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MSc Dissertation Thesis
MSc in Sustainable Energy Systems

Load Management in Distribution Networks

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Copy of the Original Mission Statement

Sustainable Energy Systems, MSc Project Mission Statement *Load Management in Distribution Networks*

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Background

In order to improve power system efficiency and security, there is interest in the widespread use of load management schemes to provide local network support. This effectively builds on the principle of demand-side management (DSM) which has been utilized by network operators for several years. Historically this functionality was offered by large consumers, who would agree to reduce demand if required. As the visibility and control in lower voltage distribution networks continues to grow, there is great potential to increase both the participation and benefit of DSM.

Ultimately, the purpose of DSM is to control the demand level in order to support network performance, and other options exist within the distribution network. One such alternative is the use of conservation voltage reduction (CVR), which is under consideration by network operators around the world. This scheme adjusts the operating voltage at a point in the network to reduce demand.

Both of these load management methods have different implementation requirements, and will be able to provide different levels of response to the network operator. This project aims to quantify these factors and provide a direct cost benefit analysis of the two load management techniques. The analysis will consider both the consumer and utility perspective and will provide recommendations for implementation.

Aims

- Classify load management techniques for distribution networks.
- Establish the potential benefits of implementing load management in improving security of supply.
- Apply techno-economic analysis of load management options in distribution networks.
- Quantify value to the network operator and provide recommendations for implementation.

Interim Targets

- Perform literature review of controllable loads and time of use tariffs.
- Identify load management techniques for distribution networks.
- Define scenarios to be analysed during the project.
- Install and learn power flow software.
- Build network models.
- Produce interim report on the above.

The proposed research will help to gain an in-depth knowledge on load management methods in distribution networks. Their individual merits and demerits will be assessed to establish a techno-efficient framework, from both consumer and utility perspectives. The characteristics of different load types will be reviewed, identifying controllable loads and an effective way to manage them. The proposed work will also help to gain general experience in load modelling and simulation of distribution networks. The knowledge gained from the research will allow the production of a thesis, in which the main aims of the Dissertation work will be discussed, further clarified and illustrated with the obtained results.

The supervisor and student are satisfied that this project is suitable for performance and assessment in accordance with the guidelines of the course documentation.

Student:..... Supervisor:..... Date:...../...../.....

Abstract

Load management is a top concern for utilities all over the world as the total electricity consumption in most countries continues to rise. Current DECC forecasts suggest a 60% rise in the total electricity demand in the UK between the years 2030 and 2050 due to the high uptake of heat pumps and electric vehicles. Since major nuclear plants that supports base load in the UK are scheduled to shut down in ten years time due to their end of life, there will definitely be a need for extra generating capacity if this trend continues and existing loads are not well managed. Conservation voltage reduction (CVR) has proved productive in North East Utilities in the US to reduce peak demand and provide energy savings, and similar savings can be achieved in the UK. This may help defer the need for extra generating capacity and provide environmental savings. The power flow simulations carried out in this work was to estimate the demand savings on UK type residential feeders in terms of the CVR factor. The analysis showed that the CVR factor is sensitive to temporal variations in load. The amount of savings realizable through CVR depends on the composition of loads on the feeder and the season effected.

Keywords: Demand Side Management; Load Management; Voltage Optimization; Load Modelling, Conservation Voltage Reduction.

Declaration of Originality

I declare that this is my original work, except where stated otherwise. This thesis has never been submitted for any degree or examination to any other University.

.....(Signature)

....../....../.....(Date)

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Acronyms and Abbreviations

AC	Alternating Current
AMI	Advanced Metering Infrastructure
ANSI	American National Standards Institute
CFL	Compact Fluorescent Lamps
CPP	Critical Peak Pricing
CVR	Conservation Voltage Reduction
DA	Distribution Automation
DAC	Distribution Automation and Control
DECC	Department of Energy and Climate Change
DG	Distributed Generation
DLC	Direct Load Control
DLM	Dispatch Load Management
DMS	Distribution Management System
ECS	Energy Conservation Scheduling
EMS	Energy Management System
EOL	End of Line
GIL	General Incandescent Lamps
HEMS	Home Energy Management System
HVAC	Heating, Ventilation and Air Conditioning
HVR	Home Voltage Reduction
LDC	Line Drop Compensation
LTC	Load Tap Changer
LTT	Load to Temperature Dependence
LTV	Load to Voltage Dependence
LM	Load Management
LV	Low Voltage

Acronyms and Abbreviations

PTR	Peak Time Rebates
RTP	Real Time Pricing
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
TOU	Time of Use
VSR	Voltage Spread Reduction
VO	Voltage Optimization
VVC	Voltage/VAR Control
VVO	Voltage/VAR Optimization
ZIP	Polynomial Load Model

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1 Introduction

1.1 The Need for Load Management in Distribution Networks

According to the International Energy Agency (IEA) statistics, the world total electricity consumption has increased from 5,116 TWh in 1973 to 18,907 TWh in 2012 [1]. This upsurge is also seen in the total electricity generation which also increased from 6,129 TWh to 22,668 TWh in the same time period [1]. The rise in electricity demand in many countries due to economic and industrial development has to be met by building more generating plants and providing sufficient reserves during emergencies. To reduce the cost of additional power plants, a more viable option is to manage the existing loads such that the power needed to meet these loads is reduced. It is also necessary to reduce the production and operating cost of generators, which is directly influenced by the varying load on the power system. As the electricity demand of consumers vary in accordance with their activities and time of usage, the load on the power system varies and this necessitates additional equipment, increasing production cost. Electricity generation must constantly match demand for the system to be balanced and the supply system must be designed to meet maximum loads to cater for peak demand periods.

Utilities must fulfill certain key objectives in order to achieve a more efficient and sustainable power system network. From Figure 1.1, it can be seen that their top key concerns are peak load management and environmental sustainability. To reduce the amount of peaking power plants required to meet peak demands and to reduce the associated emissions resulting from extra generating capacity, it is vital to manage existing loads from the demand side using various techniques by the consumer or operated directly by the utility. Different load management techniques have been established by utilities to modify the load pattern of consumers to better utilize existing generating capacity, deferring the need for extra capacity and reducing running costs of generators. Their main aim is to reduce peak loads (level and smooth the load curve), and also to reduce the dependency on expensive fuels to run plants during peak periods.

Figure 1.1: Major Concern for Utilities [2]

The various methods that exist for effective load management intend to achieve the efficient use of electricity while reducing load at peak periods. This will, to some extent, reduce the variation in load curves in power stations as an ideal load curve is one of constant magnitude and steady duration. Load management also makes the distribution system more reliable and being run at lower cost. In addition to fulfilling environmental concerns, for consumers, they also require a quality and reliable power supply (as shown in Figure 1.2) and seek ways to reduce their energy bills. Consumers can reduce their energy usage by simple energy saving housekeeping measures at little or no cost and can make some more savings if they allow the utilities to directly control their major loads.

Figure 1.2: Major Concern for Consumers [2]

1.2 Requirements of a Successful Load Management Programme

In addition to reducing demand at peak periods and offering reduced rates for consumers, a load management scheme must also meet certain criteria for it to be judged as acceptable for both the consumer and the utility. It must be cost-effective (acceptable cost/benefit ratio) and payback in good time. The implementation of some load management techniques will involve some form of costs associated to either the consumer or the utility and this has to be measured against the benefits to be gained in order to determine if the method is cost-effective. Shifting time of use of electrical appliances/equipment may cause some form of inconvenience for electricity users. A good load management scheme must have an acceptable level of consumer convenience. It should be efficient and reliable and there should be ways of measuring and verifying the effectiveness of the scheme in order to quantify its impacts on any system. The load management scheme of focus in this work is the

conservation voltage reduction method and it meets all of the above requirements to a large extent. Open-loop conservation voltage reduction is cost-effective and provides peak demand and energy savings. It provides savings in customer electricity bills and is not inconveniencing.

1.3 Objectives of the Study

This research seeks to identify the major load management techniques and discuss their merits and demerits in order to establish a techno-efficient framework, from both the consumer and utility perspectives. This work will be focused on conservation voltage reduction (CVR) as a load management measure and its costs and benefits will be analysed in the viewpoint of the main stakeholders involved. The effects of CVR on network losses and efficiency will be examined. Most importantly, this work should quantify the CVR savings that can be achieved on UK type networks to the utility. To achieve these, the open distribution system simulator software (OpenDSS) and the Matlab programs will be used to develop network models and codes necessary to perform the analysis.

1.4 Thesis Contributions to Knowledge

This research will help to gain an in-depth knowledge on load management methods in distribution networks. As CVR is being trialed in the UK, the results from this research will inform utilities and network operators on the potential peak demand savings that can be achieved in the UK type residential networks. Previous studies on CVR has focused on a daily CVR implementation which indicates a single value. It is necessary that a time-step CVR simulation be done to specify the CVR factor at different times during the day. Through this, utilities will be advised better on when best to implement CVR for peak demand reduction and what savings to expect. The Matlab code developed in this work for time-step simulation (5 minute interval) may be utilized for further research in this area. Utilities considering the implementation of advanced CVR or volt/var control will find useful, the cost-benefit analysis discussed in Chapter 3 of this work. This is necessary in order to make a more informed decision on implementation and the formation of a cost-

recovery framework. Also, the different load management and energy reduction methods discussed in this work will enlighten consumers of electricity on the best ways to save energy and reduce energy bills.

1.5 Organization of Thesis

This thesis is composed of 6 chapters.

Chapter 1 introduces this work and so far the importance of load management as tool for an efficient and reliable distribution network has been discussed.

Chapter 2 is a literature review of the existing demand side management measures and load management schemes. The different network types and key terms are defined; the major load management programmes are also compared. It also describes the existing load management schemes in the UK, the structure of the UK distribution network and voltage regulations and standards in place.

Chapter 3 is focused on CVR, its deployment and a review of load modelling. The techniques of CVR implementation and the various ways of measuring and verifying the effects of CVR is discussed. The costs and benefits associated with its operation with respect to the different parties involved is also presented. The major types of load model is reviewed with respect to CVR implementation.

Chapter 4 introduces the methodology and discusses the procedures and tools used in the simulation of typical UK LV distribution networks using Open Distribution System Simulator software (OpenDSS).

In **Chapter 5**, the outcome of the simulation is presented and discussed. The effect of conservation voltage reduction on four different feeders are analysed. Results were discussed in the line of network losses, efficiency and temporal variations in load.

Finally, **Chapter 6** concludes and summarises the work and recommends areas of further research. The limitations of this work is also presented.

2 Review of Load Management

In this chapter, existing load management schemes will be reviewed and compared, generally and also in the UK context. Their merits and demerits will be analysed in the perspectives of the utility and the consumers. The UK distribution network structure and voltage regulations will be discussed with the aim of conservation voltage reduction implementation.

Load management is one of the divisions of demand side management which involves the modification of the consumer's electricity usage pattern. To understand load management, basic terms related to load management will be defined.

2.1 Electrical Load Classification

There are different definitions of an electrical load and it can be classed into different categories based on the context in which it is used. An electrical load can be defined as a device which utilizes electrical energy to perform a specific function. Some of the different classification of electrical loads include the following.

2.1.1 Classification According to Nature of Load

- **Resistive Loads:** These are constant current loads that convert electrical energy into heat or light. An example is a resistive water heater. They consume energy in a sinusoidal manner.
- **Inductive Loads:** Examples are electric motors and fans. They require a magnetic field to operate. The applied voltage leads the current in an inductive load.
- **Capacitive Loads:** These loads store energy in the form of capacitance. The applied voltage lags the current in a capacitive load.
- **Combination Loads:** Most electrical loads are a combination of any two or the three aforementioned load types.

2.1.2 Classification According to Load Consumer Category

Loads can be classified according to the type of consumer or customer class and these include:

- Domestic Loads: Domestic loads perform functions such as space heating, lighting and cooking; they include all household appliances. The residential consumer category has poor load factors of the order of 10 to 15% as most lighting loads are used only during night time while other appliances are in use only for few hours during the day. They also have high demand factors (close to 1) since the connected load is small. The typical load curve for a residential consumer given in Figure 2.1 shows a peak demand occurring at 6pm. The peak demand usually occurs in the evening when most consumers have returned from their place of work [3].

Figure 2.1: Typical Urban and Rural Residential Load Curves [4]

In the UK, the domestic sector accounts for 29% of the total electricity consumption. According to the Department of Energy and Climate Change (DECC), space heating has taken over 60% of the domestic sector electricity consumption for the past years between 2008 and 2013 due to the country's climate [5]. This is shown in Figure 2.2 below.

Figure 2.2: Total Domestic Energy Consumption [5]

- **Commercial Loads:** These consist mainly of lighting loads for commercial establishments like malls, schools, restaurants. The commercial consumer category or service sector has high demand factor (close to 1) while their load factor is of the order of 25 to 30%. Figure 2.3 below shows the peak demand occurring at about 5pm. The peak demand depends on the type of service offered but usually occurs in the evening.

Figure 2.3: Typical Urban and Rural Commercial Load Curves [4]

- **Industrial Loads:** These include load demand in factories and industries which comprise of motor loads. Different industries will have varying industrial loads depending on the type of the industry. The industrial consumer category will have a demand factor of the order of 0.75 to 0.9 and a load factor in the range of 0.3 to 0.75, depending on the industry size. A typical load curve for an industrial consumer is shown in Figure 2.4 below (Peak demand occurring in the morning at 11am). It is usual for industrial load curves to have double or flatter peaks since the load demand is high for most hours during the day [3].

Figure 2.4: Typical Industrial Load Curve [4]

- **Municipal Loads:** These are loads that serve the public community (aside transportation). They include street lights, electric motors for public water supply pumping system and power supply for drainage systems [3].
- **Irrigation and Traction Loads:** Irrigation loads are typically electrical motor loads that drive pumps to supply water required for crops in farms or fields. Traction loads are loads demanded by transportation systems which includes trams and trains (railways).

2.2 Useful Terminologies

The definition of some key terminologies related to load management are given below [3, 4]. These terms are represented in Figure 2.5.

- **Average Load:** This is the average of all loads occurring in an installation (or in a power station) in a given time period. It is expressed mathematically in Equation 2.3.
- **Base Load and Peak Load on Power Station:** The base load on a power station is the constant load that occurs most times during the day. Peak loads are loads over and above the base load.
- **Coincidence Factor:** This is the fraction of the maximum demand of a load class that coincides in time of the system maximum demand.
- **Coincident Demand:** Demand required by a group of customers over a specified time period.
- **Coincident Peak Demand:** This occurs when the demand of groups of customers (residential, commercial or industrial) coincides in time with the maximum system demand.
- **Connected Load:** This is the total sum of the continuous ratings of all power consuming equipment in an installation (or a power supply system).
- **Demand:** Load of an installation averaged over a specific time period.
- **Demand Factor:** This is the ratio of the maximum demand to the connected load. It is expressed mathematically in Equation 2.2.
- **Diversity Factor:** Different consumer load classes will have varying maximum demands. The ratio of the sum of these maximum demands to the overall system maximum demand is known as the diversity factor. It is represented mathematically in Equation 2.4. Table 2.1 shows typical diversity factors between the elements of a distribution network.

- Load Curve and Load Duration Curve: The load curve is a curve depicting the varying load on an installation with respect to time. The load duration curve is a load curve whose elements are arranged in a descending order of magnitude.
- Load Factor: It is the ratio of average load to maximum demand over a specified time period. It is expressed mathematically in Equation 2.1.
- Maximum Demand: Highest demand occurring in an installation (or in a power station) for a specified time period.
- Non-Coincident Peak Demand: The maximum demand of a particular group of customers that does not necessarily coincide with the maximum system demand.

Figure 2.5: Key Concepts Related to Load Management [6]

$$\text{Load Factor} = \frac{\text{Average Load}}{\text{Maximum Demand}} \quad (2.1)$$

$$\text{Demand Factor} = \frac{\text{Maximum Demand}}{\text{Connected Load}} \quad (2.2)$$

$$\text{Average Load} = \frac{\text{Area (in kWh) under Daily Load Curve}}{24 \text{ hours}} \quad (2.3)$$

$$\text{Diversity Factor} = \frac{\text{Sum of Individual Maximum Demands}}{\text{Maximum Demand on Power Station}} \quad (2.4)$$

If the demand factor is low, it implies that a lesser system capacity is required to serve the load connected. For an efficient distribution system, the load factor should be high corresponding to reduced maximum demand. Load and demand factors are always less than unity [7]. Utilities take into accounts their annual load factor with the help of the annual load curve to improve their load profile. The higher the diversity factor, the lower the cost of electricity generation. Diversity factors are normally more than unity.

Table 2.1: Typical Diversity Factors in Distribution Networks [8]

Element of systems	Diversity Factors			
	Residential	Commercial	General Power	Large Industrial
Between Individual Users	2.00	1.46	1.45	
Between Transformers	1.30	1.30	1.35	1.05
Between Feeders	1.15	1.15	1.15	1.05
Between Substations	1.10	1.10	1.10	1.10
From Users to Transformers	2.00	1.46	1.44	
From Users to Feeders	2.60	1.90	1.95	1.15
From Users to Substation	3.00	2.18	2.24	1.32
From Users to Generating Stations	3.29	2.40	2.46	1.45

The Diversity factor between individual consumers is the ratio of the sum of their individual maximum demands to the maximum demand of the transformer serving them. This

value will vary for the different customer classes (residential, commercial and industrial) and for general power applications (unclassified). In such manner, the diversity factor between transformers is the ratio of the sum of the maximum demands on the individual distribution transformers to the maximum demand on the feeder supplying power to the transformers. It goes all the way, from the feeder to the substation and finally to the generating stations.

2.3 Connection Schemes of Distribution Networks

It is required of every good distribution system to provide the right voltage level to consumers with minimal fluctuations. Voltage variations should not go outside the limits specified by regulatory standards (see Section 2.6.3). Power must be readily available to consumers in their required amount and of good quality and the system should have an acceptable level of reliability. The distribution network consists generally of the following:

- **Distribution Substation:** The distribution substation is where the voltage transformation takes place. This could either be a primary distribution substation where voltage is stepped down from 33kV to 11kV (with load tap changer control) or a secondary distribution substation where voltage is reduced down to 400V via an 11/0.4kV transformer (without automatic load tap changer control).
- **Distribution Feeder and Distribution Transformer:** Distribution feeders are overhead lines or underground cables that emanates from the substation and supplies power to the service transformers (11/0.4kV). The distribution transformers reduce the voltage to a level usable for the low voltage consumers.
- **Distributor:** These are wires that supplies power from the distribution transformer to the consumer's service mains and subsequently to the loads.

The connection schemes of distribution networks include the following:

- **Radial System:** Simplest connection scheme where the distributor is fed at one end only. Different feeders emanate from a single source of supply (the substation) as

shown in Figure 2.6, and feed power to the consumers through distributors. It is the most widely used for short distances but is the least reliable and efficient.

Figure 2.6: Radial Network [9]

- **Ring Main System:** In the ring main system, the primary side of distribution transformers form a closed loop (or ring) system while the secondary side are connected to distributors which feed different loads. This is represented in Figure 2.7 below. It has the advantage of lesser voltage drops at the load end and higher reliability over the radial system.

Figure 2.7: Ring Network [9]

- **Interconnected System:** Here, two or more substations energize a feeder ring. This is a more reliable and efficient system. [3]. In these systems, managing power flows can be a complex task.

2.4 Demand Side Management Measures

Demand side management measures which involves a modification of the consumers' energy demand can be broadly classified into energy reduction, load management and load growth and conservation programmes [10].

- **Energy Reduction Programmes:** These are steps taken by consumers to reduce their energy usage and hence their energy bills. They include energy saving housekeeping measures like replacing incandescent bulbs with compact fluorescent lamps (CFLs), turning off lights when not in use (manually or automatically using sensor controls) and better home insulation. For industrial consumers, these include better utilization of equipment, using more efficient motors or employing variable speed drives and carrying out adequate preventive maintenance. Light dependent resistor circuits can also be installed with street lights to sense when the sun rises and then automatically turn off lights to save energy.
- **Load Management Programmes:** Load management schemes are designed by utilities to modify and control the load usage pattern of consumers connected to a distribution network in order to ensure that demand is met at all times, resulting in an efficient and reliable system. The ultimate aim is load leveling either by clipping peaks, filling valleys or shifting time of use.
- **Load Growth and Conservation Programmes:** Load growth programmes are implemented to improve the productivity of the consumers while promoting electricity sales for the utilities and ensuring that the environment is free from excessive emissions. They are necessary as the utilities need to increase their market share by filling valleys and increasing peaks. Load conservation measures are carried out by the utilities to

modify the energy use pattern of consumers by ensuring that buildings are well insulated, double glaze windows are used and the efficiency of appliances are improved.

2.4.1 Load Management Programmes

Electrical energy management can be carried out on the supply side or the demand side. When performed on the demand side, it can lead to peak demand reduction. Load management can be in the form of direct load control where the utilities directly interrupt (with prior notice) power supply to consumer's loads at peak periods to reduce energy demand. This will involve identifying controllable loads and setting of Time-of Use (TOU) tariffs. Utilities can vary the cost of electricity by time of use during the day or by seasons as a means of providing financial incentives to encourage consumer participation in load management. The rates will be set to be highest during peak periods, about average during base load time and low (at a discounted rate) during low demand period or at weekends. Consumers are then encouraged to shift their time of use of high energy consuming appliances to off-peak periods to reduce the peak-load in power stations. In this way consumers can save money by shifting their time of use of certain loads. Load management programmes carried out by utilities include the following:

- Load Leveling (Load Curve Smoothing): When electrical energy management is performed on the demand side, it can lead to peak clipping and valley filling.
 - Peak Clipping: High Loads during peak periods are clipped.
 - Valley Filling: Involves building capacities during off-peak periods when demand is low.
 - Load Shifting: Peak clipping and valley filling is achieved by shifting loads from peak periods to off-peak periods. All these are shown in Figure 2.8.
- Load Control: Consumer Loads are directly controlled remotely by the utilities. It can be switched on and off at pre-determined times agreed with the utility in return for reduced rates. In this case, the consumers will have the ability to store energy or some back-up source of power. When demand surpasses supply, the utilities can

reduce demand by load shedding (using rolling blackouts) but will inform consumers beforehand.

- **Dynamic Pricing Based Programmes**

- **Time-of-use Rates (TOU):** Utilities set their tariff structure to encourage energy use at off-peak periods and discourage (or penalize) energy use at peak periods. Higher rates apply during peak periods and lower rates apply for off-peak periods.
- **Power Factor Charges:** Higher power factors are required from users to reduce the amount of losses in the system. Consumers are penalized if their power factor is below a certain threshold.
- **Real-Time Pricing (RTP):** Tariff is structured on a real-time basis and varies continuously based on the market price of electricity.
- **Critical Peak Pricing (CPP):** High tariffs are allocated during peak periods when generation cost is high to achieve peak shaving [10].

These dynamic pricing based schemes can be achieved with the aid of a home energy management system (HEMS) or energy consumption scheduling (ECS) via smart meters. HEMS schedules appliances automatically according to price variations to achieve the least cost of electricity for the consumer.

Figure 2.8: Load Shape Change [11]

2.5 Load Management Methods

The different methods to achieve load management includes the following:

- Direct Load Control (Load Priority Technique): Loads are classed as high or low priority which corresponds to non-controllable (non-Interruptible) and controllable loads (interruptible Loads). Depending on the terms of contract, the consumer's controllable loads are interrupted during peak periods by direct control by the utility and this should not affect the power production or the quality of supply. The direct operation of consumer's load is achieved via communication links such as:
 - Telephone (Tele-control) signals: It is the least expensive as these systems are already built and are in service. The demerit is that it may be controlled by other agencies and not directly by the utility
 - Power line carrier (PLC) systems: This utilizes power line wires and the utilities have full control over these lines. For distribution systems, the PLC frequency range is in the order of 150Hz to 10kHz. Low frequency PLC systems in the range of 150Hz to 500Hz are known as ripple systems. They operate by superimposing frequency signals on the supply voltage whose reception point is a relay installed on the consumer's location.
 - Radio Systems: These operate at very high frequencies, utilizing the free space as a means of a two-way propagation channel.
- End-Use Equipment Control (EUEC): End-Use equipment and appliances are operated in a controlled way for better utilization of the available power supply. This does not affect the quality of supply.
- Load Management by Time Dependent Tariffs: Utilities present clear information on their tariffs structured to vary with time of day or seasons. Tariff is set such as to discourage energy consumption during peak periods as higher than normal rates apply. It also encourages energy usage at off-peak (valley) periods and lower than

normal rates apply. Shifting time of use to valley periods will make for a leveled load curve [12].

- Dispatch Load Management (DLM): Large industrial and commercial consumers shed part of their loads during peak periods in return for discounts on their energy bills. This is based on agreements with the utilities and lasts for a specified period of time.
- Rebate Programme: Utilities offer financial incentives for customers to upgrade their appliances or equipment. These include lighting rebate programmes for efficient CFLs and motor and air conditioning rebate programmes for the commercial and industrial consumers. Peak time rebates (PTR) are also available for customers who choose not to use power beyond their usual base level during peak periods.
- Thermal Energy Storage: Consumers voluntarily store thermal energy during off-peak periods and use it for water and space heating during peak periods [7, 13].
- Conservation Voltage Reduction: Load reduction is achieved by reducing the voltage fed to high energy demanding equipment and appliances. This scheme adjusts the operating voltage at a point in the network to reduce demand.

Load management programmes can be broadly classified into two main parts: The dynamic pricing programmes and the incentive based programmes. The dynamic pricing schemes are discussed in Section 2.4.1 and a good example of an incentive based scheme is the Direct Load Control by the Utility. The major problem with the Direct Load Control scheme is the level of inconvenience it poses to the consumer by taking off supply to appliances when it is most needed. The main purpose of dynamic pricing schemes is basically load shifting and they are not so effective in reducing total consumption of energy when compared to load control which operates by load shedding [14]. A summary of the comparison between dynamic pricing based programmes and incentive based direct load control is shown in Table 2.2 below.

Table 2.2: Comparison between Dynamic Pricing Based Programmes and Incentive Based DLC [2]

Dynamic Pricing Based Scheduling	Direct Load Control
Daily management scheme	Mainly used during emergencies for peak load reduction
Customer controlled	Controlled by the utility
Control is achieved by load shifting	Control is achieved by load shedding
Higher customer satisfaction	Lower customer satisfaction
Lesser capability for peak load reduction	Higher capability for peak load reduction
More devices are needed to control loads	Fewer devices are needed to control large loads
More susceptible to data theft	More secure and less susceptible to data theft
Utility's profit varies according to the pricing scheme adopted	Utility's profit is greater due to higher reduction in peak demand
Lower level of customer discomfort	Higher level of customer discomfort
More complex because of varying priorities of different customers	Simpler as the utility's priority is the same for all customers

The economic analysis of a direct load control scheme will involve an evaluation of the costs involved: The cost of purchasing the load management equipment, the financial incentives given to the customers (including payments for inconvenience costs) and the revenue lost as a result of reduced energy sales; and the benefits involved: Quantification in economic terms of the savings in cost of production, avoided cost savings of generating capacity and the reduction in system losses [12]. For dynamic pricing schemes, it may be difficult for consumers to respond manually to price changes as this occurs quickly. They may need to install a home energy management system (HEMS) in order to respond automatically to the fast variation in electricity prices. The cost of such equipment needs

to be taken into consideration when evaluating the cost-effectiveness of the scheme.

Conservation voltage reduction as a load management scheme will be the main focus in this research for reasons to be discussed in Chapter 3. Load Management techniques like the direct load control can cause some inconvenience to the user in which case the utility pays an inconvenience cost. The 'rebound effect' (appliances operating for a longer period) also occurs in direct load control schemes as all consumers turn on their appliances at the end of the peak period [2]. Demand reduction at peak periods can also be achieved using conservation voltage reduction (CVR), which is under consideration by network operators around the world. With CVR, peak demand reduction can be achieved without the consumer noticing any difference in voltage and he is free to use his appliances any time he chooses. The costs and benefits of CVR as a load management technique will also be discussed in Chapter 3.

In this work, CVR will be applied to utility networks in the UK. The following section presents a breakdown of existing load management schemes in the UK, the UK distribution network and the voltage regulations that apply. These are necessary in order to better appreciate the implementation of CVR in the UK considering their regulations and boundaries for voltage reduction.

2.6 Load Management in the UK

2.6.1 Existing Load Management Schemes

Although the electricity consumption trend in the UK saw a slight decline in 2008, over the years it has shown an increasing trend [15], which has necessitated increased electricity supply to match demand. Also the price of electricity has increased over the years to cover the costs associated with electricity generation [16]. Figures 2.9 and 2.10 below shows the UK electricity supply/consumption and domestic electricity bills trend. The UK has had a stable electricity network in terms of supply and reliability, but it now needs to manage existing loads so it may defer the need for extra generating capacity.

Figure 2.9: UK Electricity Supply and Consumption Trend (1970 to 2013) [15]

Figure 2.10: Average annual domestic standard electricity bills based on consumption of 3,800kWh/year in cash terms [16]

Major nuclear power plants (that supports base load) are scheduled to shut down in ten years time mainly due to their end of life and subsequent decommissioning [17] and these should either be replaced with new plants or with renewables since fossil powered units increase CO_2 emission. Managing the existing loads such that the need for extra generating capacity can be deferred would be a viable option. Several demand side management schemes have been existent in the UK since the oil crises in the 1970s and currently, load management and energy reduction programmes have been directed towards the residential sector as they make up to 29% of the country's electricity usage. These load management programmes are usually in the form of direct load control (which involves identifying controllable loads) and are targeted mostly towards space heating which consumes most energy in the domestic sector (see Figure 2.2). A breakdown of the existing load management and energy reduction programmes in terms of their usage is shown in Figure 2.11 below [18].

Figure 2.11: Load Management and Energy Reduction Programmes in the UK Domestic Sector [18]

The increase in the use of energy efficient appliances in the UK has aided the reduction in the total energy consumption in the domestic sector. This includes replacing inefficient

incandescent light bulbs with CFLs, more energy efficient building insulation and heating systems [5]. The multi-period tariff which is essentially the time-of-use tariff (ToU) which is being used by 19.5% of the 27.5 million domestic electricity consumers (2012 estimate) has posed some problems as many do not seem to understand how it worked and others complained about the inconvenient time of usage of appliances in a bid to save cost [19] (Economy 7 and Economy 10 consumers are time-of-use tariff systems in the UK). Although studies done in [20] on dynamic time-of-use tariff (dToU) in London Power Networks (LPN) area showed that 95% of customers (out of 922 participating households) had savings in their electricity bills during a trial period. It also proved that the dToU was effective as a peak demand reduction tool.

There have been several load management practices in the UK but CVR is currently being trialed and has large potentials for energy savings. It has advantages over other schemes for some reasons: It is non-intrusive as in the case of direct load control by the utility and it does not cause inconvenience to the user by shifting their time of use of appliances (a case of TOU scheme), but still achieves the objectives of reduced electricity bills as a result of reduced energy consumption and peak demand reduction.

2.6.2 The UK Distribution Network

The UK distribution system comprises the primary distribution system (extra high voltage 132kV and 33kV network), the high voltage secondary distribution system (11kV, 6.6kV, 6.3kV and 6.0kV) and the low voltage network (400V three-phase or 230V single-phase). The structure of the UK distribution system is shown in Figure 2.12.

- The 132kV primary distribution system is supplied from the transmission grid via a 400/132kV step down transformer at grid supply points (GSP Substations). It then supplies power to the 33kV primary distribution system at bulk supply points (BSP Substations) via a 132/33kV step down transformer. Automatic voltage control is provided here through the transformer on-load tap changers.

Figure 2.12: The UK Distribution System Structure [21]

Yy0, Yd1 and Dy11 are transformer winding configurations.

- The 11kV (or 6.6kV or 6.3kV or 6kV) secondary distribution system is supplied from the 33kV primary distribution system via 33/11kV transformers (with OLTC and usually operated in parallel). It then supplies power to secondary substations where the voltage is further reduced to 400V (three-phase with neutral) or 230V (single-phase with neutral).
- The high voltage or low voltage networks can be rural or urban depending on the location, number of customers connected and network configuration. High voltage networks can also delivered via underground cables or overhead lines. [21].

2.6.3 Voltage Regulations for Low Voltage Networks

European Standards

The EN 50160: 2000 (Voltage Characteristics of Electricity Supplied by Public Distribution Systems)

The EN 50160 is a European (EU) standard that stipulates that the allowed voltage variations in low voltage and medium voltage systems are $230V \pm 10\%$ [22]. It defines the requirements for the supply voltage at the utility's installation point. The following voltage parameters are defined according to the EN 50160.

- **Supply Voltage:** The root mean square value of the voltage at a given instant at the PCC, measured over a specified time period (The PCC which stands for the point of common connection/coupling is a point at the utility side of the meter where multiple electrical consumers are connected. It is usually at the service entrance, metering point or facility transformer [23]).
- **System Nominal Voltage:** It is the system voltage by which fulfills the operating characteristics of electrical consuming devices. It usually coincides with the rated voltage.
- **Voltage Variation:** This describes the voltage rise or fall, due to changing load conditions of the distribution system.

- **Declared Voltage:** This is the voltage that ensues after a formal agreement between the utilities and the electrical users. It normally coincides with the nominal voltage but can be different.

There have been plans to harmonize the voltage range across all European countries to $230V \pm 10\%$. This harmonization was due to take place in 2008 after a postponement from 2003. It is now indefinitely postponed pending an agreement between all parties involved and the UK is still operating at its current limits of $230V +10/-6\%$. It is envisaged that manufacturers of electrical equipment will benefit from the increase in the range and thus bring about competition within retail outlets [24].

UK Regulations

The Department of Energy and Climate Change (DECC) has the responsibility to make certain that the quality (mainly voltage and frequency) of electrical supply meets required standards.

- **The BS EN 50160: 2000 (Voltage characteristics of electricity supplied by public electricity networks)** This is the British Standard version of the EN 50160; it states that the 10 minute rms, line to neutral voltages should not exceed 10% of the nominal value. In addition, 95% of weekly measurements should not be below 6% of nominal value.
- **The ESQCR: 2002 (The Electrical Safety, Quality and Continuity Regulations)** In accordance with the Electricity Safety, Quality and Continuity Regulations, the voltage supplied to electricity consumers must fall within the ranges specified in Table 2.3 below.

Table 2.3: Allowed Voltage Variations in Accordance with ESQCR [21]

Declared Voltage	Allowed Voltage Variation
Low Voltage (400V three phase or 230V single phase)	+10% -6%
High Voltage (11kV / 6.6kV)	$\pm 6\%$
33kV	$\pm 10\%$
132kV	$\pm 10\%$

Also, according to the ENA (Energy Networks Association) Engineering Recommendations G83 [25], the low voltage system nominal voltage must fall within the range of (+10/-6%) for single phase (230V AC), three phase (400V AC) or split phase (230-460V AC) and its frequency must be within 50Hz (+/-1%)

The UK voltage regulations and standards discussed in this section should be carefully considered if CVR is to be performed in any LV distribution circuit to specify the boundaries for voltage reduction. In the following chapter, CVR will be reviewed in detail alongside load modelling.

3 Conservation Voltage Reduction & Load Modelling Review

In this chapter, the considerations of conservation voltage reduction are discussed in detail. The different techniques for implementation and the challenges are also presented. A review of load modelling was done with the aim of introducing the actual case study for this work.

3.1 Overview of Conservation Voltage Reduction

Conservation voltage reduction (CVR) is another means by which electrical utilities can lower peak demand. Some feeders operate with a voltage drop much less than permissible by standard. CVR lowers the voltage on a feeder to the minimum possible while ensuring that consumers are served with their required voltage level. During periods of high power demand, the voltage supplied to large power consuming devices is reduced in order to reduce the overall demand. Prior to the invention of smart grid technologies, CVR implementation has been associated with high costs and technical difficulties. And with lost revenues due to energy savings for the end-user, utilities saw no benefit. With smart grid technologies such as advanced metering infrastructure (AMI) and advanced load modelling/power flow algorithms, it is possible for the utilities to make savings as peak demand reductions are realized and line capacities are released. For maximum benefit of CVR, operation should be targeted towards very high voltage feeders with high concentrations of voltage-dependent loads. CVR can be accomplished in a variety of ways which include the use of load tap-changing transformers, static VAR compensators, line drop compensators, generator excitation controls, voltage regulators and line switchable capacitor banks. Voltage reduction at primary substations in distribution systems will reduce the load of consumer appliances and hence reduce peak demand. However, not all loads are good candidates for CVR as different end-use loads will respond differently to voltage reduction. The composition of loads in the system needs to be taken into consideration before implementing CVR. Pure Resistive loads like resistive water heaters are best candidates while constant power loads like induction motors will only draw more current as voltage reduces causing no net energy saving in the long run [26, 27].

Loads can also be classified depending on whether a control mechanism exists to vary load operation in order to compensate for any reduction of the supply voltage. These are:

- **Open-Loop Loads:** No control mechanism exists; a reduction in the supply voltage will lower energy consumption. Examples include lighting loads (GILs and Fluorescent lamps) and unregulated motors. For the latter, the size of the motor and its operating speed are factors that determine the overall energy reduction.
- **Closed-Loop Loads:** Control mechanism exists and therefore no net reduction in energy consumption. Examples include regulated motors, loads with thermal cycles such as HVAC (Heating, Ventilation and Air conditioning) loads and motor drives [28].

The acceptable voltage range as stipulated by the European Standard EN 50160 for distribution networks is $230V \pm 10\%$. CVR is carried out in the lower half of the range as shown in Figure 3.1 and is operated in such a way that customers are still fed with the required voltage for their appliances. The energy or peak demand reduction effect of a CVR operation is evaluated by the CVR factor (CVR_f) represented in Equation 3.1.

$$CVR_f = \frac{\Delta E\%}{\Delta V\%} \quad (3.1)$$

where: $\Delta E\%$ or $\Delta P\%$ = Percentage Reduction in Energy or Power

$\Delta V\%$ = Percentage Reduction in Voltage

Figure 3.1: CVR Operation [29]

It is a general rule that a CVR factor of 1% implies a 1% reduction in energy results from a 1% voltage drop [27]. However, this is not always the case as proven by simulations carried out in this work. Energy reduction using CVR can be carried out either on a short-term basis for just peak demand reduction (only during peak periods as shown in Figure 3.2) or on a long-term basis for a whole day (24 hours voltage reduction as shown in Figure 3.3) depending on the target savings set to be achieved.

Figure 3.2: Peak Demand Reduction [30]

Figure 3.3: 24 hours Voltage Reduction [30]

where: P_{pre} = Load consumption prior to CVR operation.

P_{post} = Load consumption after CVR operation.

P_{red} = Load consumption for the period of CVR test.

P_{est} = Estimated Load consumption at normal voltage during period of CVR test.

3.2 CVR Implementation

CVR can be implemented through LDC (Line Drop Compensation) regulation settings in a voltage regulator or through voltage spread reduction (VSR). In LDC regulation, the load tap changers (LTCs) of substation transformers or voltage regulators are controlled such that the voltage at the end of the feeder (the last customer) is within the acceptable limits, while the voltage at other parts of the circuits is allowed to vary with the loading conditions. Voltage spread reduction involves the operation of a feeder in the lower voltage range (of $230V \pm 10\%$ for EN50160) such that the voltage of the last customer is within the minimum acceptable level. For an effective CVR program, implementation is carried out in steps, with the voltage profile flattened first using appropriate voltage regulator controls and then lowered. The voltage profile can be improved by installing capacitors and voltage regulators at the sub-station and along the feeders. The load along each feeder should be balanced as well as balancing heavily loaded phases by sharing the load evenly across the phases. These are effective measures to be taken to improve the system prior to lowering the voltage using CVR [31]. While CVR has been well proven to provide peak demand reductions as a low cost energy efficiency resource, it also comes with some challenges. CVR operation must ensure that the end-of-line (EOL) voltage is within the acceptable limits. This is the case for customers connected at the end of the feeder. The feeder configuration must be taken into consideration before implementing CVR as some designs may limit some customers. Also, complicated designs poses challenges in the location of end of the feeder. A successful CVR scheme would therefore depend on the feeder configuration, the voltage profile prior to implementation and the load mix. The seasonal variations in load should be taken into consideration as types of load varies with season. Different strategies for implementation

(dynamic CVR) should be adopted following seasonal variations.

CVR has been successfully implemented by some utilities in North America. In 1979, American Electric Power implemented a 5% voltage reduction for 24 hours and got a CVR factor of 0.7 (3.55% energy savings and an average of 4% power savings) [32]. In 1988, Snohomish County PUD (Public Utility District) conducted a pilot study on 3 substations by implementing a 2.1% voltage reduction and achieved a CVR factor (energy) of 0.621 (savings of 281 kWh/yr/customer) [33].

3.2.1 Techniques for CVR Implementation

The techniques for CVR implementation includes the following.

- Open-Loop Reduction (With no voltage feedback): This can be achieved via Transformer load tap changer reduction or capacitor-based regulation. This is mostly used in sub-stations
- Closed-Loop Reduction (With voltage feedback): This is essentially Voltage/Var control (VVC) made possible with the installation of Advanced Metering Infrastructure (AMI), Supervisory Control and Data Acquisition (SCADA) and advanced optimal power flow algorithms. This is mostly used in distribution lines (feeders) [34].

The basic CVR implementation may not be possible in some feeders whose voltage (especially end-of-line) is already below the acceptable limits. In this case, the voltage profile of the feeder should be improved first with the aid of shunt or series capacitors, or voltage regulators before applying CVR. Table 3.1 below shows the stages of implementing CVR from the traditional starting point to an advanced CVR operation. It outlines the additional benefits to be derived from CVR if cost-effective measures are taken prior to the voltage reduction. Depending on the other objectives of the utility, additional equipment (AMI, SCADA) needs to be installed for real-time control, automation and appropriate co-ordination of devices. Capacitors are installed on the substation and along the feeders (stand-alone fixed or switched) for reactive power (VAR) regulation and power factor improvement.

Table 3.1: Implementation of Volt/VAR Control and CVR [35]

Step	Description	Phase	Benefit
1	Capacitors installed on substation	Traditional Starting Point	Power factor penalties are avoided
	Load tap changer on substation transformer		Substation voltage is periodically adjusted
	Substation feeder regulators		Feeder voltage can be adjusted independently
	Fixed and switched feeder capacitors (stand-alone)		Reduction of line losses (capacity and voltage is improved)
	Feeder regulators (stand-alone)		Basic voltage maintenance
2	VAR optimization with additional fixed/switched capacitors	Integrated Volt/VAR Control	Advanced reduction of line losses and improved voltage/capacity
	Voltage profile optimization		Advanced control of voltage profile and system operating efficiency
3	Manual control of regulators and capacitors using SCADA	Basic CVR	Reduction of peak demand using CVR
	Line Drop Compensation settings in regulators (not using SCADA)		Peak demand and energy reduction using CVR
	Local capacitor controls (not using SCADA)		Peak demand and energy reduction using CVR
4	Integrated monitoring with Advanced Metering Infrastructure and feeder Distribution Automation equipment	Advanced CVR	Continuous feedback for real-time decision-making
	Dynamic CVR through Distribution Management System or other Distribution Automation control software		Continuous CVR for peak optimization

3.3 Measurement and Verification of CVR Effects

Different methodologies exist for measuring and assessing the effects of a CVR program [36]. They include:

- **Comparison based Methods:** Two strongly correlated feeders (with similar properties) are compared within the same measurement period. One of the feeders (taken as the test feeder) is subject to voltage reduction while the other (taken as the control feeder) is subject to the normal voltage level. The properties to be shared between the two feeders include: topology, load mix, configuration, and load conditions. The effects of the voltage reduction can be estimated from measurements taken from the tests. Comparison can also be done on the same feeder under similar weather conditions but different time periods taken as the test and control groups. The limitations of the comparison based method is that a good control feeder may not be available and weather influences may affect measurements as load changes may be due to weather differences.
- **Synthesis based Methods:** Synthesis-based methods aggregate the load-to-voltage dependence behaviors of appliances to evaluate the effects of CVR. The synthesis can be done either from the load components or generally from the customer classes. In the first case, the total energy consumption of a circuit is evaluated by obtaining the load shares of major appliances (through surveys) and by carrying out laboratory tests to determine a relationship between the energy usage of appliances and the supply voltage. The total energy usage can be deduced from Equation 3.2 below.

$$E_c(V) = \sum_{i=1}^n E_i(V) * S_i \quad (3.2)$$

where:

$E_i(V)$ = Energy usage of appliance i , $E_c(V)$ = Total energy usage

S_i = Load share of appliance i

When the aggregation is performed from customer classes (on the basis the varying appliance load mix of different customer class), the CVR factor is evaluated as a summation of the CVR factors and load shares of each customer class as expressed in Equation 3.3.

$$CVR_f = CVR_f(R) + CVR_f(C) + CVR_f(I) \quad (3.3)$$

where: $CVR_f(R, C, I) = CVR$ factors of the different customer classes

- Simulation based methods: Time-series simulations is carried out using appropriate software to establish load consumption with and without CVR, from which the CVR factor is estimated. This requires a modelling of the loads as a function of voltage. The Open Distribution System Simulator Software (described in Section 4.1.1) utilized in this work is an appropriate tool for carrying out power flows for CVR studies.

3.4 Costs and Benefits associated with CVR Deployment

For a multi-perspective analysis, it is important to consider the following stakeholders who will be impacted in some way in the CVR programme.

- The Utility
- The Consumers
- The Society

3.4.1 The Utility

For utilities, CVR is a means of achieving peak demand and energy reduction and its effects can be easily measured and verified. A reduction in the total energy demand would possibly defer the need of building extra generating plants and also defer increases in the price of electricity. Whether this is cost-effective for the utility or not will depend on factors like: The type of CVR to be performed, the actual cost of electricity, the amount of

demand/energy reduction required, network capacity and feeder configuration. There will definitely be lost revenues as a result of reduced energy sales, but this should be balanced with some quantifiable gains, before a utility will engage in CVR. From Figure 1.1 (Major Concerns for the utility), it can be seen that aside revenues, there are other objectives like reliability and network motives which the utility must achieve to keep the system running in an efficient manner. Therefore, the utilities must define workable business plans that will include cost-recovery and lost-revenue processes. This is usually a least-cost planning approach.

Implementing CVR can help mitigate system emergencies, provide adequate fast-reserves and increase the reliability of the system. The reduction in demand during peak periods when electricity prices are high is a form of short-term demand response to market conditions. This could also relieve the strain on wires and cables, preventing outages that may occur due to overloading. Some benefits may be in the form of avoided costs of power not produced (and fuel cost savings).

The cost of implementing CVR has been estimated at around \$500/kW saved for demand reductions and \$20/MWh saved for energy reductions. This is much less than the cost of many energy sources [27]. Open-loop reduction via load tap changers is a cost-effective option for utilities (little or no cost option) but its limitation is a lack of a co-ordinated real-time control and the level of voltage reduction that can be achieved is limited. Although CVR reduces transformer core losses, but the overall circuit losses will increase (line losses increase slightly) depending on the mix of end-use load as the current drawn increases (this is seen in the results section of this work).

In a more co-ordinated volt/var control, loss reductions can be achieved (thus releasing system capacity) but with appropriate VAR support by installing capacitors for power factor correction and additional voltage regulators both on feeders and substations. For such multi-objective CVR, the overall costs increase due to the additional equipment required which may include AMI or SCADA control. However, the highly optimized voltage reduction results in more energy savings, appropriate power factor under all loading conditions and

real-time monitoring of devices.

In some cases, the voltage profile of a feeder needs to be improved before conducting CVR. This may be done by feeder reconfiguration or re-conductoring for lesser voltage drops, load balancing and placement of additional regulators or capacitors. Feeders should be well screened based on load mix and topology to identify the ones with more energy savings (more voltage-dependent end-use loads) so as to improve the cost-effectiveness of the program. Other costs that may be incurred may include staff training costs

3.4.2 The Consumers

The operation of CVR requires no active involvement of the consumer. It is less intrusive as there are no restrictions in the use of appliances and no time constraints of appliance use to save energy. It will ensure a reduction in electricity bills as demand reduces. There have been studies on the effects of reduced voltages on the efficiency and operation of electrical appliances. Results from [37] suggest that: provided the voltage does not go below the specified regulatory standards, there will be energy conservation and this will not deteriorate end-use efficiency. However, voltage reduction to $U_n - 10\%$ (as suggested in [22]) may affect the operation of incandescent lamps and motors (see Section 4.3.1). The less intrusive nature of CVR poses no discomfort or inconvenience to consumers as they are free to use their appliances at any time and still save energy and electricity bills. They will benefit more from CVR if they make it more effective by also engaging in other energy reduction measures like improving their equipment efficiency (replacing inefficient appliances) and some energy saving housekeeping measures.

3.4.3 The Society

For the society at large, the deployment of CVR will help to sustain the environment as there will be reduced greenhouse gas (GHG) emissions associated with the operation of generating plants, as demand reduces. The decreased reliance on imported fuel (oil and gas) to run these plants ensures greater energy security. CVR also stimulates economic development and increases social welfare, creating employment by leveraging the new technologies involved.

3.5 The Challenges of CVR

The challenges involved in a CVR program can be summarized in the following lines.

- A standardized measurement and verification methodology has not been established. CVR energy savings effects cannot be differentiated from energy savings via appliance energy efficiency improvement when these intersect. So the measurements may not reflect the accurate CVR gains.
- Better load-modelling tools are required for screening feeders for CVR and providing realistic results. The load response to variation in voltage may change with time (voltage sensitivity of loads). CVR factors will either decrease or increase if constant impedance loads change to constant-power loads or vice-versa.
- The high penetrations of distributed energy resources may affect CVR operation. It's impacts must be considered before implementing CVR. This is necessary since distributed generators will likely modify the voltage profile on a feeder.
- The problem of lost revenue has slowed down the uptake of CVR by utilities as they struggle to develop workable business models. If there is no cost-recovery, the utilities may be forced to raise the price of electricity to cover costs.
- CVR must ensure that all customers are within the specified voltage limits. If not carefully implemented can result in excess voltage drop for consumers at the end of the line.

3.6 Load Modelling Review

The effects of CVR on a network depends on the load composition and therefore it is necessary to determine the load characteristics of the major customer classes before implementing CVR. Loads can be categorized depending on their variation of demand as voltage changes. This variation is depicted in Figure 4.1 and can be modelled as either a constant impedance, a constant current or a constant power load.

- Constant Impedance Loads (Z): Power drawn is proportional to the square of the supply voltage. An example is a resistive water heaters
- Constant Current Loads (I): The demand is directly proportional to the supply voltage. An example is Thyristor application drives
- Constant Power Loads (P): The demand is constant irrespective of the change in supply voltage. Induction motors and electric ovens are good examples of constant power loads. They draw more current as voltage is reduced. Energy consumption actually increases if the line losses are considered due to increased current [38].

However, at any specific operating point, the load may be comprised of a mixture of all of the above load types in some proportion expressed in Equation 3.4 below.

$$Z_{\%} + I_{\%} + P_{\%} = 1 \quad (3.4)$$

From Figure 3.4, it can be deduced that the power consumption of constant power loads remains the same regardless of the changes in supply voltage. For constant current loads, there is a proportional change and demand savings exist. The savings in power is even greater for constant impedance loads where a squared relationship exists between the supply voltage and the power consumption of the load.

Figure 3.4: Effect of Voltage Change for Different Load Types

3.6.1 Load Model

In the context of this study, a load model represents mathematically, the relationship between the real (active) and apparent (reactive) power and the supply voltage. It describes the load behavior when the supply voltage varies. Load models could be static or dynamic.

- **Dynamic Load Models:** These are time-dependent load models and therefore express the relationship between the load power (active or reactive) and the supply voltage at any period in time as a function of both the previous and current state of the supply voltage.
- **Static load models:** These are time independent load models and therefore assume an instantaneous response of the load to variation in the supply voltage. The exponential load model (expressed in an exponential form) and the ZIP models (expressed in a polynomial form) are static load models.
 - **The Exponential Model:** The relationship between the active and reactive power of the load and the supply voltage is expressed in exponential form in Equations

3.5 and 3.6 below.

$$P_{load} = P_{nom} \left(\frac{V}{V_0} \right)^{n_p} \quad (3.5)$$

$$Q_{load} = Q_{nom} \left(\frac{V}{V_0} \right)^{n_q} \quad (3.6)$$

where:

P_{load}, Q_{load} = Actual active and reactive power demand of the load

P_{nom}, Q_{nom} = Rated active and reactive power demand of the load

V, V_0 = Actual supply voltage and nominal supply voltage

n_p, n_q = Exponential model coefficients for active and reactive power

- The ZIP model: The ZIP is a second order polynomial static load model where the static characteristics of the load are being categorized as constant impedance (Z), constant current (I) and constant power (P), depending on the relationship of the load power with the supply voltage. The ZIP model is used in this work because it's more representative of the load behavior and best for carrying out CVR simulation (known as load model 8 in OpenDSS). The active and reactive power relationships with the supply voltage is expressed in Equations 3.8 to 3.9 and includes the ZIP model coefficients.

Because of the complex analytical nature of the ZIP model, it can better model non-linear load characteristics when compared to the exponential model [39].

The ZIP model is a weighted sum of the aforementioned categories. Figure 3.5 is a representation of the ZIP model as a combination of the three load categories.

$$P_{load} = P_{nom} \left[Z_p \left(\frac{V}{V_0} \right)^2 + I_p \left(\frac{V}{V_0} \right) + P_p \right] \quad (3.7)$$

$$Q_{load} = Q_{nom} \left[Z_q \left(\frac{V}{V_0} \right)^2 + I_q \left(\frac{V}{V_0} \right) + P_q \right] \quad (3.8)$$

$$Z_p + I_p + P_p = Z_q + I_q + P_q = 1 \quad (3.9)$$

where:

$Z_p, I_p, P_p; Z_q, I_q, P_q = \text{Polynomial model coefficients for active and reactive power}$

Figure 3.5: ZIP Model [40]

The ZIP model will be used for the case study (see Chapter 4) of this research because it is more representative of the characteristic load response of consumer appliances with a variation of voltage. A typical household will have some proportion of constant power, constant current and constant impedance devices which can be aggregated to give a single ZIP model coefficients. Conservation voltage reduction has been reviewed in detail in this chapter and the next section will focus on the methodology for CVR implementation (open-loop voltage reduction) of UK residential feeders.

4 Methodology

The purpose of this chapter is to outline the steps, methods and tools used to examine the effects of voltage reduction on a typical UK distribution feeder. It is expected that after a CVR Operation on the feeders, the CVR factors will be compared based on load type, season (summer and winter) and feeder length. The effect of CVR on line losses and transformer losses will also be analysed. Since the network to be used consists of residential type feeders, 100% residential loads will be assumed for all simulations. It will also be ensured that the End-of-Line voltage of the feeders will still be within the acceptable limits. This work will evaluate the amount of demand savings (in terms of the CVR factor) that can be achieved in a typical UK LV distribution network. This chapter will introduce the software (OpenDSS) to be used for the simulation based method and the steps for the measurement and verification of the CVR effects. High precision results can be obtained using the simulation based methods if the load behaviours are accurately modelled. The comparison based or synthesis based methods are not used because they both respectively involve laboratory tests and on-site measurements which is beyond the scope of this work.

4.1 Software Used

4.1.1 The Open Distribution System Simulator (OpenDSS)

The OpenDSS software is an open source power system simulation tool developed by the Electric Power Research Institute (EPRI) for simulating electric utility distribution systems in a time-varying (quasi-static) manner for daily, yearly, duty cycle or snap-shot power flows. It can be implemented as an independent executable, script-driven program or in conjunction with other power system software like MATLAB, VBA, C++ etc, in an in-process component object model (COM) interface. The program structure embodies the various distribution system components which are divided into 5 classes namely:

- Power Conversion Elements (loads, generators)
- Power Delivery Elements (lines, transformers)

- Controls (regulator control, capacitor control, relays)
- Meters (Monitors, energy meter)
- General (Line code, load shape, line geometry)

Support elements can be modelled to further define the power conversion and the power delivery elements. They provide monitoring and control functions. Some of these which were included in the openDSS scripts of this work are described below.

- Line Code: Specifies line parameters (resistance, reactance, capacitance and amperage)
- Load Shape: Defines the daily or yearly load profiles.
- Monitor: Monitors current, voltage or power at lines or loads. The output of such monitors can be exported as a csv file.
- Reg Control: This performs the function of a regulator in a transformer to operate the taps
- Energy Meter: Captures energy quantities and losses.

The OpenDSS was chosen for this research because as compared to other power system software, it was specifically designed for the analysis of distribution systems with an ease in converting data sources to scripts since the scripting language is very much similar to the usual distribution system jargons. It has an object oriented structure and controls can be modeled independently of the devices being controlled [41]. The time-step simulations were done with MATLAB via the OpenDSS COM interface. MATLAB codes were also developed which performed simulations for 288 time steps (5 minute interval) and the transformer and line losses, total load power and substation power were extracted.

4.2 Network and Load Profile Data

4.2.1 The Low Voltage Network

The low voltage network used for the CVR analysis was gotten from the Low Voltage and Network Solutions, a first tier low carbon networks project by the Electricity North West Limited (ENWL) in partnership with the University of Manchester, with the aim of modelling and analyzing European-style LV distribution networks. They developed 25 such networks which were typically underground, UK residential networks with multiple feeders. The cable type and characteristics, network topology, and the connection of phases were GIS (Geographic Information Systems) files converted to Open DSS models. The first network (Network 1) was chosen for this work. Network 1 comprises of 4 feeders of different length and having different number of customers as shown in Table 4.1. These feeders are represented as OpenDSS models which were modified in distinctive ways to suit the purpose of the CVR analysis.

Table 4.1: Feeder Characteristics [42]

Feeder	Length (m)	Number of Customers
1	1289	55
2	920	31
3	868	39
4	2291	75

4.2.2 The Load Profiles and ZIP models

The summer and winter load data were residential load profiles provided by the Low Carbon Networks project. These profiles were obtained from a computational load (domestic electricity demand) model developed by the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University (Data Sets and Software Institutional repository). The model is designed in such a way that it takes into account the number of residents in a house, the day of the week, the month of the year and the appliances used. Thus a

pool of load profiles typical of the stochastic nature of UK electricity consumers were developed. For the Low Carbon Networks project (by ENWL and the University of Manchester), they converted the one-minute resolution data (1440 points) from CREST to a 5 minute resolution data (288 points).

An example of static ZIP models for a residential, small commercial and an industrial consumer gotten from [43] is presented in the Table 4.3 below. They are based on the load composition of these customer classes, an aggregation of the ZIP model coefficients of typical loads found in the different customer classes. For instance, the industrial consumer has a ZIP model constant power coefficient of 1 indicating it has mostly constant power loads like electric motors. A classification of some loads based on their ZIP model coefficients is presented in Table 4.2 below.

Table 4.2: Classification of Typical Loads [35]

Load Type	%Pf	% S_{PQ}	%Z	%I
Resistance heaters, water heaters	100	0	50	50
Heat pumps, air conditioning, refrigeration	80	15 - 35	20 - 40	45
Cloth dryers	99	0	0	100
Televisions	77	0	0	100
Incandescent Lighting	100	45	35	20
Fluorescent Lighting	90	0	0	50
Pumps, fans, motors	87	40	40	20
Arc furnace	72	0	30	70
Large industrial motors	90	60	40	0
Large agricultural water pumps	84	0	75	25
Power plant auxiliaries	80	40	40	20

Simulations were carried out considering two different load model scenarios. These are the mostly occurring load model types: The constant power model (active power and reactive power) and a ZIP model comprising of constant current (for active power, P) and constant

impedance (for reactive power, Q). This was done for the summer and winter cases.

Table 4.3: ZIP Model Coefficients for the Different Customer Classes [43]

Class	Z_p	I_p	P_p	Z_q	I_q	P_q
Residential	0.85	-1.12	1.27	10.96	-18.73	8.77
Small Commercial	0.43	-0.06	0.63	4.06	-6.65	3.59
Large Commercial	0.47	-0.53	1.06	5.30	-8.73	4.43
Industrial	0	0	1	0	0	1

4.3 CVR Implementation on the Network

Voltage reductions are usually performed at primary substations using the LTC of 33/11kV transformers or through voltage regulators. In this work, voltage reductions were carried out also in secondary substations (11/0.4 kV) transformers. This was first trialed in a rural UK generic low voltage distribution network shown in Figure 4.1; an 11/0.4 kV transformer serving 19 residential customers, each having 2.27kW load. The network was first aggregated using methods described in [44] and voltage reductions were done in both cases (detailed and aggregated network) and similar results were achieved. A voltage reduction of 4.375% yielded demand savings of 1 kW giving a CVR factor of 0.5328 (okay for residential circuits). Since, active power savings was achieved at the generic distribution network serving 19 customers, voltage reductions were applied at the 11/0.4 kV transformers on Network 1 on all four feeders.

For the rural generic LV network, the CVR factor was calculated as:

$$CVR_f = \frac{\Delta P\%}{\Delta V\%} = \frac{(42.9 - 41.9) / 42.9}{1 - 0.95625} = 0.5328 \quad (4.1)$$

This implies a savings of 0.53 kW for every 1% reduction in voltage.

Figure 4.1: Rural Generic LV Distribution Network Model

4.3.1 Boundaries for Voltage Reductions at the Secondary Substation

The voltage at the transformer secondary was changed using the taps in steps of 0.00625 pu (see Table B.1), and the response of the ZIP-modeled loads was recorded. The ESQCR was used to determine if there were voltage excursions at the end of the feeder (230V +10%, -6% which is equivalent to the range: 0.94 to 1.1 pu) The BS EN 50160 is not used because it's been known that voltage reduction in the lower range ($U_n - 10\%$) can have adverse impacts on equipment operation. Prolonged usage of an electric motor in the lower range can cause voltage dips leading to overloading (due to increased current demand) and the tripping of the motor thermal protection. Also incandescent lamps may deliver only up to 70% of their nominal luminous flux according to Equation 4.2 [22]. Due to this reasons, a more conservative range, which is the ESQCR will be applied in this work.

$$\frac{F}{F_n} = \left(\frac{U}{U_n} \right)^b \quad (4.2)$$

where:

F = luminous flux

U, U_n = Supply voltage and Nominal voltage

F_n = Luminous flux at nominal voltage

b = Constant = 3.6 for Incandescent lamps

4.4 Procedure for Carrying out CVR

All feeders are radial but they differ in length. CVR will be performed on all four feeders assuming 100% residential loads to investigate the effects of CVR on feeder length. To verify the best spot for voltage reduction (CVR will be performed on the network as a whole on the primary substation transformer (33/11 kV) and on the secondary distribution (11/04 kV) transformers with the same depth of voltage reduction. CVR will also be done considering two load model scenarios. The first scenario being constant power load (for active and reactive power), and the second scenario being constant current (for active power) and constant impedance (for reactive power) load. This is to investigate the effects of CVR on the two different load types. Time-step simulations were also done to verify how the CVR factor changes in every 5 minute interval throughout the whole day. This was done using MATLAB via the OpenDSS COM interface (see Appendix B.1 for Matlab codes). All simulations will be carried out for both summer and winter cases to examine the effects of seasonal variation in load on CVR implementation. The following steps were taken to carry out the CVR test individually on the separate feeders (on the 11/0.4kV transformers) and on the whole network (on the 33/11kV transformer).

- Formation of feeder circuits
 - Conversion of all network characteristics into openDSS scripts (see Appendix B.3)
 - Creation of the daily load shapes for each customer class (as text files). The daily load shape is based on the consumption pattern of UK electricity consumers.
 - Creation of loads text file. The loads are defined in terms of active power (kW), voltage (kV) and power factor (Pf). The loads are edited to incorporate the right

ZIP load model parameters (model 8) as it corresponds to the different load types (according to Table 5.1)

- Lines and line codes were created as separate text files.
 - The OpenDSS file of each feeder is created.
 - A daily power flow (time-sequential simulation) is performed on all four feeders individually, the network as a whole and the voltage profile, total circuit losses, transformer loss is recorded. The voltage and power of the last customer on each feeder is also recorded.
- Perform CVR by adjusting the taps on the secondary winding of the regulating transformer
 - Measurement and verification of CVR effects
 - Monitors are placed to record the power and voltage of all lines. The end of line voltage is of utmost importance. An additional monitor is set to monitor the power of the last customer.
 - Based on results from the daily power flow, verify that the voltages at every bus is within the range specified by ESQCR. If there are voltage excursions, do not perform CVR; if all voltages are well within limits, go to step 3.
 - Reduce the transformer voltage through the taps in steps (see Table B.1)
 - Voltage should be lowered as much as possible to a value that will give the highest CVR factor.
 - Check voltage profile. If End-of-line voltage is less than the desired value (0.94 pu), increase tap; if its higher than the desired value, reduce tap. These procedures can be represented as a flow chart shown in Figure 4.2 below, carried out for 288 time steps (5 minutes interval) for the specific number of loads.

Figure 4.2: Flow Chart for Basic CVR Implementation

5 Simulation Results and Discussion

In this chapter, the simulation results are presented and analysed. The results of the daily CVR simulation are given in detail in Appendix C and summarised in bar charts while that of the time-step simulation is summarised as line graphs in section 5.3.

5.1 Pre-CVR Questions and Answers

These are feasibility study questions (based on [35]) that must be answered to determine if CVR will be effective on a distribution system on a long term. They are answered based on results obtained.

Question One: Feeder load mix

1. Can voltage reduction be applied on all feeders?

Answer: Assuming all feeders consist of only residential customers, CVR can be performed on all feeders without voltage excursions

2. What is the expected CVR factor that can be achieved

Answer: CVR factors of up to 0.7 are expected on residential type feeders

Question Two: Feeder voltage profiles

1. How much voltage reduction can be achieved on the feeders without any investment in additional equipment?

Answer: The amount of voltage reduction permissible on the feeders is dependent on the load characteristics. Voltage reductions of up to 4% were possible on all feeders.

2. Are there cost-effective options available to improve voltage profiles in order to achieve greater reductions in voltage

Answer: Installing capacitors on the feeders.

Question Three What control systems available can be utilized ? (eg SCADA)

Answer: Automatic control systems were not considered. It is an open-loop voltage reduction

Question Four What is required to actually carry out CVR

Answer: A standard 32-step regulator/Load Tap changer control

Question Five Demand Reduction or Energy Reduction? Watts or Vars savings?

Answer: Demand Reduction in kW. More concerned with watts savings

5.2 Case Study

5.2.1 Network Layout

The Network used in this study is a real network in North West England managed by ENWL. It consists of 4 feeders (underground) which differ in length and configuration as given in Table 4.1. The OpenDSS codes and scripting of the distribution circuit elements can be found in Appendix B.2 and B.3. The layout of the network is shown in Figure 5.1 below. Figures 5.2 to 5.5 are the individual feeders that make up the network.

Figure 5.1: Network Layout

Figure 5.2: Feeder 1 Layout

Figure 5.3: Feeder 2 Layout

Figure 5.4: Feeder 3 Layout

Figure 5.5: Feeder 4 Layout

5.2.2 Load Profile

The simulation results for the four feeders were obtained using a 5 minute load profile from the Low Carbon Networks Project (by Electricity North West Limited and the University of Manchester). These load profiles vary for the different customers. The aggregate summer and winter load profiles for all customers used in the simulation is shown in Figures 5.6 and

5.7 below. The summer peak demand is 154.3 kW and occurs at 21:45 pm while the winter peak demand is 210.9 kW and occurs at 19:15 pm.

Figure 5.6: Aggregate Summer Load Profile for 200 Customers

Figure 5.7: Aggregate Winter Load Profile for 200 Customers

5.2.3 ZIP models and Power Factor

The ZIP models used are as represented in Table 5.1 below and do not vary with time. The summer and winter cases indicate the minimum and maximum loading conditions respectively. All simulations are for residential load profiles as the network is a typical residential network and power factor assumed is 0.95.

Table 5.1: Load Model Scenarios

Scenario	Z_p	I_p	P_p	Z_q	I_q	P_q
Scenario 1	0	0	1	0	0	1
Scenario 2	0	1	0	1	0	0

5.2.4 Summary of Daily CVR Simulation Results

1. CVR Factor

The results obtained is based on the total daily load consumption. All individual feeder results are given in detail in Appendix C.1.1 to C.1.4. CVR was done considering two load model scenarios and a voltage reduction of 0.625% was applied across all feeders. For load model scenario 1, there were no watts savings (CVR factor of zero) while for load model scenario 2, there were savings and these are compared in Figure 5.8 below. Feeder 2 had highest CVR factor, followed by feeder 4, then 3 and then 1. This result does not follow the feeder length pattern.

Figure 5.8: CVR Factor Comparison (Load Model Scenario 2)

2. Transformer Losses

For feeder 1 to 4, the percentage increase or decrease in total transformer losses was recorded for both scenario 1 and scenario 2 load model scenario (and for the summer and winter cases). The results are given in detail in Appendix C.1.1 to C.1.4. The summary of these results can be represented in the bar chart given in Figure 5.9 below.

Figure 5.9: Percentage Increase/Decrease in Transformer Losses

3. Point of Reduction

Detailed simulation results for the whole network is given in Appendix C.1.5. CVR was performed both on the 33/11 kV (TR) transformer (a voltage reduction of 0.625%) and on the secondary distribution transformers (TR1 to TR4). This was done only for scenario 2. In the first case (CVR1), the CVR was performed on the 33/11 kV (TR) transformer (a voltage reduction of 0.625%) with no reduction on the secondary distribution transformers, and in the second case (CVR2), it was performed on all 11/0.4 kV (TR1 to TR4) transformers (a reduction of 0.625% across all regulators) with no reduction on the primary distribution transformer (33/11 kV). Similar CVR factor results were achieved for both cases. The network results are given in Appendix C.1.5.

5.2.5 Analysis of Daily CVR Simulation Results

The simulation results will be analysed along the following lines.

- **Seasonal Variations:** For the seasonal variations, the summer CVR factors are greater than that in winter because the reduced total load power in summer allows for better voltage profile prior to CVR. There is a lower load requirement in summer than in winter and so the total load power is lower in all cases. Reduced load power implies reduced line losses and better voltage profile. CVR factor is therefore higher in the summer case as the percentage reduction in demand is higher for the same reduction in voltage. The difference between the summer and winter CVR factors is not large because the distribution network transformer was rated at 800kVA which is far greater than the load requirements of the individual feeders so the voltage drops is not significant for both cases. Also the aggregate winter load profile is not much greater than the aggregate summer load profile, which is usually not the case.
- **Differing Load Types:** For constant power loads (scenario 1), there are no watts savings and the CVR factor is zero. These load types increase current consumption to match the power usage when voltage is reduced. Increased current consumption causes the line and transformer losses (copper winding losses) to increase. On the other hand, there were demand savings in scenario 2 with constant current loads (for active power). The line losses remained constant since current consumption does not change with voltage reduction while the transformer losses reduced.
- **Cable and Transformer Losses:** Distribution cable losses (I^2R) increased with CVR for constant power loads but remained constant for constant current loads. The transformer losses consist of the winding loss (copper loss) and the core losses. The copper loss rises with an increase in current consumption which is the case for constant power loads (Scenario 1) and the core losses (eddy-current and hysteresis) reduces with a reduction in voltage for all loads. Transformer core losses are proportional to the square of the supply voltage. According to [45], the relationship between the eddy current ($P_e(L)$) and hysteresis losses ($P_h(L)$), the flux density of the transformer core

and the supply voltage at low frequencies (power frequency) is given by the following equations (Equations 5.1 to 5.3). Since the winding losses in a transformer is greater than the core losses, there is an increase in total transformer losses in scenario 1. For scenario 2 (constant current loads), there is a reduction in total transformer losses as the winding losses remained nearly constant. From Figures 5.8 and 5.9, it can be deduced that the higher the CVR factor, the higher the transformer loss reduction.

$$P_e(L) = \frac{\pi^2 f^2 B_{max}^2 a^2 \sigma^2}{6} \quad (5.1)$$

$$P_h(L) = \frac{2fSB_{max}^2}{\mu} \quad (5.2)$$

$$B_{max} = \frac{V}{\pi\sqrt{2}fAN} \quad (5.3)$$

where: B_{max} = Maximum flux density of transformer core

a = Lamination Thickness

f = Frequency, 50Hz

σ = Electrical Conductivity

μ = Permeability

S = Shape Factor

A = Cross sectional area of Core

N = Number of turns of the coil

- Point of Reduction: The network simulation showed similar results for CVR1 and CVR2 (In CVR1, CVR was performed on the primary substation transformer (33/11 kV) and in CVR2, CVR was performed on the secondary distribution transformers (11/0.4 kV)). The CVR factor was the same following a voltage reduction of 0.625%. In the first case, the transformer losses is reduced only for the 33/11 kV transformer while it increased for the other four sub-transformers. In the second case, the transformer loss reduced for all transformers. Therefore, considering transformer losses, it would

be better to perform the CVR on the 11/0.4 kV transformers. Although, this will need an upgrade of these transformers to incorporate load tap changing control. The primary distribution transformers inherently has load tap changing control capability so CVR is usually performed on the 33/11 kV transformers.

- CVR Factor and Feeder Length: Table 6.36 shows a comparison of the feeder results following a voltage reduction of 0.625% for load model scenario 2.

Table 5.2: Comparison of Feeder Results for Scenario 2

Feeder	CVR Factor		Length	Customers
	Summer	Winter		
1	1.10472	1.04208	1289	55
2	2.08696	2.00209	920	31
3	1.06401	0.99378	868	39
4	1.15254	1.07383	2290	75

Following the results obtained from the above simulations which does not follow the pattern of feeder length, it is not enough to draw conclusions that the CVR factor reduces with an increase in feeder length. Other factors including line resistance, feeder topology also influence the CVR factor.

5.3 Time Step Simulation Results

Time Step simulations were carried out in 5 minute intervals to verify the accuracy of the daily CVR simulations which are just a single value. This can be seen as a sensitivity analysis done to certify the results obtained above and to have CVR values for different periods during the day. Moreso, with this, utilities can spot the best time to implement CVR and have an idea of what CVR factors to expect at peak periods for peak demand reduction. Because of the uncertainty of the location of any particular customer in a feeder or network, three different load position scenarios were done for each case (summer and winter) and for all four feeders. At each time step, the CVR factors of the different load

position scenarios were recorded and the minimum and maximum values obtained. The mean of the CVR factors (of the three load position scenarios) was also recorded at each time step. In addition, the efficiency of the network was investigated for pre-CVR and post-CVR situations and comparisons were made. All time step simulations were done considering load model type 2 (constant current active power, constant impedance reactive power load) since constant power loads (load model type 1) give CVR factors of zero (based on results from the previous daily simulations - see Appendix C.1 for detailed results).

5.3.1 Feeder 1 Results

The minimum and maximum CVR factors (five minute time step) and mean value for feeder 1 (Summer and Winter) is shown in Figures 5.10 and 5.11.

Figure 5.10: Time Varying CVR Factor (Feeder 1, Summer)

N/B: The three load position scenarios were obtained by interchanging the load profiles of the customers in a systematic way such that in each scenario, all customers have load profiles different from their previous profile giving three separate CVR factors (CVRF1 to CVRF3 are the CVR factors for the three different load position scenarios). The minimum and maximum of these CVR factors are obtained for each time step.

The mean value of the power delivery efficiency for the 3 different load position scenarios at each time step was recorded and the summer and winter cases are compared in Figure 5.12.

Figure 5.11: Time Varying CVR Factor (Feeder 1, Winter)

The efficiency was calculated as:

$$Efficiency = \frac{Load\ Power}{Supply\ Power} * 100 \quad (5.4)$$

Figure 5.12: Pre and Post-CVR Efficiency (Feeder 1, Summer and Winter)

5.3.2 Feeder 2 Results

Time varying CVR factors (summer and winter) for feeder 2 is given in Figures 5.13 and 5.14

Figure 5.13: Time Varying CVR Factor (Feeder 2, Summer)

Figure 5.14: Time Varying CVR Factor (Feeder 2, Winter)

The pre and post-CVR power delivery efficiency for feeder 2 (Summer and winter) is given in Figure 5.15

Figure 5.15: Pre and Post-CVR Efficiency (Feeder 2, Summer and Winter)

5.3.3 Feeder 3 Results

Time varying CVR factors (summer and winter) for feeder 3 is given in Figures 5.16 and 5.17

Figure 5.16: Time Varying CVR Factor (Feeder 3, Summer)

Figure 5.17: Time Varying CVR Factor (Feeder 3, Winter)

The pre and post-CVR power delivery efficiency for feeder 3 (Summer and winter) is given in Figure 5.18

Figure 5.18: Pre and Post-CVR Efficiency (Feeder 3, Summer and Winter)

5.3.4 Feeder 4 Results

Time varying CVR factors (summer and winter) for feeder 4 is given in Figures 5.19 and 5.20

Figure 5.19: Time Varying CVR Factor (Feeder 4, Summer)

Figure 5.20: Time Varying CVR Factor (Feeder 4, Winter)

The pre and post-CVR power delivery efficiency for feeder 3 (Summer and winter) is given in Figure 5.21

Figure 5.21: Pre and Post-CVR Efficiency (Feeder 4, Summer and Winter)

5.3.5 Network Results

Time varying CVR factors (summer and winter) for the whole network is given in Figures 5.22 and 5.23. Voltage reduction was done on the primary substation transformer (33/11 kV).

Figure 5.22: Time Varying CVR Factor (Network, Summer)

Figure 5.23: Time Varying CVR Factor (Network, Winter)

The pre and post-CVR power delivery efficiency for the network (Summer and winter) is given in Figure 5.24

Figure 5.24: Pre and Post-CVR Efficiency (Network, Summer and Winter)

5.3.6 Analysis of Time Step Simulation Results

- CVR factor: For feeders 1 to 3: The CVR factor was erratic in the early hours of dawn, and becomes stable towards the evening. For feeder 4 and the network

simulation, this was not the case, as the CVR factor was stable in the early hours of dawn and fluctuated towards the evening. These phenomena has some connection with the number of customers connected. For feeders 1 to 3, the early erratic nature of the CVR factor was highest in feeder 2 (31 customers), followed by feeder 3 (39 customers) and then feeder 1 (55 customers). The CVR factors are both higher and erratic at dawn (12:00 am to 6:00 am) since the feeders are lightly loaded and increased depth of voltage reduction is possible. It is erratic since the load consumption during this period is irregular and varies greatly with the customers unlike the more predictable pattern during the morning and afternoon periods. This is not the case for feeder 4 (75 customers) and the network (as a whole) as these showed a more stable CVR factor in the early morning periods and increased slightly towards the evening. As the connected load increases, the aggregate consumption in the early hours becomes nearly equal for the three load position cases. The time-varying CVR factor for all individual feeders for scenario 2 (summer and winter) and the whole network is summarised in Table 5.3 as a range of values. Comparing this with the results obtained from the daily CVR simulations (Table 5.2), it can be seen that most values fall within the range.

Table 5.3: Feeder CVR factor Comparison (Time-Step and Daily Simulation)

Feeder	Summer CVRF			Winter CVRF		
	Daily	Time-Step		Daily	Time-step	
		Minimum	Maximum		Minimum	Maximum
1	1.10472	0.772947	1.422222	1.04208	0.869565	1.386482
2	2.08696	0.613027	1.616162	2.00209	0.592593	1.523810
3	1.06401	0.573477	1.616162	0.99378	0.784314	1.538462
4	1.15254	0.909091	1.992883	1.07383	0.930233	2.034976
N	1.05483	0.965645	1.629328	0.96827	0.940071	1.545894

Table 5.4 below shows the minimum and maximum values (mean range) of the mean

CVR factors throughout the day derived by taking the average of the three load position scenarios (for summer and winter cases).

Table 5.4: Feeder CVR factor Comparison (Mean Range)

Feeder	Summer CVRF		Winter CVRF	
	Minimum	Maximum	Minimum	Maximum
1	0.930670	1.241236	1.016899	1.283942
2	0.786749	1.481481	0.803746	1.430148
3	0.882492	1.328844	0.933782	1.391513
4	0.930233	1.383389	0.930233	1.502798
Network	1.052632	1.324450	1.032763	1.486486

It will be beneficial for utilities to implement CVR on the network with a high level of certitude when the CVR factor is more stable. For feeders 1 to 3 (with reference to the figures above), this is from 7:30 am to 23:55 pm for both summer and winter. For the network as a whole, it can be implemented between 12:00 pm and 15:00 pm (summer and winter). Implementation should be targeted from the afternoon towards the evening for greater watts (or kW) savings. The above mean ranges will give an insight of the values of CVR factors to be expected during summer or winter. The maximum values of CVR factor vary per feeder (Table 6.24), being highest in feeder 4, followed by feeder 2, 3 and then feeder 1. On any given day, the utility can get the minimum (worst case) or maximum (best case) CVR factors to expect at any time.

- **Cable, Transformer Losses and Efficiency:** The cable and transformer losses reduced with a reduction in voltage for the time-step simulations. This is expected of constant current loads where the supply voltage is directly proportional to the current consumption. A drop in voltage means a proportional drop in line current and therefore line and transformer winding losses (I^2R). Transformer core losses reduce with a reduction in voltage thereby causing the total transformer losses to reduce. However, the power

delivery efficiency at each time-step was almost equal for pre and post CVR (summer and winter) cases, implying that the loss reduction is not very significant. The winter case has a lower efficiency when compared to the summer case. For winter, the higher load demand causes increased line losses and thereby a lower efficiency. For feeders 1 to 3, the period of high and stable efficiency corresponds to the period of high and unstable and high CVR factors. Losses are minimum in the early hours of dawn so the efficiency is expected to be high. During the day, this fluctuates and goes a little lower as power demand increases and line losses increase too.

- **Network Peak Demand Reduction:** Simulations were done at specific times during the day (peak periods for both seasons). The peak demand of the whole network of 200 customers occurs at 21:45 pm during summer (Figure 6.8). A voltage reduction of 3.125% (0.96875 pu) at this time will result in a peak demand reduction of 3.759%. Further voltage reductions resulted in voltage excursions at the end of the line. The peak demand originally at 154.3 kW was reduced to 148.5 kW (giving a savings of 6 kW, and a CVR factor of 1.203). During winter (Figure 6.9), the peak demand of 210.9 kW, occurring at 19:15 pm can be reduced to 201.7 kW (giving savings of 9 kW, and a CVR factor of 1.16) following a voltage reduction of 3.75% (0.9625 pu).

In this chapter, the results obtained for the daily and time-step CVR simulations were analysed and discussed. It can be deduced that the CVR factor is very dynamic and depends on factors like seasonal variation in load and load model type. The difference between the results for the summer and winter cases in all simulations is minimal due to the fact that the rating of the supply transformer (11/0.4 kV) is far greater than the load requirements and this influenced the results. The transformer data for the network was already given by ENWL and could not be altered. In the following chapter, this work will be summarised with the main findings presented.

6 Conclusion

6.1 Summary of the Research

The different load management techniques employed by power system utilities for distribution networks has been analysed and their merits and demerits discussed. The non-intrusive nature of conservation voltage reduction makes it attractive to both consumers and utilities as compared to the direct load control or pricing based schemes. However, all load management programmes are useful when applied to the right situation depending on what is to be achieved. It is useful to apply a program where it is best suited. CVR has been proven to provide energy savings and peak demand reduction for utilities and a reduction in the electricity bills of consumers. Also, with the deferment of extra generation capacity, we are a step closer to the realization of the global need for the reduction of green house gas emissions from fossil powered plants. For this work, basic CVR was conducted via transformer Load tap changers (LTCs), for greater energy savings and loss reduction, advanced CVR should be considered by utilities. Although this comes with some costs, the benefits are considerable. According to a 2014 report by Navigant Research, UK, advanced CVR can save 40 TWh of energy in the UK annually, but they estimated a cost of over \$ 4.4 billion from 2014 to 2020 as the cumulative spending on CVR by utilities [46].

From the results obtained from the simulations, the following findings were made:

- The CVR factor is a dynamic ratio that depends on factors like weather (seasonal variation in load), load mix and feeder configuration. Applying CVR on UK distribution feeders will lower demand but this is mainly dependent on the load mix which varies by season. There are no watt savings for constant power loads and losses increase, while savings exist for constant current loads with the losses remaining nearly constant.
- The two major transformer losses: The winding losses and the core losses behave oppositely with voltage reduction. While the winding (transformer copper) losses increase with the reduction in voltage, the core losses (hysteresis and eddy-current) reduce. The percentage increase or reduction of these losses is linked with the CVR

factor. The higher the CVR factor (watts savings), the higher the percentage reduction in core losses with voltage reduction.

- There are no direct relationships between CVR factor and feeder length. More dependent factors are the feeder line resistance and feeder topology.
- Conservation voltage reduction applied to the network as a whole was an effective tool for peak demand reduction. During the peak periods, demand savings of 6 kW and 9 kW were obtained for the summer and winter cases respectively considering constant current loads.
- Although the secondary substation transformers (11/0.4 kV) were the preferred spot for voltage reduction because of the reduction in core losses of the transformers and their closeness to the end-use loads, they do not have automatic control capabilities (basically off-load tap changers). Therefore, the realistic alternative is to regulate voltage automatically through the OLTC-fitted primary substation transformers (33/11 kV).

6.2 Benefits of Research to the Society

As a part of the recent CVR trials in the UK, this research will serve to boost the confidence of utilities in investing in CVR for demand reduction and energy savings. Other researches in this area has focused on the daily CVR factor indicating only a single value. The CVR factor is very dynamic and varies during the day due to loading conditions and other factors. This research includes a time-step simulation (5 minute interval) on four feeders individually and together as a whole network. Through this, utilities will be advised better on when best to implement CVR for peak demand reduction and what savings to expect. Further still, they would want to consider a more coordinated volt/var control and invest in additional equipment like AMI/SCADA controls and capacitors for reactive power compensation. The cost benefit analysis discussed in Chapter 3 would be most useful to make a more informed decision. The different load management schemes covered in this work will enlighten people on the various ways to save energy as consumers or as utilities.

6.3 Data Limitations

- Conservation voltage reductions are normally performed on a yearly basis with yearly load profiles. These load profiles were not available for each customer class; daily load profiles are not enough as it does not consider the seasonal variations in load. Load types vary with seasons and different CVR strategies may be needed. Simulations were only done for summer and winter to take care of the seasonal variations in load.
- The residential load profile available from CREST was a 1-minute resolution data. The conversion to a 5-minute data, through averaging. This may not truly reflect the consumption pattern of the residential customer as better results are obtained using higher resolution data.
- It was not possible to incorporate commercial and industrial load profiles on the low voltage network since it is a typical residential network for residential type customers. The availability of commercial and industrial network would be useful to access the CVR effects on such load types. To cater for this, two common load type scenarios has been defined (Table 5.1) to show the variation of the CVR factor on different load types.

6.4 Recommendation and Future Research

Research is recommended in the following areas based on results obtained and the limitations of the study.

- A study on the quantification of reactive power (vars) savings with CVR. More laboratory tests should be done to determine the load response of more appliances to voltage variation.
- The cost benefit analysis of CVR done in this work did not include figures because of the non-existent actual cost of equipment involved. A more thorough analysis can be done to include the cost of externalities (CO_2 emissions saved), avoided cost of generation and a sensitivity analysis done.

- Optimization programs to maximize demand/energy savings while minimizing losses will be necessary.
- CVR was performed on only residential type networks, it should also be done on commercial LV networks to estimate demand savings via transformer LTC operation. This can be provided by the UKGDS. The UK generic distribution system provides test platforms for novel technical solutions including realistic load profiles, generation patterns and network models.

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Appendices

A Appendix A

A.1 Feeder 1 Voltage Profiles (Scenario 2 Load Model)

Figure A.1: Pre-CVR (Feeder 1, Summer Case)

Figure A.2: With CVR (Feeder 1, Summer Case)

Figure A.3: Pre-CVR (Feeder 1, Winter Case)

Figure A.4: With CVR (Feeder 1, Winter Case)

A.2 Network Voltage Profiles (Scenario 2 Load Model)

Figure A.5: Pre-CVR (Network, Summer Case)

Figure A.6: With CVR (Network, Summer Case)

Figure A.7: Pre-CVR (Network, Winter Case)

Figure A.8: With CVR (Network, Winter Case)

B Appendix B

B.1 Matlab Codes for Time-step Simulation

```

clear
clc

% Specify Simulation Folder
cd 'C : \Users\DONALD\Documents\Feeder_1'

% StartDSS

% Initiate the DSS Engine
Obj = actxserver('OpenDSSEngine.DSS');
Start = Obj.Start(0);
Text = Obj.Text;

% Assign the Interface Handles.
Circuit = Obj.ActiveCircuit;
Solution = Circuit.Solution;
CtrlQueue = Circuit.CtrlQueue;
DGs = Circuit.Generators;
Loads = Circuit.Loads;
Monitors = Circuit.Monitors;
Lines = Circuit.Lines;
xfmrs = Circuit.Transformers;
oltcs = Circuit.RegControls;

% Inputs defined here
% Read in load curve
Load = csvread('Load1.csv');
```

```

L=55; % The number of loads in the network

% Set some simulaion parameters

% The minimum network voltage, Vmin_limit
Vmin_limit = 0.94;
% The step change in voltage from one solution to the next
deltaV = 0.0025;
% Declare empty variable for results
V = zeros(288,2);
P1 = zeros(288,1);
Q1 = zeros(288,1);
CircuitLosses = zeros(288,2); % Total circuit losses
TransformerLosses = zeros(288,2); % Transformer losses
CableLosses = zeros(288,2); % Cable losses
LoadDemand = zeros(288,2); % Demand of connected loads

% Compile the network

Text.Command = 'Compile(C : \Users\DONALD\Documents\Feeder_1\Feeder1.dss)';

% Run a time series simulation

for t=1:288 % where t is time step

disp(t);

% initiate solution for Vsource = 1pu
Solution.mode = 0; % Snap shot mode

```

```

% For each load l, set the demand value specified for time t
for l = 1:55
string = sprintf('edit load.LOAD%d kW=%d',l,Load(t,l));
Text.Command = (sprintf('%s',string));
end

% Solve the network
Solution.Solve();

% Extract results

% Voltage
Text.Command = ('Export Voltages');
voltages = csvread('Feeder1_EXP_VOLTAGES.csv',1,1);

% Power
Text.Command = ('Export Powers');
powers = csvread('Feeder1_EXP_POWERES.csv',1,1);
% Power injected into transformer is at 1811 - this reference is from % the
Feeder1_EXP_POWERES.csv file P1(t,1) = powers(1811,2);
Q1(t,1) = powers(1811,3);

% Losses
Text.Command = ('Export Losses');
losses = csvread('Feeder1_EXP_LOSSES.csv',1,1);
TransformerLosses(t,1:2) = losses(906,1:2);
CableLosses(t,1:2) = sum(losses(1:905,1:2),1);
MytotalCircuitLosses = Obj.ActiveCircuit.Losses;

```

```

CircuitLosses(t,:) = MytotalCircuitLosses/1000;

% Load demand - calculated as power injected into network minus losses
LoadDemand(t,1) = P1(t,1) - CircuitLosses(t,1);
LoadDemand(t,2) = Q1(t,1) - CircuitLosses(t,2);

% get the minimum voltage
Vmin = min(voltages(:,5));

% If the minimum voltage is greater than the lower voltage limit,
% reduce the source voltage for CVR
% Repeat until constraint reached

% This is outside the loop as it will always be 0.4 = 1pu
StartVoltage = 0.4;

while Vmin > Vmin.limit

% Save most recent valid solution
V(t,1) = StartVoltage;
V(t,2) = Vmin;

% Calculate the next voltage at bulk supply point and pass to network
NextVoltage = StartVoltage-deltaV;
string = sprintf('edit Transformer.TR1 kVs=[11 %d]',NextVoltage);
Text.Command = (sprintf('%s',string));

% Solve this new network
Solution.Solve();

```

```

% Extract results

% Voltage
Text.Command = ('Export Voltages');
voltages = csvread('Feeder1_EXP_VOLTAGES.csv',1,1);

% Power
Text.Command = ('Export Powers');
powers = csvread('Feeder1_EXP_POWERES.csv',1,1);
% Power injected into transformer is at 1811 - this reference is from
% the Feeder1_EXP_POWERES.csv file
P2(t,1) = powers(1811,2);
Q2(t,1) = powers(1811,3);

% Losses
Text.Command = ('Export Losses');
losses2 = csvread('Feeder1_EXP_LOSSES.csv',1,1);
TransformerLosses2(t,1:2) = losses2(906,1:2);
CableLosses2(t,1:2) = sum(losses2(1:905,1:2),1);
MytotalCircuitLosses2 = Obj.ActiveCircuit.Losses;
CircuitLosses2(t,:) = MytotalCircuitLosses2/1000;

% Load demand - calculated as power injected into network minus losses
LoadDemand2(t,1) = P2(t,1) - CircuitLosses2(t,1);
LoadDemand2(t,2) = Q2(t,1) - CircuitLosses2(t,2);

% get the minimum voltage
Vmin = min(voltages(:,5));

```

```
% move to next voltage value (this may not be simulated and depends upon Vmin)
StartVoltage = NextVoltage;
end

% Reset voltage to 1pu for next time step
string = sprintf('edit Transformer.TR1 kVs=[11 0.4]');
Text.Command = (sprintf('%s',string));

end
```

B.2 OpenDSS Codes

```

clear
set datapath= C : \Users\DONALD\Documents\Feeder_1\
!! new network
New Circuit.Feeder1 BaseV=11 pu=1.0 ISC3=3000 ISC1=2500
Edit Vsource.Source

Redirect LineCode.txt
Redirect LoadShapes.txt
Plot Loadshape object=Shape_1
Redirect Lines.txt
Redirect Transformers.txt
Redirect Loads.txt
Redirect Monitors.txt

set voltagebases=[11 0.4]
calc voltagebases

new monitor.TR1 element=transformer.TR1 terminal=1 mode=1 ppolar=no
new monitor.Vbb element=transformer.TR1 terminal=2 mode=0
new monitor.Tap element=transformer.TR1 terminal=1 mode=2
new monitor.Load55PQ element=Load.load55 terminal=1 mode=1 ppolar=no
New energymeter.feeder element=Line.LINE1
set normvminpu=0.94 !set range of limit voltage
set normvmaxpu=1.10

Solve
/*
set mode=daily

```

```
set number=1
set stepsize=5m
set time=(21,2700)
```

```
solve
```

```
Show losses
```

```
*/
```

```
!!For losses study
```

```
Show losses
```

```
BusCoords XYposition.csv
```

```
Plot circuit power dots=y labels=n C1=blue
```

```
Plot profile phases=all
```

```
solve mode=daily number=288 stepsize=5m
```

```
!visualize What=voltages element=line.LINE1
```

```
!visualize What=currents element=line.LINE1
```

```
Show Voltages
```

```
Show Currents
```

```
Show Powers kVA elements
```

```
Plot monitor object=LINE905_PQ_vs_Time
```

```
Plot monitor object=LINE905_VI_vs_Time
```

```
Plot monitor object=LINE905_VI_vs_Time channel=(7,9,11)
```

```
export monitors Load55PQ
```

```
export monitors TR1
```

```
export monitors Vbb
```

```
export monitors Tap
```


B.3 OpenDSS Scripting of Circuit Elements

- Transformers:
 - New Transformer.TR Buses=[SourceBus SubBus] Conns=[Delta Wye] kVs=[33 11] kVAs=[50000 50000] XHL=12 !new regcontrol.TR transformer=TR winding=2 vreg=(6271.47) ptratio=(1) band=1
 - New Transformer.TR1 Buses=[SubBus 1] Conns=[Delta Wye] kVs=[11 0.4] kVAs= [800 800] XHL=1 !new regcontrol.TR1 transformer=TR1 winding=2 vreg=(227.125) ptratio=(1) band=1
 - Transformer Tap Steps: 0.9 to 1.1 pu in steps of 0.00625 (Shown in table 5.5 below), ESQCR voltage range: 0.94 to 1.1 pu

Nomenclature:

- ptratio: The ratio of the potential transformer that converts the controlled winding voltage to the regulator voltage. This should be set to 1.
 - Band: the bandwidth in volts for the controlled bus
 - vreg: Voltage regulator settings in volts for the winding to be controlled. This is set to the desired voltage in volts.
 - XHL: Percent reactance high (H) to low (L) winding. The value is already given from the network as 1
- Voltage Source:
 - New Circuit.Feeder1 BasekV=11 pu=1.0 ISC3=3000 ISC1=2500

where *ISC3*, *ISC1*: Three phase and single phase fault current level

Table B.1: Transformer Taps Used

Number	Tap (pu)	Voltage (V)
1	1.00000	230.0000
2	0.99375	228.5625
3	0.98750	227.1250
4	0.98125	225.6875
5	0.97500	224.2500
6	0.96875	222.8125
7	0.96250	221.3750
8	0.95625	219.9375
9	0.95000	218.5000

- Loads and Load Shape:

- New Load.LOAD1 Phases=1 Bus1=32.1 kV=0.23 kW=1 PF=0.95
Daily=Shape_1 Vmaxpu=1.2 Vminpu=0.8 Model=8 ZIPV=[0.85 -1.12 1.27
10.96 -18.73 8.77 0.8]
- New Loadshape.Shape_1 npts=48 interval=30 csvfile=C:\Users\DONALD
\Documents\2014 \ENWL_Network_Creation\Feeder_Representation\Load_files
_Model\Load_Profile\Load1.csv useactual=true

Nomenclature:

useactual=true: OpenDSS uses the actual values of the load in the csv file.

ZIPV: OpenDSS representation of Load Model 8 (ZIP Model:

$[Z_p, I_p, P_p, Z_q, I_q, P_q, V_{minpu}]$)

- Lines and Line Codes

- New Line.LINE1 Bus1=1 Bus2=2 phases=3 Linecode=4c_70 Length=1.098
Units=m

- New LineCode.4c_70 nphases=3 R1=0.446 X1=0.071 R0=1.505 X0=0.083
C1=0 C0=0 Units=km

- Monitors and Energy Meters

- New Monitor.LINE1_PQ.vs_Time Line.LINE1 2 Mode=1 ppolar=0 New
Monitor.LINE1_VI.vs_Time Line.LINE1 2 Mode=0
- new monitor.Load55PQ element=Load.load55 terminal=1 mode=1 ppolar=no
- New energymeter.feeder element=Line.LINE1

C Appendix C

C.1 Results for Daily CVR Simulation

C.1.1 Feeder 1 Results

1. Scenario 1: Constant Power (P and Q) Load

A. Summer Results: Simulation results for feeder 1 (Scenario 1, Summer case)

Table C.1: Feeder 1 Simulation Results (Scenario 1, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	182.9	6.00	10.8	11.0	0.19229	
CVR	0.99375	182.9	6.08	10.9	11.1	0.19262	0

where: SSV = Substation Voltage in pu, TLP = Total Load Power in kW

CL = Percentage Circuit Losses, LL = Line Losses in kW

TL = Total Losses in kW, TRL = Transformer Losses in kW

B. Winter Results: Simulation results for feeder 1 (Scenario 1, Winter case)

Table C.2: Feeder 1 Simulation Results (Scenario 1, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	211.8	7.01	14.6	14.9	0.26066	
CVR	0.99375	211.8	7.12	14.8	15.1	0.26116	0

2. **Scenario 2:** Constant Current, P and Constant Impedance, Q Load

A. Summer Results Simulation results for feeder 1 (Scenario 2, Summer case)

Table C.3: Feeder 1 Simulation Results (Scenario 2, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	173.8	5.56	9.5	9.7	0.17156	
CVR	0.99375	172.6	5.59	9.5	9.7	0.16942	1.10472

B. Winter Results Simulation results for feeder 1 (Scenario 2, Winter case)

Table C.4: Feeder 1 Simulation Results (Scenario 2, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	199.6	6.46	12.7	12.9	0.22841	
CVR	0.99375	198.3	6.50	12.7	12.9	0.22556	1.04208

C.1.2 Feeder 2 Results

1. **Scenario 1:** Constant Power (P and Q) Load

A. Summer Results Simulation results for feeder 2 (Scenario 1, Summer case)

Table C.5: Feeder 2 Simulation Results (Scenario 1, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	95.3	4.23	4.0	4.0	0.05110	
CVR	0.99375	95.3	4.35	4.1	4.1	0.05123	0

B. Winter Results Simulation results for feeder 2 (Scenario 1, Winter case)

Table C.6: Feeder 2 Simulation Results (Scenario 1, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	99.5	4.40	4.3	4.4	0.05546	
CVR	0.99375	99.5	4.52	4.4	4.5	0.05560	0

2. **Scenario 2:** Constant Current, P and Constant Impedance, Q Load

A. Summer Results Simulation results for feeder 2 (Scenario 2, Summer case)

Table C.7: Feeder 2 Simulation Results (Scenario 2, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	92.0	4.01	3.6	3.7	0.04712	
CVR	0.99375	90.8	4.06	3.6	3.7	0.04595	2.08696

B. Winter Results Simulation results for feeder 2 (Scenario 2, Winter case)

Table C.8: Feeder 2 Simulation Results (Scenario 2, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	95.9	4.16	3.9	4.0	0.05098	
CVR	0.99375	94.7	4.22	3.9	4.0	0.04972	2.00209

C.1.3 Feeder 3 Results

1. Scenario 1: Constant Power (P and Q) Load

A. Summer Results Simulation results for feeder 3 (Scenario 1, Summer case)

Table C.9: Feeder 3 Simulation Results (Scenario 1, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	126.5	5.92	7.4	7.5	0.09018	
CVR	0.99375	126.5	6.00	7.5	7.6	0.09033	0

B. Winter Results Simulation results for feeder 3 (Scenario 1, Winter case)

Table C.10: Feeder 3 Simulation Results (Scenario 1, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	135.2	5.48	7.8	7.9	0.19229	
CVR	0.99375	135.2	5.93	7.9	8.0	0.10557	0

2. Scenario 2: Constant Current, P and Constant Impedance, Q Load

A. Summer Results Simulation results for feeder 3 (Scenario 2, Summer case)

Table C.11: Feeder 3 Simulation Results (Scenario 2, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	120.3	5.47	6.5	6.6	0.08085	
CVR	0.99375	119.5	5.50	6.5	6.6	0.07984	1.06401

B. Winter Results Simulation results for feeder 3 (Scenario 2, Winter case)

Table C.12: Feeder 3 Simulation Results (Scenario 2, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	128.8	5.33	6.8	6.9	0.09418	
CVR	0.99375	128.0	5.36	6.8	6.9	0.09300	0.99378

C.1.4 Feeder 4 Results

1. **Scenario 1:** Constant Power (P and Q) Load

A. Summer Results Simulation results for feeder 4 (Scenario 1, Summer case)

Table C.13: Feeder 4 Simulation Results (Scenario 1, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	260.9	14.01	36.1	36.5	0.46019	
CVR	0.99375	260.9	14.01	36.1	36.5	0.46019	0

B. Winter Results Simulation results for feeder 4 (Scenario 1, Winter case)

Table C.14: Feeder 4 Simulation Results (Scenario 1, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	285.0	15.61	43.9	44.5	0.56213	
CVR	0.99375	285.0	15.74	44.1	44.7	0.56300	0

2. Scenario 2: Constant Current, P and Constant Impedance, Q Load

A. Summer Results Simulation results for feeder 4 (Scenario 2, Summer case)

Table C.15: Feeder 4 Simulation Results (Scenario 2, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	236.0	11.95	27.8	28.2	0.35862	
CVR	0.99375	234.3	12.03	27.8	28.2	0.35416	1.15254

B. Winter Results Simulation results for feeder 4 (Scenario 2, Winter case)

Table C.16: Feeder 4 Simulation Results (Scenario 2, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	TRL	CVR_f
No CVR	1	253.3	12.82	32.1	32.5	0.41828	
CVR	0.99375	251.6	12.90	32.0	32.5	0.41303	1.07383

C.1.5 Network Results

A. Summer Results Simulation results for whole network (Scenario 2, Summer case)

Table C.17: CVR 1: Network Simulation Results (Scenario 2, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	CVR_f
No CVR	1	621.9	7.74	47.5	48.2	
CVR1	0.99375	617.8	7.80	47.5	48.2	1.05483

Table C.18: CVR 2: Network Simulation Results (Scenario 2, Summer Case)

Case	SSV (pu)	TLP	% CL	LL	TL	CVR_f
No CVR	1	621.9	7.74	47.5	48.2	
CVR2	0.99375	617.8	7.79	47.5	48.1	1.05483

Table C.19: Comparison of Network Transformer Losses (Summer Case)

Transformer	Transformer Losses (kW)		
	No CVR (1 pu)	CVR1 (0.99375 pu)	CVR2 (0.99375 pu)
TR	0.03629	0.03584	0.03584
TR1	0.17157	0.17157	0.16943
TR2	0.04712	0.04712	0.04653
TR3	0.08085	0.08085	0.07984
TR4	0.35862	0.35863	0.35416

B. Winter Results Simulation results for whole network (Scenario 2, Winter case)

Table C.20: CVR 1: Network Simulation Results (Scenario 2, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	CVR_f
No CVR	1	677.5	8.30	55.4	56.3	
CVR1	0.99375	674.3	8.36	55.4	56.3	0.96827

Table C.21: CVR 2: Network Simulation Results (Scenario 2, Winter Case)

Case	SSV (pu)	TLP	% CL	LL	TL	CVR_f
No CVR	1	677.5	8.30	55.4	56.3	
CVR2	0.99375	674.3	8.36	55.4	56.2	0.96827

Table C.22: Comparison of Network Transformer Losses (Winter Case)

Transformer	Transformer Losses (kW)		
	No CVR (1 pu)	CVR1 (0.99375 pu)	CVR2 (0.99375 pu)
TR	0.04327	0.04273	0.04273
TR1	0.22841	0.22840	0.22556
TR2	0.05098	0.05098	0.05035
TR3	0.09418	0.09418	0.09300
TR4	0.41828	0.41824	0.41303