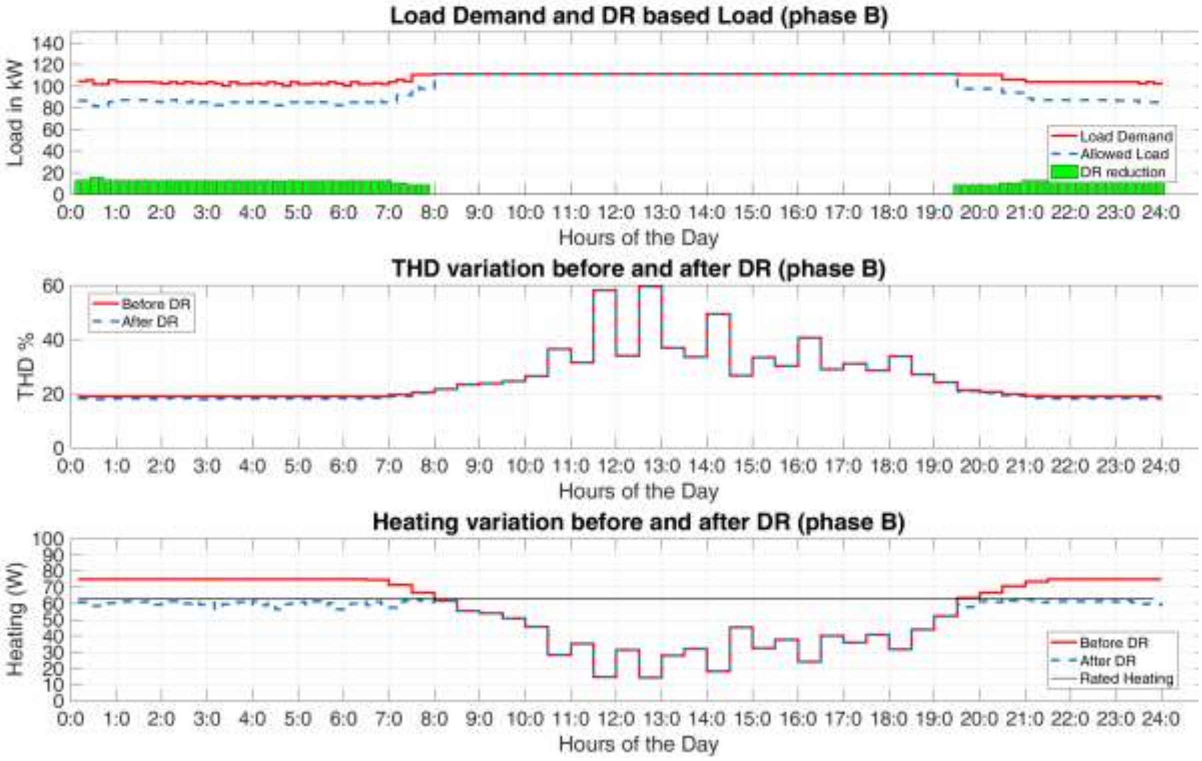


Figure 5.11 Load, THD and heating variation for a day in phase B

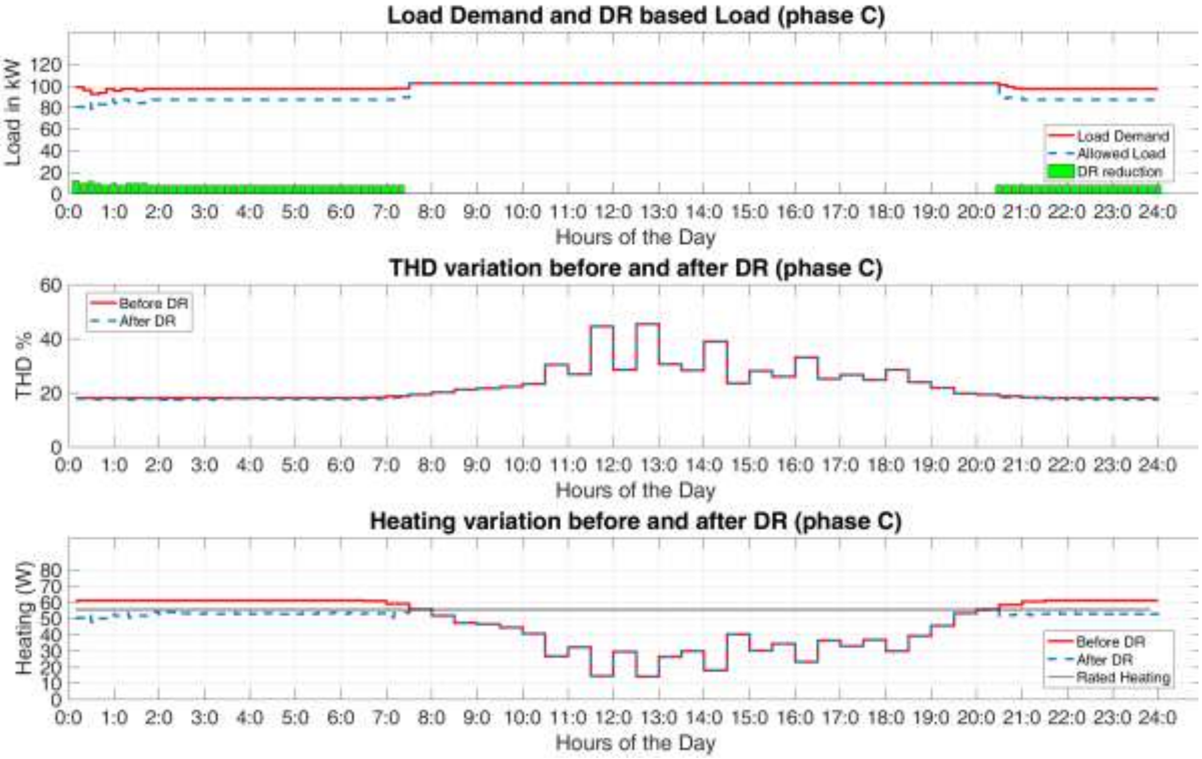


Figure 5.12 Load, THD and heating variation for a day in phase C

The implication from these results is that the proposed algorithm efficiently detects overheating scenarios and then recommends a solution to deescalate the situation using demand response even under high PVDG penetration while ensuring minimum consumer inconvenience.

Table 5.7 cumulates system parameters for three separate time instances to compare the impact of SPVDG operation. The times considered are 12:30 PM, 7:30 PM and 9:30 PM. The selection was arbitrary with the intention to show the level of PVDG operation towards the performance of HC-C-DR and associated parameters. At the same time instances, the penetration in each phase is given by the ratio of SPVDG power generated to the total load in the particular phase (Table 5.8). With load demand being the same during these instances, the reduction required is not the same due to the generation of SPVDG. However, the load curtailment is not proportional to the generation. In fact, the load curtailment is not governed by the demand in the network, rather the heating in the cable. The SPVDG generation is only contributing to the fundamental current requirement in the network and hence during the generation period, the THD% on the cable section AB is high, as evident from Table 5.7 (At 12:30). Yet, the cable section's heating is lower than the rated value, and hence DR is not initiated. However, at 7:30 PM, the PVDG generation is low, which demand higher current flow in the cable. This results in higher heating loss and initiates DR in phase B. Now, at 9:30 PM when no PVDG generation is available, the HC-C-DR operates similar to Scenario 1. The SPVDG generation at each of these times are given in Table 5.8. The total load reduction per phase in the network for each engagement plan is given in Table 5.9.

Table 5.7.System parameters before and after DR at different time of day for Scenario 2 high penetration condition

	High PV injection (12:30PM)			**Low PV injection (7:30PM)**			**No PV injection (9:30PM)**		
	Before DR	**After DR**	**Change**	**Before DR**	**After DR**	**Change**	**Before DR**	**After DR**	**Change**
Total Network Load (kW)	316.49	316.49	-	313.07	304.40	2.77%	288.17	255.99	11.17%
Total Load Phase A (kW)	102.65	102.65	-	102.65	102.65	0.00%	93.37	81.50	12.71%
Total Load Phase B (kW)	111.20	111.20	-	107.78	99.11	8.04%	99.76	87.05	12.74%
Total Load Phase C (kW)	102.65	102.65	-	102.65	102.65	0.00%	95.04	87.44	8.00%
THDi % Phase A	81.83	81.83	-	21.60	21.60	0.02%	18.74	17.92	4.37%
THDi % Phase B	59.55	59.55	-	21.23	20.85	1.81%	18.99	18.21	4.07%
THDi % Phase C	45.51	45.51	-	19.87	19.88	0.04%	18.22	17.54	3.74%
Iab Phase A (A)	132.56	132.56	-	429.32	429.04	0.07%	481.57	442.46	8.12%
Iab Phase B (A)	198.38	198.38	-	477.15	462.24	3.12%	520.35	472.21	9.25%
Iab Phase C (A)	210.97	210.97	-	438.75	438.74	0.00%	472.06	439.06	6.99%
Heating line-ab Phase A(W)	7.82	7.82	-	51.43	51.36	0.13%	63.99	53.86	15.83%
Heating line-ab Phase B (W)	14.21	14.21	-	63.43	59.43	6.30%	74.78	61.41	17.87%
Heating line-ab Phase C (W)	14.32	14.32	-	53.34	53.34	0.00%	61.38	52.97	13.70%
Total Network Inconvenience	41.48	41.48	-	41.48	41.60	0.29%	41.48	43.32	4.44%
Inconvenience A	14.35	14.35	-	14.35	14.35	0.00%	14.35	14.89	3.76%
Inconvenience B	15.38	15.38	-	15.38	15.50	0.78%	15.38	16.56	7.67%
Inconvenience C	11.75	11.75	-	11.75	11.75	0.00%	11.75	11.87	1.02%

Table 5.8.PV injection levels in the network at different time of the day for Scenario 2 high penetration condition

	High PV injection (12:30PM)		**Low PV injection (7:30PM)**		**No PV injection (9:30PM)**	
	Power (kW)	**% Penetration**	**Power (kW)**	**% Penetration**	**Power (kW)**	**% Penetration**
PV Output power phase A	74.75	73%	9.11	8.9%	-	-
PV Output power phase B	63.25	57%	7.71	7.8%	-	-
PV Output power phase C	46.00	45%	5.61	5.5%	-	-

Table 5.9.Demand reduction per phase for different engagement plan in kWh

All values in kWh	**SGS**	**GS**	**GA**	**R**	**Total**
Phase A	90	24	-	-	114
Phase B	105	46	-	-	151
Phase C	87	-	-	-	87
Total	282	70	-	-	351

A representative consumer in each engagement plan for each phase is presented in Appendix C. A lower penetration scenario with the maximum hosting capacity of 18% is presented next as a sensitivity study with different levels of DG penetration and HC-C-DR performance evaluation.

5.3.2.2 Low Penetration Condition

The low penetration condition is created by halving the PVDG profile used in high penetration condition as given in Figure 5.7 thus creating an 18% hosting capacity scenario. The condition is used to evaluate the subtle differences between the performance of HC-C-DR under different penetration levels and its capability to respond to the situation at hand.

Similar to high penetration condition, the cumulative consumer tolerance per phase (Figure 5.13) is varying depending on the SPVDG generation. The magnitude of change depends on the participation of consumers towards load reduction. The PVDG is able to provide for the fundamental current demand of consumers. Hence, the DT supplies the deficit fundamental current (Figure 5.14) and all harmonic current demanded by the loads. When compared with high penetration condition (Figure 5.9) the shape of current demand from DT is the same in Figure 5.14, but its magnitude is higher in the low penetration condition. For instance, at 2:00 PM, the high penetration condition had phase A current just above 160A. At the same time for low penetration, it is just above 300A, which almost double from high penetration.

Figure 5.13 Cumulative consumer tolerance per phase for a day

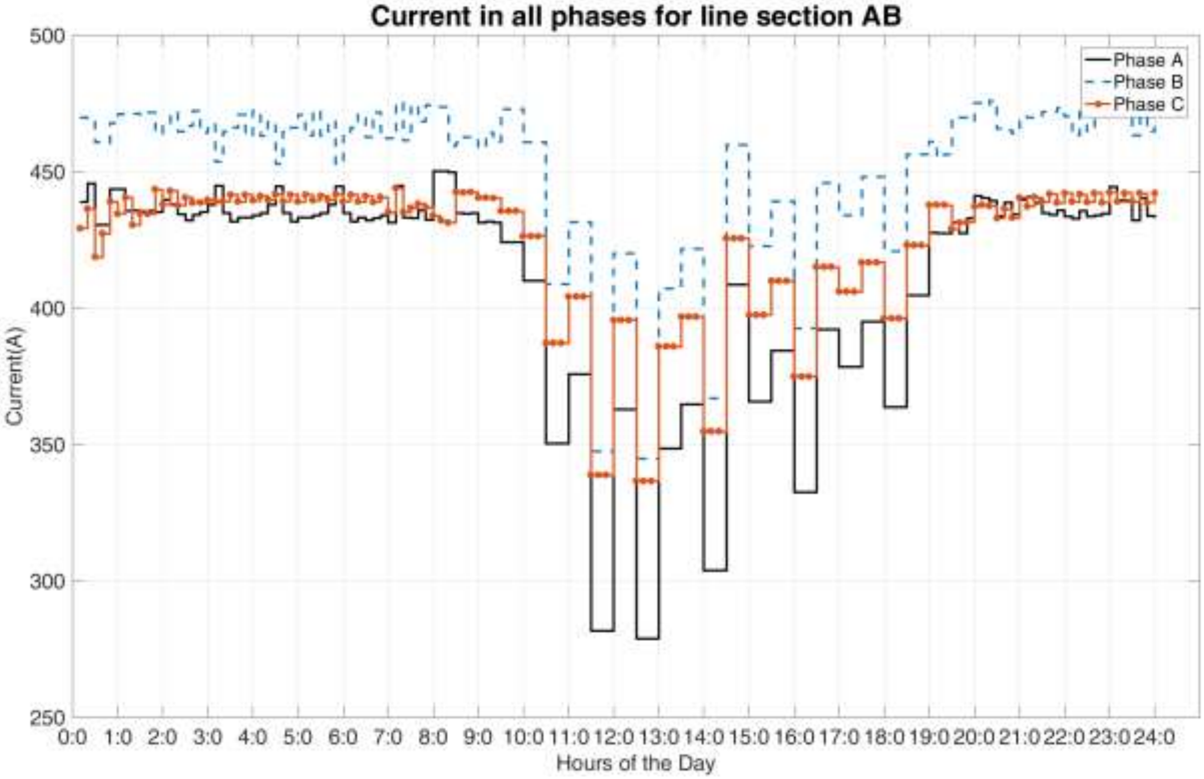
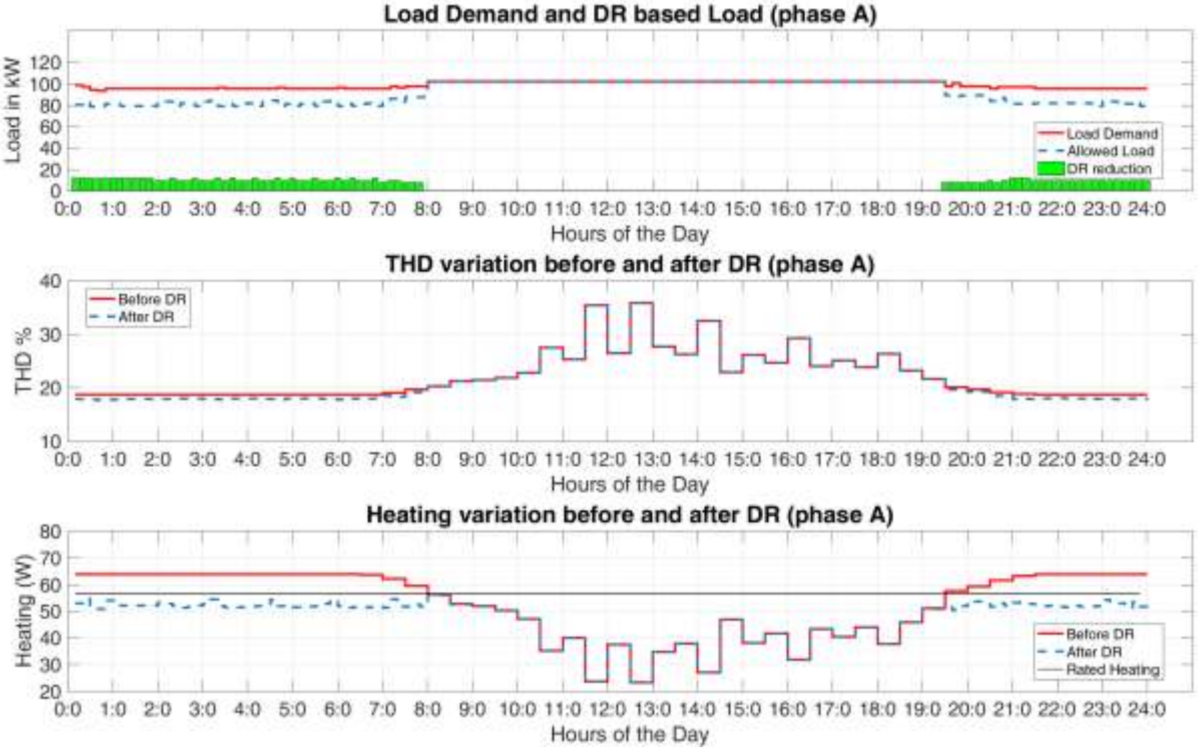


Figure 5.14 Current flow per phase for a day in section AB

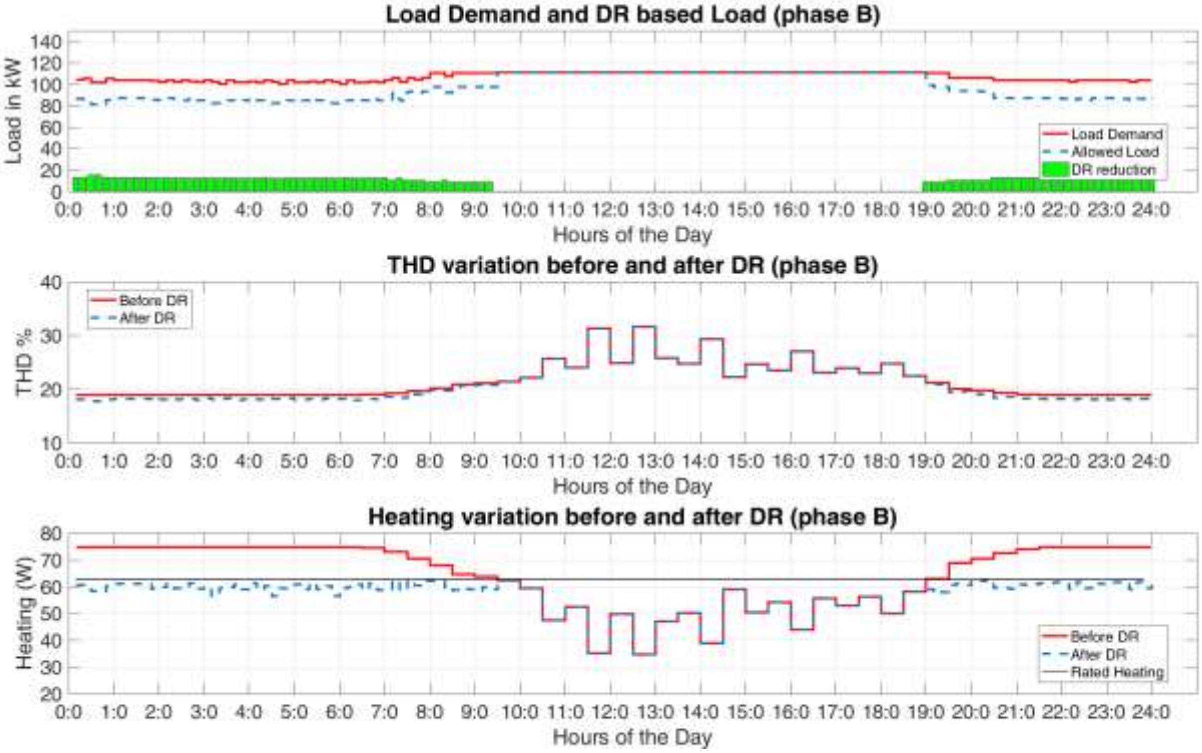
Figure 5.15 - Figure 5.17 shows the load demand, reduction, THD%, and heating in cable section AB for phases A, B, and C. Like the high penetration condition, the THD increases with respect to the PVDG injecting power into the network. However, the increase in THD% when compared to the high penetration condition is lower. Further, the correlation between DG penetration and the harmonics is visible as the shape is similar to the PV generation portfolio. In Phase B, at 8 AM in high penetration scenario, the algorithm is not initiated as the heating loss is below the rated value, whereas, in low penetration condition, this has to wait up to 9:30 AM. Further, the heating loss is high at low penetration scenario due to the increased magnitude of fundamental current in the cable. Thus, with respect to the harmonics issue, the high penetration is favourable for the network operator.


Load Demand and DR based Load (phase A)

THD variation before and after DR (phase A)

Heating variation before and after DR (phase A)

Figure 5.15 Load, THD and heating variation for a day in phase A


Load Demand and DR based Load (phase B)

THD variation before and after DR (phase B)

Heating variation before and after DR (phase B)

Figure 5.16 Load, THD and heating variation for a day in phase B

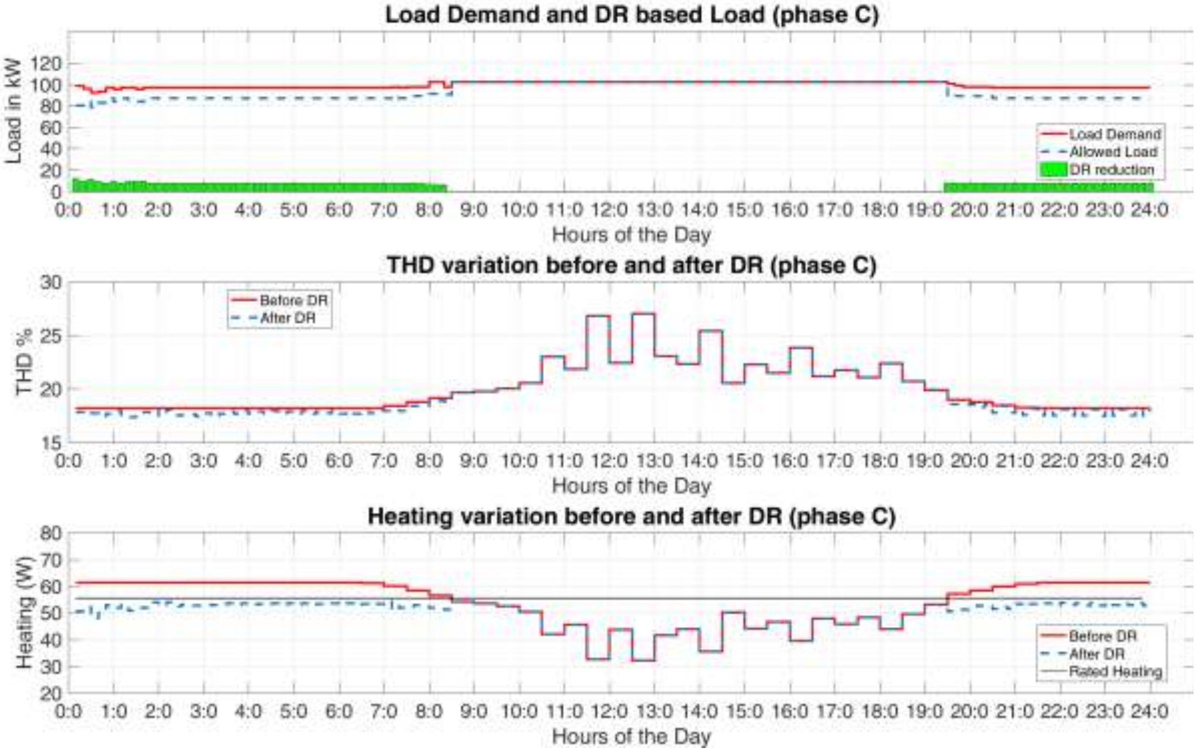


Figure 5.17 Load, THD and heating variation for a day in phase C

The Table 5.10 shows cumulative network parameters for the three different time instances to represent the system with PVDG generation and without PVDG generation. Like high penetration condition, the THD in cable section AB has increased with PVDG actively supplying the fundamental current component of the loads connected in the network. Table 5.11 gives the penetration level of PVDG with respect to these time instances. Comparing Table 5.7 and Table 5.11, penetration being halved. Higher levels of demand reductions are initiated at 7:30 PM as sufficient PVDG power is not available to reduce the current drawn from the grid. However, there is a significant variation in THD %, as was expected. Apart from that, the heating loss change between high and low penetration scenario at 7:30 PM is 5-10% per phase (Table 5.10). With an increase in penetration, the heating loss has decreased in the cable section in consideration. However, there is an upper bound to this as the quadratic dependencies between heating and THD value will outweigh the positive impact of PVDG after a certain level. The total reductions per phase per engagement plan is given in Table 5.12. A representative consumer in each engagement plan in each phase is given in Appendix C.

Table 5.10.System parameters before and after DR at different time of day for Scenario 2 high penetration condition

	High PV injection (12:30PM)			**Low PV injection (7:30PM)**			**No PV injection (9:30PM)**		
	Before DR	**After DR**	**Change**	**Before DR**	**After DR**	**Change**	**Before DR**	**After DR**	**Change**
Total Network Load (kW)	316.49	316.49	-	297.52	271.61	8.71%	286.27	256.62	10.36%
Total Load Phase A (kW)	102.65	102.65	-	97.27	89.62	7.86%	91.47	82.13	10.21%
Total Load Phase B (kW)	111.20	111.20	-	104.23	93.84	9.96%	99.76	87.05	12.74%
Total Load Phase C (kW)	102.65	102.65	-	96.02	88.15	8.20%	95.04	87.44	8.00%
THDi % Phase A	35.85	35.85	-	20.09	19.64	2.23%	18.74	18.03	3.78%
THDi % Phase B	31.62	31.62	-	20.06	19.47	2.92%	18.99	18.23	4.01%
THDi % Phase C	27.01	27.01	-	19.02	18.61	2.18%	18.22	17.54	3.75%
Iab Phase A (A)	278.81	278.81	-	455.50	431.36	5.30%	481.57	434.74	9.72%
Iab Phase B (A)	344.89	344.89	-	498.84	468.87	6.01%	520.35	471.91	9.31%
Iab Phase C (A)	336.63	336.63	-	455.40	428.90	5.82%	472.06	438.99	7.01%
Heating line-ab Phase A(W)	23.38	23.38	-	57.54	51.52	10.47%	63.99	52.02	18.71%
Heating line-ab Phase B (W)	34.88	34.88	-	69.00	60.83	11.85%	74.78	61.34	17.97%
Heating line-ab Phase C (W)	32.41	32.41	-	57.29	50.74	11.43%	61.38	52.95	13.73%
Total Network Inconvenience	41.48	41.48	-	41.48	41.95	1.13%	41.48	44.33	6.87%
Inconvenience A	14.35	14.35	-	14.35	14.47	0.84%	14.35	15.15	5.57%
Inconvenience B	15.38	15.38	-	15.38	15.61	1.50%	15.38	17.31	12.55%
Inconvenience C	11.75	11.75	-	11.25	11.87	5.51%	11.25	11.87	5.51%

Table 5.11.PV injection levels in the network at different time of the day for Scenario 2 high penetration condition

	High PV injection (12:30PM)		**Low PV injection (7:30PM)**		**No PV injection (9:30PM)**	
	Power (kW)	**% Penetration**	**Power (kW)**	**% Penetration**	**Power (kW)**	**% Penetratio n**
PV Output power phase A	37.38	36.41%	4.56	5.08%	-	-
PV Output power phase B	31.63	28.44%	3.86	4.11%	-	-
PV Output power phase C	23.00	22.41%	2.80	3.18%	-	-

Table 5.12.Demand reduction per phase for different engagement plan in kWh

All values in kWh	**SGS**	**GS**	**GA**	**R**	**Total**
Phase A	100	25	-	-	125
Phase B	121	52	-	-	173
Phase C	101	-	-	-	101
Total	322	77	-	-	399

5.3.3 Scenario 3: With Recorded Consumer Load Profile

Contrary to all load ON scenarios (scenarios 1 and 2), the real load scenario uses recorded consumer load profiles. Eight consumer load profiles are utilized to create 74 load profiles for 74 consumers in the network. Each profile pertains to consumers with distinct socio-economic classification. The properties used to form this classification is given in Table 3.5 (Chapter 3). Each of these categories represents a change in electricity consumption pattern represented in Figure 3.11. These consumers are also allocated to different engagement plans (as provided in Table 5.12), which defines their tolerance/inconvenience value (Section 3.3) towards the load changes. The load categorization produces different loading levels in each phase, resulting in varying levels of harmonic emission. The harmonic emission and the loading levels produces harmonic heating in the cable. Similar to the previous scenarios, cable section AB is considered as the critical point in the network and heating of this section is considered to trigger the HC-C-DR. The DR programs reduce the loads whenever the heating in any one phase of cable section AB is greater than the nominal heating produced during rated linear current flow. The load reduction is applied only to the phase which has violated the heating constraint. Thus, the consumers connected to other phases are not impacted due to power quality issues in other phase/s.

Table 5.13. Distribution of consumers to consumer profiles

Profile 1	**Profile 2**	**Profile 3**	**Profile 4**	**Profile 5**	**Profile 6**	**Profile 7**	**Profile 8**	**Engagement Plans**
1	2	3	4	5	6	7	8	SGS
9	10	11	12	13	14	15	16	GS
17	18	19	20	21	22	23	24	GA
25	26	27	28	29	30	31	32	R
33	34	35	36	37	38	39	40	SGS
41	42	43	44	45	46	47	48	GS
49	50	51	52	53	54	55	56	GA
57	58	59	60	61	62	63	64	R
65	66	67	68	69	70	71	72	SGS
73	74							GS

The cable in section AB has a maximum rated current to be 360A with a resistance of 0.25mΩ per meter. The normal operation maximum heating loss would be 32.5 watts. Different loading levels cause different levels of harmonic emission at different times. The applied load curves/profiles (in Figure 3.11) are of the typical residential consumer load curve pattern and have a peak in the morning and evening times. Apparently, these are also the times when there are high levels of harmonic current in the system (but not high THD). Since THD% depends on the fundamental current, high levels of THD occur during low loading levels or with a lower fundamental current component.

The table below (Table 5.14) presents the system parameters for before and after the HC-C-DR algorithm is applied to manage cable heating at 8:40 PM. The total network load is reduced by 22.41% by HC-C-DR to manage high levels of cable heating in each phase. Compared to this scenario, scenario 1 had an 18.9% load reduction in the network. However, the change in the inconvenience level in this scenario is only 15.6% compared to 20.9% in scenario 1. The increase in inconvenience in an interval can be viewed as the effort required by the algorithm to achieve the necessary reduction. When considered individual phases, the reduction in load is

20%, 26% and 27% in each phase compared to their demand. The heating loss in each phase was reduced by 31%, 42% and 42% in phase A, B and C respectively. This was attributed by load reduction to a certain extent, but with a high reduction in THD, the contribution of harmonic emission to the reduction of cable heating is also significant. The current flowing through phase B, if linear, would produce a heating loss of 48.5 watts in the cable, but with a THD% of 16.5%, it would result in a heating loss of 53.2 watts, according to equation 4.5. The difference emphasises the need for the utilization of harmonic heating analysis to manage heating loss in the cable. Table 5.15 shows the demand reduction imposed for each consumer engagement category.

Table 5.14.System parameters before and after DR at 8:40 PM for Scenario 3

	Before DR	**After DR**	**% Change**
Total Network Load (kW)	202.91	157.45	22.41%
Total Load Phase A (kW)	67.03	53.60	20.03%
Total Load Phase B (kW)	68.84	50.68	26.37%
Total Load Phase C (kW)	67.05	53.16	20.70%
THDi % Phase A	15.97	14.22	10.94%
THDi % Phase B	16.39	13.85	15.50%
THDi % Phase C	16.01	14.47	9.64%
Iab Phase A (A)	395.29	326.99	17.28%
Iab Phase B (A)	440.82	336.62	23.64%
Iab Phase C (A)	419.61	319.81	23.78%
Heating line-ab Phase A (W)	42.71	29.08	31.92%
Heating line-ab Phase B (W)	53.19	30.79	42.13%
Heating line-ab Phase C (W)	48.14	27.83	42.18%
Total Network Inconvenience	41.00	47.46	15.76%
Inconvenience A	14.20	14.78	4.08%
Inconvenience B	15.20	19.12	25.79%
Inconvenience C	11.25	13.56	5.50%

Table 5.15.Demand reduction per phase for different engagement plan in kWh

All values in kWh	**SGS**	**GS**	**GA**	**R**	**Total**
Phase A	26	4	-	-	30
Phase B	36	24	1	-	61
Phase C	35	2	-	-	37
Total	98	30	1	-	128

The Figure 5.18 shows the cumulative change in the inconvenience parameter for the day in each phase. The inconvenience parameter updates only during the demand reduction or application of HC-C-DR to reduce heating in the cable. Different phases have different loading levels as they accommodate different numbers of consumers with different sets of load profiles. This results in varying levels of heating in cables in each phase. The HC-C-DR algorithm will initiate demand reduction only if there is a violation of maximum cable heating and cause an update in the cumulative inconvenience in each phase as given in Figure 5.18. The Figure 5.19 - Figure 5.21 shows the load demand, demand reduction, THD % and cable heating in section AB in respective phases throughout the day. Compared to scenario 1, in scenario 3, load reduction is occurring only during peak demand. During peak demand, the current demand is high. However, from Figure 5.19 - Figure 5.21 a high level of THD % can be observed during midday due to low fundamental current. Each phase has different levels of load reduction depending on the reduction requirement. In Figure 5.19, the HC-C-DR initiates only for a few times, but for Figure 5.20 in phase B it is triggered for a much larger number of instances and even during midday. The sensitivity of the algorithm is only towards heating loss, while the objective is to minimize consumer inconvenience.

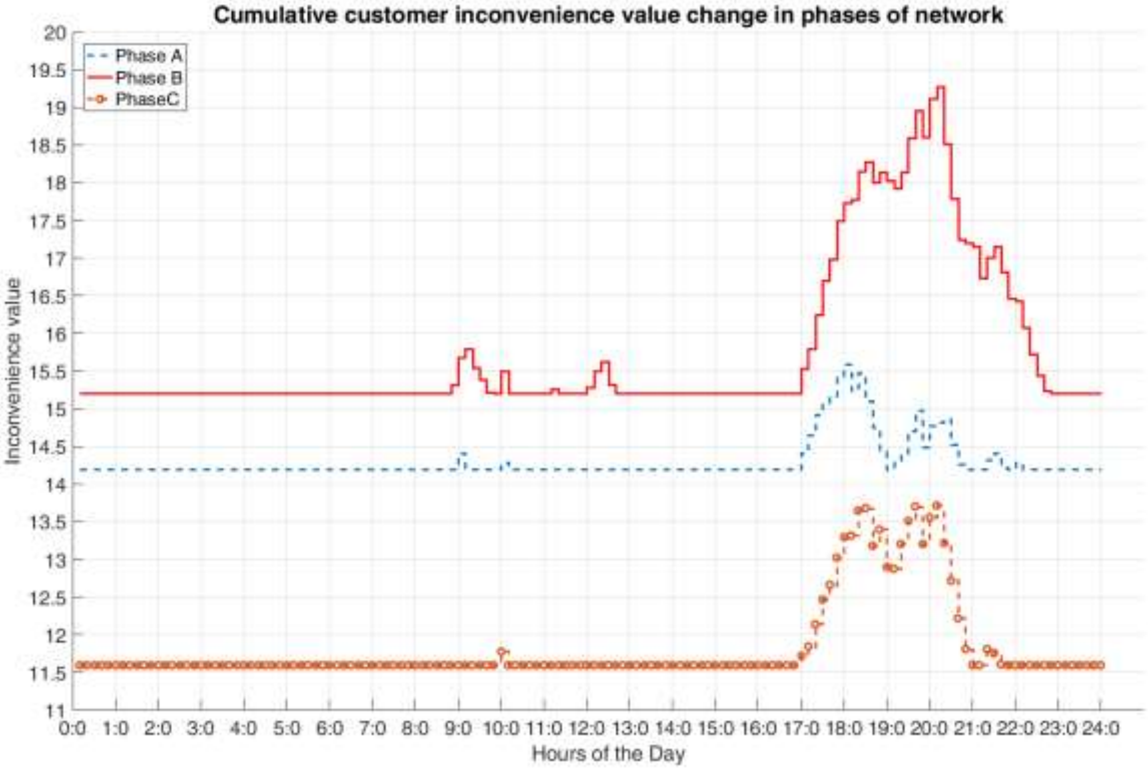


Figure 5.18 Cumulative consumer tolerance per phase for a day

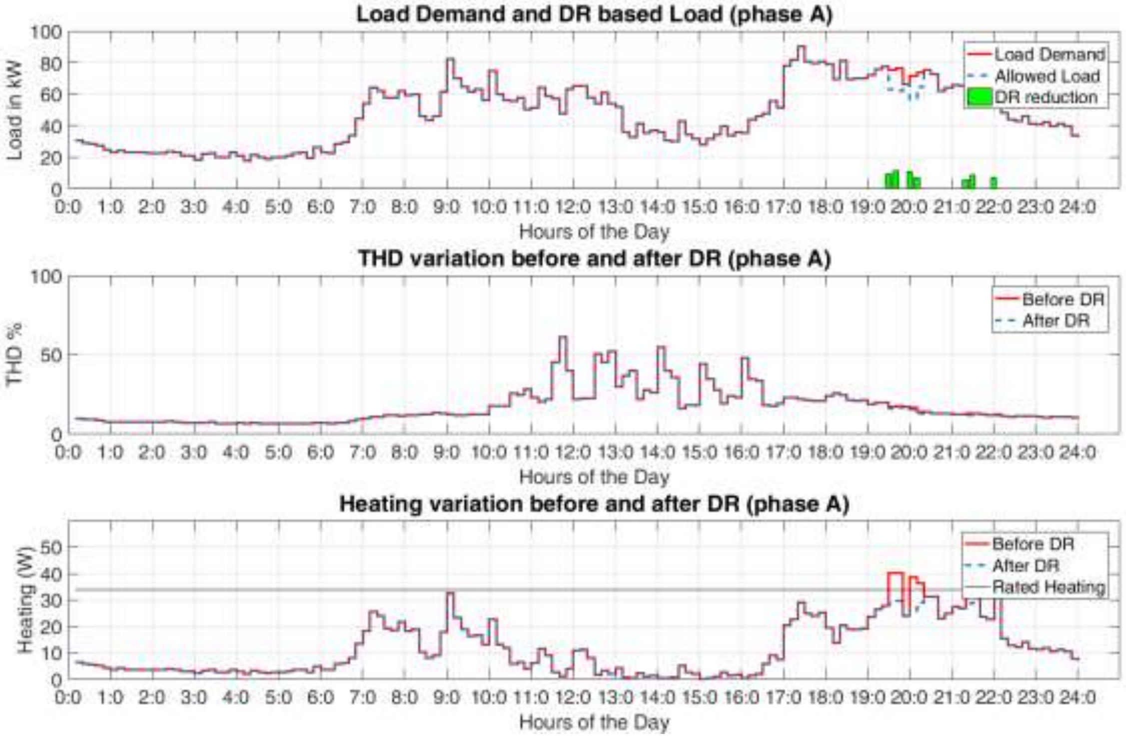


Figure 5.19 Load, THD and heating variation for a day in phase A

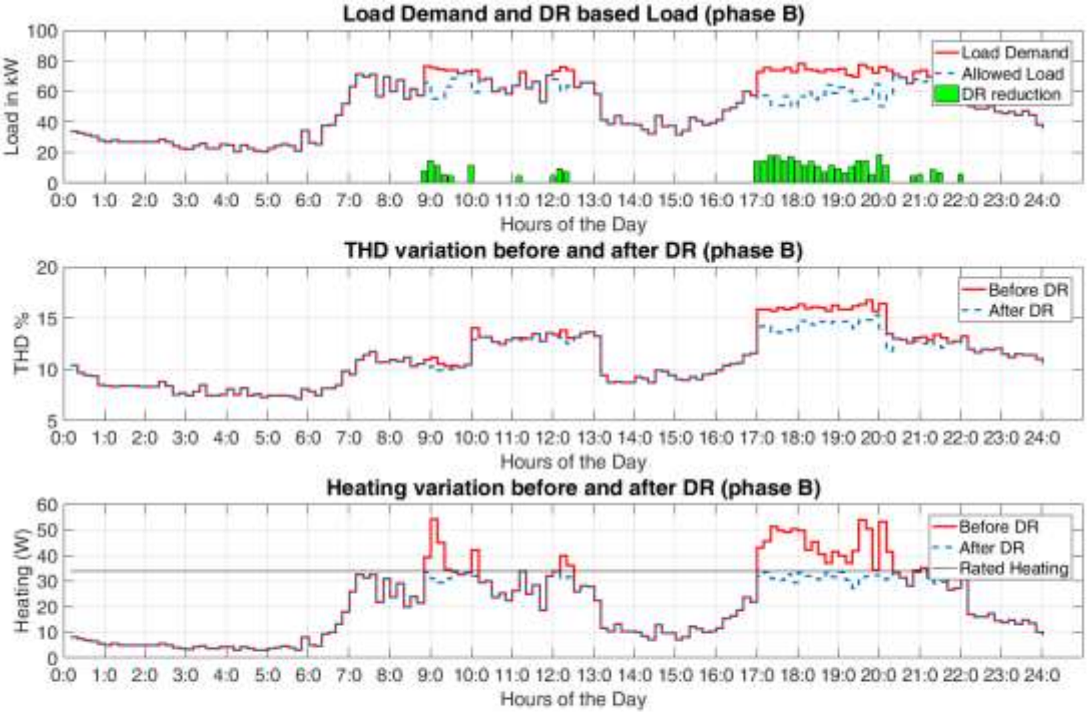


Figure 5.20 Load, THD and heating variation for a day in phase B

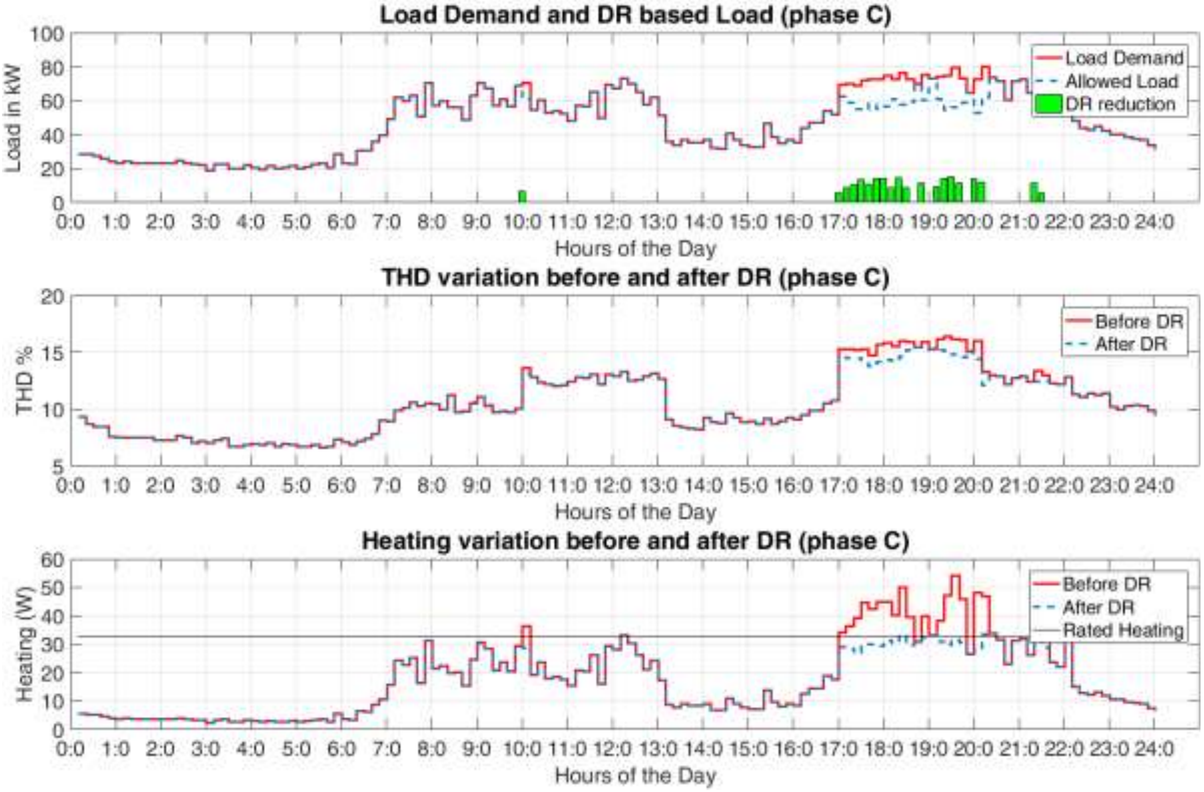


Figure 5.21 Load, THD and heating variation for a day in phase C

5.4 Comparison of Load Reduction Between Scenarios

The percentage load reduction with respect to total reduction in each scenario is given in Figure 5.22 along with per phase reduction. The consumers in engagement plan Green Aware is not utilized for DR. The consumers in Reluctant engagement plan are not participating towards load reduction at all as per their choice. The major part of the reduction is implemented through Super Green Savvy consumer. This could easily translate to higher benefit to the consumer but under higher inconvenience. When compared to total network load demand, the reduction contribution by each consumer is less than 2.5% from Figure 5.23. While the study scenarios individually had high demand reduction instances, the overall reduction impact is minimum and is well distributed between the engagement plans.

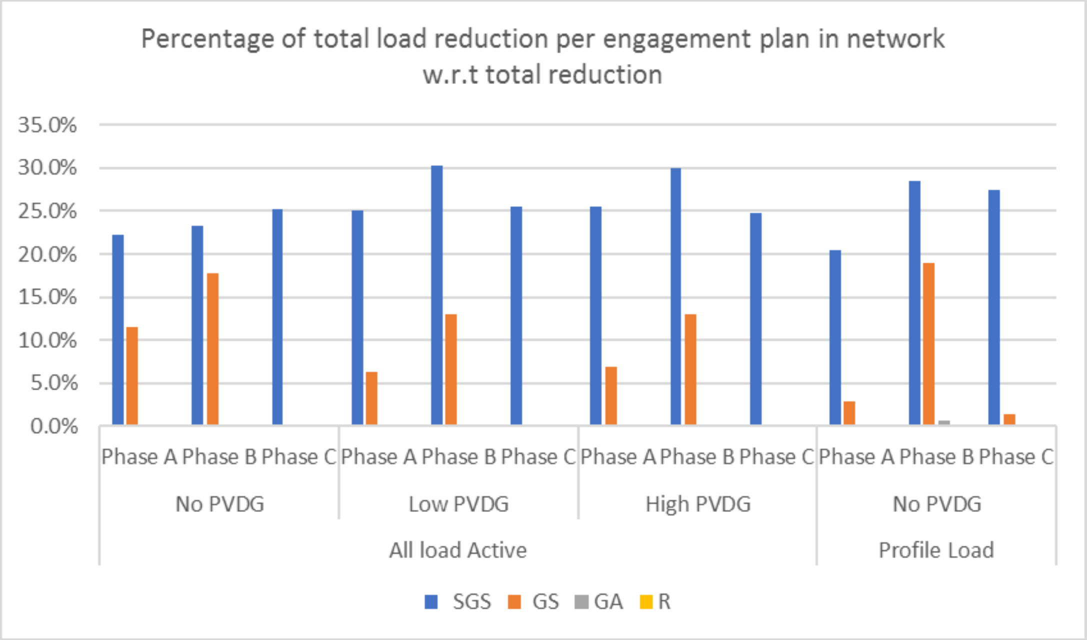


Figure 5.22 Percentage of total load reduction per engagement plan in network w.r.t total reduction

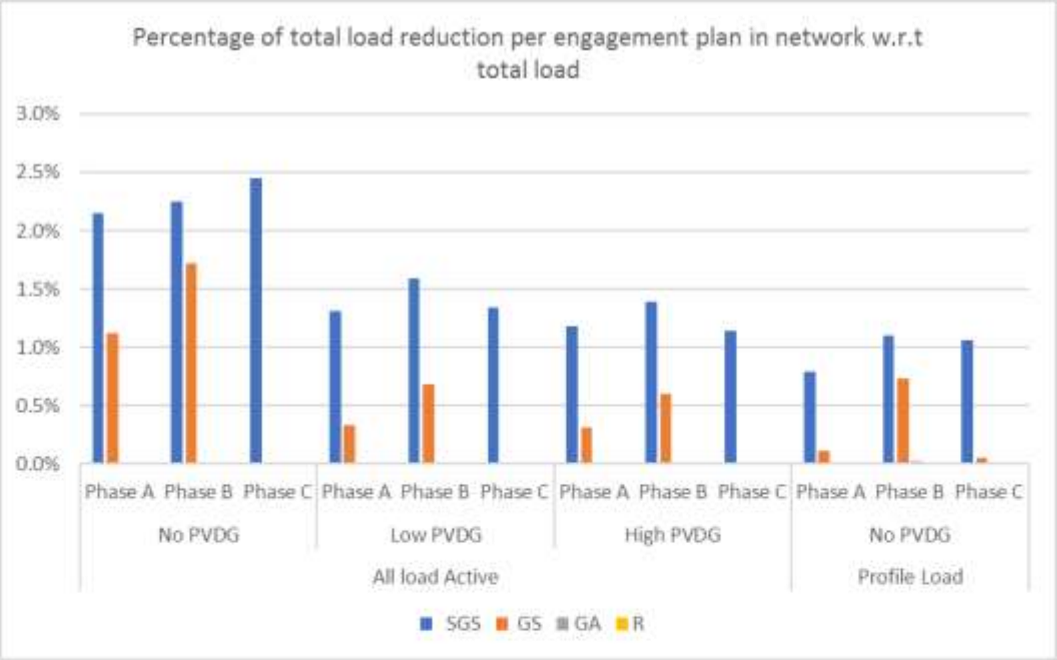


Figure 5.23 Percentage of total load reduction per engagement plan in network w.r.t total load

5.5 Application of Demand Response to Improve Voltage Regulation with High DG Penetration

The application of the DR program for managing harmonic emission and its associated impact is explored in the previous sections. This section intends to strengthen the idea of utilizing an improvised DR-based program to manage a further power quality issue; voltage drop/rise. The dependencies of the voltage profile of radial feeder towards active power flow is presented in Section 4.10. The methodology applied to manage undervoltage and overvoltage is described in Section 4.11 and Section 4.12, respectively. The following sections investigate the application of the incremental generation reduction based voltage control (DR-VC) algorithm.

5.6 The analysis and Results

The level of voltage profile is dependent on the amount of PVDG penetration. Hence, the presented study has adopted limits of hosting capacity suggested by the authors in [95] (also used in scenario 2). For simplicity, the stochasticity associated with consumers load consumption pattern is ignored, and all consumers are modelled to have the same generalised daily load curve given in Figure 5.24. The generalized load curve was generated using an average model utilizing the load consumption of 300 consumers obtained from the Irish Social Science Data Archive (ISSDA) [167]. The maximum loading of the LVDN is restricted by the thermal limit or the current carrying capacity. The network used for analysis is a radial urban distribution network with 74 customers. The network parameters are consistent with Section 4.6. This network has the maximum current carrying capacity limited by the first section (line AB) and is 360A (185 mm2 XLPE). The transformer set at the beginning of the feeder is 500kVA (3 winding, 20kV/440V) capacity and is set to provide a voltage rating of 1p.u. at its secondary. Generally, the regulation suggests a tolerance of ±10% for LVDN voltage level, and hence, the upper limit is 1.1 p.u and the lower limit is set to 0.9 p.u (light bounding). A scenario was also analysed to regulate the voltage profile between 1.05 – 0.95 p.u and ascertain the algorithm's capability to operate in tightly bound conditions.

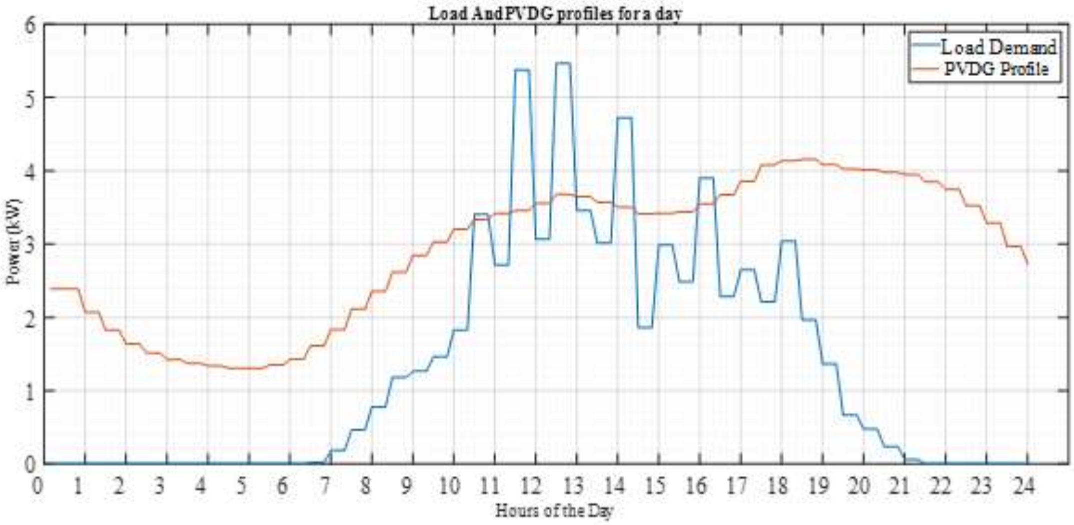


Figure 5.24 Load and PVDG profile of a day

Similar to Scenario 2, this study used 32 PVDG's distributed (as in Table 5.6) throughout the LVDN with a maximum rating of 5.75kVA each and constituting a maximum generation of 184kVA in total. Different conditions were simulated with a range of loading and generation levels and is represented in Table 5.16. The LVDN is subjected to different loading and DG penetration levels while voltages of each phase at the node A and J are noted. The node A being close to the DT, has a minimum voltage drop/rise, whereas node J (farthest) has the highest voltage drop/rise. It can be noted that with an increase in loading, the voltage varies progressively (increases/decreases) with a constant trend. With PVDG generation operating at different levels, the voltage magnitude at node J varies with respect to the amount of generation increase (Table 5.16).

An interesting observation from Table 5.16 is that higher penetration of PVDG at high loading can compensate for the voltage drop at node J. Correlating with equation (4.14), the reduction of the active power component would significantly impact the voltage regulation. However, with a light load, the voltage rise at the lower end of LVDN can increase and violate the upper bound. Hence, managing the penetration level of DGs in the LVDN allows the operator to directly manage the system's loading. If in complement with DR, the program has an advantage as it would induce less inconvenience to the consumers.

Table 5.16. Voltages at 1st and last pillar at different loading levels

% PVDG Output	Loading %	Voltage at node A (p.u)			Voltage at node J (p.u)		
		Phase			Phase		
		A	B	C	A	B	C
0	100	0.95	0.95	0.95	0.86	0.84	0.84
20	100	0.97	0.96	0.96	0.90	0.86	0.86
35	100	0.97	0.96	0.97	0.92	0.88	0.87
50	90	0.99	0.98	0.98	0.96	0.92	0.90
50	50	1.0	1.0	1.0	1.02	1.0	0.97
70	45	1.01	1.01	1.0	1.05	1.01	0.98
70	25	1.03	1.02	1.01	1.08	1.05	1.0
100	20	1.05	1.04	1.02	1.11	1.07	1.03
100	0	1.05	1.05	1.03	1.19	1.12	1.06

The PVDG active power curtailment is implemented for the case with 100% PVDG and 0% loading (Table 5.16). The active power injection of PVDG is incrementally decreased to meet the upper bound of the voltage level of 1.1/1.05p.u. As shown in Figure 5.25, the DG output power in the network is curtailed to maintain the voltage within limits. The consumers DG’s can still generate at least 50% of its capacity while maintaining the voltage at the node. The amount of active power curtailed is also significantly less for the last consumer’s DG. Ideally, the DG connected to the end of the radial feeder has to be curtailed to manage the overvoltage at the last node (node J). However, the incremental curtailment algorithm in DR-VC reduces the DG generation throughout the network starting from the overvoltage node. The inclusion of adjacent consumers in successive iteration ensures fairness to the affected node consumer by not overburdening the consumer to reduce only his generation to manage the network issue.

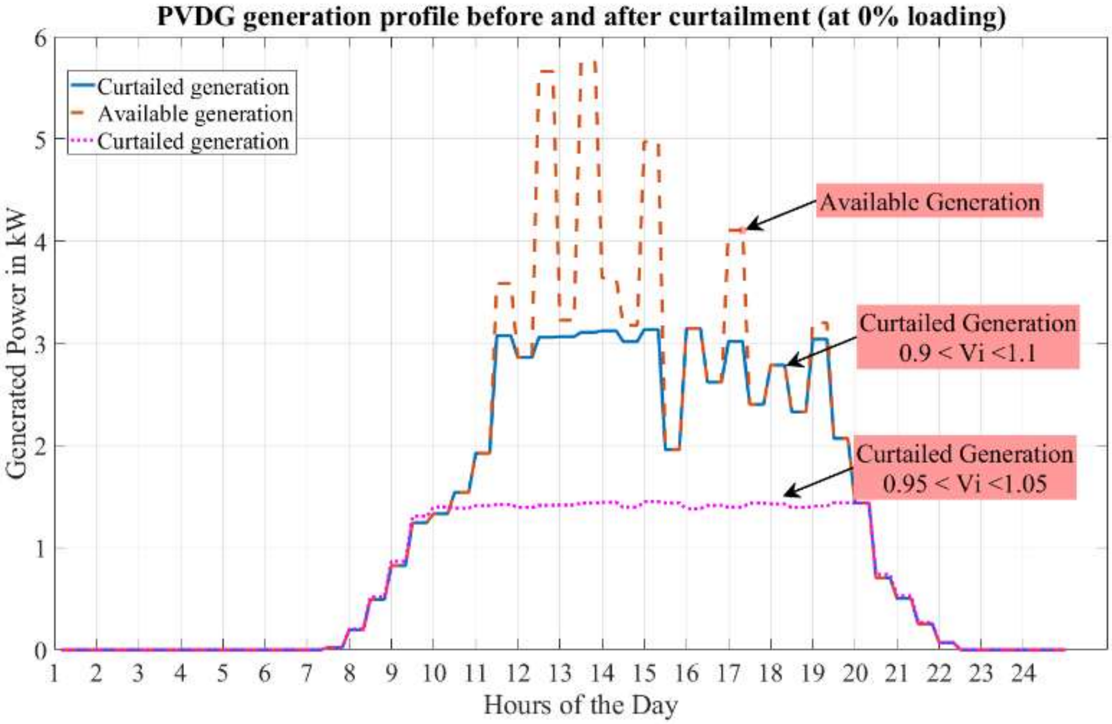


Figure 5.25 PVDG generation and curtailment with light and tight bounding for consumers at pillar 9

For tight bounding (0.95 < Vi < 1.05), the amount of curtailed generation is higher, and generation is much restricted. Figure 5.26 and Figure 5.27 illustrate the voltage profile at node J for phases A and C across a single day for a range of scenarios. The voltage regulation achieved during high DG penetration and high loading is also represented while utilizing the proposed algorithm. The tight bounding case is a sensitivity study that demonstrates the ability of DR to perform with challenging input constraints (undervoltage /overvoltage).

Demand response is applied as the lower bound voltage violation occurs at high load and low DG levels. The DR-VC used to reduce the load during an under-voltage scenario utilizes the consumer engagement plans to decide each consumer's amount of participation. The fairness algorithm, by increasing/decreasing the inconvenience value ensures avoidance of consumer from overburdening. The DR essentially drives an active power curtailment method in the LVDN to minimize the overall load on the network.

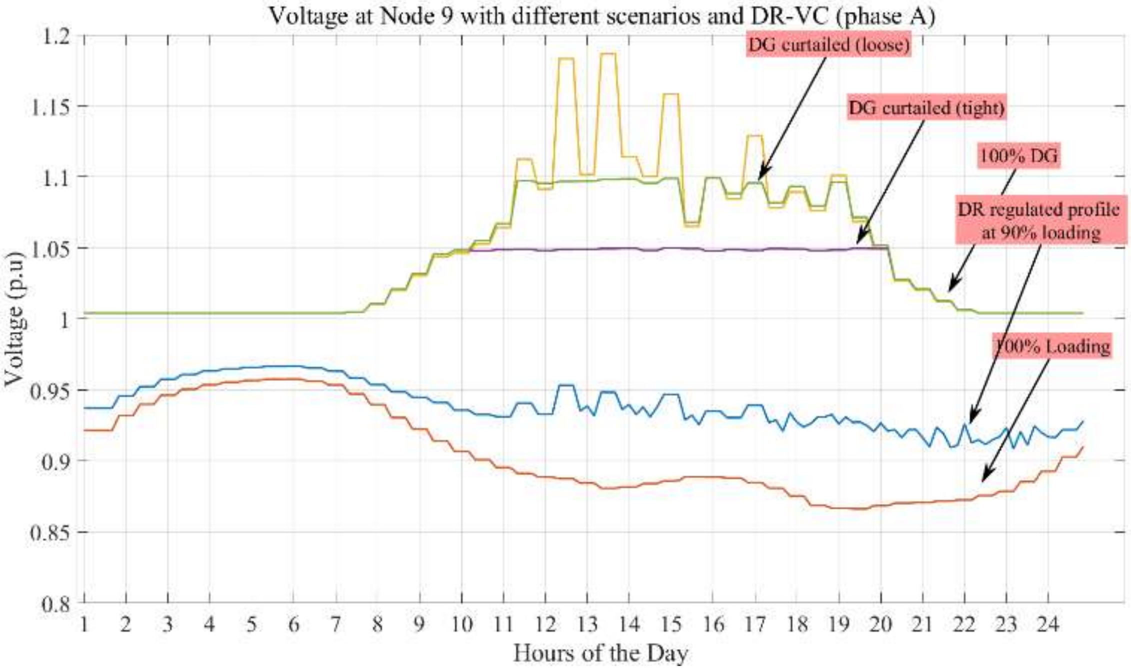


Figure 5.26 Voltage at node J (Phase A) under different scenarios

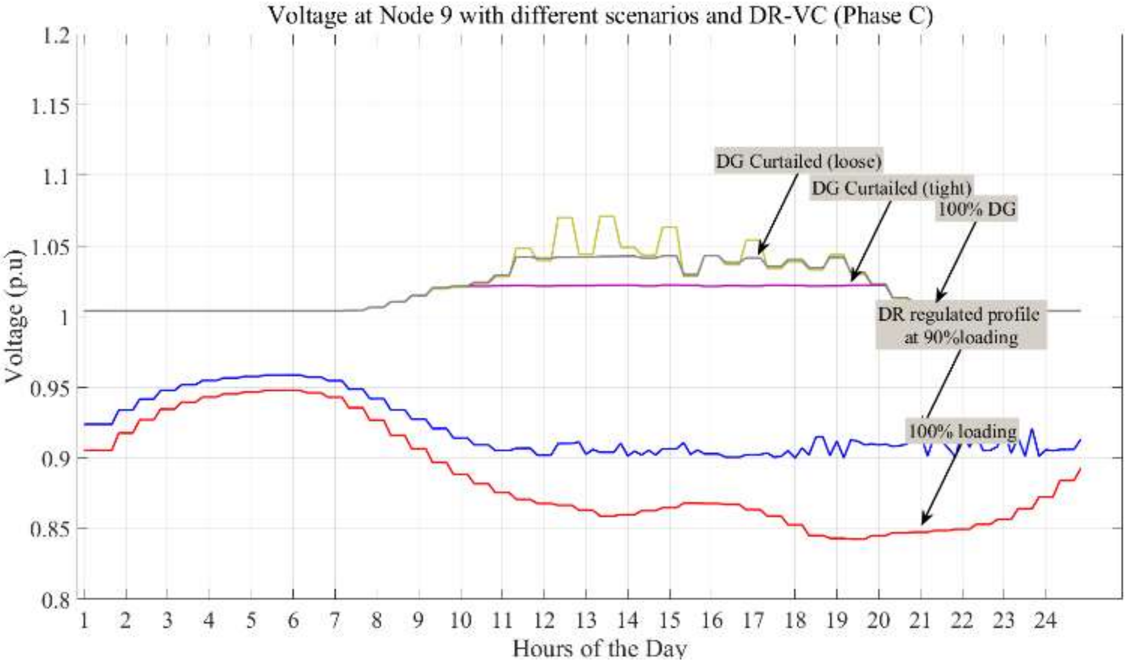


Figure 5.27 Voltage at node J (Phase C) under different scenarios

The use of an engagement plan (Section 3.3) based DR could enhance the consumer acceptance of the DR program. Lower levels of inconvenience and an opportunity to choose the type of engagement can create better conviction towards the DR program, which is essential for a DR programs success. Figure 5.28 shows load reduction and the associated tolerance value change for a consumer engaged in the different engagement plans in phase A. It exemplifies the capability of the proposed algorithm to regulate the participation of consumers. The corresponding voltage profiles of each phase at node J is given in Figure 5.26 to Figure 5.27 for 100% loading and 0% DG.

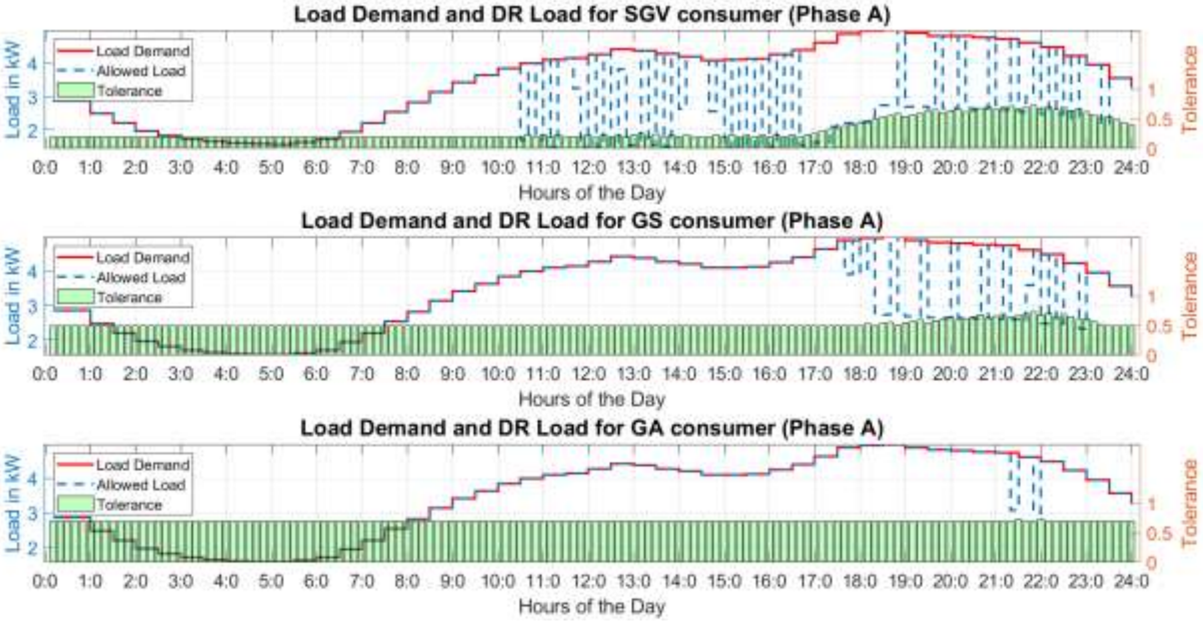


Figure 5.28 Demand and DR allowed load for consumers under three engagement plan and their corresponding tolerance change

The cumulative consumer inconvenience during DR operation is given in Figure 5.29. As observed in previous scenarios, the inconvenience of consumers stays constant until they are engaged in load reduction. The generation curtailment is not considered as an inconvenience as they are not directly causing any demand denial. Further, it is generally the obligation of the consumer to maintain the operation of DG connected within the safe operating limit. If violated, the DG is completely isolated in normal case. However, with the DR-VC algorithm, the consumer has the option of partially cashing in the generation available, maintaining fairness in the DG generators. Figure 5.30 - Figure 5.32 shows the load demand and allowed load for phase A, B and C during high demand and low generation conditions.

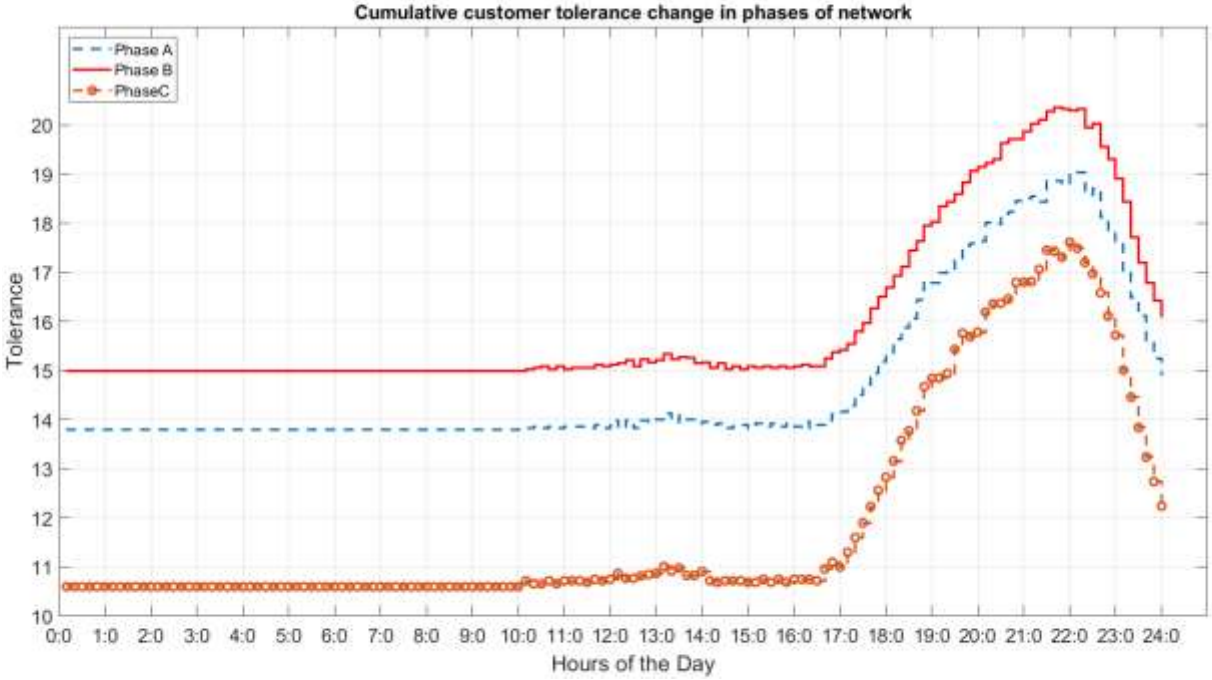


Figure 5.29 Cumulative consumer tolerance per phase for a day

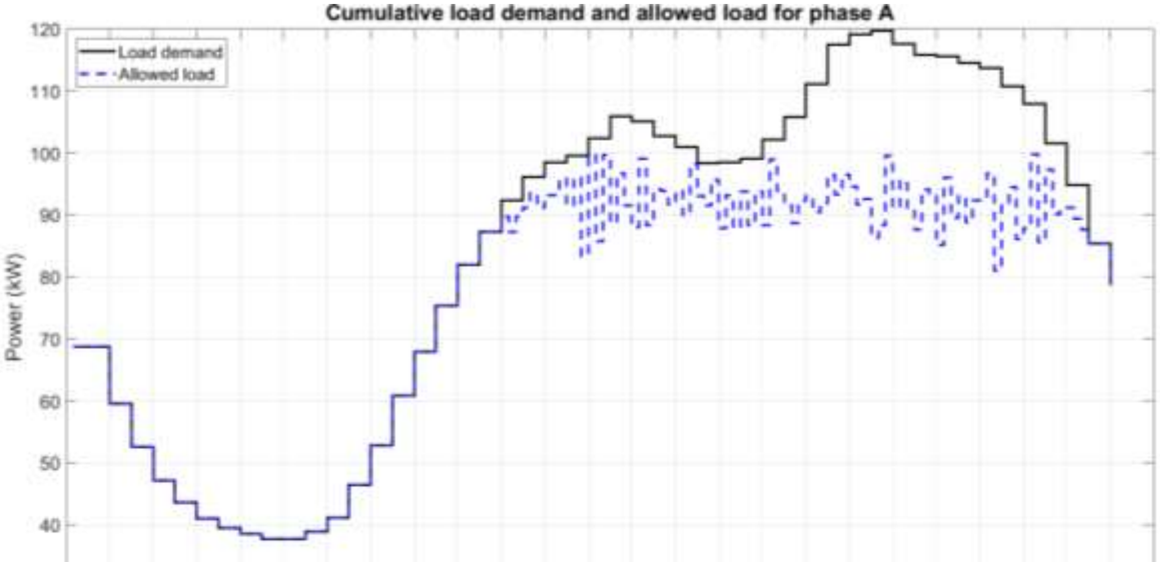


Figure 5.30 Load demand and allowed for Phase A

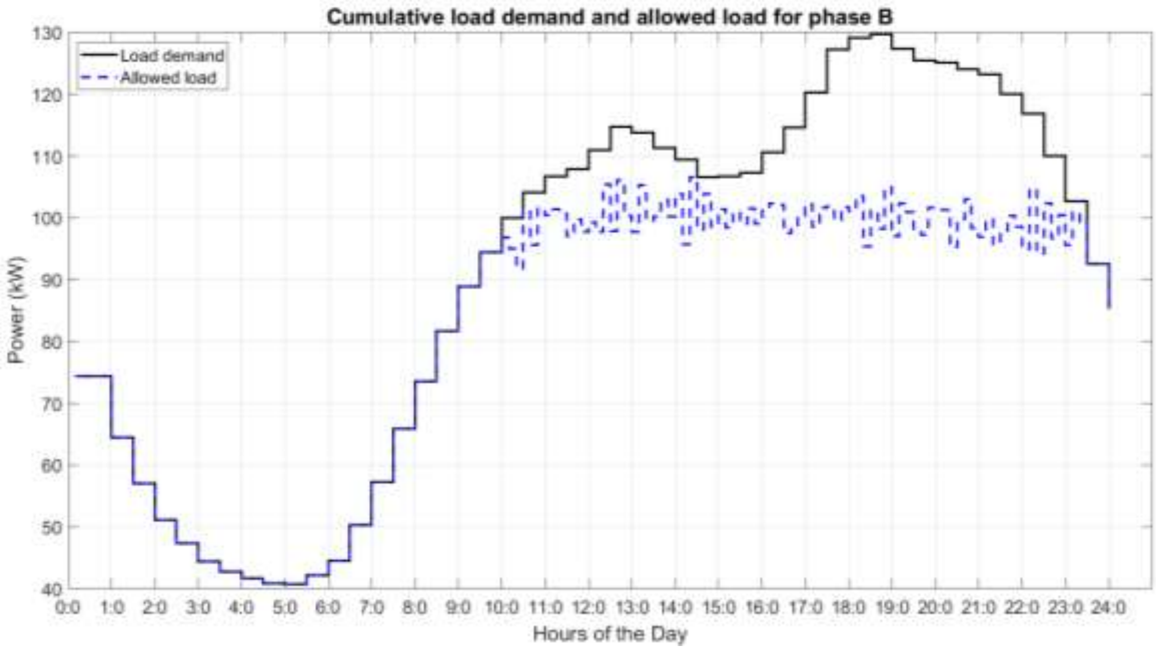


Figure 5.31 Load demand and allowed for Phase B

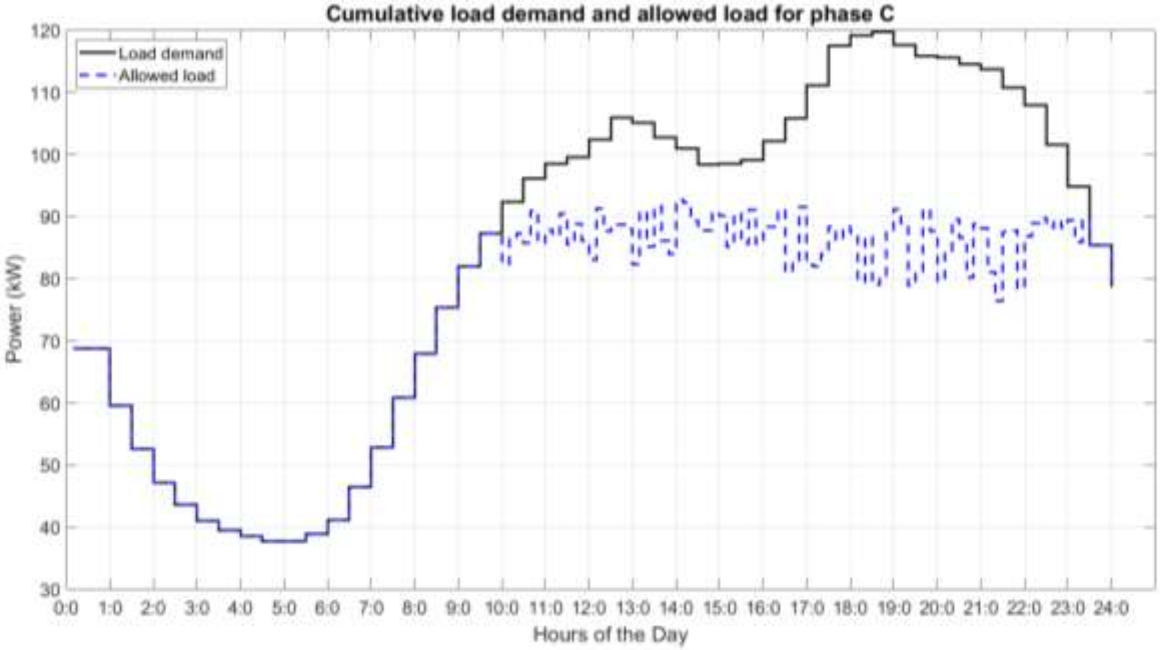


Figure 5.32 Load demand and allowed for Phase C

5.7 Conclusion

The ability of HC-C-DR to manage the load to alleviate power quality issues in the network by micromanaging consumer loads is presented in the chapter. The proposed algorithm becomes a valuable tool in the arsenal of a network operator to manage/market flexibility and manage power quality issues in the network efficiently. Having such an algorithm with network operators enables them to create boundary conditions with predicted load in the network to create a safe operating environment.

The variation of THD depending on the PVDG generation showcases instances with large THD% while the total current being much lower. With a stiff grid, the impact of a non-linear current may not severely distort the voltage waveform. Yet maybe sufficient to have increased harmonics heating loss that is potentially unsafe to the network.

The sensitivity of the HC-C-DR algorithm towards load profiles, consumer loads, socio-demographic condition were evaluated. The algorithm was able to account for each variable change while achieving the necessary load reduction with minimum consumer inconvenience.

Applying an incremental curtailment and DR algorithm to simultaneously manage the load and generation to regulate the maximum and minimum voltage levels in the LVDN further enhances the concept of using DR to mitigate power quality issues. The DR-VC algorithm is also designed to instil a minimum level of inconvenience during load and generation management.

Chapter 6 Conclusion and Future Work

6.1 Conclusion

Application of power quality constraint consumer-friendly demand response in low voltage distribution network is explored in this thesis. With increased level of non-linear loads in the consumer electronics market along with higher number of EV’s and heat pumps in future, the harmonic emission in the LVDN will create critical bottleneck for secure network operation. Further, the increased variable loading scenario with DG could potentially create unfavourable voltage profile in a radial system. Managing load operation can be considered as a reasonable and cheap solution technique rather than investing for reinforcements. The main conclusions of the thesis can be summarized as,

- The thesis independently developed a consumer-friendly DR program while establishing the correlation between the DR and consumer inconvenience. The consumer inconvenience factor (α) can categorize consumers to different engagement plan which provide consumer with choice of participation. An engagement plan proposed for consumers was incorporated to DR with an update algorithm to update α depending on consumer participation. This updating of α ensures fairness to consumers choosing high participation engagement plans.
- The DR program was tested under constant load and variable load condition for 74 consumer network. With constant load scenario, the DR program was able to allocate load reduction to consumers explicitly based on their engagement plan without any bias. When evaluated with different consumer profiles, the DR program was still unbiased and depended on the engagement plan while being sensitive to the available dispatchable load.
- An investigation of harmonic flow in the distribution network revealed THD% as an insufficient metric to represent harmonics impact in the system. The system at low loading can potentially have high levels of THD% if all loads are non-linear and yet be safe to operate. Hence, a harmonic heating factor was considered as a constraint factor to limit potential negative impact of harmonics in the network. Harmonic heating factor represents thermal loading of the cable sections in network.

- A radial feeder with different levels of loading and generations can create scenarios of high and low voltage levels violating the upper and lower limits [mainly] at far end of network. The dependency of voltage to active power was exploited to create a voltage constraint to incorporate to DR program.
- The consumer-friendly DR program was incorporated with harmonic constraint and implemented on an urban 74-consumer radial distribution network. The constraint restricted the levels of harmonics in the system that leads to unhealthy thermal loading to network cable/PCC.
- The DR program along with fair curtailment algorithm was implemented in the radial distribution network with high loading and high generation scenario to manage voltage violations. The load and generations were varied by the DR-VC program when voltage violations were observed. The results showed under all conditions, the DR-VC was able to level the voltage profile within the allowable limit.

6.2 Thesis Contribution

- Consumer engagement plan based on consumer inconvenience that correlates to consumer comfort.
- A simple and robust consumer-friendly DR program with two stage optimizations with low levels of computational burden.
- A harmonic analysis to represent inefficiency of THD % to represent harmonics severity. Application of harmonic heating factor for harmonic impact analysis.
- A harmonic constraint consumer-friendly DR program which manages harmonic levels in the network using load operation management.
- The application of an incremental reduction/increase and DR algorithm to manage the load and generation simultaneously to regulate the maximum and minimum voltage levels in the LVDN.
- Finally, the thesis opens up a new horizon on DR program capable of providing ancillary service to network operator creating additional channel for monetary benefit.

6.3 Future Work

This utilization of DR program to provide ancillary PQ service opens up various new horizon. Further, enhancing the algorithm would overcome certain assumptions can improve robustness of the algorithm. With these in mind, a set of future possible development of presented research is given below,

- The consumer-friendly DR can be used to provide frequency regulation as ancillary service by regulating loading in the network. The DR can generate load reduction possibility list/look-up table at each area for operator to send decision signal. The look-up table can also provide a glimpse of network flexibility at any given time for the operator.
- The DR can also provide primary, secondary, and tertiary reserve services to power system operators. This can be studied with respect to operation delay with the communication network. Such service also provides additional revenue source.
- Sensitivity case studies can be performed with DG being modelled as non-linear and with harmonic angle consideration. The harmonic cancellation cases can provide insight to practical network conditions.
- When considered a factor, α can directly co-relate with the incentive offering and thus be utilised to formulate the incentive program in the later stage.
- The engagement plan can be reformulated to generate plans based on dispatchable loads with consumer and their participation level. This creates tailor-made engagement plans for consumers to their choices.
- Additional consumers socio-economic impact factors like, environmental impact (CO2 emission), economic impact, and community impact. can be modelled to provide flexible engagement plans with higher consumer conviction.
- Load predicting algorithm can be incorporated locally to predict consumer load requirement.
- Hardware model prototype for local and global controller optimization (Stage1 and Stage 2) can be implemented to test the feasibility of the commercial product.

6.4 Publication

- Journal
  1. Chittesh Veni Chandran, Keith Sunderland, Malabika Basu, An analysis of harmonic heating in smart buildings and distribution network implications with increasing non-linear (domestic) load and embedded generation, Renewable Energy, Volume 126, 2018, Pages 524-536, ISSN 0960-1481
  2. Chandran, C.V., Basu, M., Sunderland, K., Pukhrem, S. and Catalão, J.P., 2020. Application of demand response to improve voltage regulation with high DG penetration. Electric Power Systems Research, 189, p.106722.
  3. Chittesh Veni Chandran, Malabika Basu, Keith Sunderland, Community feed in tariff with incremental curtailment algorithm for overvoltage management in a radial distribution network (In Progress)
  4. Chittesh Veni Chandran, Malabika Basu, Keith Sunderland, Harmonic constraint consumer-friendly demand response (In Progress)
- Conferences
  1. VC, Chittesh, M. Basu, Sunderland K, "Comparative Study between Direct Load Control and Fuzzy Logic Control Based Demand Response," 2016 51st International Universities Power Engineering Conference (UPEC), 2016
  2. Power Quality Analysis using Harmonic Heating factor by Multiple Energy Efficient Appliances in Smart Building, BIRES 2017
  3. VC, Chittesh, M. Basu, and K. Sunderland, "Demand Response and Consumer Inconvenience," 2019 International Conference on Smart Energy Systems and Technologies (SEST), Porto, Portugal, 2019, pp. 1-6.
  4. VC, Chittesh, Sunderland K, M. Basu, "Impact of Consumer Profiles on Demand Response," In 2016 54th International Universities Power Engineering Conference (UPEC) (pp. 1-6). IEEE.
  5. VC, Chittesh, M. Basu and K. Sunderland, S. Pukerem, João P. S. Catalão, Application of Demand Response to improve voltage regulation with high DG penetration, Power System Computation Conference, 2020

Reference

[1] S. L. Jie Yang, Tongyu Liu , Huaibao Wang, Zhenhua Tian, “Optimizing the Regulation of Aggregated Thermostatically Controlled Loads by Jointly Considering Consumer Comfort and Tracking Error,” *Energies*, 2019.

[2] S. Rönnberg and M. Bollen, “Power quality issues in the electric power system of the future,” *Electr. J.*, vol. 29, pp. 49–61, 2016.

[3] B. Buzdugan, Mircea Ion; Horia, “Power System Harmonics Issues in Some End User Facilities,” *52nd Int. Univ. Power Eng. Conf. (UPEC). IEEE*, vol. 2, no. 2, 2017.

[4] EirGrid, “Harmonic Issues and their impact on Customer connections,” *Note 1*, no. EirGrid, pp. 1–14, 2013.

[5] SEAI, “Changes to domestic solar PV scheme |SEAI.” [Online]. Available: https://www.seai.ie/news-and-media/changes-to-domestic-solar/. [Accessed: 05-May-2020].

[6] M. Bajaj and A. K. Singh, “Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques,” *Int. J. Energy Res.*, vol. 44, no. 1, pp. 26–69, Jan. 2020.

[7] C. V. Chandran, M. Basu, K. Sunderland, S. Pukhrem, and J. P. S. Catalão, “Application of demand response to improve voltage regulation with high DG penetration,” *Electr. Power Syst. Res.*, vol. 189, p. 106722, Dec. 2020.

[8] M. Shahidehpour, F. Tinney, and Yong Fu, “Impact of Security on Power Systems Operation,” *Proc. IEEE*, vol. 93, no. 11, pp. 2013–2025, Nov. 2005.

[9] D. Chattopsdhyay, “Operational Planning of Power System: An Integrated Approach,” *Energy Sources*, vol. 16, no. 1, pp. 59–73, Jan. 1994.

[10] “The Paris Agreement | UNFCCC.” [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. [Accessed: 01-Jan-2021].

[11] European Commission, “2050 long-term strategy | Climate Action,” *2050 Long-Term Strategy*, 2018. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2050_en. [Accessed: 21-Dec-2020].

[12] EirGrid & SONI, “All-Island Generation Capacity Statement 2020-2029 All-Island,” 2020.

[13] “2030 climate & energy framework | Climate Action.” [Online]. Available:

https://ec.europa.eu/clima/policies/strategies/2030_en. [Accessed: 07-May-2020].

[14] “gov.ie - Climate Action Plan 2021.” [Online]. Available: https://www.gov.ie/en/publication/6223e-climate-action-plan-2021/#infographic-booklet. [Accessed: 30-Dec-2021].

[15] “REFIT Schemes and Supports.” [Online]. Available: https://www.dccae.gov.ie/en-ie/energy/topics/Renewable-Energy/electricity/renewable-electricity-supports/refit/Pages/REFIT-Schemes-and-Supports.aspx. [Accessed: 07-May-2020].

[16] G. A. Fogli, I. D. N. Souza, M. C. Fernandes, P. M. Almeida, and P. G. Barbosa, “Dispatchable distributed generation using a back-to-back converter for grid-forming improvements based on feed-forward action with load current prediction,” *IET Power Electron.*, vol. 13, no. 16, pp. 3686–3696, Aug. 2020.

[17] Y. Ling, Y. Li, Z. Yang, and J. Xiang, “A Dispatchable Droop Control Method for Distributed Generators in Islanded AC Microgrids,” *IEEE Trans. Ind. Electron.*, pp. 1–1, Aug. 2020.

[18] E. F. Fuchs and M. A. S. Masoum, *Power quality in power systems and electrical machines*. Academic Press/Elsevier, 2008.

[19] MIGRATE - Massive InteGRATion of power Electronic Devices, “Critical PQ phenomena and sources of PQ disturbances in PE rich power systems - Deliverable 5.1,” 2016.

[20] S. Lineweber, D. and McNulty, “The Cost of Power Disturbances to Industrial & Digital Economy Companies,” *EPRI*, 2001.

[21] S. Bhattacharyya, J. M. A. Myrzik, and W. L. Kling, “Consequences of poor power quality - An overview,” *Proc. Univ. Power Eng. Conf.*, no. 1, pp. 651–656, 2007.

[22] “ESB - Distribution Code Summary,” no. April, pp. 1–34, 2017.

[23] *BS EN 50160/ BS EN 50160:2010+A3:2019, CENELEC*. BSI - BRITISH STANDARDS INSTITUTION, 2010.

[24] “ETSI EN 301 489-34 V2.1.1 (2019-04) - ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 34: Specific conditions for External Power Supply (EPS) for mobile phones; Harmonised Standard covering the essential requirements of article 6 of Directive 2014/30/EU,” 2019.

[25] “Electromagnetic Compatibility (emc) - Part 3-2: Limits - Limits For Harmonic Current

Emissions (equipment Input Current <= 16 A Per Phase) (iec 61000-3-2:2014)," *CENELEC - Eur. Comm. STDS - Electr.*, 2014.

[26] Y. Luo, S. Wang, D. Yang, B. Zhou, and T. Liu, "Direct prediction compensation strategy of unified power quality conditioner based on FCS-MPC," *IET Gener. Transm. Distrib.*, vol. 14, no. 22, pp. 5020–5028, Nov. 2020.

[27] A. I. Omar, S. H. E. Abdel Aleem, E. E. A. El-Zahab, M. Algablawy, and Z. M. Ali, "An improved approach for robust control of dynamic voltage restorer and power quality enhancement using grasshopper optimization algorithm," *ISA Trans.*, vol. 95, pp. 110–129, Dec. 2019.

[28] N. Mohd Zainuddin *et al.*, "Review of Thermal Stress and Condition Monitoring Technologies for Overhead Transmission Lines: Issues and Challenges," *IEEE Access*, vol. 8, pp. 120053–120081, 2020.

[29] T. Pfajfar, B. Blažič, and I. Papič, "Harmonic contributions evaluation with the harmonic current vector method," *IEEE Trans. Power Deliv.*, vol. 23, no. 1, pp. 425–433, 2008.

[30] S. Afotey and S. M. Aliadeh, "Investigation into the Impact of Cable Failure Localisation Methods on the Underground Cable Life Time in a Medium Voltage Distribution Network," *IEEE Int. Symp. Ind. Electron.*, vol. 2020-June, pp. 898–903, 2020.

[31] F. A. Yusuf Gurcan Sahin, "Investigation of harmonic effects on underground power cables," in *In 2007 International Conference on Power Engineering, Energy and Electrical Drives*, 2007, no. 7, pp. 589–594.

[32] R. Pragale and D. D. Shipp, "Investigation of Premature ESP Failures and Oil Field Harmonic Analysis," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 3175–3181, 2017.

[33] J. Blackledge, K. O 'connell, M. Barrett, and A. Sung, "Cable Heating Effects due to Harmonic Distortion in Electrical Installations," *Proc. World Congr. Eng.*, vol. 2, 2012.

[34] A. Benjamin and S. K. Jain, "A Review of Literature on Effects of Harmonics on Protective Relays," *Int. Conf. Innov. Smart Grid Technol. ISGT Asia 2018*, pp. 407–412, 2018.

[35] F. D. La Rosa, *Harmonics and power systems*. Boca Raton: CRC press, 2006.

[36] S. Mousavi, B. Tavan, and H. Bakhtiari, "The review and analysis the destructive

effects of harmonics on a sample MV/LV transformer," in *IET Conference Publications*, 2009, no. 550 CP, pp. 1047–1047.

[37] P. Jain, A. K. Tiwari, and S. K. Jain, "Harmonic source identification in distribution system using estimation of signal parameters via rotational invariance technique-total harmonic power method," *Trans. Inst. Meas. Control*, vol. 40, no. 12, pp. 3415–3423, Aug. 2018.

[38] W. Xu, R. Bahry, H. E. Mazin, and T. Tayjasanant, "A method to determine the harmonic contributions of multiple loads," in *2009 IEEE Power and Energy Society General Meeting, PES '09*, 2009.

[39] M. H. J. Bollen, L. Yao, S. K. Rönnberg, and M. Wahlberg, "Harmonic and interharmonic distortion due to a windpark," in *IEEE PES General Meeting, PES 2010*, 2010.

[40] Z. Leonowicz, "Analysis of sub-harmonics in power systems," in *2010 9th Conference on Environment and Electrical Engineering, EEEIC 2010*, 2010, pp. 125–127.

[41] E. F. Fuchs and M. A. S. Masoum, *Power quality in power systems and electrical machines*. Academic Press/Elsevier, 2008.

[42] Y. H. Lo, Y. C. Chen, K. L. Lian, H. Karimi, and C. Z. Wang, "An iterative control method for voltage source converters to eliminate uncharacteristic harmonics under unbalanced grid voltages for high-power applications," *IEEE Trans. Sustain. Energy*, vol. 10, no. 3, pp. 1419–1429, 2019.

[43] D. Pejovski, K. Najdenkoski, and M. Digalovski, "Impact of different harmonic loads on distribution transformers," in *Procedia Engineering-4th International Colloquium "Transformer Research and Asset Management"*, 2017, vol. 202, pp. 76–87.

[44] X. Luo, Y. Du, X. H. Wang, and M. L. Chen, "Tripping characteristics of residual current devices under nonsinusoidal currents," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1515–1521, May 2011.

[45] J. S. Maan, S. Singh, and A. Singh, "Impact of Harmonics on Power Transformer Losses and Capacity Using Open DSS," *Int. J. Emerg. Electr. Power Syst.*, vol. 20, no. 4, Aug. 2019.

[46] D. M. Said and K. M. Nor, "Simulation of the Impact of Harmonics on Distribution Transformers," *2nd IEEE Int. Conf. Power Energy (PECon 08)*, no. PECon 08, pp.

335–340, 2008.

[47] P. M. Donohue, S. Islam, and S. Member, “The Effect of Nonsinusoidal Current Waveforms on Electromechanical and Solid-State Overcurrent Relay Operation,” *IEEE Trans. Ind. Appl.*, vol. 46, no. 6, pp. 2127–2133, 2010.

[48] G. Todeschini, D. R. Mueller, and G. Y. Morris, “Telephone interference caused by harmonics in distribution systems: Analysis and simulations,” *IEEE Power Energy Soc. Gen. Meet.*, pp. 1–5, 2013.

[49] G. Lemieux, “Power System Harmonic Resonance- A Documented Case,” *Trans. Ind. Appl.*, vol. 26, no. 3, pp. 483–488, 1990.

[50] P. Bhatt and S. Kumar, “Comprehensive Assessment and Mitigation of Harmonic Resonance in Smart Distribution Grid with Solar Photovoltaic,” *Int. J. Renew. Energy Res.*, 2017.

[51] X. Liang, S. Member, C. A. Karim, and S. Member, “Harmonics and Mitigation Techniques Through Advanced Control in Grid-Connected Renewable Energy Sources : A Review,” *IEEE Trans. Ind. Appl.*, vol. 54, no. 4, pp. 3100–3111, 2018.

[52] C. Toader, P. Postolache, N. Golovanov, R. Porumb, I. Mircea, and P. M. Mircea, “Power quality impact of energy-efficient electric domestic appliances,” *2014 Int. Conf. Appl. Theor. Electr. ICATE 2014 - Proc.*, 2014.

[53] D. Zhang, F. Wang, R. Burgos, R. Lai, T. Thacker, and D. Boroyevich, “Interleaving Impact on Harmonic Current in DC and AC Passive Components of Paralleled Three-Phase Voltage-Source Converters,” *Twenty-Third Annu. IEEE Appl. Power Electron. Conf. Expo.*, pp. 219–225, 2008.

[54] I. Santiago, M. A. López-Rodríguez, A. Gil-de-Castro, A. Moreno-Munoz, and J. J. Luna-Rodríguez, “Energy consumption of audiovisual devices in the residential sector: Economic impact of harmonic losses,” *Energy*, vol. 60, pp. 292–301, Oct. 2013.

[55] A. B. Nassif, “Assessing the Impact of Harmonics and Interharmonics of Top and Mudpump Variable Frequency Drives in Drilling Rigs,” *IEEE Trans. Ind. Appl.*, vol. 55, no. 6, pp. 5574–5583, 2019.

[56] K. Abe, H. Haga, K. Ohishi, and Y. Yokokura, “Fine Current Harmonics Reduction Method for Electrolytic Capacitor-Less and Inductor-Less Inverter Based on Motor Torque Control and Fast Voltage Feedforward Control for IPMSM,” *IEEE Trans. Ind.*

Electron., vol. 64, no. 2, pp. 1071–1080, 2017.

[57] J. H. Shazly, M. A. Mostafa, D. K. Ibrahim, and E. E. Abo El Zahab, "Thermal analysis of high-voltage cables with several types of insulation for different configurations in the presence of harmonics," *IET Gener. Transm. Distrib.*, vol. 11, no. 14, pp. 3439–3448, 2017.

[58] P. N. Gokhale and S. M. Bakre, "Impact of Harmonics on Accuracy of Metering," *IEEE Int. Conf. Information, Commun. Eng. Technol.*, 2018.

[59] T. Tarasiuk, "Angular frequency variations at microgrids and its impact on measuring instruments performance," *IET Gener. Transm. Distrib.*, vol. 10, pp. 3234–3240, 2016.

[60] EirGrid, "EirGrid Grid Code, version 8," *Comm. Regul. Util.*, no. July, pp. 1–349, 2019.

[61] E. N. Distribution System Operator, "Distribution Code version V2.0." pp. I-VII + 1-120, 2007.

[62] A. Klajn and M. Bątkiewicz-Pantuła, "Application Note Standard EN50160 Voltage Characteristics of Electricity Supplied by Public Electricity Networks," *Eur. Copp. Inst.*, no. 02, 2013.

[63] D. Salles, C. Jiang, W. Xu, W. Freitas, and H. E. Mazin, "Assessing the Collective Harmonic Impact of Modern Residential Loads—Part I: Methodology," *IEEE Trans. Power Deliv.*, vol. 27, no. 4, pp. 1937–1946, Oct. 2012.

[64] A. J. Collin, J. L. Acosta, B. P. Hayes, and S. Z. Djokic, "Component-based aggregate load models for combined power flow and harmonic analysis," in *7th Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2010)*, 2010, pp. 171–171.

[65] M. T. Au and J. V. Milanovi, "Establishing Harmonic Distortion Level of Distribution Network Based on Stochastic Aggregate Harmonic Load Models," *IEEE Trans. Power Deliv.*, vol. 22, no. 2, pp. 1086–1092, Apr. 2007.

[66] W. L. Kling, J. F. G. Cobben, V. Ćuk, and P. F. Ribeiro, "Analysis of harmonic current summation based on field measurements," *IET Gener. Transm. Distrib.*, vol. 7, no. 12, pp. 1391–1400, Dec. 2013.

[67] G. Ye, M. Nijhuis, V. Cuk, and J. F. G. Cobben, "Appliance-based residential harmonic load modelling," in *2017 IEEE Manchester PowerTech*, 2017, pp. 1–6.

[68] M. Nijhuis, M. Gibescu, and J. F. G. Cobben, “Bottom-up Markov Chain Monte Carlo approach for scenario based residential load modelling with publicly available data,” *Energy Build.*, vol. 112, pp. 121–129, Jan. 2016.

[69] M. J. H. Rawa, D. W. P. Thomas, and M. Sumner, “Experimental Measurements and Computer Simulations of Home Appliances Loads for Harmonic Studies,” in *2014 UKSim-AMSS 16th International Conference on Computer Modelling and Simulation*, 2014, pp. 340–344.

[70] M. J. Ghorbani, M. S. Rad, H. Mokhtari, M. E. Honarmand, and M. Youhannaie, “Residential Loads Modeling by Norton Equivalent Model of Household Loads,” in *2011 Asia-Pacific Power and Energy Engineering Conference*, 2011, pp. 1–4.

[71] M. Lamich, J. Balcells, M. Corbalan, and E. Griful, “Nonlinear Loads Model for Harmonics Flow Prediction, Using Multivariate Regression,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 6, pp. 4820–4827, Jun. 2017.

[72] A. R. A. Manito, E. O. de Matos, U. H. Bezerra, B. C. Costa, T. Mota Soares, and M. E. de L. Tostes, “Using linear and non-parametric regression models to describe the contribution of non-linear loads on the voltage harmonic distortions in the electrical grid,” *IET Gener. Transm. Distrib.*, vol. 10, no. 8, pp. 1825–1832, May 2016.

[73] M. Brunoro, L. F. Encarnação, and J. F. Fardin, “Modeling of loads dependent on harmonic voltages,” *Electr. Power Syst. Res.*, vol. 152, pp. 367–376, Nov. 2017.

[74] A. Y. Hatata and M. Eladawy, “Prediction of the true harmonic current contribution of nonlinear loads using NARX neural network,” *Elsevier, Alexandria Eng. J.*, Apr. 2017.

[75] J. Balcells, M. Lamich, E. Griful, and M. Corbalan, “Influence of data resolution in nonlinear loads model for harmonics prediction,” in *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, 2016, pp. 6560–6565.

[76] J. A. Palmer, R. C. Degeneff, T. M. McKernan, and T. M. Halleran, “Determination of the effect of harmonics on pipe-type power cable AC/DC resistance ratios,” *IEEE Trans. Magn.*, vol. 29, no. 2, pp. 1427–1433, Mar. 1993.

[77] F. Waite, D. Payne, J. Pilgrim, P. Lewin, and A. Gorwadia, “Quantifying possible transmission network benefits from higher cable conductor temperatures,” *IET Gener. Transm. Distrib.*, vol. 7, no. 6, pp. 636–644, Jun. 2013.

[78] *Wide Variations in State Adoptions of the NEC Reveal Neglect of Electrical Safety on*

Electrical Safety. 2018.

[79] "ET 101: National rules for electrical installations," 2004.

[80] C. H. Duarte and R. Schaeffer, "Economic impacts of power electronics on electricity distribution systems," *Energy*, vol. 35, no. 10, pp. 4010–4015, 2010.

[81] M. Patsalides, A. Stavrou, V. Efthymiou, and G. E. Georghiou, "Towards the establishment of maximum PV generation limits due to power quality constraints," *Int. J. Electr. Power Energy Syst.*, vol. 42, no. 1, pp. 285–298, 2012.

[82] M. Elbuluk, "The Role Power Electronics in Future Energy Systems and Green Industrialization," *Power*, no. PECon 08, pp. 1–6, 2008.

[83] K. McKenna and A. Keane, "Electrical and Thermal Characteristics of Household Appliances: Voltage Dep endency, Harmonics and Thermal RC Parameters," *Res. Repos. UCD*, vol. 40, no. 1, pp. 67–77, 2016.

[84] A. Anees and Y. P. P. Chen, "True real time pricing and combined power scheduling of electric appliances in residential energy management system," *Appl. Energy*, vol. 165, pp. 592–600, 2016.

[85] H. Hu, C. Gao, X. Shi, Y. Liu, and D. Li, "Aggregation and scheduling methods of electric vehicle agents divided by regions," *2016 3rd Int. Conf. Syst. Informatics, ICSAI 2016*, no. Icsai, pp. 208–216, 2017.

[86] A. Ipakchi and F. Albuyeh, "Grid of the future," *IEEE Power Energy Mag.*, vol. 7, no. 2, pp. 52–62, Mar. 2009.

[87] A. K. Singh and S. K. Parida, "A review on distributed generation allocation and planning in deregulated electricity market," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 4132–4141, Feb. 2018.

[88] S. Das, D. Das, and A. Patra, "Operation of distribution network with optimal placement and sizing of dispatchable DGs and shunt capacitors," *Renew. Sustain. Energy Rev.*, vol. 113, p. 109219, Oct. 2019.

[89] P. Chiradeja and R. Ramakumar, "An Approach to Quantify the Technical Benefits of Distributed Generation," *IEEE Trans. Energy Convers.*, vol. 19, no. 4, pp. 764–773, Dec. 2004.

[90] Entso-e, "Requirements for Generators." ENTSO-E, 2016.

[91] J. E. Quiroz, M. J. Reno, and R. J. Broderick, "Time series simulation of voltage

regulation device control modes," in *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)*, 2013, pp. 1700–1705.

[92] A. M. Howlader, S. Sadoyama, L. R. Roose, and Y. Chen, "Active power control to mitigate voltage and frequency deviations for the smart grid using smart PV inverters," *Appl. Energy*, vol. 258, no. November 2019, p. 114000, 2020.

[93] D. I. Brandao, F. E. G. Mendes, R. V. Ferreira, S. M. Silva, and I. A. Pires, "Active and reactive power injection strategies for three-phase four-wire inverters during symmetrical/asymmetrical voltage sags," *IEEE Trans. Ind. Appl.*, vol. 55, no. 3, pp. 2347–2355, 2019.

[94] "Power Generating Plants in the Low Voltage Grid (VDE-AR-N 4105), VDE VERLAG GMBH, Berlin, Germany," 2019.

[95] S. Pukhrem, M. Basu, M. F. Conlon, and K. Sunderland, "Enhanced Network Voltage Management Techniques Under the Proliferation of Rooftop Solar PV Installation in Low-Voltage Distribution Network," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 5, no. 2, pp. 681–694, Jun. 2017.

[96] V. Behravesh, R. Keypour, and A. Akbari Foroud, "Control strategy for improving voltage quality in residential power distribution network consisting of roof-top photovoltaic-wind hybrid systems, battery storage and electric vehicles," *Sol. Energy*, vol. 182, pp. 80–95, Apr. 2019.

[97] P. Mishra, A. K. Pradhan, and P. Bajpai, "Voltage control of PV inverter connected to unbalanced distribution system," *IET Renew. Power Gener.*, vol. 13, no. 9, pp. 1587–1594, Jul. 2019.

[98] J. H. Braslavsky, J. K. Ward, and L. Collins, "A stability vulnerability in the interaction between Volt-VAR and Volt-Watt response functions for smart inverters," in *2015 IEEE Conference on Control Applications (CCA)*, 2015, pp. 733–738.

[99] J. H. Braslavsky, L. D. Collins, and J. K. Ward, "Voltage Stability in a Grid-Connected Inverter With Automatic Volt-Watt and Volt-VAR Functions," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 84–94, Jan. 2019.

[100] R. S. Al Abri, E. F. El-Saadany, and Y. M. Atwa, "Optimal placement and sizing method to improve the voltage stability margin in a distribution system using distributed generation," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 326–334, 2013.

[101] Q. Tao, D. Wang, B. Yang, H. Liu, and S. Yan, “Voltage Control of Distribution Network with Distributed Generation Based on Voltage Sensitivity Matrix,” in *2018 IEEE International Conference on Energy Internet (ICEI)*, 2018, pp. 298–302.

[102] EirGrid and SONI, “Annual Renewable Energy Constraint and Curtailment Report 2018,” no. May, pp. 1–28, 2018.

[103] “ECP-1 constraint reports for solar and wind.” [Online]. Available: https://www.eirgridgroup.com/customer-and-industry/general-customer-information/constraint-reports-solar/. [Accessed: 20-Apr-2021].

[104] J. Ma, H. Ye, Z. Li, P. Han, Z. Lin, and J. Shi, “Research on Source-Network Coordination Voltage Control Strategy of Photovoltaic Power Plant Considering the Stability of Inverter Port Voltage,” *E3S Web Conf.*, vol. 143, pp. 1–7, 2020.

[105] X. Su, M. A. S. Masoum, and P. J. Wolfs, “Optimal PV Inverter Reactive Power Control and Real Power Curtailment to Improve Performance of Unbalanced Four-Wire LV Distribution Networks,” *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 967–977, Jul. 2014.

[106] J. Yang, Y. Sun, G. Liu, X. Cui, C. Wang, and K. Ma, “Global Voltage Sensitivity Calculation for power system including transmission and distribution networks,” *2019 IEEE PES Innov. Smart Grid Technol. Asia, ISGT 2019*, pp. 186–190, 2019.

[107] European Comission, “Delivering the internal electricity market and making the most of public intervention, COM(2013) 7243 final,” p. 19, 2013.

[108] W. Clark, “Management Working Group tions and Substations .,” no. August, 1981.

[109] C. De Jonghe, B. F. Hobbs, and R. Belmans, “Optimal generation mix with short-term demand response and wind penetration,” *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 830–839, 2012.

[110] FERC, “2017 Assessment of Demand Response and Advanced Metering,” 2017.

[111] M. H. Albadi and E. F. El-Saadany, “A summary of demand response in electricity markets,” *Electr. Power Syst. Res.*, vol. 78, no. 11, pp. 1989–1996, Nov. 2008.

[112] M. A. Piette *et al.*, “Open Automated Demand Response Communications Specification (Version 1.0),” Berkeley, CA, Feb. 2009.

[113] “Demand Side Response in the domestic sector-a literature review of major trials Demand Side Response in the domestic sector-a literature review of major trials

Executive summary," 2012.

[114] A.-H. Mohsenian-Rad, V. W. S. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous Demand-Side Management Based on Game-Theoretic Energy Consumption Scheduling for the Future Smart Grid," *IEEE Trans. Smart Grid*, vol. 1, no. 3, pp. 320–331, Dec. 2010.

[115] P. Mandatova, E. – Eu, M. Massimiano, D. Verreth, and C. Gonzalez, "NETWORK TARIFF STRUCTURE FOR A SMART ENERGY SYSTEM."

[116] T. Samad, E. Koch, and P. Stluka, "Automated Demand Response for Smart Buildings and Microgrids: The State of the Practice and Research Challenges," *Proc. IEEE*, vol. 104, no. 4, pp. 726–744, 2016.

[117] C. V. Chandran and K. Sunderland, "Comparative Study between Direct Load Control and Fuzzy Logic Control Based Demand Response," 2016.

[118] C. Chen, J. Wang, Y. Heo, and S. Kishore, "MPC-based appliance scheduling for residential building energy management controller," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1401–1410, 2013.

[119] K. Dehghanpour, M. Hashem Nehrir, J. W. Sheppard, and N. C. Kelly, "Agent-Based Modeling of Retail Electrical Energy Markets with Demand Response," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3465–3475, 2018.

[120] Y. Guo *et al.*, "Machine learning-based thermal response time ahead energy demand prediction for building heating systems," *Appl. Energy*, vol. 221, no. March, pp. 16–27, 2018.

[121] P. Samadi, A.-H. Mohsenian-Rad, R. Schober, V. W. S. Wong, and J. Jatskevich, "Optimal Real-Time Pricing Algorithm Based on Utility Maximization for Smart Grid," 2010, pp. 415–420.

[122] A. Soroudi, P. Siano, and A. Keane, "Optimal DR and ESS scheduling for distribution losses payments minimization under electricity price uncertainty," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 261–272, Jan. 2016.

[123] P. Carrasqueira, M. J. Alves, and C. H. Antunes, "Bi-level particle swarm optimization and evolutionary algorithm approaches for residential demand response with different user profiles," *Inf. Sci. (Ny).*, vol. 418–419, pp. 405–420, 2017.

[124] Z. Zhu, J. Tang, S. Lambotharan, W. H. Chin, and Z. Fan, "An integer linear

programming based optimization for home demand-side management in smart grid," in *2012 IEEE PES Innovative Smart Grid Technologies, ISGT 2012*, 2012.

[125] J. Li and R. R. Rhinehart, "Heuristic random optimization," *Comput. Chem. Eng.*, vol. 22, no. 3, pp. 427–444, Feb. 1998.

[126] M. Alipour, K. Zare, and M. Abapour, "MINLP Probabilistic Scheduling Model for Demand Response Programs Integrated Energy Hubs," *IEEE Trans. Ind. Informatics*, vol. 14, no. 1, pp. 79–88, Jan. 2018.

[127] A. Nikoobakht, J. Aghaei, M. Shafie-Khah, and J. P. S. Catalao, "Assessing Increased Flexibility of Energy Storage and Demand Response to Accommodate a High Penetration of Renewable Energy Sources," *IEEE Trans. Sustain. Energy*, vol. 10, no. 2, pp. 659–669, Apr. 2019.

[128] T. Logenthiran, D. Srinivasan, and T. Z. Shun, "Demand side management in smart grid using heuristic optimization," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1244–1252, 2012.

[129] L. P. Qian, Y. J. A. Zhang, J. Huang, and Y. Wu, "Demand response management via real-time electricity price control in smart grids," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 7, pp. 1268–1280, 2013.

[130] F. Pallonetto, M. De Rosa, F. Milano, and D. P. Finn, "Demand response algorithms for smart-grid ready residential buildings using machine learning models," *Appl. Energy*, vol. 239, no. January, pp. 1265–1282, 2019.

[131] C. Chen, J. Wang, Y. Heo, and S. Kishore, "MPC-Based Appliance Scheduling for Residential Building Energy Management Controller," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1401–1410, Sep. 2013.

[132] A. Miara, C. Tarr, R. Spellman, C. J. Vörösmarty, and J. E. Macknick, "The power of efficiency: Optimizing environmental and social benefits through demand-side-management," *Energy*, vol. 76, pp. 502–512, 2014.

[133] W. Huang, N. Zhang, C. Kang, M. Li, and M. Huo, "From demand response to integrated demand response: review and prospect of research and application," *Prot. Control Mod. Power Syst.*, vol. 4, no. 1, 2019.

[134] T. Mount, L. Anderson, R. Zimmerman, and J. Cardell, *Coupling Wind Generation wtih Controllable Load and Storage: A Time Series Application of the Super OPF*.

2012.

[135] M. Qadrdan, M. Cheng, J. Wu, and N. Jenkins, “Benefits of demand-side response in combined gas and electricity networks,” *Appl. Energy*, vol. 192, pp. 360–369, 2017.

[136] R. E. Brown, V. President, B. Hwang, P. Manager, and R. Touzel, “Demand response as a dispatchable resource,” no. May, pp. 1–5, 2013.

[137] I. Lampropoulos, W. L. Kling, P. F. Ribeiro, and J. van den Berg, “History of demand side management and classification of demand response control schemes,” *2013 IEEE Power Energy Soc. Gen. Meet.*, vol. 1, pp. 1–5, 2013.

[138] N. U. Hassan *et al.*, “Framework for minimum user participation rate determination to achieve specific demand response management objectives in residential smart grids,” *Int. J. Electr. Power Energy Syst.*, vol. 74, pp. 91–103, 2016.

[139] P. T. Baboli, M. Eghbal, M. P. Moghaddam, and H. Aalami, “Customer behavior based demand response model,” *IEEE Power Energy Soc. Gen. Meet.*, pp. 1–7, 2012.

[140] “Survey Shows Utility-Customer Relationship Hinges on a Few Key Moments - MarketWatch.” [Online]. Available: https://www.marketwatch.com/press-release/survey-shows-utility-customer-relationship-hinges-on-a-few-key-moments-2015-04-01. [Accessed: 18-May-2019].

[141] N. Ul Hassan, Y. I. Khalid, C. Yuen, and W. Tushar, “Customer engagement plans for peak load reduction in residential smart grids,” *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 3029–3041, 2015.

[142] T. Woolf, M. Erin, L. Schwartz, and S. John, “A Framework for Evaluating the Cost-Effectiveness of Demand Response Prepared for the National Forum on the National Action Plan on Demand Response: Cost-effectiveness Working Group U.S. Department of Energy: Washington, DC, USA,” 2013.

[143] A. Naeem, A. Shabbir, N. Ul Hassan, C. Yuen, A. Ahmad, and W. Tushar, “Understanding customer behavior in multi-tier demand response management program,” *IEEE Access*, vol. 3, pp. 2613–2625, 2015.

[144] “Power companies dangle free nights and weekends - CBS News.” [Online]. Available: https://www.cbsnews.com/news/power-companies-dangle-free-nights-and-weekends/. [Accessed: 18-May-2019].

[145] “European Commission - PRESS RELEASES - Press release - Commission welcomes

political agreement on conclusion of the Clean Energy for All Europeans package." [Online]. Available: http://europa.eu/rapid/press-release_IP-18-6870_en.htm. [Accessed: 18-May-2019].

[146] E. Cutter, C. K. Woo, F. Kahrl, and A. Taylor, "Maximizing the Value of Demand response," *Electr. J.*, vol. 25, no. 7, pp. 6–16, 2012.

[147] O. Ma *et al.*, "Demand Response for Ancillary Services," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1988–1995, 2013.

[148] H. M. Marco Zugnoa, Juan M. Moralesa, Pierre Pinsona, "Modeling Demand Response in Electricity Retail Markets as a Stackelberg Game," *12th IAEE Eur. Energy Conf. Energy Chall. Environ. Sustain.*, 2012.

[149] T. Molla, B. Khan, B. Moges, H. H. Alhelou, R. Zamani, and P. Siano, "Integrated energy optimization of smart home appliances with cost-effective energy management system," *CSEE J. Power Energy Syst.*, vol. 5, no. 2, pp. 249–258, 2019.

[150] "EirGrid Launches Demand Response Pilot for Householders." [Online]. Available: http://www.eirgridgroup.com/newsroom/eirgrid-launches-demand-r/. [Accessed: 27-Dec-2020].

[151] D. Phelan, R. Mcdermott, and T. Fallon, "Project Initiation Document for the Residential Consumer Demand Response Programme Residential Consumer Demand Response Programme DOCUMENT CONTROL."

[152] N. Good, "Using behavioural economic theory in modelling of demand response," *Appl. Energy*, vol. 239, no. July 2018, pp. 107–116, 2019.

[153] "Energy label and ecodesign | European Commission." [Online]. Available: https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign_en. [Accessed: 07-Dec-2020].

[154] Y. Lin, "Novel smart home system architecture facilitated with distributed and embedded flexible edge analytics in demand-side management," *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 6, Jun. 2019.

[155] R. P. Gheorghiu, Cristian, Ștefan GHEORGHE, Mircea SCRIPCARIU, "Energy Efficiency and Power Quality Indicators of a Micro Grid . Case study : Lighting Systems," *2019 8th Int. Conf. Mod. Power Syst.*, pp. 1–7, 2019.

[156] T. J. Ross and Wiley InterScience (Online service), *Fuzzy logic with engineering applications*. John Wiley, 2010.

[157] “Met Éireann Forecast - The Irish Meteorological Service.” [Online]. Available: https://www.met.ie/. [Accessed: 14-Feb-2021].

[158] “DRED Data Set.” [Online]. Available: http://www.st.ewi.tudelft.nl/akshay/dred/. [Accessed: 30-Apr-2020].

[159] “Energy Consumption in the UK - GOV.UK.” [Online]. Available: https://www.gov.uk/government/collections/energy-consumption-in-the-uk. [Accessed: 28-May-2019].

[160] BSI, “Requirements for electrical installations,” *IET wiring Regul. 18th Ed.*, vol. 2, no. 2, p. 560, 2018.

[161] S. Khadem, R. Kerrigan, M. Basu, and B. Basu, “A Study on the Power Quality of DG Integrated Building Energy System in Virtual Environment,” *Conf. Pap.*, Jan. 2013.

[162] Chauvin-Arnoux, “Single phase power quality analyser, C.A 8230.” [Online]. Available: http://www.chauvin-arnoux.com/sites/default/files/D00QPA50_4.PDF. [Accessed: 24-Jul-2017].

[163] anexo 2 Gobeirna De Espana, Guía técnica de aplicación en BT, “Cálculo DE Caídas De Tensión, (Technical Guide for application to the Low Voltage Electrotechnical Regulation),” 2003.

[164] “OpenDSS Documentation,” *p/electricdss/code - Revision 2496: /trunk/Distrib/Doc*. [Online]. Available: http://svn.code.sf.net/p/electricdss/code/trunk/Distrib/Doc/. [Accessed: 22-Jan-2019].

[165] K. Sunderland, M. Coppo, M. Conlon, and R. Turri, “A correction current injection method for power flow analysis of unbalanced multiple-grounded 4-wire distribution networks,” *Electr. Power Syst. Res.*, vol. 132, pp. 30–38, 2016.

[166] J. Yong, L. Chen, and S. Chen, “Modeling of Home Appliances for Power Distribution System Harmonic Analysis,” *IEEE Trans. Power Deliv.*, vol. 25, no. 4, pp. 3147–3155, Oct. 2010.

[167] “ISSDA | Commission for Energy Regulation (CER).” [Online]. Available: http://www.ucd.ie/issda/data/commissionforenergyregulationcer/. [Accessed: 06-Feb-2020].

[168] T. M. Gruzs, "A Survey of Neutral Currents in Three-Phase Computer Power Systems," *IEEE Trans. Ind. Appl.*, vol. 26, no. 4, pp. 719–725, 1990.

[169] F. Ding, B. Mather, and P. Gotseff, "Technologies to increase PV hosting capacity in distribution feeders," *IEEE Power Energy Soc. Gen. Meet.*, vol. 2016-Novem, no. August, 2016.

[170] ENTSO-E, "Requirements for Generators," 2016. [Online]. Available: https://www.entsoe.eu/network_codes/rfg/. [Accessed: 07-May-2020].

[171] N. C. Scott, D. J. Atkinson, and J. E. Morrell, "Use of load control to regulate voltage on distribution networks with embedded generation," *IEEE Trans. Power Syst.*, vol. 17, no. 2, pp. 510–515, 2002.

[172] M. G. L. K. P. Neal J. Balu, "Power system stability and control." New York: McGraw-hill, 1994.

[173] "Engineering Recommendation G100 Issue 1 Amendment 2 2018 Technical Requirements for Customer Export Limiting Schemes," no. 1, pp. 1–39, 2018.

[174] "EPRI | Smart Grid Resource Center > Simulation Tool – OpenDSS." [Online]. Available: http://smartgrid.epri.com/SimulationTool.aspx. [Accessed: 01-Sep-2019].

[175] D. N. Doc--ffn, "Public Consultation on the Smarter HV and MV Customer Connections Project New Approaches to Distribution Planning and Security of Supply Standards," no. November, pp. 1–44, 2019.

Appendix

A. Demand Response: The Concept

A simple DR model can be represented using a direct load control (DLC) based DR scheme. The DLC technique has been utilized for demand response implementation from the onset of load management program implementation. In this technique, the utility has remote access to certain individual consumer loads and DLC is remotely operated by the utility whenever needed. DLC schedules the loads based on simple priority list where lowest priority devices are turned off or on. The method has been implemented in various forms and strategies. Generally, scheduling of load using a direct load method uses two approaches: price-based methods and time of use-based method Figure 0.1.

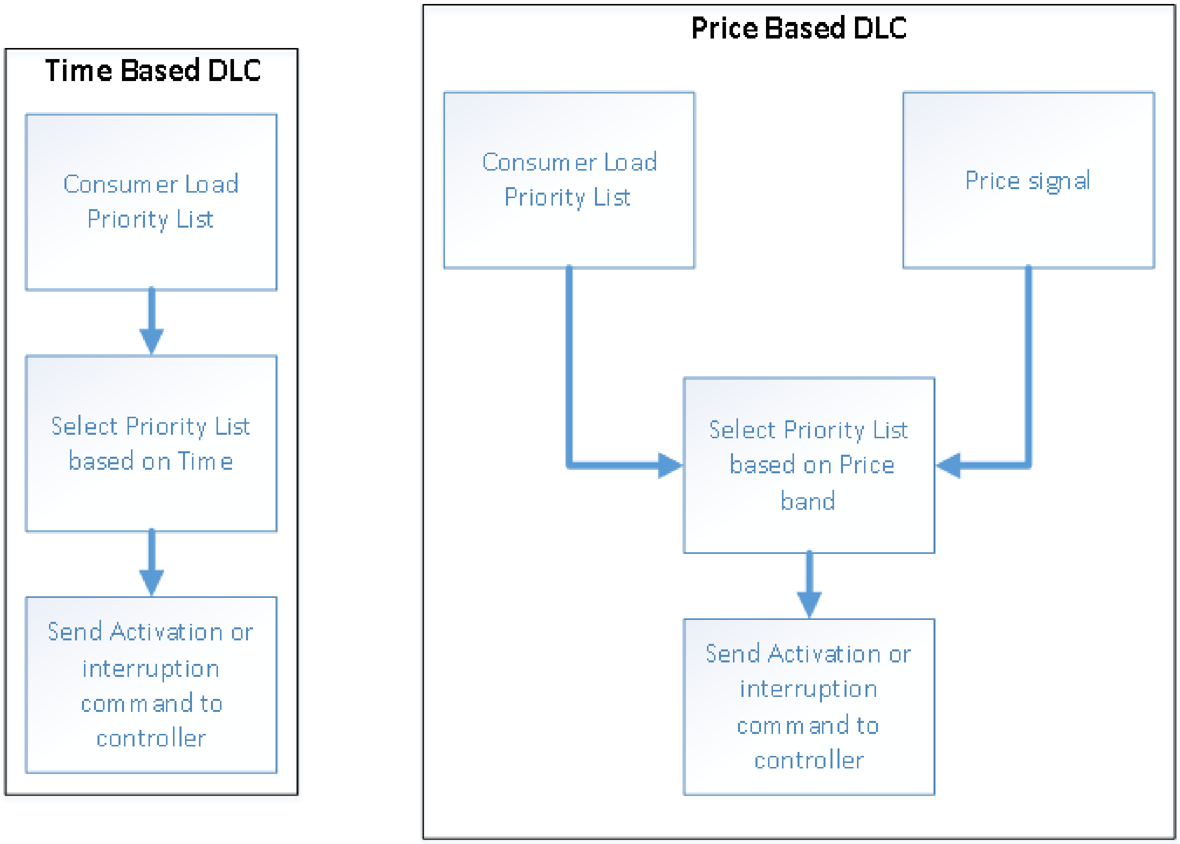


Figure 0.1 Simple DLC DR

Price based methods utilize the day ahead price of electricity that is available through the electricity market or from the utility itself. A priority list is formulated for a set of consumer loads according to the price per unit of electricity, and the scheduling is organized accordingly. When the price is high, only high-priority devices are set to operate with the remaining (controlled) devices are ‘off’. When the price is low all (listed) devices in the house are permitted to operate and hence no regulation or reduction is implemented. However, this method relays on effective communication and would require additional infrastructure and operation time to put into action.

A time based method utilizes the consumer’s basic load curve characteristics to identify the demand peaks and accordingly a schedule/priority list is made for modifying the consumption pattern. However, the morning and evening times are usually designated as peak consumption times and during these times, fewer devices are operated. As illustrated in Figure 0.1, the load regulation/reduction is conducted based on the time of peak occurrence.

For instance, if the DLC method is implemented using Price based and Time based method for a smart house with 6 controllable devices. The power rating of the devices, the price bases and time based priority lists are given in Table 0.1, Table 0.2 and Table 0.3. Figure 0.3 illustrates the base load demand and price based DR load for the device list (Table 0.1) according to the priority list specified (Table 0.2) and the price signal available (Figure 0.2). According to the price at a given time, the price band is selected. Based on the price band, the output is obtained. When the price is high during the 6-9am period (as provided in fig 5), the load is reduced from 3.1kW demand to lower than 1.5kW. This type of DR is not concerned with the customer comfort and only deals with reduction of the load during high price. The method is purely based on cost savings and will be profitable for both customers and the utility at the same time.

Table 0.1 : load and respective power consumption

Loads	**Rated Power(W)**
Light	300
TV	200
Washing Machine	500
Water Pump	1000
Heating	1000
Computer	150

Table 0.2 : price based priority list

Equipment	**Price Band**					
	I	II	III	IV	V	VI
Light	1	1	1	1	1	1
TV	1	1	1	1	0	0
Washing Machine	1	1	0	0	0	0
Water Pump	1	1	0	0	0	0
Heating	1	1	1	1	1	0
Computer	1	1	1	1	1	0

Similarly, a time based DLC implemented using Table 0.3 is given in Figure 0.4. Time based demand response is obtained by scheduling the load based on a respectively assigned time based priority list. The method primarily depends on the general nature of peak curve. The peak is assumed to be in the morning and evening hours. During these times a specific set of equipment (appliances) are allowed to work which are considered to be inevitably required at those particular times. During the evening peak which is assumed to be during 6-9 PM the load is reduced close to 1.5kW from 3.1kW. This method doesn’t consider peak magnitude and works like a strict controller bounded by specific time-based rules without any alterations. The method is useful if the load reduction required is small and the peak time is constant. In all other cases however, the method is not so useful. Moreover, this method, like price based DR, is not considerate of customer comfort, rather it dictates a strict rule set irrespective of the consumer inconvenience. Such algorithms are seldom appreciated by the consumers and in that regard could present a major bottleneck for the success of a DR program. Contrary to DLC DR, a fuzzy controller based DR can effectively map non-deterministic inputs like consumer comfort to produce logical decisions.

Table 0.3 : Time based priority list

Equipment	**Time (Interval of 3 Hours)**							
	1	2	3	4	5	6	7	8
Light	0	0	x	0	0	1	x	3
TV	0	0	1	0	0	4	x	4
Washing Machine	2	2	4	2	4	6	3	6
Water Pump	1	1	3	1	3	5	2	5
Heating	x	x	x	0	1	2	x	1
Computer	0	0	2	0	2	3	1	2

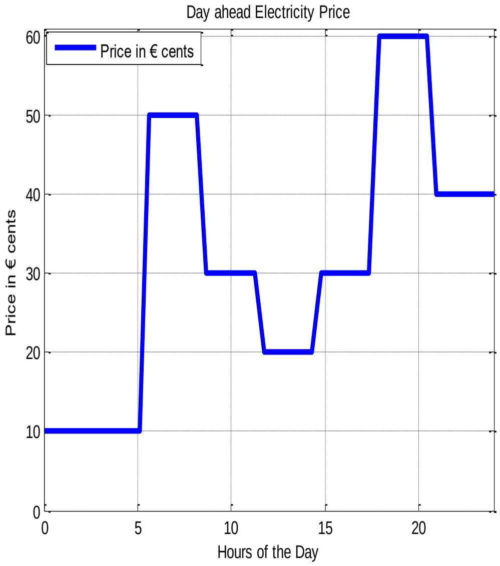


Figure 0.2 Price signal for a day

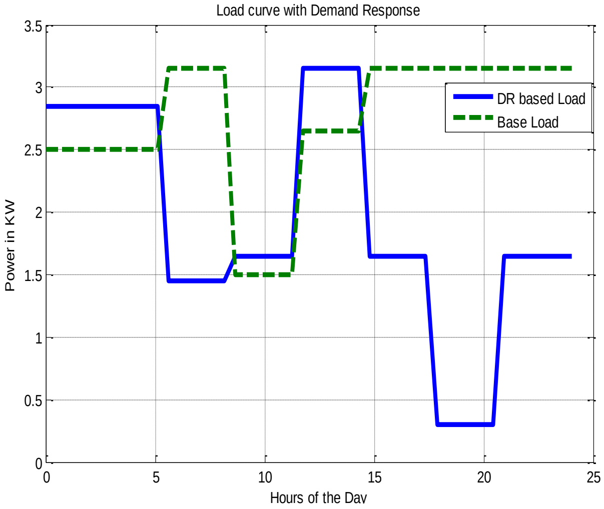


Figure 0.3 Base load and demand response

(Price based)

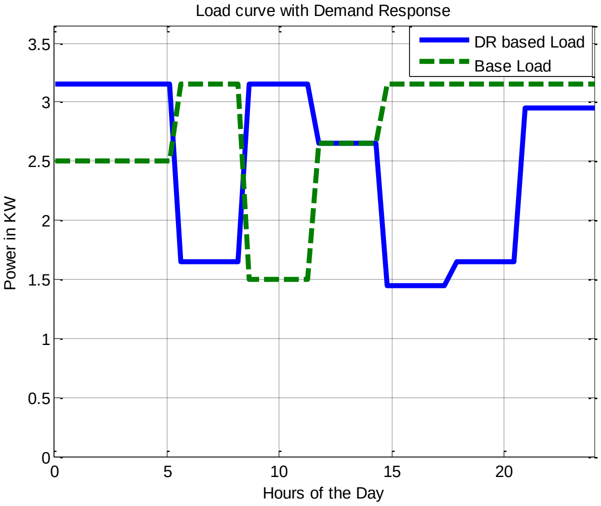


Figure 0.4 Base load and demand response

(Time based)

B. Scenario 1: All Load Active

Figure 0.5 - Figure 0.7 provides load demand and reduction along with changes in tolerance level for representative consumers participating in each engagement plan (Table 3.2) in each phase. The consumer in reluctant engagement plan is not included here as they are inherently not participating in the DR program. As observed in earlier results for C-DR in Chapter 3, the consumers participating in SGS engagement plan participate extensively compared to any other due to their low tolerance value. Also, it can be observed from Figure 0.5 - Figure 0.7 that the tolerance value updates in each interval based on the participation of the consumer in the DR program. Once the tolerance value of SGV consumer reaches 0.5 or above, the SGV consumer is treated as a GS consumer and the particular SGV consumer may not participate in the next demand reduction call. The algorithm performs similarly for consumers in GA and GS plans. However, the amount of load reduction accommodated by SGV consumer is always higher than GS or GA and thus should receive a higher incentive for it. Write on % reduction for different consumer plan consumers or put a table for it

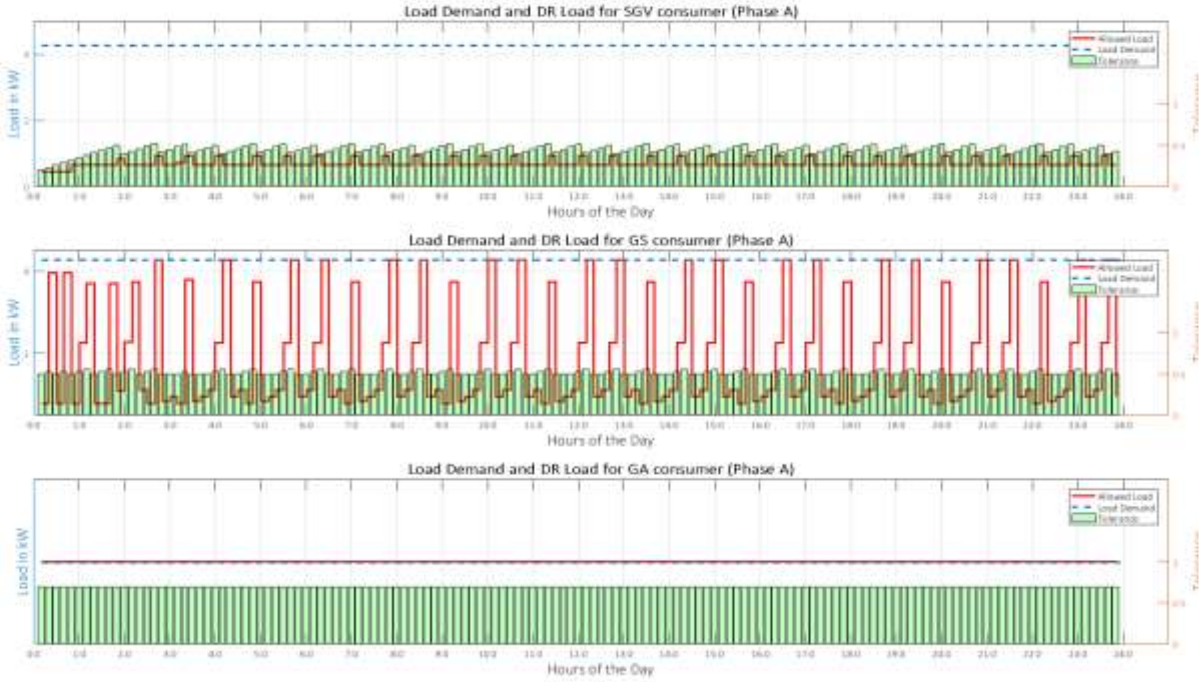


Figure 0.5 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase A

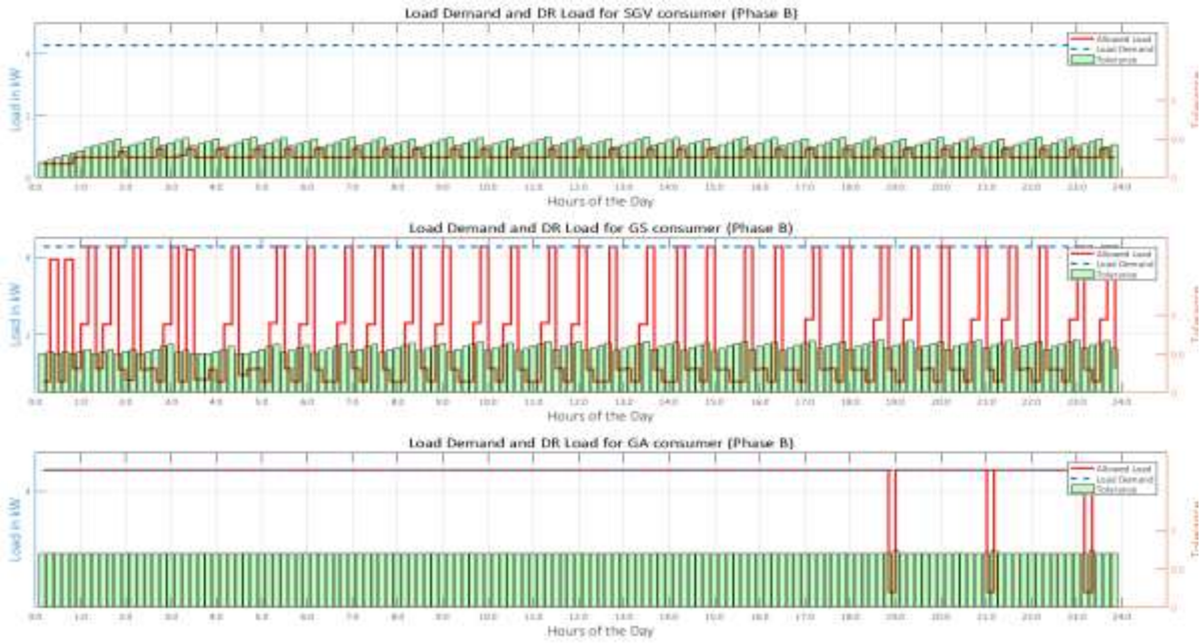


Figure 0.6 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase B

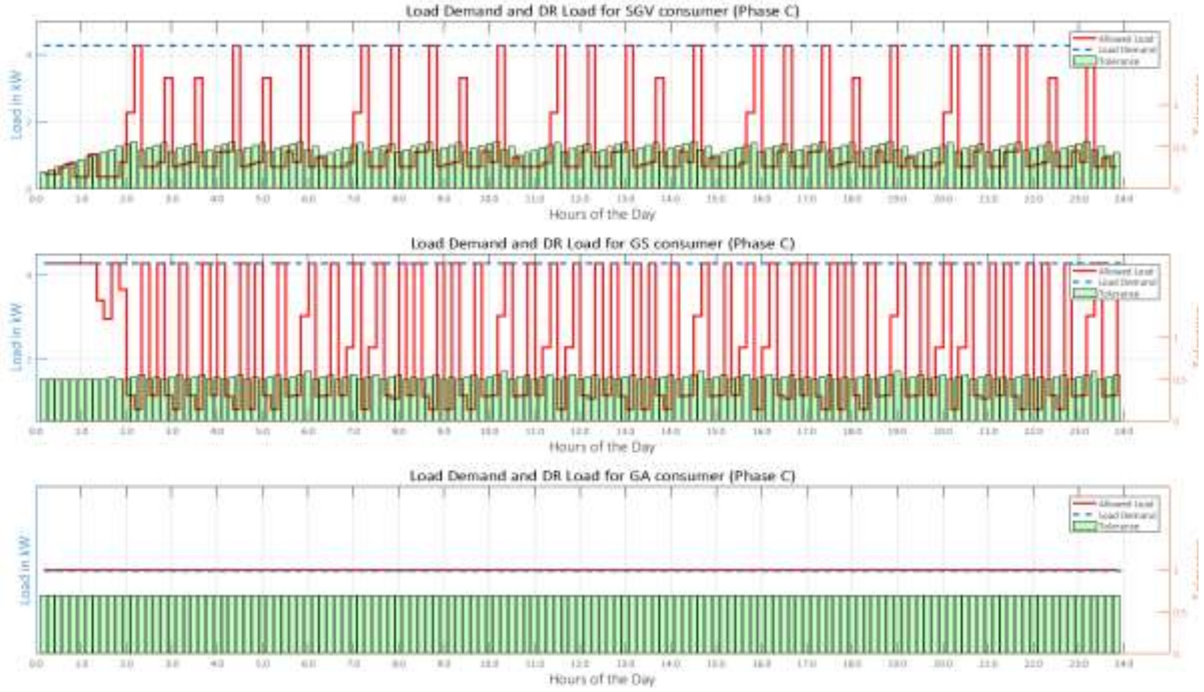


Figure 0.7 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase C

C. All Load Active

High Penetration Scenario

A representative consumer in each engagement plan for each phase is presented in Figure 0.14 - Figure 0.16. Consumer participating in DR would see a change in their tolerance value. The participation of each consumer would depend on their respective engagement plan with SGV consumer highly engaging compared to GS and GA. As usual, the reluctant consumer would not see a change in their load consumption as they are not participating in the DR program. The HC-C-DR algorithm responds to the increased heating in the cable section AB by generating a demand reduction request per phase. The request is then distributed to the consumer connected according to their engagement plan.

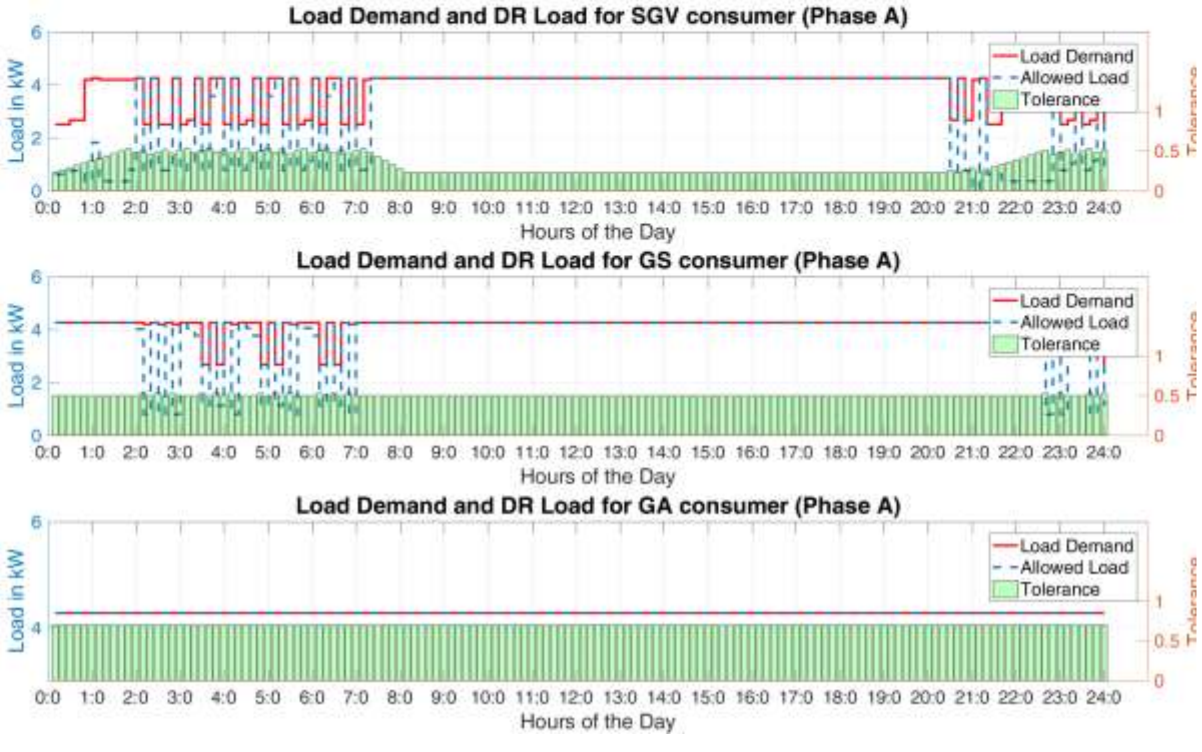


Figure 0.8 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase A

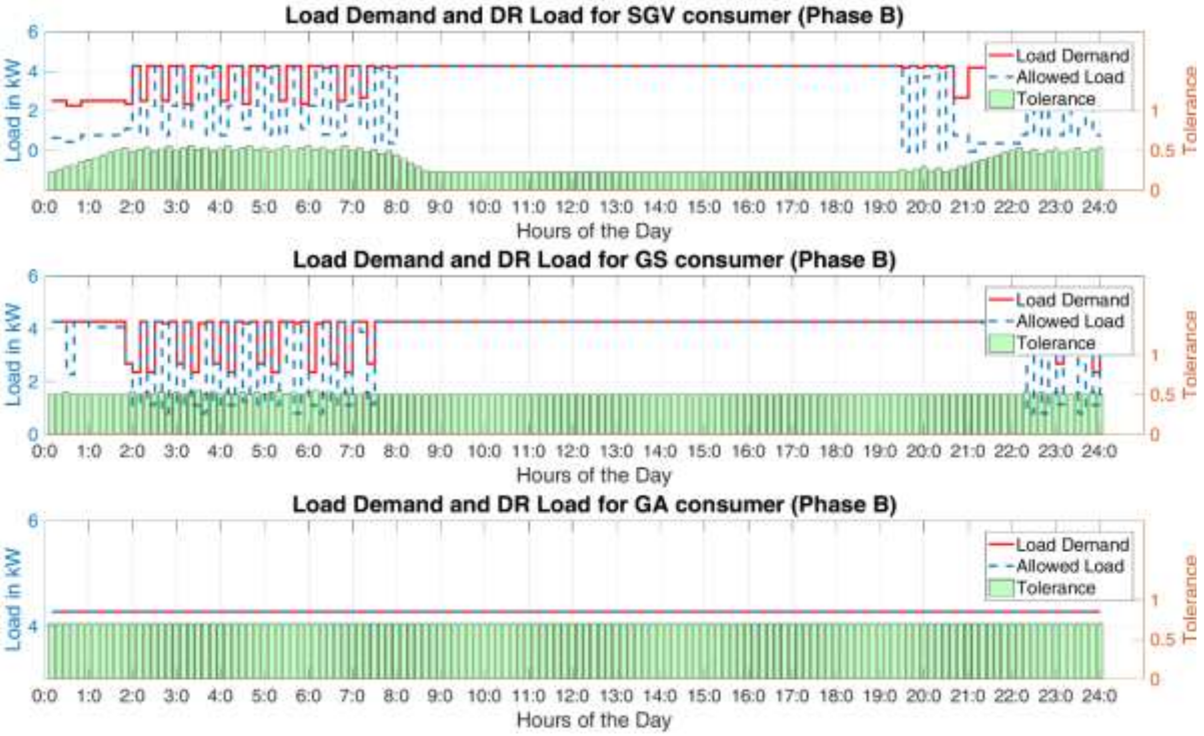


Figure 0.9 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase B

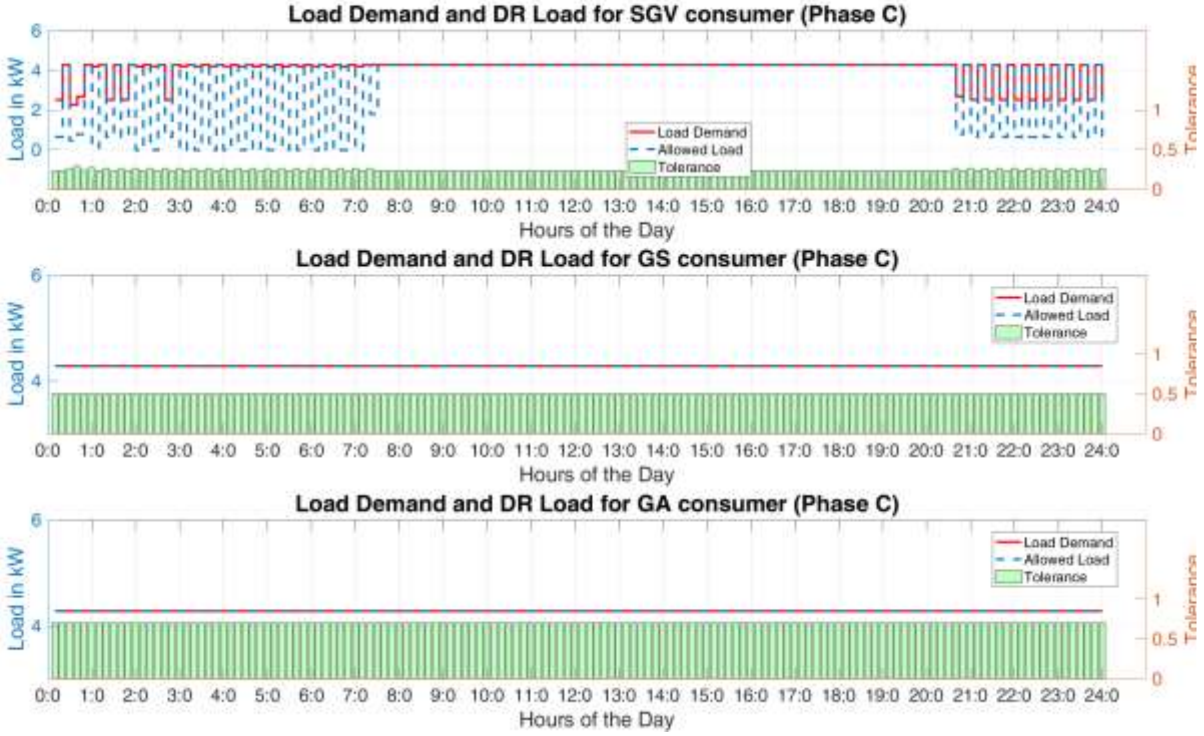


Figure 0.10 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase C

Low Penetration Scenario

A representative consumer in each engagement plan for each phase are presented in Figure 0.14 - Figure 0.16. Consumer participating in DR would see a change in their tolerance value. The participation of each consumer would depend on their respective engagement plan with SGV consumer highly engaging compared to GS and GA. As usual the reluctant consumer would not see a change in their load consumption as they are not participating in DR program.

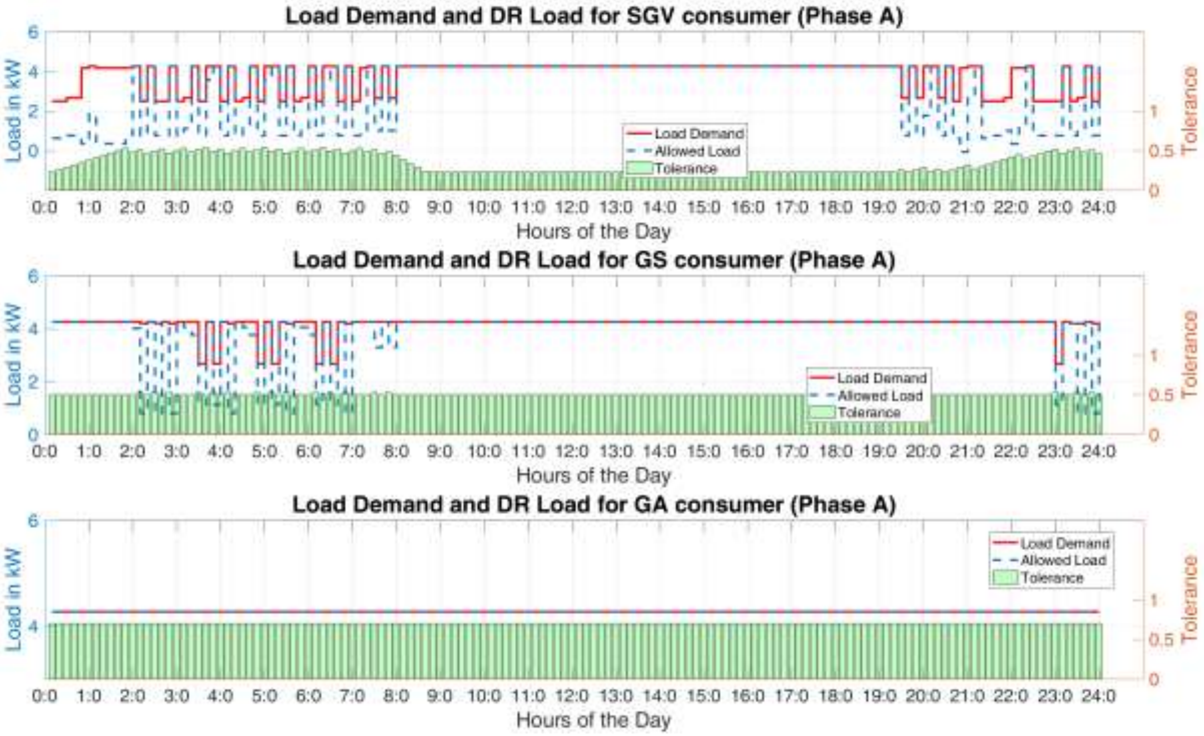


Figure 0.11 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase A

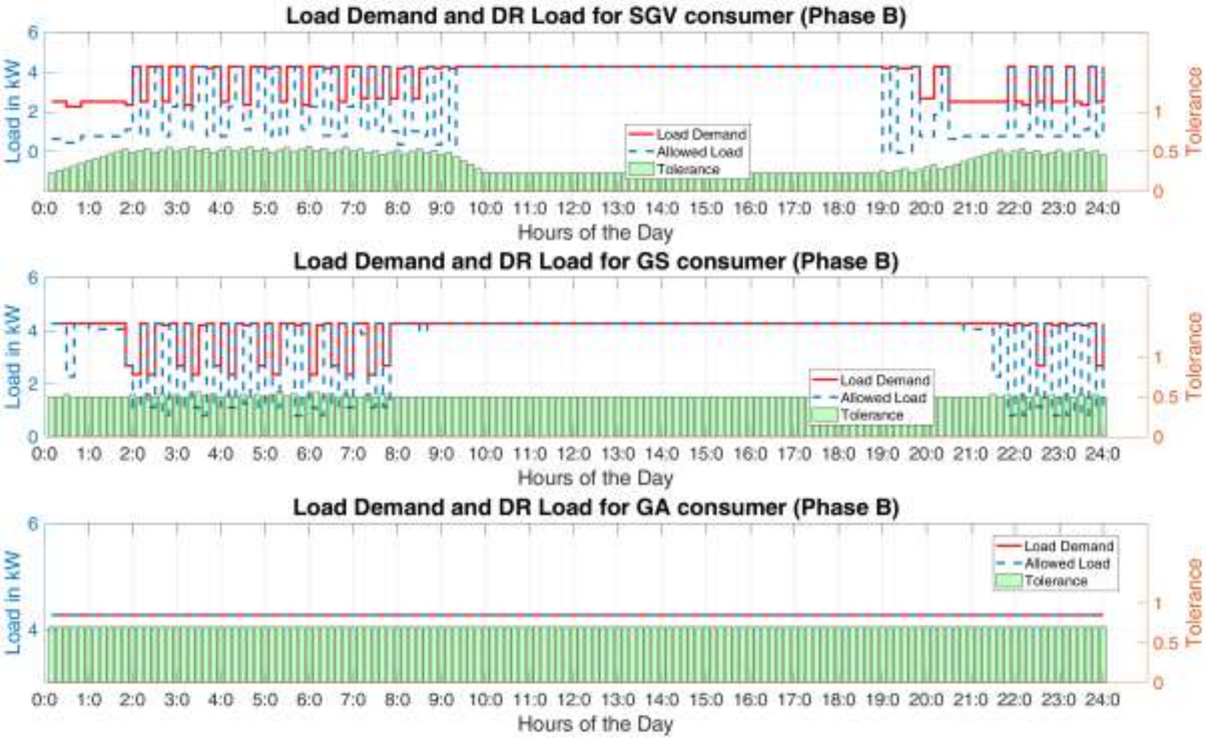


Figure 0.12 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase B

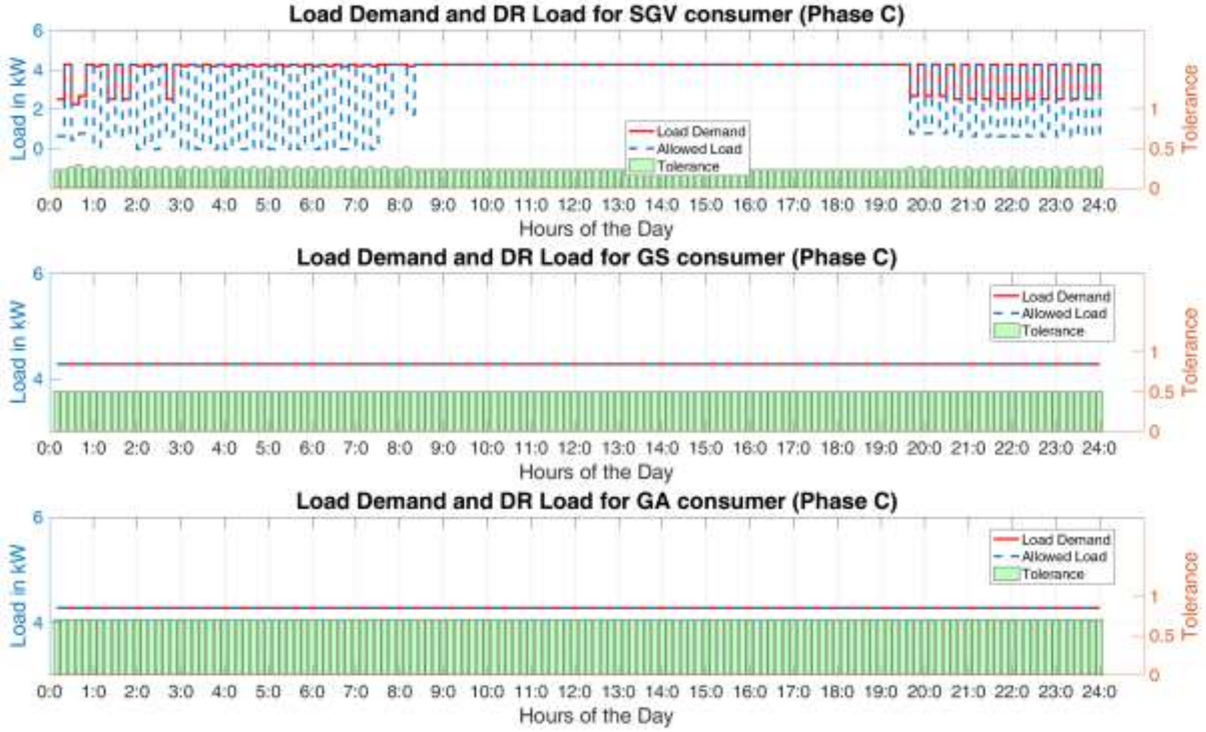
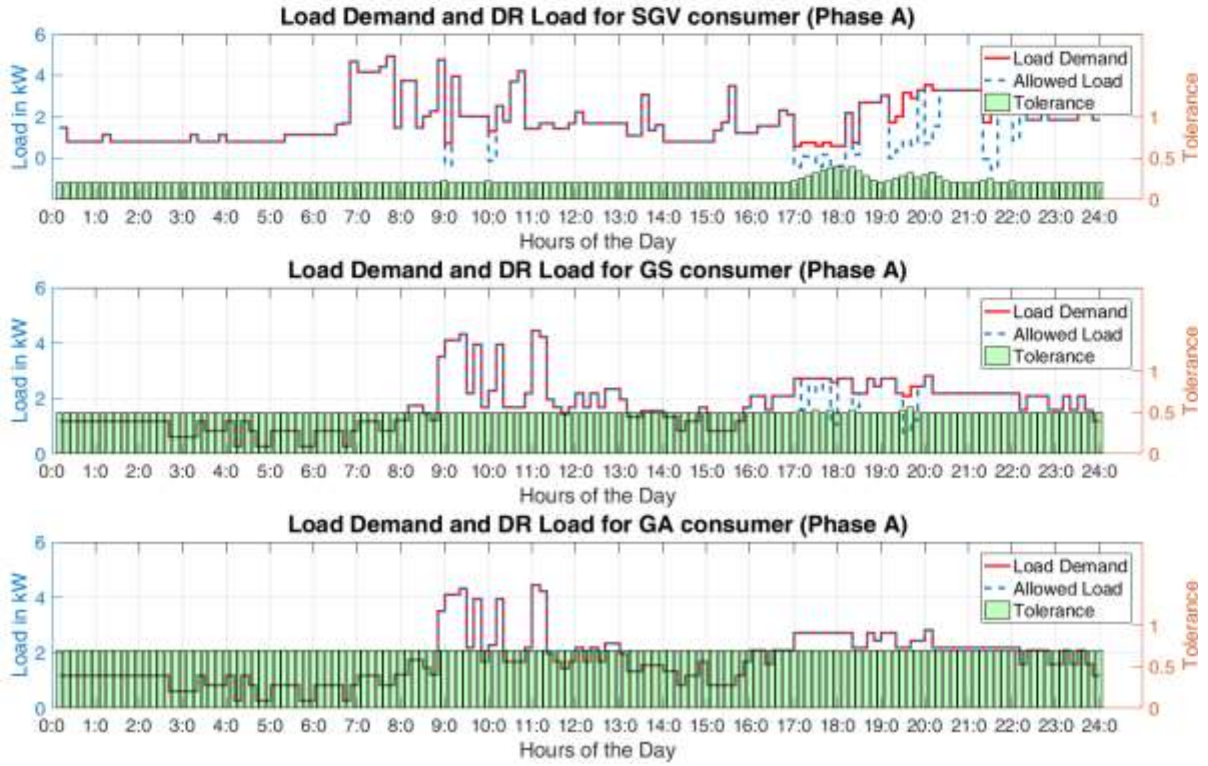


Figure 0.13 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase C

D. With Recorded Consumer Load Profile

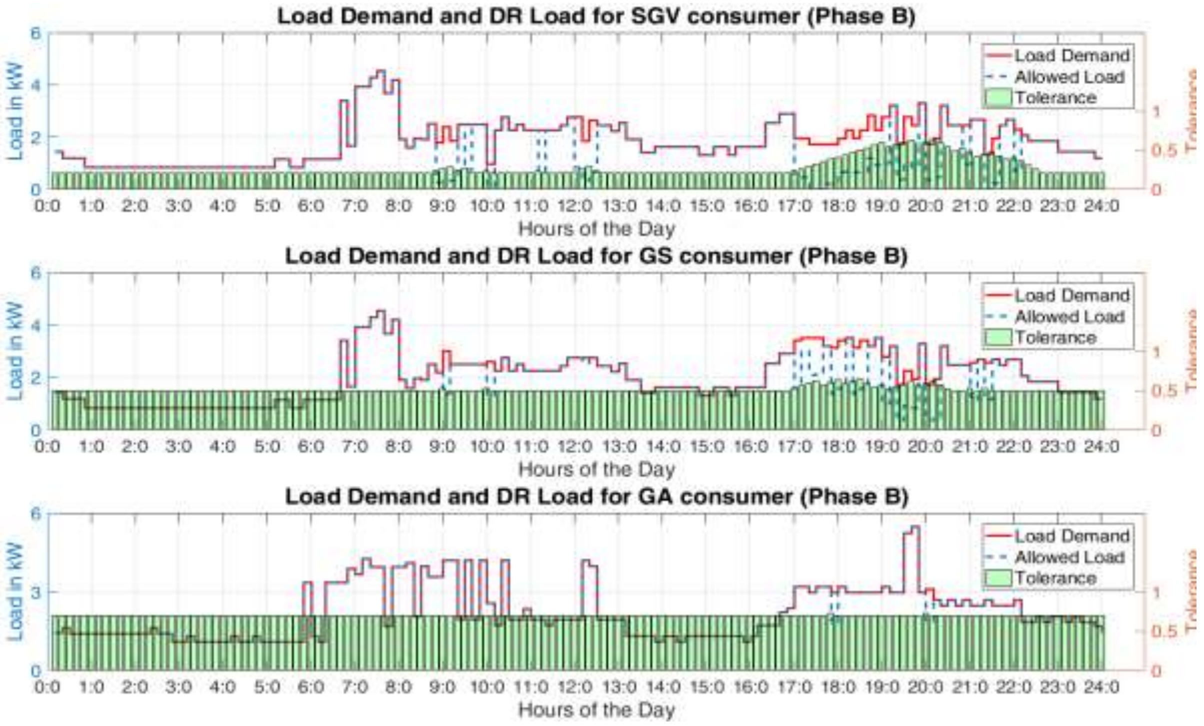
A representative consumer in each engagement plan for each phase are presented in Figure 0.14 - Figure 0.16. Consumer participating in DR would see a change in their tolerance value. The participation of each consumer would depend on their respective engagement plan with SGV consumer highly engaging compared to GS and GA. As usual the reluctant consumer would not see a change in their load consumption as they are not participating in DR program.


Load Demand and DR Load for SGV consumer (Phase A)

Load Demand and DR Load for GS consumer (Phase A)

Load Demand and DR Load for GA consumer (Phase A)

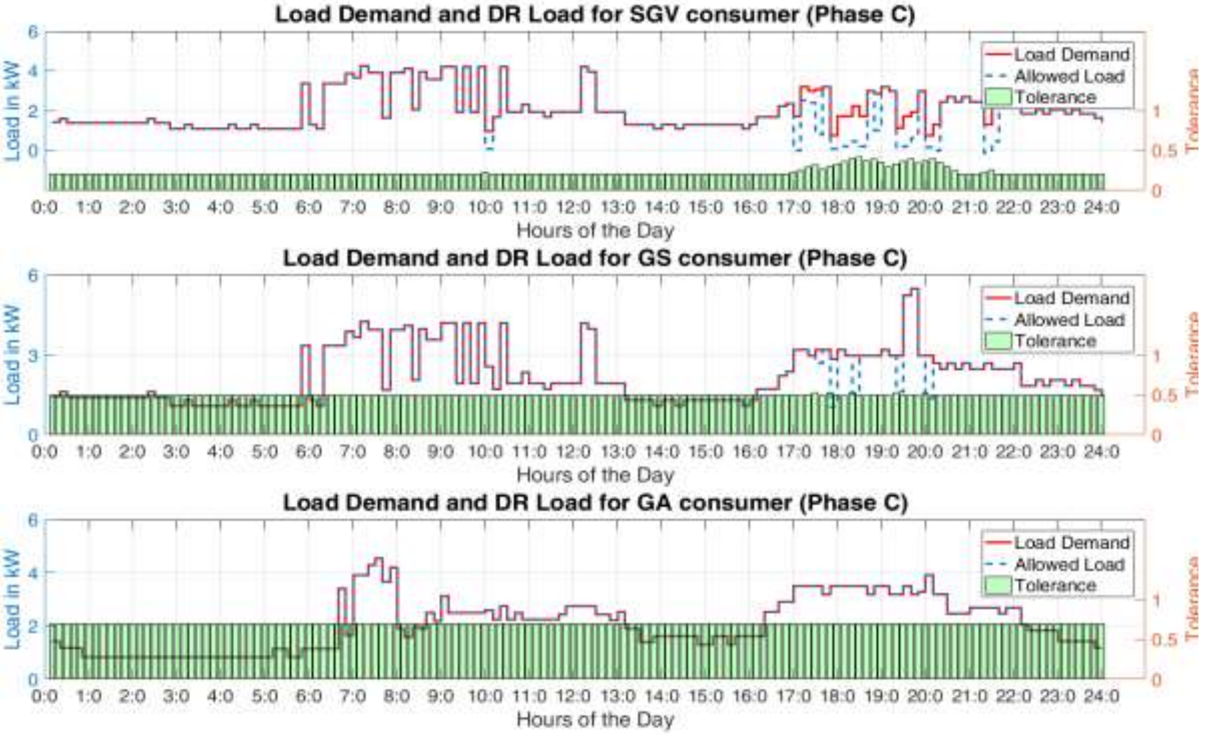
Figure 0.14 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase A


Load Demand and DR Load for SGV consumer (Phase B)

Load Demand and DR Load for GS consumer (Phase B)

Load Demand and DR Load for GA consumer (Phase B)

Figure 0.15 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase B


Load Demand and DR Load for SGV consumer (Phase C)

Load Demand and DR Load for GS consumer (Phase C)

Load Demand and DR Load for GA consumer (Phase C)

Figure 0.16 Load demand and DR load for consumers in different tolerance level corresponding to their engagement plan in a day in phase C