5-1-2014

Evaluation of Conservation Voltage Reduction as a tool for demand side management

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Dorrody, Ali, "Evaluation of Conservation Voltage Reduction as a tool for demand side management" (2014). *UNLV Theses, Dissertations, Professional Papers, and Capstones*. 2075.
http://dx.doi.org/10.34917/5836094

EVALUATION OF CONSERVATION VOLTAGE REDUCTION AS A TOOL FOR DEMAND SIDE MANAGEMNET

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2000

A thesis submitted in partial fulfillment of the requirements for the

Master of Science in Engineering - Electrical Engineering

Department of Electrical and Computer Engineering

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The Graduate College

University of Nevada, Las Vegas

May 2014

THE GRADUATE COLLEGE

We recommend the thesis prepared under our supervision by

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entitled

Evaluation of Conservation Voltage Reduction as a Tool for Demand Side Management

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering

Department of Electrical and Computer Engineering

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May 2014

Abstract

To ensure stability of the power grid, electricity supply and demand must remain in balance in real time. Traditionally utilities, call upon peaking power plants to increase power generation to meet the peak demand during the afternoons of the hot summer months. Demand-side management (DSM), which includes energy efficiency and demand response (DR), works from the other side of the equation – instead of adding more generation to the system, it pays energy users to reduce consumption as it is cheaper and easier to procure than traditional generation. As a consequence, demand-side management allows utility customers to act as a "virtual power plant": by voluntarily lowering their demand for electricity, they help stabilize the grid, and they are paid for providing this important service. Utilities and grid operators treat demand response capacity as a dispatchable resource that is called upon only when needed.

This thesis reviews the different DMS methods, and then it evaluates one possible means of reducing demand by operating at the low end of the acceptable voltage supply a method known as Conservation Voltage Reduction (CVR). This method was used effectively in the past to conserve energy and it is still being applied in some regions. But as the load is becoming more and more

nonlinear and more energy efficient, the CVR is becoming a less effective tool for demand-side management.

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Chapter 1:

Introduction

1.1. History of smart grids

A smart grid is an updated electrical grid which uses analogue or digital information and communications technology to collect and act on information, such as information about the behaviors of suppliers and consumers, in an automated way to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity. (U.S Department of Energy., 2012)

Smart grid policy in the United States is defined in 42 U.S.C. The first alternating current power grid system was installed in 1886. At that time, the grid was a centralized unidirectional system of electric power transmission, electricity distribution, and demand-driven control.

Between the 1970s and the 1990s, growing of demand led to a growing number of power stations. In some areas, supply of electricity, mostly at peak times, could not supply the demand, resulting in poor power quality including blackouts, power cuts, and brownouts. More and more, electricity was depended on by industry, heating, communication, lighting, and entertainment, and consumers demanded ever higher levels of reliability.

Towards the end of the 20th century, electricity demand patterns were established: domestic heating and air-conditioning led to daily peaks in demand that were met by an array of 'peaking power generators' that would only be turned on for short periods each day. The relatively low utilization of these peaking generators (commonly, gas turbines were used due to their relatively lower capital cost and faster start-up times), together with the necessary redundancy in the electricity grid, resulted in high costs to the electricity companies, which were passed on in the form of increased tariffs. In the 21st century, some developing countries like China, India and Brazil were seen as pioneers of smart grid deployment. (Nejad et al., 2013)

1.2. Smart Grids and Efficiency

Numerous contributions to the overall improvement of the efficiency of energy infrastructure is expected from the placement of smart grid technology, especially including demand-side management, for example turning off air conditioners during short-term effects electricity price. The overall effect is less redundancy in transmission and distribution lines, and greater utilization of generators, leading to lower power prices.

The total load connected to the power grid can vary significantly over time. Although the total load is the sum of many individual choices of the clients, the overall load is not a stable, slow varying, growth of the load if a popular television program starts and millions of televisions are turned on simultaneously. Traditionally, to respond to a rapid increase in power consumption, faster than the start-up time of a large generator, some reserved generators are put on standby mode. A smart grid may warn all individual television sets, or another larger customer, to reduce the load temporarily (to allow time to start up a larger generator) or continuously (in the case of limited resources) (Sinitsyn, Kundu, & Backhaus, 2013). Using mathematical prediction algorithms, it is possible to predict how many standby generators need to be used, to reach a certain failure rate. In the traditional grid, the failure rate can only be reduced at the cost of more standby generators. In a smart grid, the load reduction by even a small portion of the clients may remove the problem.

To reduce demand during the high cost peak usage periods, communications and metering technologies inform smart devices in the home and business when energy demand is high and track how much electricity is used and when it is used. It also gives utility companies the ability to reduce consumption by communicating to devices directly in order to prevent system overloads. Examples would be a utility reducing the usage of a group of electric vehicle charging stations or shifting temperature set points of air conditioners in a city (Sinitsyn et al., 2013). To encourage them to cut back use and perform what is called peak curtailment or peak leveling, prices of electricity are increased during high demand periods, and decreased during low demand periods. It is assumed that consumers and businesses will tend to consume less during high demand periods if it is possible for consumers and consumer devices to be aware of the high price for using electricity at peak periods. This could mean making trade-offs such as cycling on/off air conditioners or running dishes at 9 pm instead of 5 pm. When businesses and consumers see a direct economic advantage of using energy at off-peak times, they can include energy cost of operation into their consumer device and building construction decisions and hence become more energy efficient.

According to supporters of smart grid plans, this will reduce the amount of spinning reserve that electric utilities have to keep on stand-by, as the load curve will level itself through a combination of "invisible hand" free-market capitalism and central control of a large number of devices by power management services that pay consumers a portion of the peak power saved by turning their device off.

1.3. Smart grids and Demand response support

Demand response support allows generators and loads to cooperate in an automated fashion in real time, coordinating demand to flatten spikes. Removing the portion of demand that occurs in these spikes removes the cost of adding reserve generators, and extends the life of equipment, and allows users to reduce their energy bills by telling low priority devices to use energy only when it is cheapest. (ACT,)

Currently, power grid systems have varying degrees of communication within control systems for their high value properties, such as in generating plants, transmission lines, substations and major energy users. In general information runs one way, from the users and the loads they control back to the utilities. The utilities attempt to meet the demand and succeed or fail to varying degrees (brownout, rolling blackout, uncontrolled blackout). The total amount of power demand by the users can have a very wide probability distribution which requires spare generating plants in standby mode to respond to the quickly changing power usage. This one-way flow of information is expensive; the last 10% of generating capacity may be required as little as 1% of the time, and brownouts and outages can be costly to consumers.

Latency of the data flow is a major concern, with some early smart meter architectures allowing actually as long as 24 hours delay in receiving the data, stopping any possible reaction by either supplying or demanding devices.

1.3.1. Demand-side management

Energy demand management, also known as demand side management (DSM), is the adjustment of consumer demand for energy through different methods such as financial encouragements and education. Usually, the goal of demand side management is to encourage the consumer to use less energy during peak hours, or to move the time of energy use to off-peak times such as nighttime and weekends. (Office of Energy., 2010). Peak demand management does not necessarily decrease total energy consumption, but could be expected to reduce the need for investments in networks and/or power plants for meeting peak demands. An example is the use of energy storage units to store energy during off-peak hours and discharge them during peak hours. (Chiu et al., 2012)

There are different types of demand-side management:

<u>Energy Efficiency</u>: Using less power to perform the same tasks.

<u>Demand Response</u>: Any reactive or preventative method to reduce, flatten or shift peak demand. Demand Response includes all intended changes to consumption patterns of electricity of end user customers that are intended to alter the timing, level of instantaneous demand, or the total electricity consumption. Demand Response refers to a wide range of actions which can be taken at the customer side of the electricity meter in response to particular conditions within the electricity system (such as peak period network congestion or high prices) (Torriti, Hassan, & Leach, 2010). Chapter 2 presents concept of demand response and its relatives.

Dynamic Demand: Advance or delay appliance operating cycles by a few seconds to increase the Diversity factor of a set of loads. The concept is that by monitoring the power factor of the power grid, as well as their own control parameters, individual, intermittent loads would switch on or off at optimal moments to balance the overall system load with generation, reducing critical power mismatches. As this switching would only advance or delay the appliance operating cycle by a few seconds, it would be unnoticeable to the end user (Schweppe, 1982)

1.3.1.1. Demand-side management and Conservation voltage reduction

Most U.S. utilities practice some form of system voltage reduction as part of System Emergency Procedures for control of short term demand related emergencies. They use single step or multiple step reduction of distribution system voltage such as 2.5 % or 3%, 5% and 8% voltage reduction. The system used to do this includes communications to automatic voltage regulating relays on LTC Power Transformers and Step-Voltage Regulators. Through a dry contact closure to the tap-changer control relay, its regulating center band voltage is reduced to a lower level by boosting the sensed voltage level of the voltage regulating relay. This causes an overall reduction in the Distribution System

Automatic Regulating Voltage Schedule. Various specific schemes are in practice due to a variety of Voltage Regulating Relays in service.

Chapter 2:

Demand Response (DR)

2.1. History of Demand Response(DR)

For many years, utilities called large industrial and commercial customers to reduce load, working their phones to find good corporate citizens willing to turn off non-essential lighting, motors or other equipment. To validate this relationship, some utilities offered “interruptible” electric rates that exchanged regularly cheaper power for the right to demand infrequent usage reductions. Except in very extreme cases, power flow was never cut off; instead, customers might be penalized if they did not reduce usage to the level promised to receive the lower rate. Because utilities infrequently made such calls, interruptible rates gradually became the “normal” price for industrial power. To minimize their electric bills, many large institutions also signed such agreements, even when they did not have an easy way to cut their load.

In the 1990s, however, several factors soured this relationship. For some reasons, the addition of new power plants failed to keep pace with load growth. As regional grids originally created for reliability transformed into interstate wholesale power markets, power sales between utilities and private generators were no longer regulated at the state level. This resulted in commodity speculators that increase on price instability.

Sudden price spikes appeared in 1998 during a very hot Midwest summer, but it was the 2000-01 California power disaster that concentrated national attention on the problem. When called upon to reduce load, many “interruptible” customers failed to do so just when power prices were going very high. To regain their losses, utilities tried to penalize those customers. Many of them declined to pay, stating they had been assured that such calls would never come. They tried to escape their pricing agreements, but utilities and regulators would not allow them to escape. A better way was needed to secure load reductions on very short notice.

2.2. Demand Response Definition

Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized (Balijepalli, Pradhan, Khaparde, & Shereef, 2011).

Demand response (DR) is normally used to refer to mechanisms used to encourage consumers to reduce demand, thus reducing the peak demand for electricity. Since electrical generation and transmission systems are commonly sized to correspond to peak demand (plus margin for forecasting error and unexpected events), lowering peak demand reduces overall plant and capital cost requirements. Depending on the configuration of generation capacity, however, demand response may also be used to increase demand (load) at times of high production and low demand. Some systems may by this means encourage energy storage to arbitrage between periods of low and high demand (or low and high prices).

In electricity grids, demand response (DR) is similar to dynamic demand mechanisms to manage customer consumption of electricity in response to supply conditions, for example, having electricity customers reduce their consumption at critical times or in response to market prices. The difference is that demand response mechanisms respond to obvious requests to shut off, but dynamic demand devices passively shut off when stress in the grid is sensed. (Albadi & El-Saadany, 2008)

Any program which communicates with the end customer regarding price changes in the market and/or their own energy use and encourages them to reduce or shift their consumption (demand) of energy is called demand response. The active participation of the end-customers is a response to factors such as incentive pricing, new tariffs schemes, education and feedback. Feedback can be categorized as direct and indirect feedback. Indirect feedback is provided at set times by a third party. Informative bills with graphical representations of the consumer’s historical consumption data would be one example of indirect feedback. Direct feedback is accessible to the consumer at any time and comes directly to their through, for example, an in-house display, computer site or text message.

2.3. Types of demand response

Three types of demand response are: emergency demand response, economic demand response and ancillary services demand response. Each will be:

2.3.1. Emergency demand response:

Emergency demand response is engaged to avoid involuntary service interruptions during times of supply shortage.

2.3.2. Economy demand response:

Economic demand response is engaged to allow electricity customers to limit their consumption when the productive or convenience of consuming that electricity is worth less to them than paying for the electricity.

2.3.3. Ancillary service demand response:

Ancillary services demand response consists of a number of specialty services that are needed to ensure the secure operation of the transmission grid and which have traditionally been provided by generators.

Also, “Demand Response” can be categorized in other aspects like: Dispatchable and Non-Dispatchable.

2.3.4. Dispatchable Demand Response (DDR):

“Dispatchable demand response” refers to planned changes in consumption that the customer agrees to make in response to direction from someone other than the customer. It includes direct load control of customer appliances such as those for air conditioning and water heating, directed reductions…and a variety of wholesale programs offered by RTOs/ISOs that compensate participants who reduce demand when directed for either reliability or economic reasons.

This direction to reduce load can be in response to acceptance of the consumer’s bid to sell its demand reduction at a price in an organized market (a wholesale price - responsive demand response) or to a retail provider. (Federal Energy Regulatory Commission, 2010)

2.3.5. Dynamic Pricing (DP) response:

“Non-Dispatchable demand response” refers to programs and products in which the customer decides whether and when to reduce consumption based on a retail rate design that change over time. This is sometimes called retail price - responsive demand and includes dynamic pricing programs that charge higher prices during high-demand hours and lower prices at other times. (Federal Energy Regulatory Commission, 2010)

Different types of demand-side management are illustrated in figure-2-1.

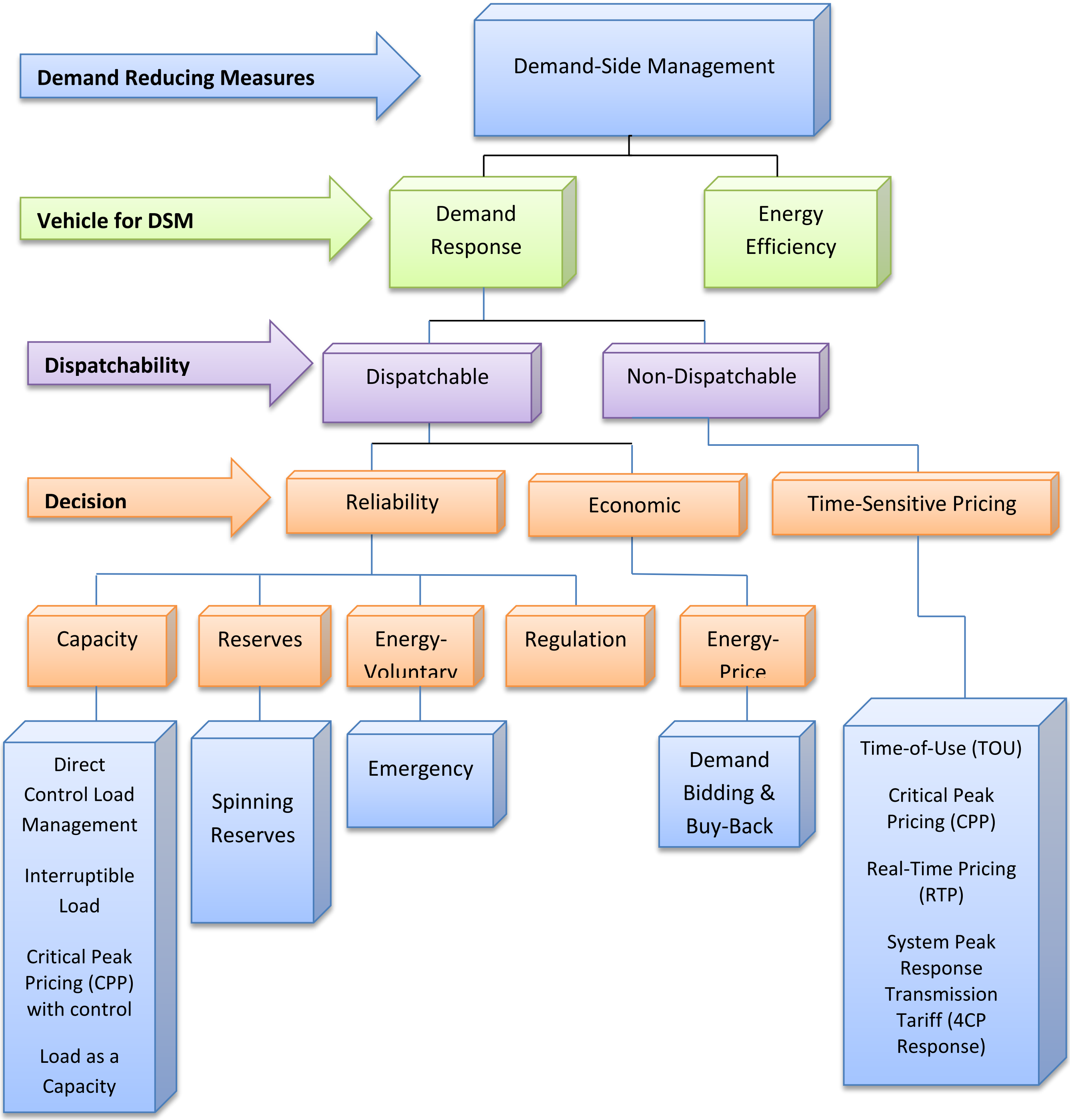


Figure-2-1: Demand-Side Management Categories (NERC 2011)

2.4. Demand Response Techniques

There are many demand response techniques available to utility companies. They may be active or passive, direct or indirect. Active techniques allow the consumer to take a hands-on role in determining the programs they will participate through and to what extent. The consumer can choose in or out at any time, sometimes even during an event. Energy cutoff solutions, time-of-use rate plans and utility-controlled thermostats are the examples of active DR. In passive demand response, the consumer has little to no control. The utility applies the solution without informing or consulting the customer, and does not let choose-in or choose-out capability. Examples of passive demand management techniques include rolling blackouts and voltage reduction.

Demand response techniques can also be direct or indirect. A direct method results in measurable, quantifiable outcomes, and directly affects demand; examples might include air conditioner and pool pump cutoff controllers. For direct demand side management, it is possible to relate the action to the reaction. Indirect demand response includes influencing someone or something to behave differently, e.g., showing a user the amount of energy currently being consumed and provide an incentive to turn off lights or appliances by showing how such a shift in behavior could positively affect the bill at the end of the month. Examples of indirect demand response techniques include real-time information displays, or distribution of real-time requests to limit energy use through instant messaging or social networking sites. With the indirect methods, it is difficult to directly relate the action to the response. (Office of Energy., 2010)

Technologies are available, and more are under development, to automate the process of demand response. Such technologies detect the need for load shedding, communicate the demand to participating users, automate load shedding, and verify compliance with demand-response programs. Grid-Wise and Energy-Web are two major federal initiatives in the United States to develop these technologies.

Some utilities are considering and testing automated systems connected to industrial, commercial and residential users that can reduce consumption at times of peak demand, essentially delaying draw marginally. Although the amount of demand delayed may be small, the consequences for the grid (including financial) may be considerable, since system stability planning often involves building capacity for extreme peak demand events, plus a margin of safety in reserve. Such events may only happen a few times per year.

The process may involve turning down or off certain appliances or sinks (and, when demand is unexpectedly low, potentially increasing usage). For example, heating may be turned down or air conditioning or refrigeration may be turned up (turning up to a higher temperature uses less electricity), delaying slightly the draw until a peak in usage has passed. (Sinitsyn et al., 2013). In the city of Toronto, certain residential users can participate in a program (Peak saver AC) whereby the system operator can automatically control hot water heaters or air conditioning during peak demand; the grid benefits by delaying peak demand (allowing peaking plants time to cycle up or avoiding peak events), and the participant benefits by delaying consumption until after peak demand periods, when pricing should be lower. Although this is an experimental program, at scale these solutions have the potential to reduce peak demand considerably. The success of such programs depends on the development of appropriate technology, a suitable pricing system for electricity, and the cost of the underlying technology.

Other methods for implementing demand response approach the issue of tact reducing duty cycles rather than implementing thermostat setbacks. These can be implemented using customized building automation systems programming, or through swarm-logic methods coordinating multiple loads in a facility.

It was recently announced that electric refrigerators will be sold in the UK fitted with a frequency sensing device which will delay or advance the cooling cycle based on monitoring grid frequency.

2.5. Technologies for Demand Response

2.5.1. Metering

The technology available from today’s metering devices will play a key role in enabling many of the benefits of increased demand response. The traditional role of electricity meters has been to determine how much electricity consumers’ use over a long time interval; in the case of demand response, a measurement is required to determine how much electricity use has been avoided or displaced over much shorter time intervals.

Traditionally, most small customers have been provided with a basic accumulation meter that provides a single consumption figure for the period between meter readings. The liberalization of markets has seen the value of electricity captured in wholesale markets according to timed intervals, reflecting the true cost of marginal production according to such externalities as primary fuel cost, weather, and time of day. These timed intervals at the wholesale level represent the smallest unit of timed electricity that could be used for tariff or billing purposes. Support of tariffs which reflect this real-time price component, whether through time-of-use, real-time pricing or critical-peak-pricing tariffs, has placed increased demands on the metering device beyond its traditional energy billing function.

Minimum core functional requirements to enable the metering device to accommodate basic forms of price-response tariff require additional accumulating registers to record timed periods of consumption, such as peak and off-peak usage. In addition, a timing capability is required to determine start and stop times for the timed periods. This switching capability may be provided by an internal clock device or by an external source via Radio (RF), Ripple Control (PLC) or Time-switch (clock).

Meters which support functionality beyond traditional accumulation of consumption are often referred to as Advanced Meters or Interval Meters. The highest resolution of consumption recording provided by Advanced Meters is so-called interval recording, whereby data is recorded to the timed interval, typically in 15, 30 or 60 minute periods. Consumption recorded period-by-period provides a complete daily profile per consumer. Once this data has been recorded, in addition to providing a level of data resolution able to support complex price response tariffs, the profile can also be used to determine changes to, or movements away from, the baseline consumption, often used to verify performance of restriction programs. (Willis, 2010)

2.5.2. Remote Communications

Networks which support metering infrastructure are categorized as being either one-way or two-way in design. There are various design topologies delivering a range of functionalities, costs and benefits. Figure-2-2 below provides an indication of the different technical solutions implemented and available in the current market.

The design solution chosen will be governed by the application requirements and the meter reading environment. Geographic areas of high population density are typically required for fixed network infrastructure and for topologies which require data routers and concentrators. All the topologies shown below are able to support both one-way and two-way communications. One-way systems are often referred to as those that enable outgoing readings to be collected, although they can also indicate a one-way solution involving signaling a price or rate change to the end customer. Full two-way communications refer to those systems that are able to both receive and send data. (Willis, 2010)

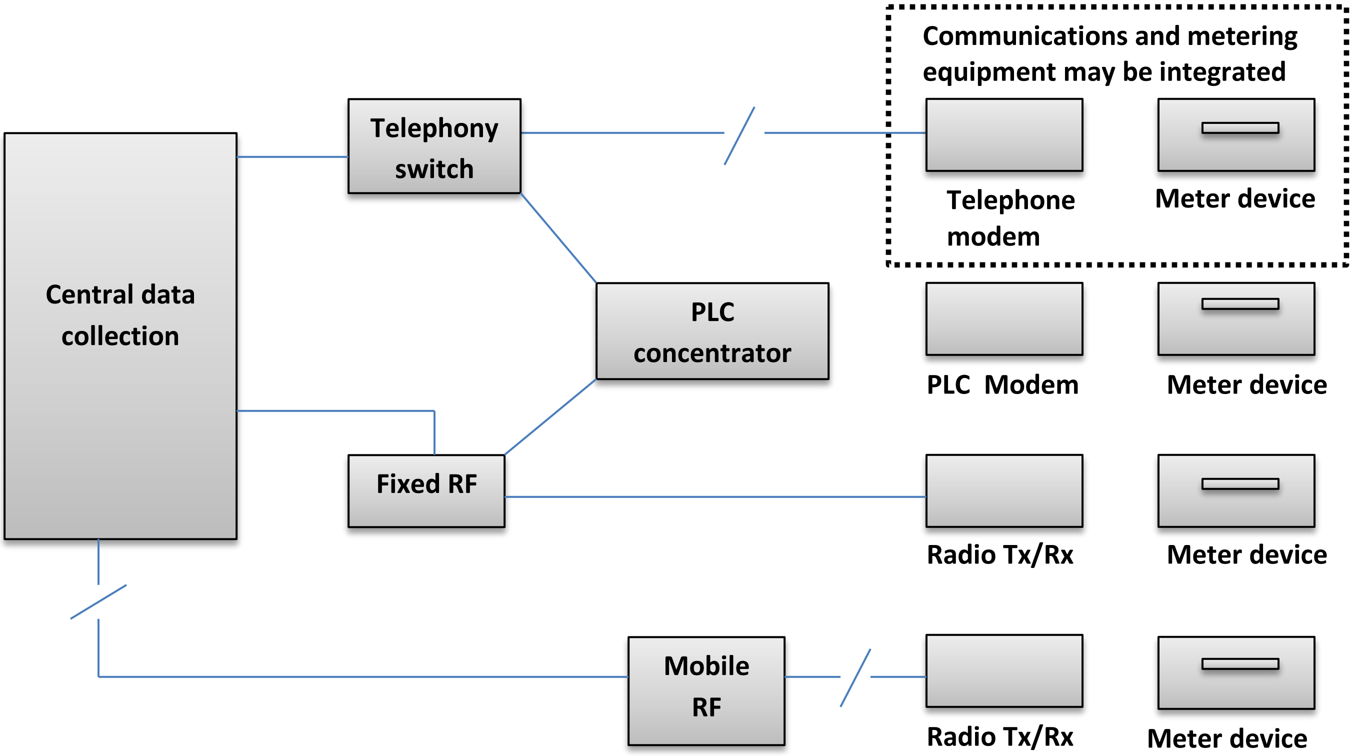


Figure-2-2: Metering and communication Topologies (Willis, 2010)

Automatic Meter Reading (AMR) has been the term traditionally used to represent metering solutions which incorporate a communications solution and whose prime function is to replace manual meter reading. The acronym itself, which remains widely used within Organization for Economic Cooperation and Development (OECD) markets, suggests that the real benefits of communications are directed to the meter reading function – principally for utility cost saving. Automatic Meter Reading technologies have achieved little penetration in most OECD liberalized markets, but have seen significant recent growth in the United

States market as shown in Table-2-1. This is for the most part accounted for by the fact that the economic justification for Automatic Meter Reading investments was based upon obviating the need to manually read meters, and in the United States utilities read meters more frequently76 than in many other OECD markets.

Table-2-1: US AMR Shipments Forecast (Frost et al., 2003)

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Optimistic Outlook	1757	1146	2320	2311	2375	3064	3308	3330	3319	3494	3703	3934
Current Outlook	1757	1146	2320	2311	1884	2130	1947	1988	2080	2124	2182	2248

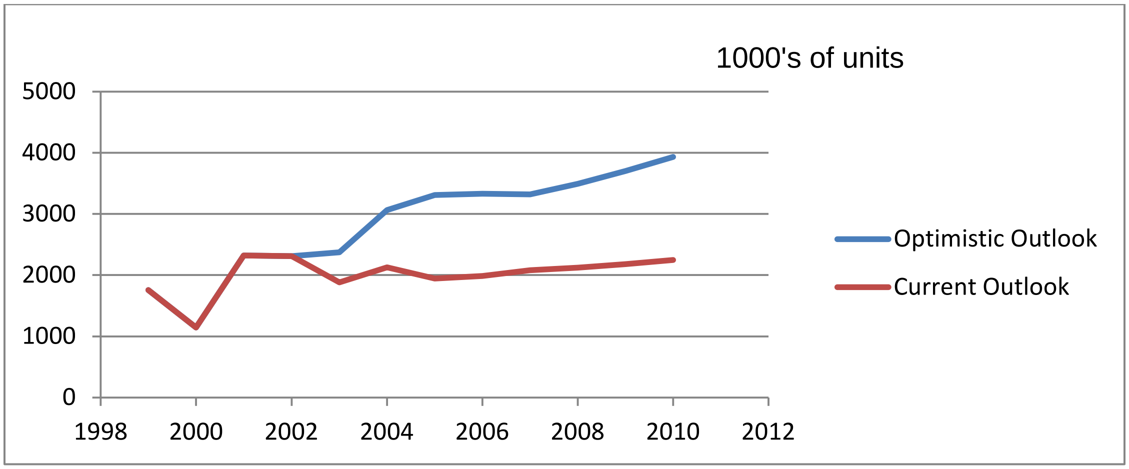


Figure-2-3: US AMR Shipment Forecast (Frost et al., 2003)

The detailed study of the United States Automatic Meter Reading market illustrated above considers an optimistic outlook for growth of traditional Automatic Meter Reading contingent on:

- Federal tax incentives for technology investment will be included in a Federal energy bill.
- Utilities achieve expected improvements in their balance sheets.
- The technical success of pilot test either underway or planned within forecast period.
- Benefit analysis of pilot test either underway or planned within forecast period;
- SMD (Standard Market Design) is implemented by (Federal Energy Regulatory Commission (FERC).
- Higher wholesale electric prices.

Communication links and Automatic Meter Reading technologies provide the capability to automate and add value to traditional utility metering functions such as meter reading, field operations, billing and customer services. These same metering systems can provide customers with both the capability to interrogate and read meter information on demand, and to receive up-to-date energy pricing. More significantly, interval metering combined with integrated communications enables fully flexible information architecture capable of delivering a full range of demand response options. (Ellens, Berry, & West, 2012)

A brief summary of the usual communications technologies is presented below:

2.5.2.1. Internet

The growth and availability of the Internet as a technology will probably have the greatest impact on the commercial viability of demand response technologies. Systems are now available which enable the connection of consumers and aggregators with Independent System Operators and with retailers. The common language of the Internet and its ability to remotely serve applications will enable software suppliers to distribute control, measurement and settlements software directly through the consumers' browser.

2.5.2.2. Power Line Carrier (PLC)

Power Line Carrier systems used for utility applications are typically low bandwidth devices capable of utilizing existing in-home wiring networks, providing two-way communications of metering and related control data. Whilst the signaling technique has the advantage of not requiring the installation of a local area network (LAN), the wide area network (WAN) signaling between the host utility and the consumer does require access to the network infrastructure. Most metering commercial Power Line Carrier metering systems operate without using the high and medium voltage network for Wide Area Network Power Line

Carrier communications. Instead they use data concentrators connected to utility systems by means of remote telephony or existing utility communications infrastructure.

As well as providing remote two-way communications, the system will support in-home communications, and appliance control and monitoring. The meters also provide functionality for remote meter reading and are capable of supporting full time-of-use tariffs.

2.5.2.3.Telephone and Cellular

Telephony services have long been used as a means of remote collection of metering data, making use of existing infrastructure and commercial and communication technology. The growth of telephony and cellular metering applications is linked to the commercial viability of network access provided by the local telephone operator. Some OECD telephony markets have developed specific tariffs for use by metering applications, which enable low-cost calling during defined timing windows.

There has been a recent growth in remote telephony applications including both cellular data calling and digital messaging. These systems typically have low bandwidths and relatively high costs, although they have the advantage of not requiring additional infrastructure investment beyond the metering end-point.

Telephony systems are traditionally one-way, whereby the reading agency will dial up the end device to collect metering data. Depending on the line-sharing arrangements of the local service provider, there are advanced metering devices that have the capability to dial out (initiate the call), functionality which can be used both to deliver meter readings and potentially to provide a confirmation of load reduction actions.

2.5.2.4. Radio Frequency (RF) – Fixed Network

The costs per point, or node, of fixed radio systems are dependent on a number of factors: the number of customers connected to the system; the geographic density of the customers; the topology of the area (which affects the propagation of the radio waves) and the location of meters (indoors vs. outdoors). Furthermore, fixed-radio networks are more economically-efficient when all (or almost all) the customers in a particular area are served by the same infrastructure. These radio systems are typically owned and operated by third-party vendors, which sell the service to utilities on a dollar-per-meter-month basis. The costs vary from about $1 to $5/meter-month, depending on the frequency of meter reading and the amount of data transferred. (Lefebvre et al., 2008)

2.5.2.5. Radio Frequency (RF) – Mobile / Drive-By

Drive-by metering systems use low-power radio signals to transmit meter data to walk-by or drive-by receivers. Such systems are used to reduce operational costs associated with meter reading. Radio modules can be either retrofitted to existing meters or installed into traditional electricity meters at manufacture.

2.5.3. Control Technologies

The function of the control equipment is to effect the necessary change in electricity consumption in response to a demand signal. In this role, control equipment is used to switch on and off the relevant electrical load to execute an agreed load reduction or to provide an automated consumer response to a pre-determined price threshold. The major differences between the various control products relate to the speed or notice required for switching, and whether the process control is manual or automatic.

In the case of rapid response, the control technology is usually fully automatic. For example, for frequency control, load is switched off when an automatic frequency relay detects a change in frequency of a fixed amount. Control to switch the process back on may also be automatic, or it may be manual, activated upon delivery of notification that the process can be restored. Advanced process control technologies may also be required to determine the optimal schedule of loads to deliver the agreed load reduction and still give satisfactory performance of the process.

Consumer control technologies represent the point of intervention between the end user and the demand response service provider. For larger industrial and commercial customers demand response event notification may be provided utilizing existing pathways such as email, cellular telephone and paging devices. (Goldman, Kintner-Meyer, & Heffner, 2002)

2.6. Technology Applications

2.6.1. System and Transmission Operators

Transmission or systems operators at either the local retail level or the national transmission level are required to perform complex load scheduling and dispatch functions to ensure the reliability and security of supply. In traditional electricity markets this process has been developed almost exclusively with supply-side resources, with a consequent focus on generation performance characteristics as illustrated in Table 2-2. (Willis, 2010)

Direct consumer access to network markets for ancillary or congestion relief services is often effectively prevented by service requirements that have been designed for traditional supply side resources: a requirement for scaled loads, with system-operator-specified minimum contract positions often starting at around 5 MW of service capacity, and further standards set for such parameters as response time, ramp rates and minimum/maximum load cycles(Willis, 2010).

Table-2-2: Characteristics of Supply Side Resources (Willis, 2010)

Reliability Resources	**Traditional Supply Side Resources**
Fast Reserve	Partially loaded thermal plant Hydro Electric (Inc. Pumped Storage) Peaking Plant Renewables Plants
Standing Reserve	Stand-by Generation (Uneconomical base load plant) Peaking Plant
Voltage/Frequency Response	Synchronous Generators / Compensators Capacitors and Inductors Transformers (Tap Changers and Voltage Boosters)

Dispatchable generator metering and communications equipment consistent with the resources shown in the table above will be specified to supply the Independent System Operator with output data in the order of seconds. This requirement is consistent with the security of supply objectives of the system operator, since the loss of one large generator must be compensated for immediately. It follows that since virtually all loads are small compared to generators, the statistical averaging across loads greatly reduces the need to closely monitor any one individual load.

To establish demand resources on an equal footing with supply side resources at the control desk of network operators would require high degrees of process – and technology-integration. In the United Kingdom, the National Grid Company typically issues in excess of 500 instructions a day to market participants to balance supply and demand on a second by- second basis. Network operators often use technical standards and dispatch control technologies and software, which have been developed and refined over the course many years of market operation.

In this situation, only very large individual consumers will have the required resources to perform the necessary technology assessments and investments to enable direct participation in Independent System Operator markets. It therefore follows that the effective integration of smaller demand resources in the delivery of network operation services will only become feasible when an intermediary has a scale of aggregated response to justify such investments.

Whilst the emergence of such aggregators is feasible, it is becoming clear that there may not be enough “critical mass” representation from the demand-side to support and sustain such initiatives, at least without stronger incentives for such representation. Network operators may be willing to adapt and modify their control and technology requirements; however, greater demand will be required from consumers to drive such change. Regulators and public bodies should give consideration to the formation of research programs to consider the potential for increased demand side participation, and particularly to consider the potential to adapt Independent System Operator systems to specific demand-side practices and technical approaches.(Willis, 2010)

2.6.2. Commercial and Industrial Technologies

Advanced metering is often a mandatory requirement for large commercial and industrial loads to enable, or make eligible, a load to participate in a demand response program. In part this is due to the need for accuracy in the amount and value of net demand reductions.

Direct load programs are usually those that need some form of signal sent from either the market operator or an intermediary to the demand resource, to request a demand side load reduction. The loads concerned will vary considerably by OECD markets, where heating and cooling load requirements especially vary according to local climate and economic conditions. Detailed analysis of specific load types is a critical step in selecting technology according to the potential for demand reduction.

For larger commercial and industrial customers, utility interfaces are often centered on traditional Buildings Energy Management Systems (BEMS) and more and more on internet-served energy management applications. BEMS technologies are implemented to provide in-building and process efficiencies and as such are synergistic with the objectives of both system-led and market-led response programs. Furthermore, as the potential for load control emerged as a market resource, a new market emerged for instantaneous power monitoring and recording, with low cost devices for on-site and load management being introduced. Under load participation programs, the requirements for accurate settlement and performance measurement has increased the accuracy and security requirements of these monitoring and measurement devices in order to match on-site control with billed or contracted data.

The emergence of the internet in OECD markets during the 1990s provided a significant spur to automation technologies, providing a stimulus to lighting, heating, cooling and motive power equipment manufacturers. Increasing standardization of information exchanges, using XML and Microsoft Net standards, has provided increased opportunities for technology developers to connect consumers' loads to commercial and industrial BEMS and with utility control and billing systems. (Willis, 2010)

2.6.3. Residential Technologies

Because of the relatively small amounts of energy and capacity used at residential loads, installed technology is required to serve the consumer in a non-intrusive manner. For this reason technologies usually serve two primary applications:

- Delivery of real-time pricing/time-of-use functionality.
- Control of heating/cooling/lighting and other application loads (swimming pools, irrigation systems, etc.).

Neither application requires automatic control, although residential demand response programs on offer today are able to deliver this if required.

The Advanced Energy Management program architecture (Figure-2-4) includes of a Main gate System local area network which is used to receive pricing signals, to alert the consumer and to automate control of end uses according to pre-programmed customer preferences. The wide area network includes of a switched telephone uplink, to retrieve billing information, and a Very High Frequency (VHF) paging link to transmit pricing signals to the consumer and the LAN.(Willis, 2010)

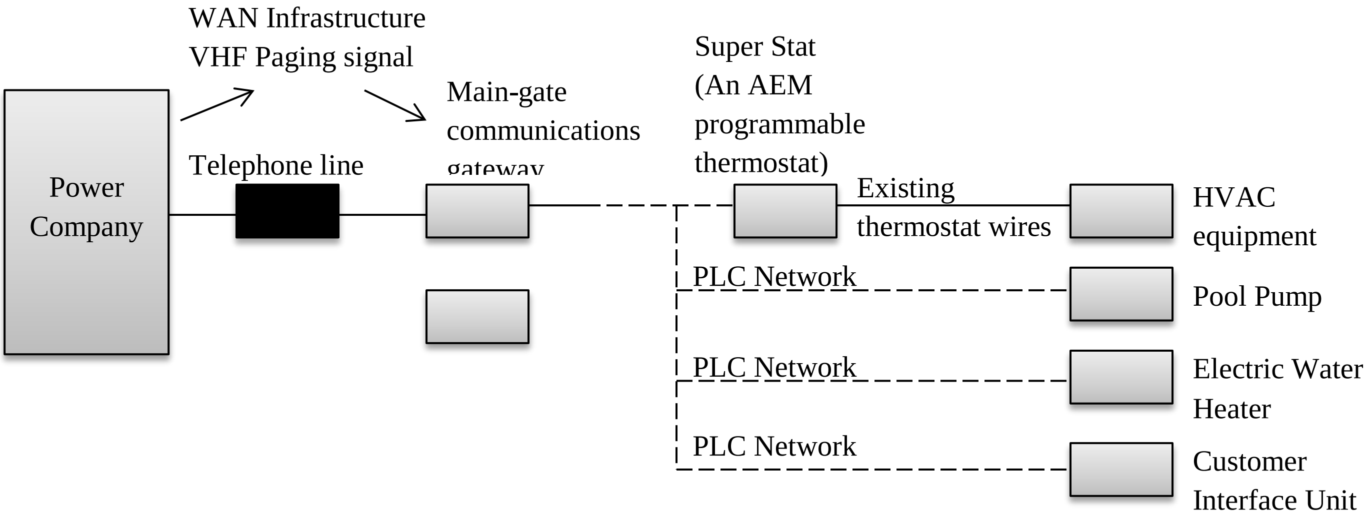


Figure-2-4: Residential Automation for Real-Time Pricing (Willis, 2010)

Chapter 3:

Conservation Voltage Reduction

(CVR)

3.1. CVR Definition

CVR (also known as Voltage Optimization), is one of the ways for Energy Conservation through Dynamic Voltage Management.

According to the US Department of Energy, because of inefficiencies in the electrical grid, up to 67% of energy used to create electricity is wasted by the time the consumer uses the electricity. Conservation Voltage Regulation (CVR) or Voltage Optimization (VO) is a technique for improving the efficiency of the electrical grid by optimizing voltage on the feeder lines that run from substations to homes and businesses. Utilities have been experimenting with CVR for over 30 years. Although it was partially implemented in California in 1977, CVR has not been widely implemented because of high costs and technical limitations. In the past, broad implementation of CVR would require extensive additions to the utility infrastructure, adding many substations and shortening feeder lines. New technologies enable CVR to be implemented easily and economically.

CVR is not a new energy conservation measure; tests have been performed as early as in 1973. However, recent developments in the field of smart grids have drawn new attention to CVR, now also called voltage optimization.

Integrated Volt-Var Control (also known as Volt-Var management), which is an important feature of the future grid, enables the application of CVR. Traditionally, the substation voltage is set to the maximum allowed voltage in order to guarantee a minimum voltage level to customers at the end of the distribution lines. In future energy networks, it will be possible to control the voltage level along the distribution lines in order to supply all customers with approximately the same voltage, such that low-voltage substations can operate close to the minimum voltage level, without exposing customers at the end of the lines to under-voltage conditions.

In the US, regulations require that voltage be made available to consumers at 120V +/- 5% – which yields a range of 126V to 114V (European Standards: 230V +/- 10%). On any feeder line, especially those are over three miles length, voltage on the line gradually decreases as the cumulative load (number of customers) on the line increases. This is called "line drop." Because of line drop, power must be transmitted at a high enough voltage that the last customer on the end of the line gets at least 114V. So, power is often transmitted from the substation at 126V. US homes receive an average of 122.5V, with approximately 90% of homes and businesses receiving more voltage than they need.

The objective of CVR is to have the customer's utilization voltage at the lowest level consistent with proper operation of equipment, within nameplate ratings of utilization equipment and within levels set by regulatory agencies and standards setting organizations. American National Standards Institute (ANSI) Standard

C84.1 sets the range for voltages at the distribution transformer secondary terminals at 120 volts +/- 5% or between 114 volts and 126 volts.

3.2. The Effects of Conservation Voltage Reduction (Ellens et al., 2012)

Assuming that household devices require no reactive power, the effect of CVR on energy consumption can be explained as follows. By Joule's law, the power P, voltage V and current I in a resistive circuit satisfy P = VI. It follows from Ohm's Law V = I R that lowering the voltage level reduces the power when the load consists of pure resistors with constant resistance R, because in that case we have $P = V^2/ R$. In reality, this is true if loads are constant-resistance (hot water system, fridge, oven, incandescent lighting, pool pump, etc.), but not if loads are constant-power (computer, TV, etc.). If we have constant-power loads, dropping the voltage will mean that the current has to increase, which leads to higher energy loss in the lines, according to the power loss formula $P_{\mathrm{Lines}} = I^2 R_{\mathrm{Lines}}$. Also, many constant-resistance devices (hot-water system, fridge, oven, etc.) have a feedback loop - mostly measuring the temperature - that extends the operating time, leading to constant energy consumption (the energy consumption U satisfies U=PT, where T is the duration of the power consumption). Some lighting technologies (compact fluorescent lighting) keep the current constant. The power consumption of these devices decreases linearly with the voltage according to P=VI. The savings are therefore smaller than for constant-resistance devices, for which the power consumption is quadratic in V. Because CVR effectiveness depends on the type of device, we categorize electrical devices into four load categories:

1) Constant-resistance loads without a feedback loop, which we call constant-resistance loads, reduce the energy consumption for both the loads and the lines;

2) Constant-resistance loads with a feedback loop, which we call constant-energy loads, have a constant energy consumption (for time-scales that are longer than the duration of the feedback loop);

3) Constant-power loads increase the energy consumption, because of increasing line losses due to increased current draw caused by the lowered voltage.

4) Constant-current loads reduce the energy consumption for the loads.

Table-3-1 lists some experimental results in the US. The list shows that CVR savings for residential areas are usually 0.6% to 0.8% for each percent of voltage reduction, the savings being higher for commercial areas and lower for industrial areas. The average savings across the three market sectors are approximately 0.6%.The experimentally determined CVR factors (relative savings per 1 % voltage reduction) differ significantly from utility to utility. Therefore most utilities feel that another utility's voltage regulation results are not necessarily transferable to their own service territory. Although the need for models assessing the factors that determine CVR effectiveness is clear, no such models have been found in the literature.

Table-3-1: Results of CVR tests in terms of the CVR factor (Relative energy saving per percent of voltage reduction) (Ellens et al., 2012)

Year	Source	Residential	Commercial	Industrial	Overall
1973	(Preiss & Warnock, 1978)	0.61 %	0.89 %	0.35 %	0.62 %
1977	(Kirshner & Giorsetto, 1984)	0.76 %	0.99 %	0.41 %	
1979	(Warnock & Kirkpatrick, 1986)	0.73%	0.84 %	0.49 %	0.71 %
1989	(Kennedy & Fletcher, 1991)				0.62 %

3.3. CVR's Benefits

CVR lowers the voltage at which electrical power is delivered and yields on average, a 1% energy savings for each 1% in voltage reduction down to 114V. Electrical equipment, including air conditioning, refrigeration, appliances and lighting is designed to operate most efficiently at 114V. If power is delivered at a voltage higher than 114V, energy is wasted. Higher necessary voltage also shortens the useful life of many types of equipment, since the extra energy is degenerate as heat.

Delivering voltages at the optimal levels reduces consumption, improves service quality and extends the life of equipment. Utilities and consumers save energy and lower operating costs by reducing the need to generate additional energy at power plants.

CVR also helps to lower greenhouse gas emissions; CVR is expected to have considerable environmental benefits, because the reduction of the energy consumption will lead to fewer CO2 emissions associated with energy production.

Besides the obvious advantages of energy conservation, there are other benefits of CVR and of AVC based CVR. One advantage to utility customers is that incandescent lamps and electric hot water heater elements will have a longer life. It is not uncommon to have incandescent lamps and hot water heater elements fail well before their rated lifetime hours.

Electrical energy is saved through reduced distribution system losses due to the lower voltage.

Consumers benefit through lower energy bills, and quicker response to power outage.

Utilities benefit through lower losses, longer transformer life and increased knowledge of their system’s current condition. Operating costs are reduced during outages due to a better understanding of the fault location. The information provided can form the basis of a predictive maintenance system.

Utilities may control the amount of conservation and demand by quickly adjusting set points from the Master station. (T. Wilson, 2002)

3.4. Conservation Voltage Reduction Strategies

Historically CVR has been implemented using two different strategies (De Steese, Merrick, & Kennedy, 1990). The first method is Line Drop Compensation (LDC) and the second is Voltage Spread Reduction (VSR). In LDC a distribution feeder is modeled and the Load Tap Changer (LTC) controls or voltage regulator controls are set so that the end of line voltage remains at 114 volts while the source voltage will be adjusted as the load varies. With VSR the voltage limits are narrowed from the +/-5% range to something less, typically +/-2.5% using the regulator or LTC controls. This usually requires enhancements to the distribution lines such as load balancing, reconductoring, and addition of capacitors.

Utility engineers tend to be conservative and because of changes from light load hours (LLH) to heavy load hours (HLH), the LDC settings or voltage bandwidth settings on distribution LTCs or regulators are often made very conservatively to assure that the end of the line voltage never droops below a preset value. In addition, daily changes in temperature, day-of-the-week, etc. can lead to load changes that reduce the effectiveness of CVR settings.

In fact, in many utilities the distribution LTC or regulator controls are set so that the nearest customer never has voltages above 126 volts and the end of line voltage drops and rises as loads vary. The reasons for this are many. Lack of engineering resources to perform the required studies or prepare the distribution line models design the line upgrades are often a major reason. Another is the lack of capital resources or the inability to justify the capital and expenses needed to upgrade distribution.

A third strategy is to regulate the voltage at the customer's meter and the utility does not need to try to set controls for CVR. There is at least one company that is manufacturing a device that is installed at the customers meter and will regulate the voltage at the lower level within the customer's premises. A drawback to this strategy is that it depends on the customers to install equipment on their site and to pay the capital costs. Additionally, it does not have the benefit of less distribution transformer iron loss (iron loss in transformers is a function of transformer voltage) nor does it provide quite as much energy savings for line losses.

A fourth strategy is to use an Adaptive Voltage Control (AVC) system to implement CVR. This strategy makes use of new automatic control and communications technologies that were unavailable at the time of earlier CVR efforts. (T. Wilson, 2002)

3.5. Effects of Capacitors on CVR

Capacitors reduce the kVAR demand on the system, and since the total kVA demand consists of a real and reactive component, the capacitors provide the needed kVAR to the loads rather than the reactive power coming from the source and flowing through the distribution lines. Load amps are a function of the total kVA, and reducing the kVAR reduces the kVA, thus reducing the amount of current and line losses. Losses are function of current squared, so that is another important benefit of using capacitors to deliver kVAR to loads rather than from the generation source.

In addition to reducing the amount of line losses, capacitors help to increase line voltage delivered to the end-use consumer. Obviously this can cause an adverse effect during periods of full CVR implementation since capacitors raise line voltage. The voltage drop through the line is a function of the voltage drop through the line resistance as well as the drop through the line reactance,

$V = I.R.Cosø + I.X.Sinø$. So reducing the line current will reduce the voltage drop, or conversely stated will increase the voltage utilized at the loads.

Care should be taken when deciding how many capacitors should be turned on or off during times of running CVR on the system.

3.6. CVR Factor

The CVR factor is a measure of how effective voltage reduction is from an energy and demand standpoint. It is simply the ratio between the percent demand (Or energy) and voltage:

(3-1) $$\text{CVR Factor} = \frac{\%\text{demand reduction}}{\%\text{voltage reduction}}$$

It is the term commonly used to refer to the ratio between voltage reduction and energy load consumption for a particular part of a distribution system (load, feeder, substation, or utility).

The CVR factor is a measure of how effectively voltage reductions can be converted to calculate energy savings or reactive power savings. Mathematically, CVR factor can be calculated as shown in equations (3-2) and (3-3): (Singh, Tuffner, Fuller, & Schneider, 2011)

(3-2) $$\text{CVR fACTOR}_{\text{Real}} = \frac{\%\text{kWh Savings}}{\%\text{Voltage Reduction}}$$

(3-3) $$\text{CVR fACTOR}_{\text{Reactive}} = \frac{\%\text{kVAR Savings}}{\%\text{Voltage Reduction}}$$

CVR factor is also occasionally expressed as the change in kilowatts or kVAR divided by the change in volts to show a reduction in peak demand.

Factors vary widely from substation to substation, feeder to feeder, and especially load to load. Contributions to the overall factor for a utility include consumers' load mix, transformer and conductor characteristics, and voltage control schemes as moderated by voltage regulators, line drop compensators, and switched capacitor banks. Because of the large number of components involved, CVR factors for feeders and substations typically are measured experimentally, not theoretically generated.

Progress is being made in calculating CVR factors theoretically, with an eye toward predicting control scheme performance before installation. Load behavior is a large contributor to feeder CVR factor. Many load modeling studies have been completed; a good recent study is the 2010 report by the Pacific Northwest National Laboratory (PNNL), which evaluated CVR on a national level and built models that divided loads into two primary classes: those with and without thermal cycles. In the first category, lighting loads, for example, will consume energy as a function of voltage when on. In the second category, loads with thermal cycles, such as a hot water heater, will vary their duty cycles depending on the supply voltage. Moreover, inside each of these classes, loads' response can be described by their ratio of constant power, impedance and current characteristics—ZIP models. ZIP models can be constructed from experimental results on load behavior under changing voltage conditions.

3.7. Modeling Principles

To efficiently model CVR, as well as most distribution level behaviors, it is necessary to perform time series simulations. Examining the peak load behavior and concluding behavior for the rest of the year is not sufficient.

Furthermore, standard power flow solutions are insufficient for analyzing the effects of CVR. Many loads within distribution systems cannot be defined as simple constant impedance, constant current and constant power loads (ZIP). Many are thermostatically controlled, provide constant mechanical power, or draw a constant amount of energy over different time periods. To properly understand the effects of voltage reduction on the distribution system, such loads must be properly modeled. Additionally, standard distribution solvers ignore the effects of residential transformers (typically split-phase or center-tapped) and the cabling that connects the consumer to the transformer. While ignoring these components may be acceptable for traditional capacity planning studies, when studying the effects of voltage reduction, they must be included. (Willis, 2010)

3.7.1. Determination of Load Type

Load information in the original feeder models was limited. The original models limited a small amount of information on commercial loads and no information on residential loads. Loads were defined as static spot loads, where blocks of individual commercial and residential loads were summed to a single peak spot load on the primary system (no secondary voltage loads were defined). To more accurately classify the loads, Google Earth images of the feeders were located and the physical dimensions of the feeder overlaid. The loads provided by the original model were then manually classified by the type of building found at that location, and were categorized into nine different load types via visual inspection. These were classified as Residential 1-6, Commercial 1-2, and Industrial. Brief descriptions are provided in Table 3-2. Each load classification describes the properties of the load in that area. (Willis, 2010)

Table-3-2: End Use Load Classifications (Willis, 2010)

Load Class	Description
Residential 1	Pre-1980<2000 square feet
Residential 2	Pos-1980<2000 square feet
Residential 3	Pre-1980>2000 square feet
Residential 4	Pos-1980>2000 square feet
Residential 5	Mobile Homes
Residential 6	Apartment Complex
Commercial 1	>35KVA
Commercial 2	<35KVA
Industrial	All Industrial

By defining each building as older or newer, and larger or smaller, approximate physical properties for those homes could be assumed. These were then used to define multiple building models at each load location, depending upon the type of building that was found through observation in Google Earth©. Defining these properties gives insight into the benefits of voltage reduction not only at a single given load level, but as a function of seasonal and daily variations in load. Once again, while a particular building model at that location does not accurately represent a specific building in reality, the aggregate of the distribution of the buildings should approximate the response of all of the real buildings. Within each building, appliance loads were also modeled, as will be seen in the following sections. (Willis, 2010)

3.7.2. Load Models

Once each of the points of interconnection were categorized in compliance with Table-3-2, it was necessary to completely represent the load. Due to the complexity of end use load behavior, load models can be divided into two separate classes: those without thermal cycles and those with thermal cycles. Loads without thermal cycles consume energy in a time-invariant manner, with the exception of voltage variations. Specifically, there is no control feedback loop. As an example, a light bulb will consume energy when turned on, as a function of voltage, in a fixed manner. In contrast, a load with a thermal cycle, such as a hot water heater, will have a varying duty cycle dependent on the supply voltage. For example, if the supply voltage is lowered, the hot water heater will draw less instantaneous power, but it must remain on for a longer time to heat the same amount of water. (Willis, 2010)

3.7.2.1. Loads without Thermal Cycles

The traditional method for modeling a load without a thermal cycle is to use a ZIP model. The ZIP model is a load which is composed of time-invariant constant impedance (Z), constant current (I), and constant power (P) elements. Figure-3-1 shows the circuit representation of the ZIP model.

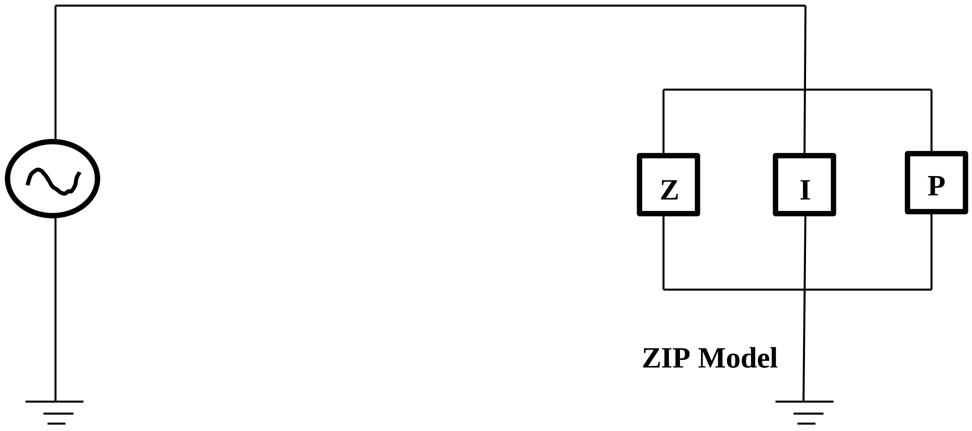


Figure-3-1: The Traditional ZIP Load Model

The total real power consumed by a ZIP load at a given voltage is shown in equations (3-4) and (3-5) gives the reactive power consumption. The values of the constants within equations (3-4) and (3-5) are limited by the constraint of equation (3-6).

(3-4): $P_i=\frac{Va^2}{Vn^2}*S_n*\text{Z}_{\%}*\text{Cos}(\text{Z}_\theta)+\frac{V_a}{V_n}*S_n*\text{I}_{\%}*\text{Cos}(\text{I}_\theta)+S_n*\text{P}_{\%}*\text{Cos}(\text{P}_\theta)$

(3-5): $Q_i=\frac{Va^2}{Vn^2}*S_n*\text{Z}_{\%}*\text{Sin}(\text{Z}_\theta)+\frac{V_a}{V_n}*S_n*\text{I}_{\%}*\text{Sin}(\text{I}_\theta)+S_n*\text{P}_{\%}*\text{Sin}(\text{P}_\theta)$

(3-6): $1=\text{Z}_{\%}+\text{I}_{\%}+\text{P}_{\%}$

Where:

Pi: Real power consumption of the i_{th} load

$\mathrm{Q_i}$: Reactive power consumption of the i_{th} load

V_a: Actual terminal voltage

V_n: Nominal terminal voltage

S_n: Apparent power consumption at nominal voltage

Z%: Fraction of load that is constant impedance

I%: Fraction of load that is constant current

P%: Fraction of load that is constant power

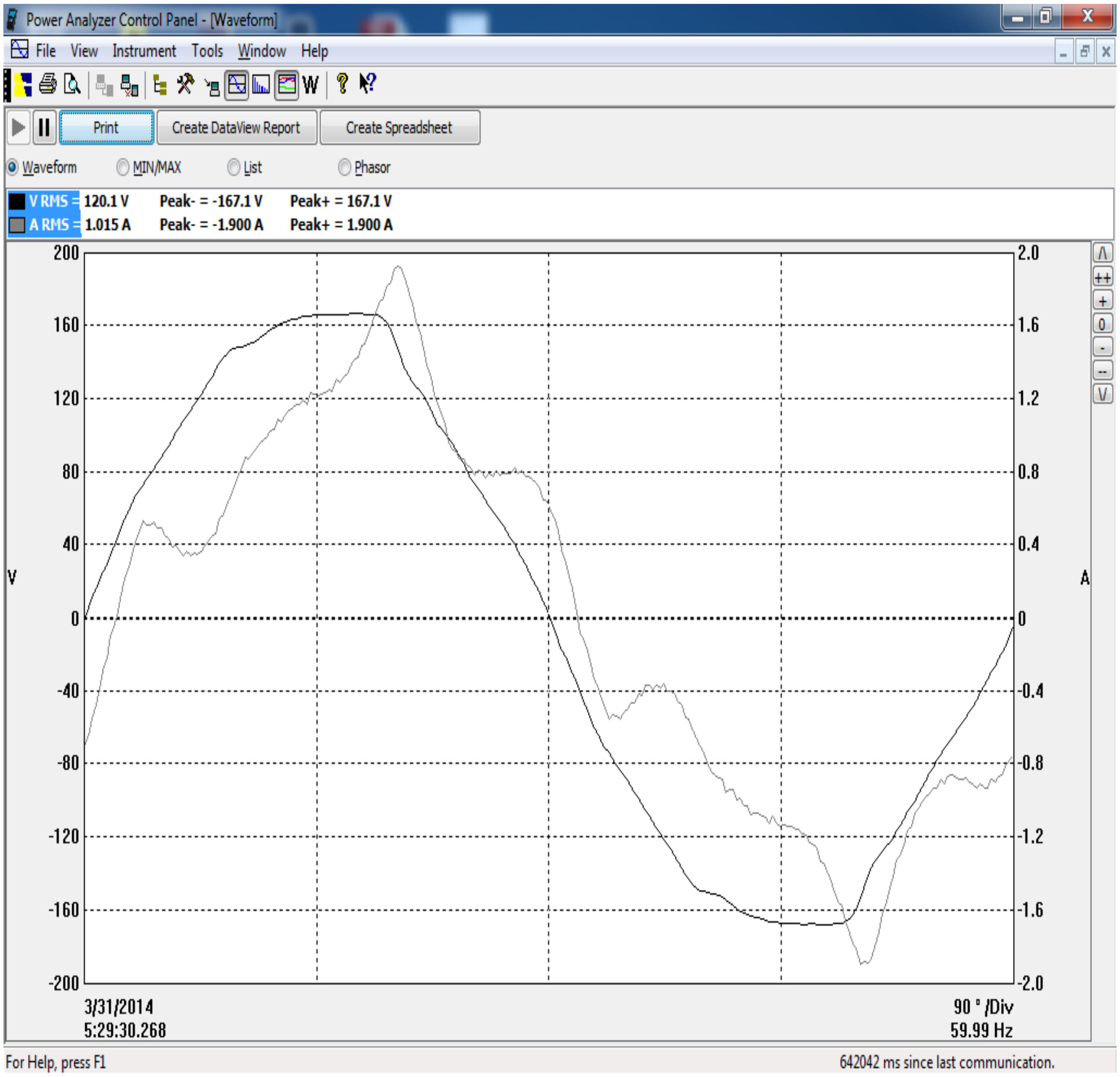
$\mathrm{Z_\theta}$: Phase angle of the constant impedance component

$\mathrm{I_\theta}$: Phase angle of the constant current component

$\mathrm{P_\theta}$: Phase angle of the constant power component

In equations (3-4) and (3-5), there are six constants that define the voltage dependent behavior of the ZIP load: Z%, I%, P%,$\mathrm{Z_\theta}$, $\mathrm{I_\theta}$ and$\mathrm{P_\theta}$. Because CVR changes the voltage of a feeder, it is critical to understand how typical end use loads will respond to changes in voltage. Specifically, what the six constants that accurately reflect various end use loads are. For loads such as a heating element, it is clear that the load is 100% Z, but for more complicated loads such as a Liquid Crystal Display (LCD) or Compact Fluorescent Light (CFL), the proper ratios are not as obvious.(Willis, 2010)

Some practical experiments which are done in UNLV power lab are shown in figure 3-2 to figure 3-6.



● Waveform ○ MIN/MAX ○ List ○ Phasor

V RMS = 120.1 V Peak- = -167.1 V Peak+ = 167.1 V

A RMS = 1.015 A Peak- = -1.900 A Peak+ = 1.900 A

3/31/2014
5:29:30.268

90 ° /Div
59.99 Hz

For Help, press F1

642042 ms since last communication.

Figure-3-2: Voltage and Current waveforms for a sample refrigerator

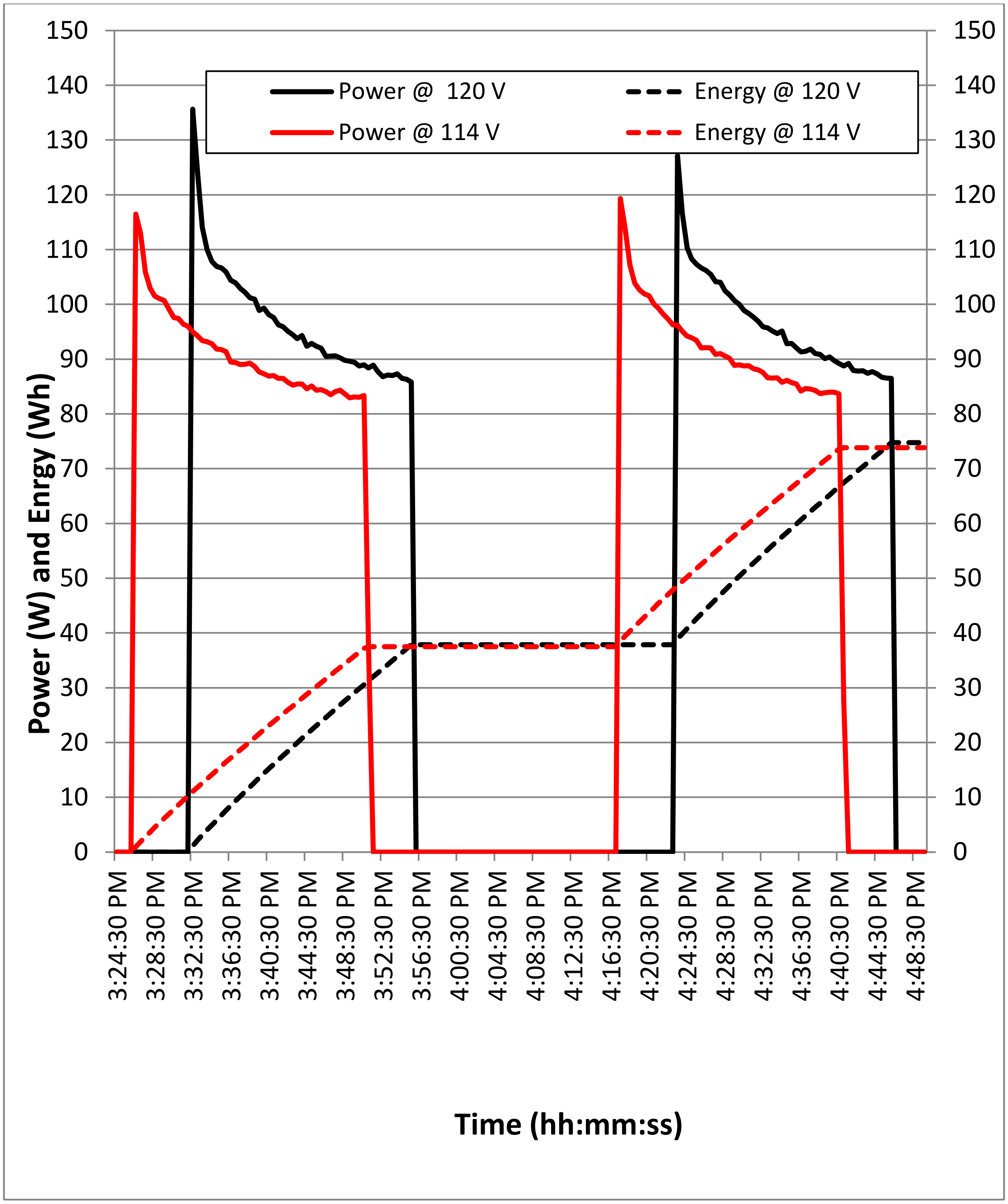


Figure-3-3: Power and Energy Graphs for a sample refrigerator

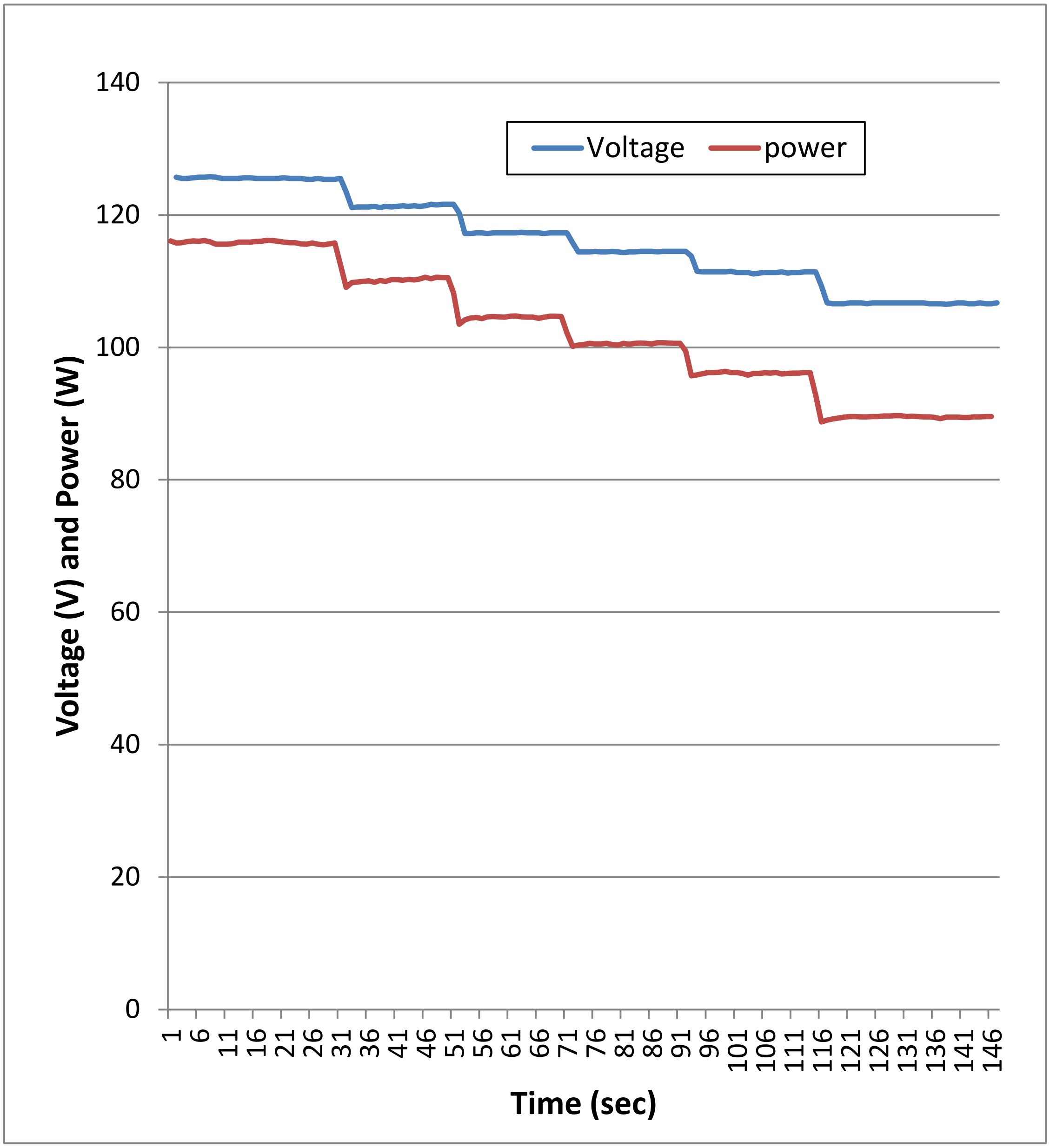


Figure-3-4: Power and Voltage Graphs for a sample Fan

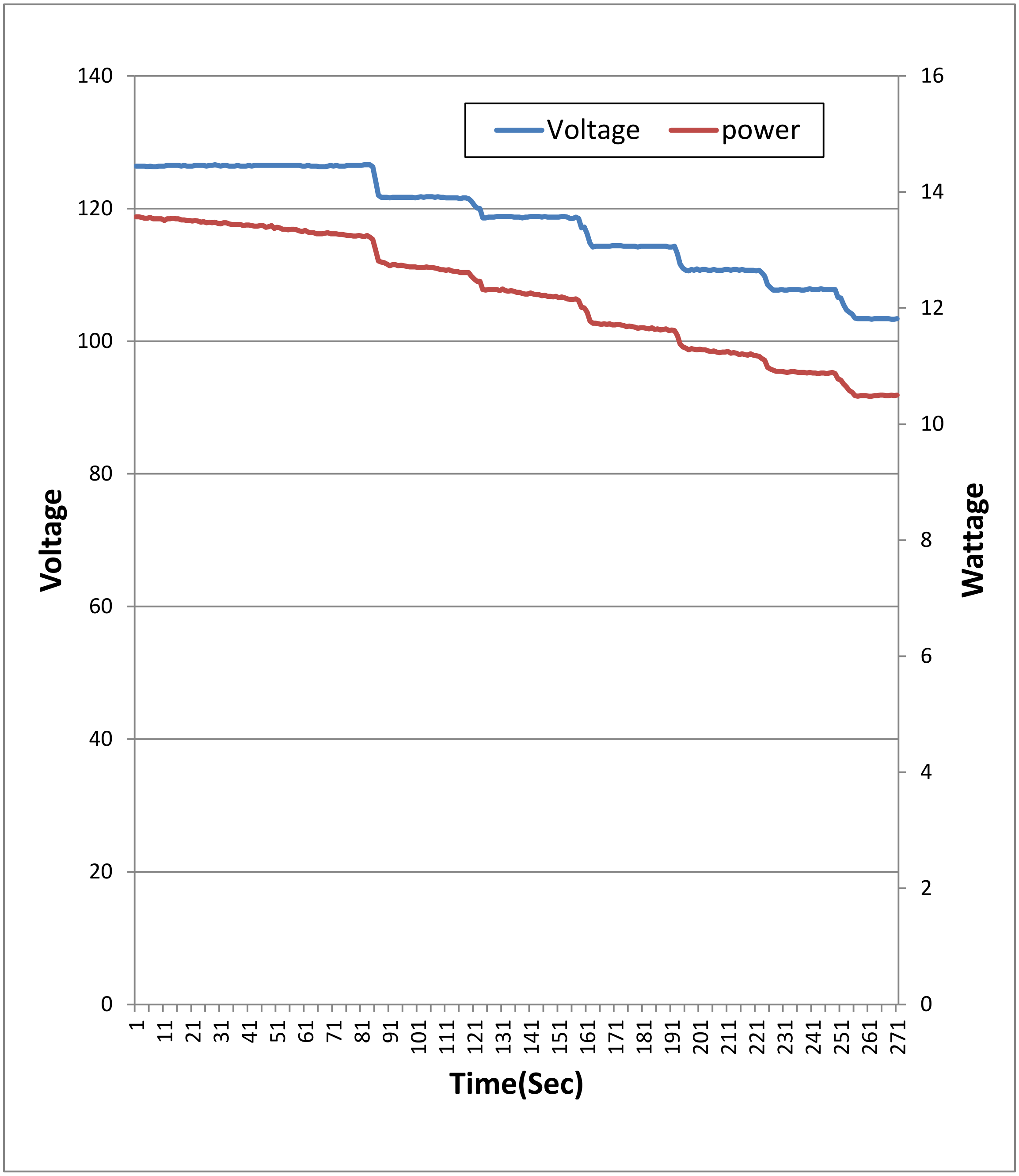


Figure-3-5: Power and Voltage Graphs for a sample Compact Fluorescent

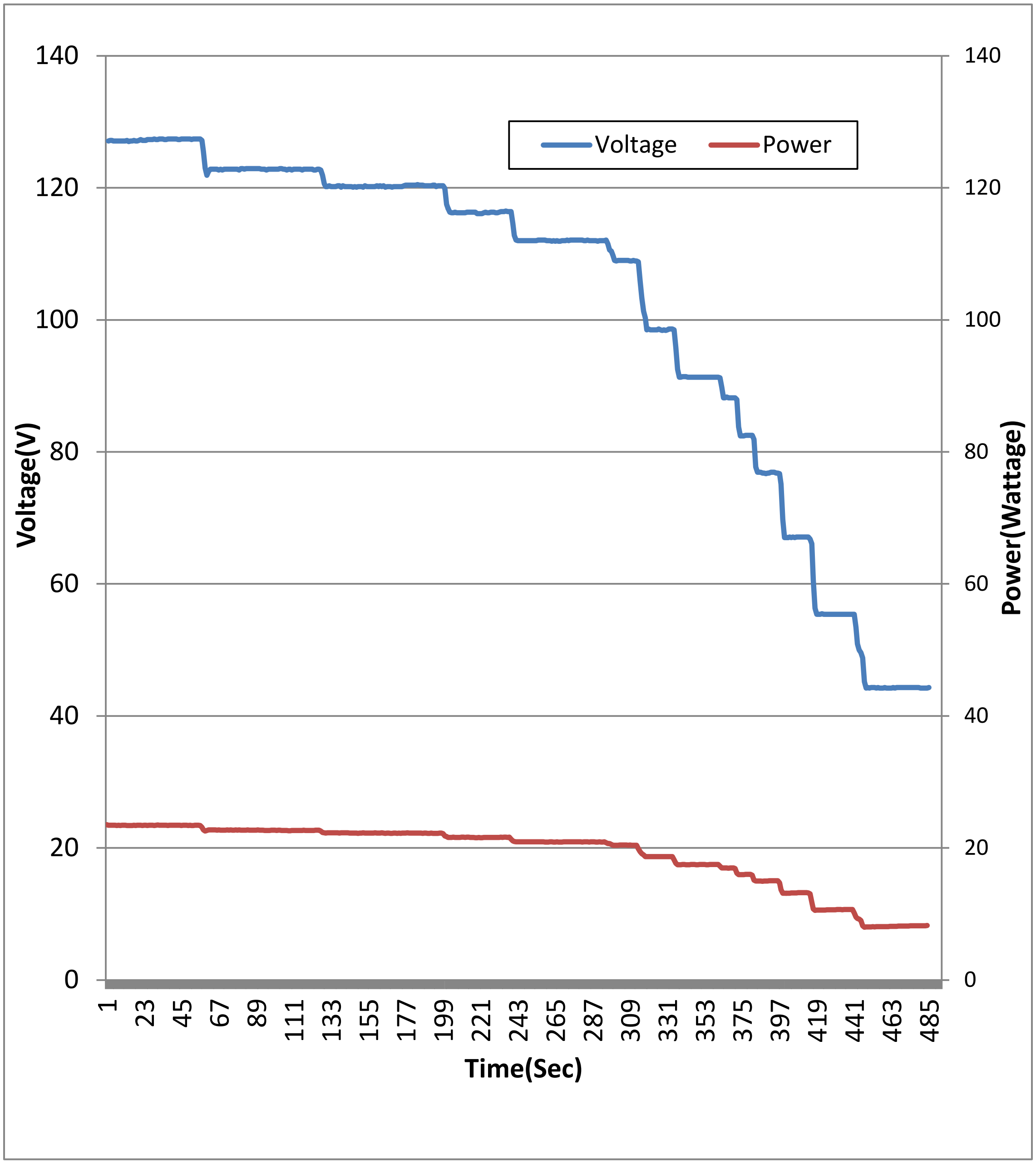


Figure-3-6: Power and Voltage Graphs for a sample Fluorescent lamp (T5)

3.7.2.2. Loads with Thermal Cycles

Whether a load has a thermal cycle or not, it must have the voltage dependent energy consumption of a ZIP loads. If the load does have a thermal cycle, there is the added complexity of an additional control loop, which determines when the load is energized, and for how long. One of the largest load types that have a thermal cycle are Heating, Ventilation, and Air Conditioning (HVAC) systems. An equivalent thermal parameter (ETP) model is used to approximate the response of the electrical demand of the HVAC system as a function of solar input, temperature, humidity, voltage, and thermostatic set points. (Sonderegger, 1978; N. Wilson, Wagner, & Colborne, 1985)The thermal parameters of the building are the mass of the building, which defines how much stored thermal energy is in the building, and the envelope, which defines how quickly the energy moves from inside to outside the building and can loosely be described as the insulation quality. These parameters are determined by the actual physical properties of the building, and include such things as floor area, ceiling height, aspect ratio, window types, air exchange rate, etc. Additionally, HVAC properties such as heating and cooling set points, heat type (gas, electric, or heat pump), fan power, motor losses, etc. can be defined. Figure-3-3 is a diagram of the ETP model for a residential HVAC system.

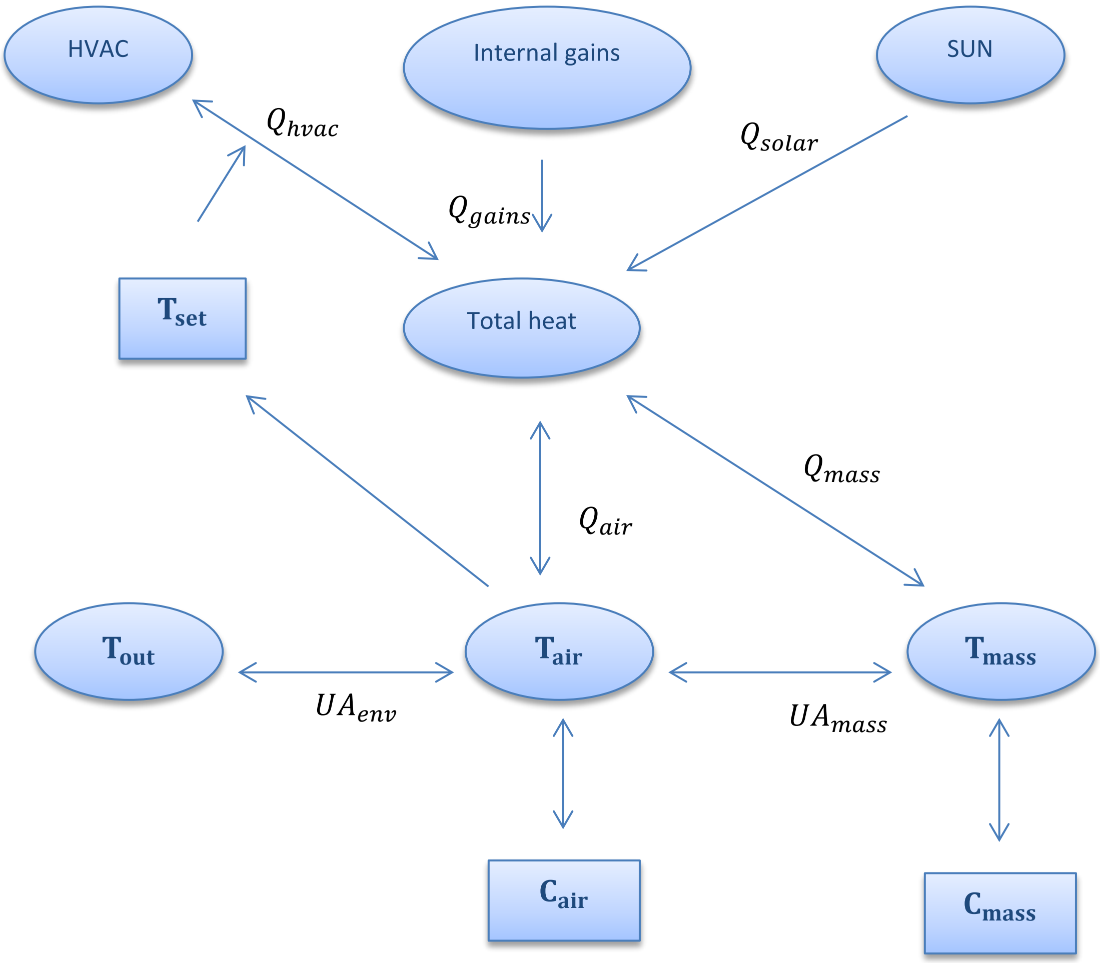


Figure-3-7: The ETP model of a residential HVAC system (Willis, 2010)

Where,

C_{air}: Air heat capacity

C_{mass}: Mass heat capacity

UA_{env}: The gain/heat loss coefficient between air and outside

UA_{mass}: The gain/heat loss coefficient between air and mass

T_{out}: Air temperature outside the house

T_{air}: Air temperature inside the house

T_{mass}: Mass temperature inside the house

T_{set}: Temperature set points of HVAC system

Q_{air}: Heat rate to house air

Q_{gains}: Heat rate from appliance waste heat

Q_{hvac}: Heat rate from HVAC

Q_{mass}: Heat rate to house mass

Q_{solar}: Heat rate from solar gains

Equations (3-7) and (3-8) are the two ordinary differential equations (ODEs) which describe the heat flows shown in Figure-3-7. These equations are used to determine the thermal behavior of the house in response to the three heat sources and the user defined thermostatic set points. The solution to equations (3-7) and (3-8) represents the thermal behavior of the house and forms the basis for determining the electrical power consumption of the HVAC system.

$$\textbf{(3-7)} \qquad \frac{\mathrm{dT_{air}}}{dt} = \frac{1}{\mathrm{C_{air}}} \left[T_{mass}\, \mathrm{U}\, A_{mass} - T_{air}(\mathrm{U}A_{env} + \mathrm{U}A_{mass}) + Q_{air} + T_{out}\, \mathrm{U}A_{env}\right]$$

$$\textbf{(3-8)} \qquad \frac{\mathrm{dT_{mass}}}{dt} = \frac{1}{\mathrm{C_{mass}}} \left[\mathrm{U}\, A_{mass}(T_{air} + T_{mass}) + Q_{mass}\right]$$

Equations (3-7) and (3-8) can also be represented by a single second order differential equation as shown in Equation (3-9).

(3-9) $$a\frac{d^2T_{air}}{dt^2}+b\frac{dT_{air}}{dt}+cT_{air}=d$$

Where:

$a = \frac{C_{mass}C_{air}}{U\,A_{mass}}$

$b = \frac{C_{mass}(UA_{env}+U\,A_{mass})}{UA_{mass}} + C_{air}$

$c = UA_{env}$

$d = Q_{mass}+Q_{air}+UA_{env}T_{out}$

3.7.3. Description of the Model

The model takes the part of the electrical network that is affected by CVR. It is part of the network which is from the low voltage substations to the consumers. The energy consumption for a given voltage level is calculated as the sum of the energy consumption of the devices. For all devices, the circuit looks like a load in series with a resistor representing the line resistance, together connected to the source voltage, with equal source voltage $V_{source}$and line resistance R_{lines} for all devices. The energy consumption of a device consists of energy consumed by the load and line losses.

3.7.3.1.Energy Consumption of Constant-Resistance Devices

The load resistance of constant-resistance devices is derived by applying the Formula (3-10) to the power consumption data:

(3-10) $$R_{load} = \frac{V_{source}^{2}}{P^{*}_{load}}$$

Where we have assumed that the nameplate power (P^{*}_{load}) is measured at a voltage of V_{source}. For constant-resistance devices the actual power consumption $\overline{P}_{load}$ at 120 V is somewhat lower than the nameplate power, because the actual voltage over the load is slightly less than 120 V (as the line resistance is non-zero). It is

(3-11) $$\overline{P}_{load} = I^{2} R_{load} = \frac{V_{source}^{2}}{R_{tot}} R_{load} = \frac{V_{source}^{2}}{(R_{load}+R_{lines})} R_{load}$$

Similarly we have for the line loss and the total power consumption:

(3-12) $$P_{lines} = \frac{V_{source}^{2}}{(R_{load}+R_{lines})} R_{lines}$$

(3-13) $$P_{tot} = \frac{V_{source}^{2}}{(R_{load}+R_{lines})}$$

The energy consumption of the load, the lines and the total energy consumption of the device are now easily calculated by multiplication by the operating time. For the standard voltage of 120 V, the calculated energy consumption of the load will be equal to the yearly energy consumption given in the data. (Ellens et al., 2012)

3.7.3.2. Energy Consumption of Constant-Energy Devices

The load consumption and line losses for constant-energy devices are easier to calculate.

For every voltage level the load consumption is equal to the yearly energy consumption in the data. The line loss can be calculated by:

(3-14) $$U_{lines} = \frac{U_{load}\ R_{lines}}{R_{load}}$$

The load resistance is derived by the nameplate power in the same way as for constant-resistance devices. (Ellens et al., 2012)

3.7.3.3. Energy Consumption of Constant-Power Devices

As for constant-energy devices, for constant-power devices the energy consumed by the load is equal to the yearly energy consumption data, regardless of the voltage level. The power consumed by the lines is:

(3-15) $$P_{lines} = I^{2}\ R_{lines} = \frac{(V_{source} - \sqrt{V_{source}^{2} - 4P_{load}R_{lines})}\ )^{2}}{4R_{lines}}$$

Where, P_{load}, is the nameplate power of the device. The line energy consumption is a product of the line power consumption and the operating time, which is simply the yearly energy consumption divided by the power consumption. (Ellens et al., 2012)

3.7.3.4. Energy Consumption of Constant-Current Devices

For constant-current devices, the current through the load and lines and the Power consumptions by the lines are constant:

(3-16) $$I = \frac{P^{*}_{load}}{V_{source}} \quad \text{and} \quad P_{lines} = I^{2}\ R_{lines}$$

The total and load power consumption are given by

(3-17) $P_{tot} = V_{source} I$ and $P_{load} = P_{tot} - P_{lines}$

The operating time of a constant-current device is calculated as follows:

(3-18) $$T = \frac{U^*_{load}}{120\,I - I^2 R_{lines}}$$

With U^*_{load} (the given yearly power consumption), which is used to find the energy consumption for the load, lines and the total energy consumption.(Ellens et al., 2012)

3.7.4. A sample load modeling project

It is a well-known fact that stable operation of a power system depends on the ability to continuously match the electrical output of generating units to the electrical load on the system. Hence, load representation is an important element in power system dynamic performance (W. Price et al., 1993; W. Price et al., 1995). Traditional load modeling concerns that dealt with the impact PF load characteristics on angular stability have been expanded to other system dynamic studies. For instance, it is found that voltage dependency of loads affect both the voltage secure operating region and rate of voltage collapse. While significant progress has been made in this field over the past two decades, a recent survey shows that nearly half of the electric utility companies are dissatisfied with their present load models and are pursuing further work.

Load representation is a complicated task because a typical load bus is composed of a large number of devices such as compressors, lamps, and electronic loads.

The exact composition is difficult to estimate since it changes continuously. Even if the exact composition is known, it is impossible to represent each individual component involved and there are uncertainties regarding to the characteristics of individual load components. Furthermore, the common practice is to represent the composite load as seen from the power substation including feeders, compensation devices and distribution transformers. Consequently, considerable simplification is necessary when deriving load models.

In the past, loads have been modeled as constant impedance, constant current, or constant power. These models, however, do not take into account the load mix, nor the short term dynamic response and the long-term effect encountered in other loads. A solution to the load mix problem is to use a combination of the three models above; namely the so-called ZIP model representing a weighted sum of constant impedance (Z), constant current (I) and constant power (P). These weights are derived using either the components-based approach or the measurement-based approach. The component-based approach involves building up a load model from detailed information on its class mix, and load components, and their characteristics in the form required for dynamic studies. LOADSYN program (W. W. Price et al., 1988) offers an automated way for developing static and dynamic models based on the above methodology.

In the measurement-based approach, load models are derived from staged tests or actual system transients (W. W. Price et al., 1988; Sabir & Lee, 1982) Ways to produce a staged voltage disturbance include changing substation transformer taps, switching station capacitors, and switching off a transformer from a parallel set. Switched feeder capacitors and voltage regulators are blocked to obtain meaningful results during the tests. The measured real and reactive powers are then fitted to polynomial expression of voltage.

This section presents the results of a load modeling where the measurement or field-test method was used to provide adequate models for local pure residential loads, combined residential/commercial, commercial/light industrial loads, industrial loads and pure commercial loads including hotel/casino loads which are unique to the State of Nevada. The voltage disturbance is caused by quickly tapping down (up) the transformer taps till the minimum (maximum) voltage limits at the feeder end are reached. One of the objectives is to find out if a small (5%) voltage change is sufficient for the load parameter estimation, and to derive these parameters if such a disturbance is sufficient.

First, a test plan and fall back procedure developed specifically for this project summarized. This is followed by the analysis of the load response of the two feeders tested at each of the following substations: Warm Spring Substation, and Quail Substation (All Tests were implemented in 1999). Static load parameters in the form of ZIP models are then derived from the recorded data using curve fitting techniques. The generic dynamic load model is also considered by examining the load recovery from the staged disturbance. As to the fast load dynamics, the slow mechanical tap changers (4-5 seconds per step and one second to change steps) did not permit the capture of such characteristics. However, noticeable load recovery in reactive power is noted in half of feeders tested even for such small voltage increments. The dynamic response is best derived from sudden a large voltage disturbance.

3.7.4.1. Test Preparation and procedure

Three of the important factors that were of concern during the testing period are listed in table-3-3 along with the corresponding preventive actions, the test preparation addressed several issues, some of which include a) selection of the feeders to be tested, b) selection of test equipment, c) types of tests to be conducted, d) transformers tap switching schedule, e) test schedule, f) detailed test procedure and Fall-back. Each of these subjects is briefly discussed below.

Table-3-3: Test Concerns and Preventive Actions

Concern	Method of Prevention
Fluctuation of the high voltage supply feeding the substation, and the natural fluctuation of the load. These variations will interfere with the load response to staged disturbance, thus the collected data will be limited use.	Pre-disturbance monitoring of load and voltage at selected feeders was planned few days before the testing date to determine the best time windows near peak load with minimal fluctuations.
Automatic switching of shunt capacitors and voltage regulators along the feeders. These switching will also affect both the real and reactive power responses.	Switched capacitors locations along each feeder were identified for locking off prior to testing. Due to their relatively short length, none of the tested feeders had voltage regulators.
Potential effects on sensitive loads and customer service. The planned voltage disturbances will affect the quality of voltage supply to all customers served by the substation under testing, which in turn might cause some electronic loads such as variable-frequency derives to trip.	Critical customers, including a fruit juice processing plant, were identified and a plan for switching them to other substation prior to testing was drafted. Customer service concerns led to limiting voltage disturbance within the limits specified by operating standards, i.e., between 114V and 126V (on 120V base) at the feeder end.

3.7.4.1.1. Selection of feeders to be tested

It is desired to test a variety of feeders serving pure residential loads, pure commercial loads, pure hotel/casino loads, combined residential/commercial loads, and combined commercial/light industrial loads, and pure industrial loads. Potential candidate feeders corresponding to each of the above load class and load mix are identified and those selected for testing are shown in table-3-4. The initial plan was to include the BMI plant at the pure industrial load, but complication were faced due to the fact that this industrial plant is supplied by Western Ares Power Administration (WAPA).

Table-3-4: Feeders Selected for Testing

Substation	Feeder #	Ref.#	Type of Load
Warm Springs	1203	WS1203	Mall (Commercial)
	1208	WS1208	Hotel/Casino
Haven	1202	H1202	Residential
Haven	1203	H1203	Commercial/Light Industrial
Quail	1210	Q1210	Residential/Commercial
Quail	1213	Q1213	Pump Load (Industrial Motor)

3.7.4.1.2. Selection of Test Recorder

The instrument should be capable of recording and storing all currents, voltages, system frequency and active and reactive powers for a sufficient length of time. Its sampling rate should be fast enough to accurately compute the RMS current and voltage at each cycle. The leading manufacturers of such instruments are Dranetz/BMI and Reliable Power Meters (RPM). The latter was chosen due to its higher data storage capability and its ability to capture all events without specifying a threshold. The recorder has a very fast sampling rate of 8 kHz. The recorder is to be installed at feeder main breaker point in the substation as shown in figure-3-8. The figure also shows the voltage monitor at the feeder end to be read by a crew member during staged voltage disturbances. Since two feeders have been selected for testing at each substation, test procedures have been set up such that testing will be conducted in parallel to conserve testing time and maximize crew utilization. Consequently, two test instruments have been leased so that two feeders can be tested simultaneously.

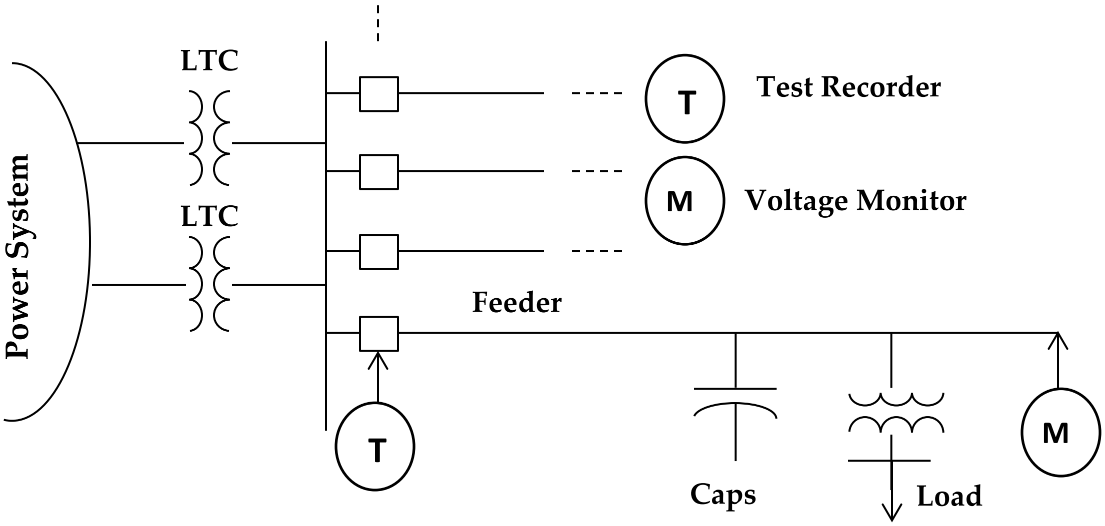


Figure-3-8: Power and Voltage Monitoring Points

3.7.4.1.3. Types of Tests to be Conducted

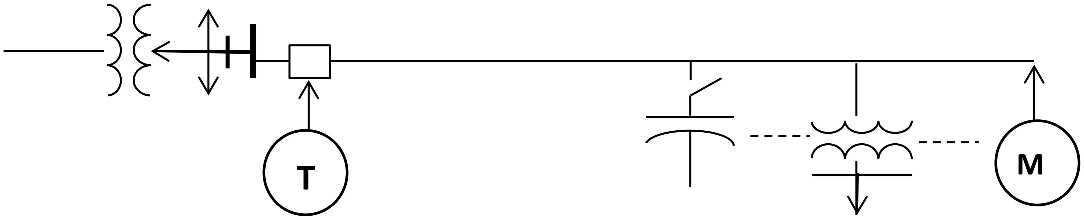
First, the pre-disturbance monitoring of load and voltage at selected feeders is to be conducted a day or two prior to the testing date in order to determine the best time window near peak load with minimal fluctuations. During the test day, load response to the following tests is to be recorded: transformer tap changing with feeder capacitors OFF, capacitors switching, and transformer tap changing with capacitors ON. These tests are summarized in table-3-5 and are illustrated by schematics in figure-3-9 below.

Switching OFF on of the parallel transformers to cause a sudden voltage disturbance was considered initially. Before the switching, the two parallel transformers should be set to different tap positions. When the transformer that gives higher secondary open circuit voltage is switched off, the secondary voltage drops to the value determined by the remaining transformer; thus a sudden voltage drop is created. This complex method of causing voltage disturbance was not experimented as it is known to lead to circulating currents that may trip proactive devices and cause a power outage.

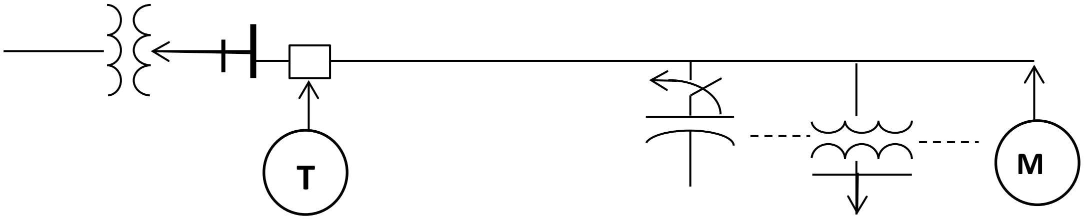
Table-3-5: Types of Tests Conducted

Test	Description
A	Base Case
B	Transformer Tap Switching with Feeder Capacitors OFF
C	Feeder Capacitor Switching
D	Transformer Tap Switching with Feeder Capacitors ON

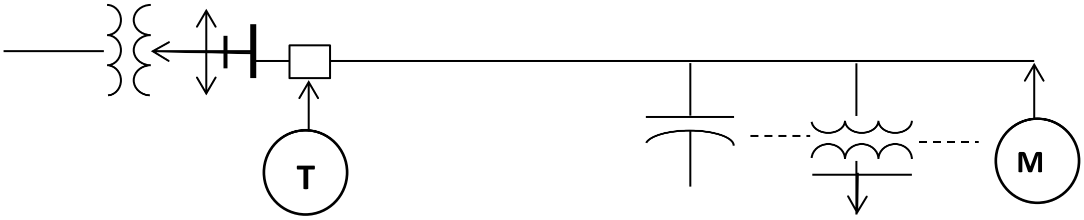
A. Pre-Test (Base Case)



B. LTC Operation w/o Caps.



C. Capacitors Switching



D. LTC Operation with Caps

Figure-3-9: Planned Test Types: (A) Base Case, (B) LTC Operation without Capacitors, (C) Capacitor Switching, (D) LTC Operation with Capacitors.

3.7.4.1.4. Transformer Tap Switching

All the 3 substations selected for the testing are supplied by two 138/12.47 kV station transformers operated in parallel, each is equipped with 32 taps. Sudden voltage changes on the secondary side are induced by simultaneous and rapid tap movement on both transformers to avoid circulating currents. A 5-minute voltage dip is initially caused, and it is followed by a voltage by a rise to the maximum value allowed under normal operating conditions. The voltage is then restored to its initial value 5 minutes later. The voltage

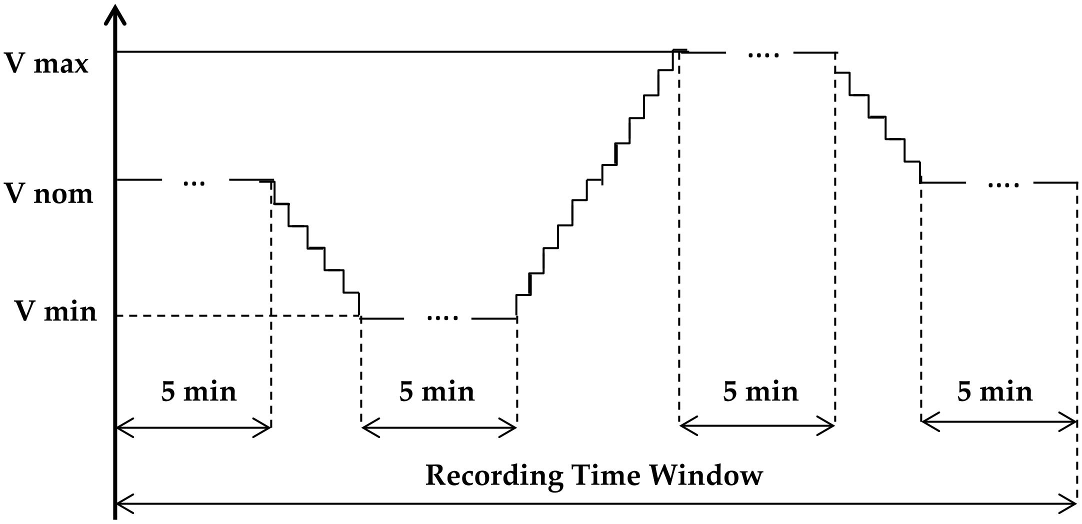


Figure-3-10: Planned Voltage Disturbance by Transformer Tap Changing

3.7.4.2. Load Modeling

Load models are classified into two broad categories: static models and dynamic models. A static load model expresses the characteristics of the load at any instant of time as an algebraic function of the bus voltage magnitude and frequency (the active and reactive powers are considered separately). The dynamic load, on the other hand, represents the load components that respond to disturbances dynamically, i.e., responses to disturbances do not occur instantly but require some time. Depending on the nature of the disturbances and the purpose of the study, the dynamics with a certain range of response times become more important.

3.7.4.2.1. Static Load Model

Traditionally, the voltage dependency of load characteristics has been represented by the exponential model

(3-19) $P = P_0(\frac{V}{V_0})^{\alpha}$

(3-20) $Q = Q_0(\frac{V}{V_0})^{\beta}$

Where, the subscript "0" identifies the values of the respective variables at the initial operating condition. For composite system loads, the exponents α and β typically vary between 0.5 -1.8 and 1.5 -6.0, respectively (Kundur, Balu, & Lauby, 1994)

An alternative model which is widely being used in industry (e.g., including EPRI/ETMS, GE/PSLF Dynamics, and WSCC stability programs) to represent the voltage dependency of the load is the polynomial model:

(3-21) $P = a_0 + a_1V + a_2V^2$

(3-22) $Q = b_0 + b_1V + b_2V^2$

Where the powers represent the total MW and MVAR, and the voltage represents that phase voltage in kV. The above model is often referred to as the ZIP model as it is composed of constant impedance (Z), constant current (I) and constant power (P) components corresponding to the third, second and first elements in Eqns. (3-21)-(3-22), respectively . this model is adopted since it is of interest to NPC, and its parameters from recorded data is to match the P-V and Q-V data during voltage change to these second-order polynomial expressions using lest-squared error technique. The mathematical steps for this method are listed next.

The problem of approximating as set of recorded data (v_i, p_i) , i= 1,2,…,n with a second-order polynomial $P(V) = a_0 + a_1 V + a_2 V^2$ using least-squares procedure requires choosing the constants a_0, a_1, a_2 that minimize the following expression:

(3-23) $E = \sum_1^n (p_i - P(v_i))^2$

In order for E to be minimized, it is necessary that

(3-24) $a_0 \sum_1^n v_i{}^0 + a_1 \sum_1^n v_i{}^1 + a_2 \sum_1^n v_i{}^2 = \sum_1^n p_i v_i{}^0$

(3-25) $a_0 \sum_1^n v_i{}^1 + a_1 \sum_1^n v_i{}^2 + a_2 \sum_1^n v_i{}^3 = \sum_1^n p_i v_i{}^1$

(3-26) $a_0 \sum_1^n v_i{}^2 + a_1 \sum_1^n v_i{}^3 + a_2 \sum_1^n v_i{}^4 = \sum_1^n p_i v_i{}^2$

The above conditions result in specific values of a_0, a_1 *and* a_2 which satisfy the following set of linear equations:

(3-28) $x_0 a_0 + x_1 a_1 + x_2 a_2 = y_1$

(3-29) $x_1 a_0 + x_2 a_1 + x_3 a_2 = y_2$

(3-30) $x_2 a_0 + x_3 a_1 + x_4 a_2 = y_3$

Where,

(3-31) $x_0 = n,\ x_1 = \sum_1^n v_i, \quad x_2 = \sum_1^n {v_i}^2, \quad x_3 = \sum_1^n {v_i}^3, \quad x_4 = \sum_1^n {v_i}^4$

(3-32) $y_1 = \sum_1^n p_i, \quad y_2 = \sum_1^n p_i v_i, \quad y_3 = \sum_1^n p_i {v_i}^2$

The solution of the above equation is as follows:

(3-33) $a_0 = \frac{1}{d}(y_1(x_2 x_4 - {x_3}^2) - x_1 * (y_2 x_4 - y_3 x_3) + x_2(y_2 x_3 - y_3 x_2))$

(3-34) $a_1 = \frac{1}{d}(x_0(y_2 x_4 - y_3 x_3) - y_1 * (x_1 x_4 - x_2 x_3) + x_2(x_1 y_3 - y_2 x_2))$

(3-35) $a_2 = \frac{1}{d}(x_0(x_2 y_3 - y_2 x_3) - x_1 * (x_1 y_3 - y_2 x_2) + y_1(x_1 x_3 - {x_2}^2))$

Where,

(3-36) $d = x_0(x_2 x_4 - {x_3}^2) - x_1 * (x_1 x_4 - x_2 x_3) + x_2(x_1 x_3 - {x_2}^2)$

The reactive power parameters (b_0, b_1, b_2) are found in a similar manner by replacing the P-V data set with that of the Q-V data.

The resulting parameters are listed in Table-3-6 for each feeder tested, except for Q1213 which did not have the expected pump load on the test day.

Table-3-6: Static load model parameters

Feeders	a_0	a_1	a_2	b_0	b_1	b_2
WS 1203	10.95	-1.75	0.15	15.22	-4.5	0.36
WS 1208	69.8	-19.6	1.44	78.3	-21.48	1.52
H 1202	23.33	-4.80	0.37	36.66	-10.85	0.86
H 1203	7.84	-0.46	0.06	18.58	-5.65	0.50
Q 1210	6.23	-0.48	0.05	16.82	-5.20	0.44

The significant deviations of the load on WS 1208 are due to the random momentary changes indicated earlier. To take this into account, a static-random load model is proposed. It is basically a sum of the derived static components and the random components: (p_s+p_r), (Q_s+Q_r), where the random components (p_r, Q_r) are calculated by subtracting the static components above from the measured values at each voltage level. These random components can only be expressed analytically by probability functions. Their histograms are found to resemble normal probability density function with a standard deviation σ = 0.2. Mathematically, these functions are:

(3-37) $S(S_r) = \exp(-\frac{{S_r}^2}{2\sigma^2}), \qquad S_r = p_r, Q_r$

The P-V and Q-V Correlation model is sometimes expressed in terms the initial quantities (p_0,Q_0,V_0) of the load and feeder voltage before the disturbance, i.e.,

(3-38) $P = p_0(a'_0 + a'_1\left(\frac{V}{V_0}\right) + a'_2(\left(\frac{V}{V_0}\right)^2),$

(3-39) $Q = Q_0(b'_0 + b'_1\left(\frac{V}{V_0}\right) + b'_2(\left(\frac{V}{V_0}\right)^2),$

The values of the new load parameters (with primes) are calculated from the old ones (without primes) as follows:

(3-40) $\alpha'_0 = \alpha_0 / S_0$

(3-41) $\alpha'_1 = \alpha_1 / S_0$

(3-42) $\alpha'_2 = \alpha_2 / S_0$

Where (α_0,α'_0,S_0)= (a_i,a'_i,P_0) for active power, and (b_i,b'_i,Q_0) for reactive power. The resulting modified parameters are listed in Table-3-7.

Table-3-7: Modified static load model parameters

Feeders	V_0	P_0	α'_0	α'_1	α'_2	Q_0	b'_0	b'_1	b'_2
WS1203	7.55	6.58	1.66	-2.00	1.30	2.12	7.18	-16.02	9.68
WS1208	7.55	3.80	18.37	-38.94	21.6	2.75	28.47	-58.97	31.50
H1202	7.48	7.92	2.94	-4.53	2.61	3.98	9.21	-20.39	12.10
H1203	7.48	7.87	0.91	-4.37	0.42	4.27	4.34	-9.89	6.55
Q1210	7.52	5.75	1.08	-0.68	0.49	2.85	5.90	-13.72	8.73

The frequency dependency of load characteristics is usually represented by multiplying the polynomial model by a factor as follows:

(3-43) $$P = (P_0 + P_1V + P_2V^2)(1 + K_P\Delta f)$$

(3-44) $$Q = (Q_0 + Q_1V + Q_2V^2)(1 + K_q\Delta f)$$

Where Δf is the frequency deviation from the nominal value (i.e.,60 HZ). The parameter K_P ranges from 0 to 3 and K_q ranges from -2 to 0. Load-frequency characteristics require an isolated system, a request that is rarely acceptable by system operation/dispatch. Furthermore, to obtain valid data, care must be taken to separate the effects of voltage changes and frequency changes.

Finally, it is important to mention that static models above are not realistic at low voltages and may lead to computational problems. This is why stability programs usually switch to constant impedance model when the bus voltage falls below a specified value.

3.7.4.2.2. Dynamic Load Model

Dynamic models of composite loads are complicated due to the fact that there are a number of phenomena in power system dynamic performance analysis spanning from a fraction of a second to several minutes. There are also different load types with diverse response times and characteristics. Currently, representation of loads in system dynamic studies include the static ZIP model and the dynamic load model of induction motors, since their dynamic contribution is most significant as the consume over half of the power generated. The motor dynamics characteristics have been studies extensively and their dynamics are quite noticeable during the first few seconds, right after the disturbance, after which the motor basically behaves with its steady-state characteristics. There are basically four levels of details of the induction motor model, and the adequate model to use depends on the type PF dynamic study to be conducted.

In long-term dynamic studies, the induction motor can be represented by its steady-state circuit since its steady response to modest amplitudes of voltage changes is reached very quickly (within seconds). The induction motor equivalent circuit is shown in figure-3-11, and its electrical torque calculated by

(3-45) $T_e = 3\frac{p}{2}\frac{R_r}{Sw_s}{I_r}^2$

Where p is the number of motor poles, S is the rotor slip,   is the synchronous angular frequency (= 2πf), R_r is the rotor resistance referred to the stator side, and I_r is the rotor current which can easily be expressed in terms of the stator supply voltage and the motor circuit parameters.

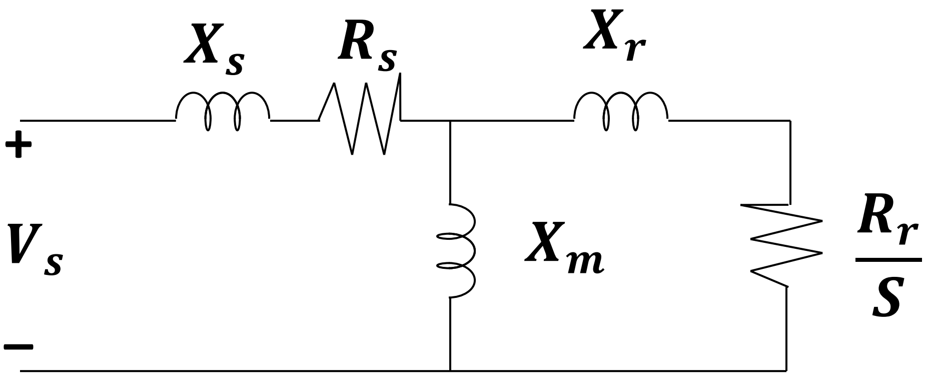


Figure3-11: Steady-State Equivalent Circuit of Induction Motor

In extended mid-term dynamic stability, the rotor acceleration equation is necessary, i.e., the motor is modeled by a first-order differential equation:

(3-46) $\frac{dw_r}{dt} = \frac{1}{2H}(T_e - T_m)$

Where T_e is a function of the rotor speed (obtained by replacing the slip $S = w_s - w_r$ in the equation above).

In short-term and mid-term stability studies, the stator flux dynamics are often neglected and only the rotor flux dynamics in addition to the mechanical equation above are considered. This model is derived in the d-q reference frame (Ertem & Baghzouz, 1989; W. Price et al., 1993)and the resulting differential equations are:

(3-47) $dv_d/dt = -(v_d + (X_s - X_s')i_{qs})/T_0 + \ v_q d\theta_r/dt$

(3-48) $dv_q/dt = -(v_q - (X_s - X_s')i_{ds}/T_0 + \ v_d d\theta_r/dt$

(3-49) $d\theta_r/dt = \frac{w_s - w_r}{w_s}$

The tests conducted are considered for long-term stability or voltage stability studies since one transformer tap change requires an average of 4-5 sec. the fast dynamic response of induction motors requires fast and relatively large voltage changes (e.g., transformer or large capacitor switching). The intent was to examine whether the small and slow LTC operation will result is noticeable dynamic on Quail 1213. Unfortunately this pump load was disconnected during the testing period.

For voltage stability analysis, the load-voltage response characteristics can be represented by a generic dynamic load model where the load model parameters are obtained from field measurements showing load recovery. Three parameters are sufficient to describe such a response: the transient characteristics parameter (defined as the instantaneous demand change of load under a sudden voltage change), the steady state characteristic parameter defines the steady-state load demand as a function of steady-state supply voltage), and the time constant characterizes the time span needed for a load changes while lowering the voltage in necessary.

3.8. Computer Simulation for a sample project

Base Scenario: For computer simulating a sample project and evaluate the CVR on it by "Easy Power" software, has been considered a 10 mile long feeder that serve a 4MVA (85% Power Factor) uniformly distributed load from a 69kv/13.2kv 15MVA substation transformer with 8% impedance. The uniform load can be lumped at 20 uniformly spaced nodes (each supplying 0.2MVA).The voltage at the substation is kept constant at 1 PU by means of a LTC. The feeder consists of ACC/266.8 kcmil with a GMD of 4' and an operating temperature of 25deg.

Scenario-1: In this scenario, loads increased by 10% more. After load flow analysis, results show that in some part of the grid, there is a voltage drop over the 5% allowable. So, in next scenario, some solution applied to solve extra existence voltage drop.

Scenario-2: In this scenario, two sets of capacitors which each are two sets of 0.15kVAR added to system and also tap changer of transformer increased to 4%. The voltage drop issues were solved along the grid. Finally, voltage behavior of each scenario was compared together which are shown by some graphs.

Voltage drops One-Line diagrams for all scenarios are illustrated in Figure-3-12 to Figure-3-14.

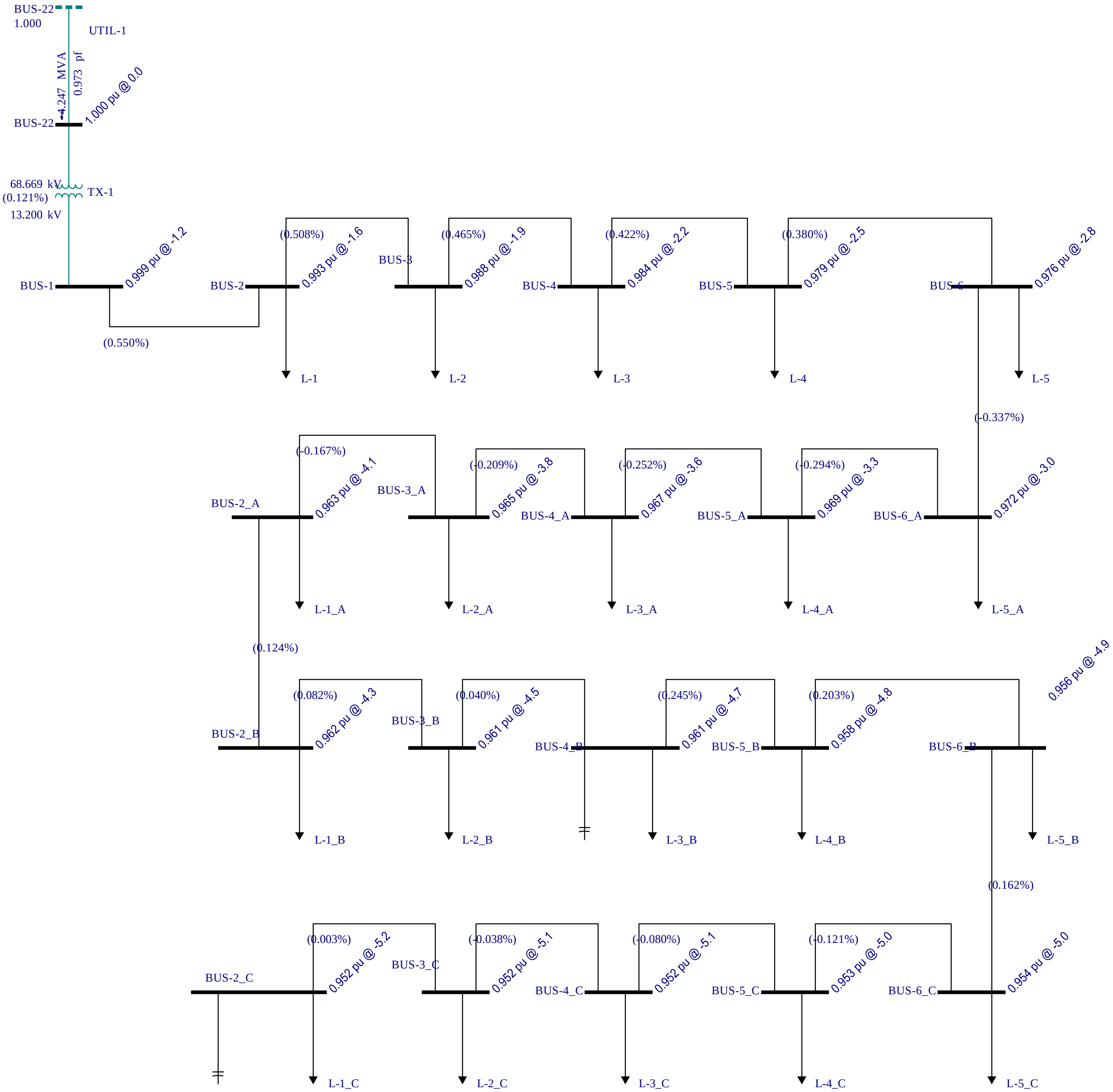


Figure-3-12: Voltage drops one-line diagram (Base scenario)

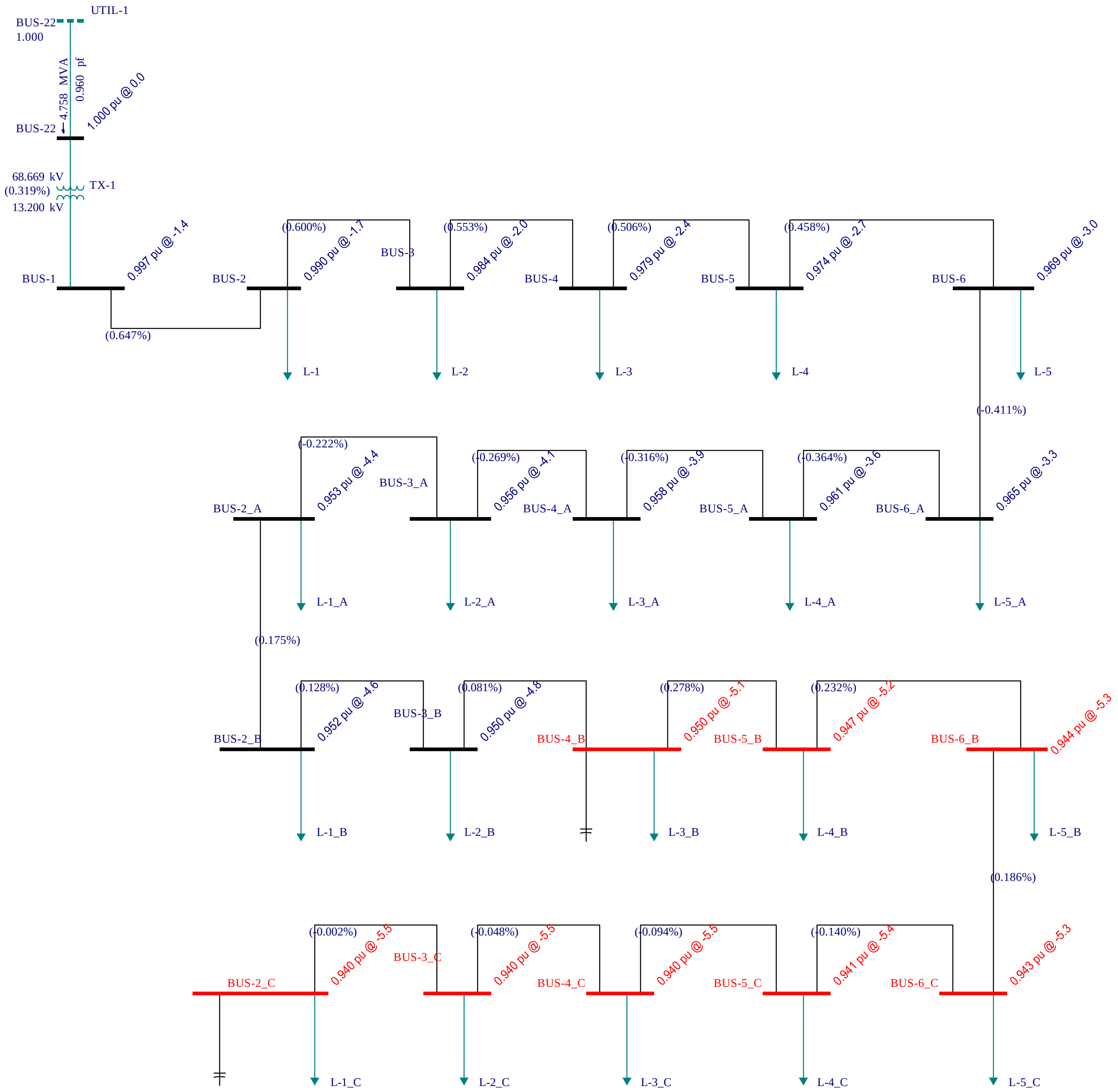


Figure-3-13: Voltage drops one-line diagram (Scenario-1)

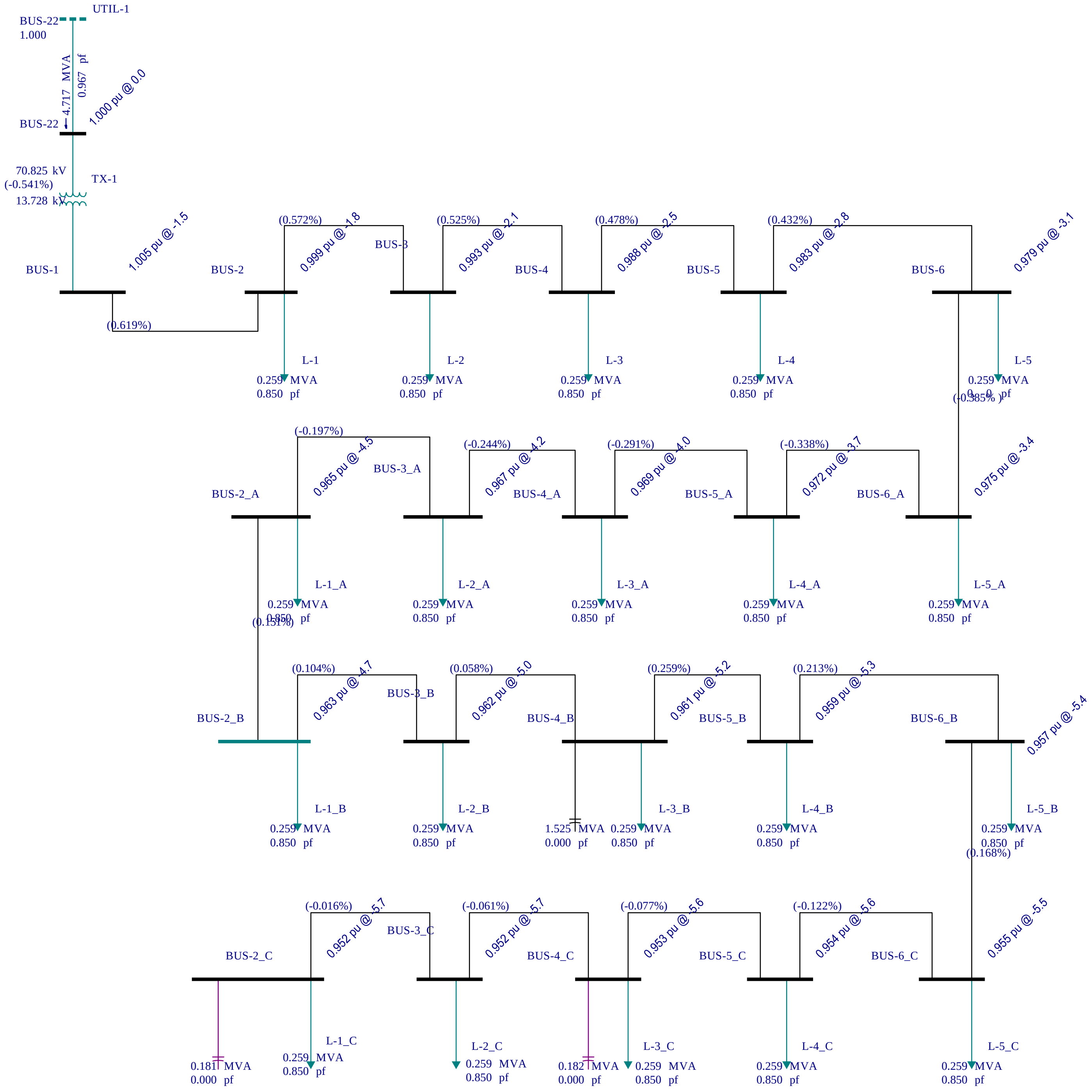


Figure-3-14: Voltage drops one-line diagram (Scenario-2)

Table-3-11: Buses Voltage level of each Scenario

Bus	Base Scenario(V_{PU})	Scenario-1(V_{PU})	Scenario-2(V_{PU})
22	1	1	1
1	0.999	0.997	1.005
2	0.993	0.99	0.999
3	0.988	0.984	0.993
4	0.984	0.979	0.988
5	0.979	0.974	0.983
6	0.976	0.969	0.979
6A	0.972	0.965	0.975
5A	0.969	0.961	0.972
4A	0.967	0.958	0.969
3A	0.965	0.956	0.967
2A	0.963	0.953	0.965
2B	0.962	0.952	0.963
3B	0.961	0.95	0.962
4B	0.961	0.95	0.961
5B	0.958	0.947	0.959
6B	0.956	0.944	0.957
6C	0.954	0.943	0.955
5C	0.953	0.941	0.954
4C	0.952	0.94	0.953
3C	0.952	0.94	0.952
2C	0.952	0.94	0.952

According to Table-3-11, voltage changes along the feeder can be compared which are illustrated in Figure-3-15 to Figure-3-17.

Also, power flow summary reports for all three scenarios are illustrated in Appendix-A (Table-A1 to Table-A3).

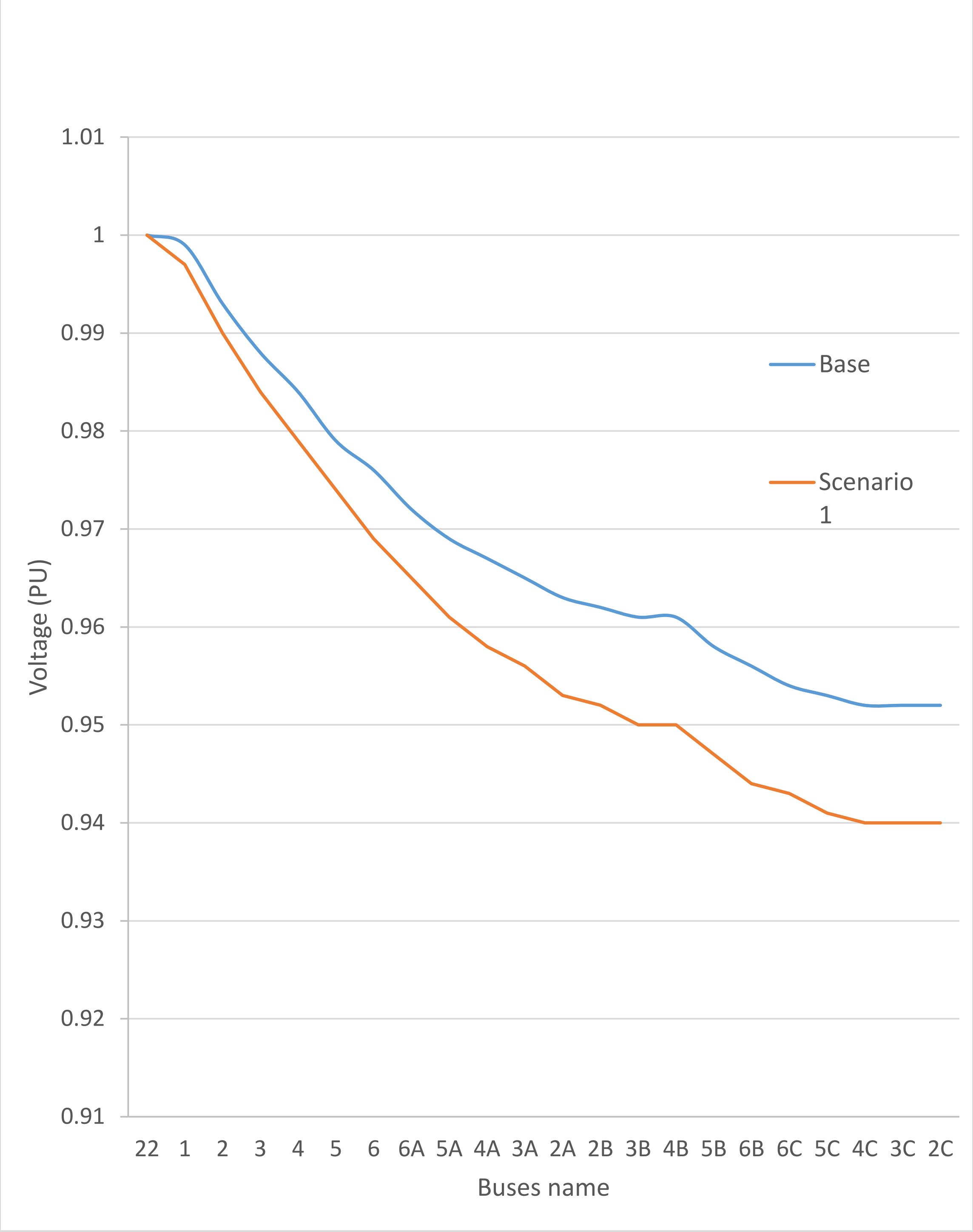


Figure-3-15: Voltage changes along the feeder (Base and first scenarios comparison)

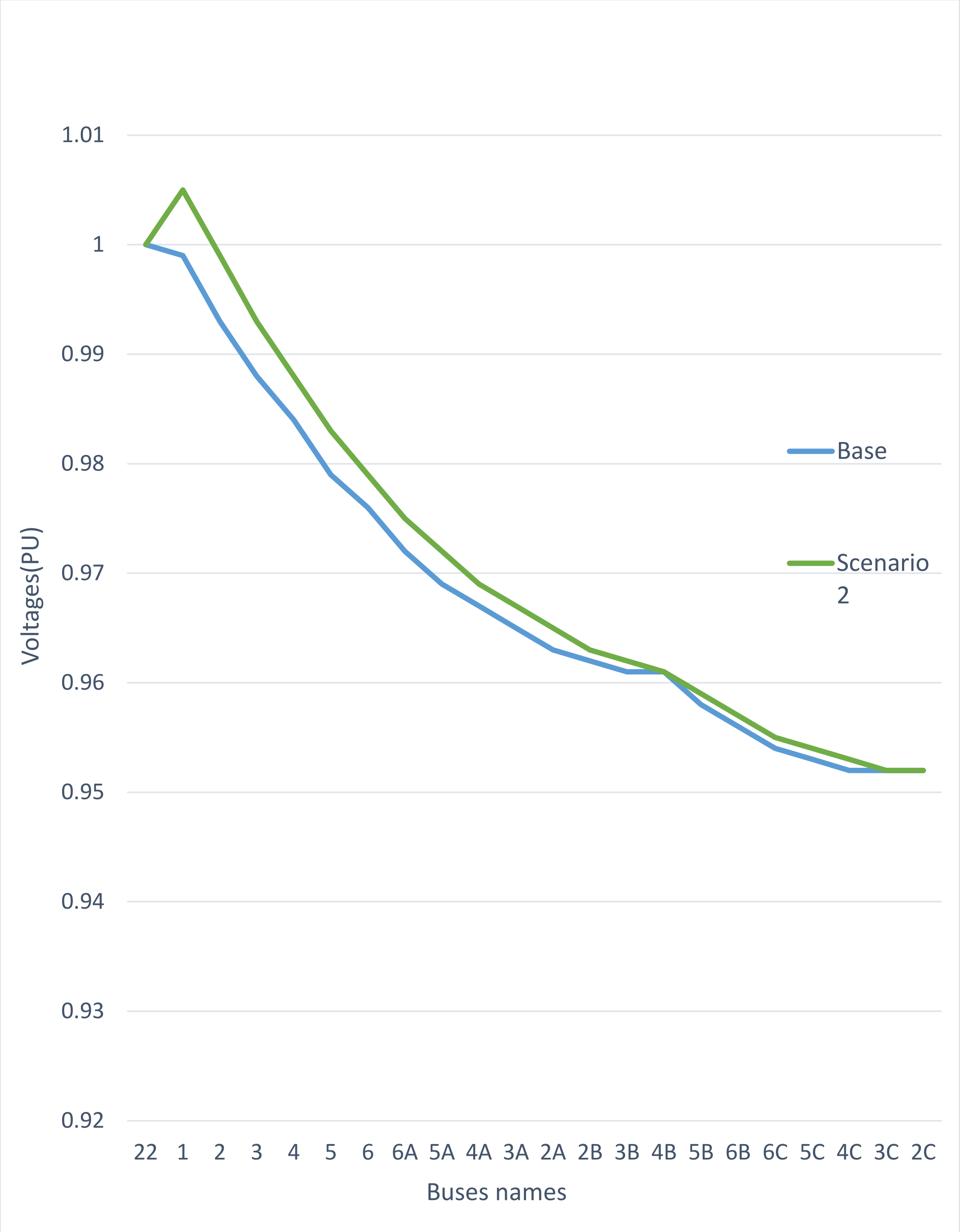


Figure-3-16: Voltage changes along the feeder (Base and second scenarios comparison)

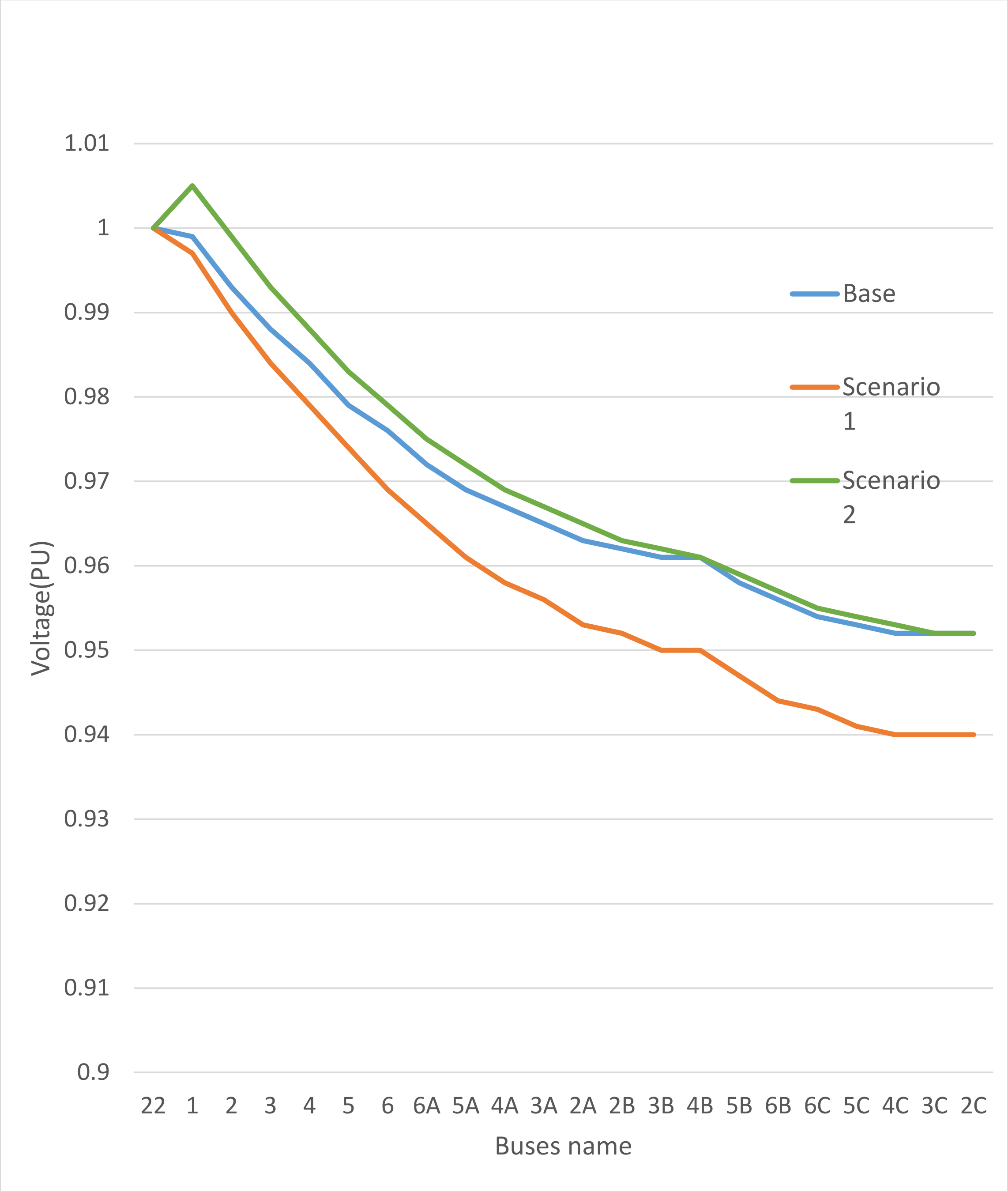


Figure-3-17: Voltage changes along the feeder (All scenarios comparison)

Chapter 4:

Conclusion

The amount of permissible CVR program voltage reduction allowable on utility system varies depending on design, load characteristics, etc. However, in general Rarely can one implement a "theoretical" across the board constant reduction. Most often, reduction affect only part each feeder. Most feeders can engage reductions of averaging about 1-1.5% without too much re-engineering. There will be exceptions, feeders where no CVR can be applied without major re-engineering and additions.

Reduction of about 3% can be effected through significant refinement of voltage engineering on feeders and the installation of properly tailored line regulators and switched capacitors.

Reduction of up to 5% and in some cases a bit more than 6% can be effected during emergencies, if the utility has formerly prepared to handle a 3% reduction without issues.

On many utilities systems, for the emergency condition listed above, the voltage delivered to customers near the end of feeders will drop markedly below the minimum dictated by the utility's standards for normal voltage service. Such conditions are acceptable for a brief period because the "emergency conditions" permit application of emergency voltage standards.

For instance, utilities using ANSI standard C84.1-1989 as their voltage standard can get beyond three additional volts for emergency CVR. The standard lists

105% to 91.7% as allowable for certain temporary on occasional operation conditions, i.e., emergencies.

Undeniable reducing voltage reduces loads. This is easy to see with what is called a “notched test”: drop the voltage at the substation low side bus by adjusting LTC controls or regulation by a total reduction of 5% while monitoring current. The reduction in power usage is noticeable. System normally responds slightly better than linearly: a 5% CVR gives about a 5-6% reduction in load. Raise the voltage to its original level fifteen minutes later and the load instantly goes up by a like amount. It is hard to argue with this type of “notch test” (short-term drop and raise back in voltage). The voltage reduction reduces load by about or a little more than 1:1 ratio.

But this does not mean CVR works this well as an energy reduction measure. What is often not recognized is that such “notch tests” do not mean that reduction lasts permanently. In fact, CVR cooperates with variety of appliance called “duty cycle rebound”.

At the end, in aspect of economical, CVR’s major cost impact of implementing CVR is at the distribution level, where it can increase cost of feeders in some cases. In other feeder cases, it can be applied at no cost, occasionally with the little more effort than the resetting of transformer taps and LDC setting. However, CVR reduces the voltage drop allowed to distribution planners to distribute power, a consideration in systems that are well designed from a load reach standpoint and have no margin in voltage.

In some cases, CVR can be implements only by modifying the feeder system (adding regulators or reconductoring) to overcome voltage drop problems caused by CVR's effective change in voltage standards. Beyond this, by limiting the voltage drop available, feeders will have fewer margins to accept new load growth before the (now revised) voltage drop criteria are exceeded. They will need to be reinforced more often and perhaps in a more costly manner.

Furthermore, the utility needs to consider the impacts of CVR on load reach and the loss in value of that. In some cases, the loss in capability of the distribution system is considerable. And the overall cost of the future additions and expansion is considerable. This is not say that CVR is not economical or that it should not be examined as an option, just to point out that the present and future costs on distribution should be taken into account in developing evaluations of benefit/cost.

Appendix-A: Power flow summary reports

Table-A1: Power flow summary reports (For Base Scenario)

Mismatch Report

Iteration	MW Mismatch		MVAR Mismatch	
Number	Bus Name	pu	Bus Name	pu
0	BUS-2_C	0.00000	BUS-2_C	0.00000
1	BUS-2_C	0.00000	BUS-2	0.00000
2	BUS-2_C	0.00000	BUS-3_C	0.00000
3	BUS-2_C	0.00000	BUS-3_C	0.00000
4	BUS-2_C	0.00000	BUS-3_C	0.00000

Generator Summary Report

Generator			Scheduled			Limits		Solution							
Name	Type	Rated kVA	kW	kVAR	Vpu	kVAR Min	kVAR Max	kW	kVAR	kVA	Pf	V pu	Deg	Eq'pu	Deg
UTIL-1	Sw				1.000			4134	973	4247	0.973	1.000	0.00	1.000	0.00

Load Summary Report

Bus		Solution						
Name	Base kV	kV	Vpu	Deg	kW	kVar	kVA	Pf
BUS-1	13.200	13.184	0.999	-1.24	0	0	0	0.000
BUS-2	13.200	13.111	0.993	-1.56	200	124	235	0.850
BUS-2_A	13.200	12.711	0.963	-4.06	200	124	235	0.850
BUS-2_B	13.200	12.695	0.962	-4.29	200	124	235	0.850
BUS-2_C	13.200	12.567	0.952	-5.16	200	-148	249	-0.804
BUS-3	13.200	13.044	0.988	-1.88	200	124	235	0.850
BUS-3_A	13.200	12.733	0.965	-3.82	200	124	235	0.850
BUS-3_B	13.200	12.684	0.961	-4.50	200	124	235	0.850
BUS-3_C	13.200	12.567	0.952	-5.13	200	124	235	0.850
BUS-4	13.200	12.983	0.984	-2.18	200	124	235	0.850
BUS-4_A	13.200	12.761	0.967	-3.57	200	124	235	0.850
BUS-4_B	13.200	12.679	0.961	-4.71	200	-1398	1412	-0.142
BUS-4_C	13.200	12.572	0.952	-5.09	200	124	235	0.850
BUS-5	13.200	12.927	0.979	-2.48	200	124	235	0.850
BUS-5_A	13.200	12.794	0.969	-3.31	200	124	235	0.850
BUS-5_B	13.200	12.646	0.958	-4.81	200	124	235	0.850
BUS-5_C	13.200	12.582	0.953	-5.03	200	124	235	0.850
BUS-6	13.200	12.877	0.976	-2.77	200	124	235	0.850
BUS-6_A	13.200	12.833	0.972	-3.04	200	124	235	0.850
BUS-6_B	13.200	12.620	0.956	-4.89	200	124	235	0.850
BUS-6_C	13.200	12.598	0.954	-4.97	200	124	235	0.850
BUS-22	69.000	69.000	1.000	0.00	0	0	0	0.000

System Summary Report

--				
Total	kW	kVAR	kVA	PF
Generation in System	4134	973	4247	0.973
Load in System	4000	2480	4706	0.850
Shunt Load in System	-0	-1794		
Losses in System	134	287	-	-
Check of Balance	-0	-0		

Table-A1: Power flow summary reports (For Base Scenario)-Continued

Transformer Tap Report

Transformer	Connection		Base kV		Tap kV		LTC Description							
Name	From Bus Name	To Bus Name	From	To	From	To	Type	LTC	LTC Type	Control Side	LTC Side	Control Value pu	Limits Min kV	Limits Max kV
TX-1	BUS-22	BUS-1	69.000	13.200	68.669	13.200	2Wnd	Yes	kV	To	From	1.000	0.100	1500.000

Line Overload Report

Overload Threshold = 10.00 %

Line				Load			
From Bus Name	To Bus Name	Branch Name	Rated Amps	Load Amps	Loaded%	OverLoaded%	Comment
BUS-1	BUS-2	X-1	460.0	184.9	40.2%	-59.8%	
BUS-2	BUS-3	X-2	460.0	175.2	38.1%	-61.9%	
BUS-2_A	BUS-3_A	X-2_A	460.0	102.5	22.3%	-77.7%	
BUS-2_A	BUS-2_B	X-15	460.0	94.8	20.6%	-79.4%	
BUS-2_B	BUS-3_B	X-2_B	460.0	87.8	19.1%	-80.9%	
BUS-2_C	BUS-3_C	X-2_C	460.0	11.4	2.5%	-97.5%	
BUS-3	BUS-4	X-3	460.0	165.6	36.0%	-64.0%	
BUS-3_A	BUS-4_A	X-3_A	460.0	110.6	24.1%	-75.9%	
BUS-3_B	BUS-4_B	X-3_B	460.0	81.6	17.7%	-82.3%	
BUS-3_C	BUS-4_C	X-3_C	460.0	18.4	4.0%	-96.0%	
BUS-4	BUS-5	X-4	460.0	156.0	33.9%	-66.1%	
BUS-4_A	BUS-5_A	X-4_A	460.0	119.2	25.9%	-74.1%	
BUS-4_B	BUS-5_B	X-4_B	460.0	69.7	15.2%	-84.8%	
BUS-4_C	BUS-5_C	X-4_C	460.0	27.9	6.1%	-93.9%	
BUS-5	BUS-6	X-5	460.0	146.5	31.9%	-68.1%	
BUS-5_A	BUS-6_A	X-5_A	460.0	128.1	27.8%	-72.2%	
BUS-5_B	BUS-6_B	X-5_B	460.0	59.1	12.9%	-87.1%	
BUS-5_C	BUS-6_C	X-5_C	460.0	38.1	8.3%	-91.7%	
BUS-6_A	BUS-6	X-14	460.0	137.2	29.8%	-70.2%	
BUS-6_B	BUS-6_C	X-16	460.0	48.6	10.6%	-89.4%	

Transformer Overload Report

Overload Threshold = 10.00 %

Transformer				Load			
Name	From Bus Name	To Bus Name	Rated Amps	Load Amps	Loaded%	OverLoaded%	Comment
TX-1	BUS-22	BUS-1	125.5	35.5	28.3%	-71.7%	

Table-A1: Power flow summary reports (For Base Scenario)-Continued

Branch Losses Report

From Bus		To Bus		Losses	
Name	Base kV	Name	Base kV	kW	kVAR
BUS-1	13.200	BUS-2	13.200	17.9	27.3
BUS-2	13.200	BUS-3	13.200	16.1	24.5
BUS-2_A	13.200	BUS-3_A	13.200	5.5	8.1
BUS-2_A	13.200	BUS-2_B	13.200	4.7	6.9
BUS-2_B	13.200	BUS-3_B	13.200	4.0	5.8
BUS-2_C	13.200	BUS-3_C	13.200	0.1	-0.3
BUS-3	13.200	BUS-4	13.200	14.4	21.8
BUS-3_A	13.200	BUS-4_A	13.200	6.4	9.5
BUS-3_B	13.200	BUS-4_B	13.200	3.5	5.0
BUS-3_C	13.200	BUS-4_C	13.200	0.2	-0.2
BUS-4	13.200	BUS-5	13.200	12.8	19.3
BUS-4_A	13.200	BUS-5_A	13.200	7.5	11.1
BUS-4_B	13.200	BUS-5_B	13.200	2.5	3.5
BUS-4_C	13.200	BUS-5_C	13.200	0.4	0.2
BUS-5	13.200	BUS-6	13.200	11.3	17.0
BUS-5_A	13.200	BUS-6_A	13.200	8.6	12.9
BUS-5_B	13.200	BUS-6_B	13.200	1.8	2.4
BUS-5_C	13.200	BUS-6_C	13.200	0.8	0.7
BUS-6_A	13.200	BUS-6	13.200	9.9	14.9
BUS-6_B	13.200	BUS-6_C	13.200	1.2	1.5
BUS-22	69.000	BUS-1	13.200	4.8	95.2
Total System Losses				134.4	287.2

Voltage Drop Report

From Bus		To Bus		Drop
Name	Base kV	Name	Base kV	%
BUS-1	13.200	BUS-2	13.200	0.6%
BUS-2	13.200	BUS-3	13.200	0.5%
BUS-2_A	13.200	BUS-3_A	13.200	-0.2%
BUS-2_A	13.200	BUS-2_B	13.200	0.1%
BUS-2_B	13.200	BUS-3_B	13.200	0.1%
BUS-2_C	13.200	BUS-3_C	13.200	0.0%
BUS-3	13.200	BUS-4	13.200	0.5%
BUS-3_A	13.200	BUS-4_A	13.200	-0.2%
BUS-3_B	13.200	BUS-4_B	13.200	0.0%
BUS-3_C	13.200	BUS-4_C	13.200	-0.0%
BUS-4	13.200	BUS-5	13.200	0.4%
BUS-4_A	13.200	BUS-5_A	13.200	-0.3%
BUS-4_B	13.200	BUS-5_B	13.200	0.2%
BUS-4_C	13.200	BUS-5_C	13.200	-0.1%
BUS-5	13.200	BUS-6	13.200	0.4%
BUS-5_A	13.200	BUS-6_A	13.200	-0.3%
BUS-5_B	13.200	BUS-6_B	13.200	0.2%
BUS-5_C	13.200	BUS-6_C	13.200	-0.1%
BUS-6_A	13.200	BUS-6	13.200	-0.3%
BUS-6_B	13.200	BUS-6_C	13.200	0.2%
BUS-22	69.000	BUS-1	13.200	0.1%

Table-A2: Power flow summary reports (For Scenario-1)

Mismatch Report

Iteration	MW Mismatch		MVAR Mismatch	
Number	Bus Name	pu	Bus Name	pu
0	BUS-2_C	0.00194	BUS-4_B	0.00007
1	BUS-2_C	0.00010	BUS-6_A	0.00002
2	BUS-2	0.00003	BUS-2_C	0.00002
3	BUS-2_C	0.00003	BUS-2_C	0.00002
4	BUS-2_C	0.00002	BUS-2_C	0.00001
5	BUS-2_C	0.00001	BUS-2_C	0.00000
6	BUS-2_C	0.00000	BUS-2_C	0.00000

Generator Summary Report

Generator			Scheduled			Limits		Solution							
Name	Type	Rated kVA	kW	kVAR	Vpu	kVAR Min	kVAR Max	kW	kVAR	kVA	Pf	V pu	Deg	Eq'pu	Deg
UTIL-1	Sw				1.000			4567	1335	4758	0.960	1.000	0.00	1.000	0.00

Load Summary Report

Bus		Solution						
Name	Base kV	kV	Vpu	Deg	kW	kVar	kVA	Pf
BUS-1	13.200	13.158	0.997	-1.37	0	0	0	0.000
BUS-2	13.200	13.072	0.990	-1.71	220	136	259	0.850
BUS-2_A	13.200	12.584	0.953	-4.37	220	136	259	0.850
BUS-2_B	13.200	12.561	0.952	-4.61	220	136	259	0.850
BUS-2_C	13.200	12.404	0.940	-5.55	220	-129	255	-0.863
BUS-3	13.200	12.993	0.984	-2.05	220	136	259	0.850
BUS-3_A	13.200	12.613	0.956	-4.12	220	136	259	0.850
BUS-3_B	13.200	12.544	0.950	-4.84	220	136	259	0.850
BUS-3_C	13.200	12.404	0.940	-5.52	220	136	259	0.850
BUS-4	13.200	12.920	0.979	-2.37	220	136	259	0.850
BUS-4_A	13.200	12.649	0.958	-3.85	220	136	259	0.850
BUS-4_B	13.200	12.534	0.950	-5.06	220	-1351	1369	-0.161
BUS-4_C	13.200	12.410	0.940	-5.47	220	136	259	0.850
BUS-5	13.200	12.854	0.974	-2.69	220	136	259	0.850
BUS-5_A	13.200	12.691	0.961	-3.58	220	136	259	0.850
BUS-5_B	13.200	12.497	0.947	-5.17	220	136	259	0.850
BUS-5_C	13.200	12.423	0.941	-5.42	220	136	259	0.850
BUS-6	13.200	12.793	0.969	-2.99	220	136	259	0.850
BUS-6_A	13.200	12.739	0.965	-3.29	220	136	259	0.850
BUS-6_B	13.200	12.466	0.944	-5.26	220	136	259	0.850
BUS-6_C	13.200	12.441	0.943	-5.35	220	136	259	0.850
BUS-22	69.000	69.000	1.000	0.00	0	0	0	0.000

System Summary Report

--				
Total	kW	kVAR	kVA	PF
Generation in System	4567	1335	4758	0.960
Load in System	4400	2728	5177	0.850
Shunt Load in System	-0	-1752		
Losses in System	167	360	-	-
Check of Balance	0	0		

Table-A2: Power flow summary reports (For Scenario-1)-Continued

Transformer Tap Report

Transformer	Connection		Base kV		Tap kV		LTC Description							
Name	From Bus Name	To Bus Name	From	To	From	To	Type	LTC	LTC Type	Control Side	LTC Side	Control Value pu	Limits Min kV	Limits Max kV
TX-1	BUS-22	BUS-1	69.000	13.200	68.669	13.200	2Wnd	Yes	kV	To	From	1.000	0.100	1500.000

Voltage Violation Report
Limits (MAX: 1.05, Min: 0.95)

	--		
Bus Name	Base kV	Vpu	kV
BUS-2_C	13.200	0.940	12.404
BUS-3_C	13.200	0.940	12.404
BUS-4_B	13.200	0.950	12.534
BUS-4_C	13.200	0.940	12.410
BUS-5_B	13.200	0.947	12.497
BUS-5_C	13.200	0.941	12.423
BUS-6_B	13.200	0.944	12.466
BUS-6_C	13.200	0.943	12.441

Line Overload Report
Overload Threshold = 10.00 %

Line				Load			
From Bus Name	To Bus Name	Branch Name	Rated Amps	Load Amps	Loaded%	OverLoaded%	Comment
BUS-1	BUS-2	X-1	460.0	207.1	45.0%	-55.0%	
BUS-2	BUS-3	X-2	460.0	196.2	42.7%	-57.3%	
BUS-2_A	BUS-3_A	X-2_A	460.0	112.5	24.5%	-75.5%	
BUS-2_A	BUS-2_B	X-15	460.0	103.3	22.5%	-77.5%	
BUS-2_B	BUS-3_B	X-2_B	460.0	94.7	20.6%	-79.4%	
BUS-2_C	BUS-3_C	X-2_C	460.0	11.9	2.6%	-97.4%	
BUS-3	BUS-4	X-3	460.0	185.3	40.3%	-59.7%	
BUS-3_A	BUS-4_A	X-3_A	460.0	122.2	26.6%	-73.4%	
BUS-3_B	BUS-4_B	X-3_B	460.0	86.8	18.9%	-81.1%	
BUS-3_C	BUS-4_C	X-3_C	460.0	20.5	4.5%	-95.5%	
BUS-4	BUS-5	X-4	460.0	174.5	37.9%	-62.1%	
BUS-4_A	BUS-5_A	X-4_A	460.0	132.3	28.8%	-71.2%	
BUS-4_B	BUS-5_B	X-4_B	460.0	78.3	17.0%	-83.0%	
BUS-4_C	BUS-5_C	X-4_C	460.0	31.4	6.8%	-93.2%	
BUS-5	BUS-6	X-5	460.0	163.8	35.6%	-64.4%	
BUS-5_A	BUS-6_A	X-5_A	460.0	142.6	31.0%	-69.0%	
BUS-5_B	BUS-6_B	X-5_B	460.0	66.5	14.5%	-85.5%	
BUS-5_C	BUS-6_C	X-5_C	460.0	43.0	9.3%	-90.7%	
BUS-6_A	BUS-6	X-14	460.0	153.1	33.3%	-66.7%	
BUS-6_B	BUS-6_C	X-16	460.0	54.7	11.9%	-88.1%	

Table-A2: Power flow summary reports (For Scenario-1)-Continued

Transformer Overload Report
Overload Threshold = 10.00 %

Transformer				Load			
Name	From Bus Name	To Bus Name	Rated Amps	Load Amps	Loaded%	OverLoaded%	Comment
TX-1	BUS-22	BUS-1	125.5	39.8	31.7%	-68.3%	

Branch Losses Report

From Bus		To Bus		Losses	
Name	Base kV	Name	Base kV	kW	kVAR
BUS-1	13.200	BUS-2	13.200	22.5	34.4
BUS-2	13.200	BUS-3	13.200	20.2	30.9
BUS-2_A	13.200	BUS-3_A	13.200	6.6	9.9
BUS-2_A	13.200	BUS-2_B	13.200	5.6	8.2
BUS-2_B	13.200	BUS-3_B	13.200	4.7	6.9
BUS-2_C	13.200	BUS-3_C	13.200	0.1	-0.3
BUS-3	13.200	BUS-4	13.200	18.0	27.5
BUS-3_A	13.200	BUS-4_A	13.200	7.8	11.7
BUS-3_B	13.200	BUS-4_B	13.200	4.0	5.7
BUS-3_C	13.200	BUS-4_C	13.200	0.2	-0.1
BUS-4	13.200	BUS-5	13.200	16.0	24.3
BUS-4_A	13.200	BUS-5_A	13.200	9.2	13.8
BUS-4_B	13.200	BUS-5_B	13.200	3.2	4.6
BUS-4_C	13.200	BUS-5_C	13.200	0.5	0.4
BUS-5	13.200	BUS-6	13.200	14.1	21.4
BUS-5_A	13.200	BUS-6_A	13.200	10.7	16.1
BUS-5_B	13.200	BUS-6_B	13.200	2.3	3.2
BUS-5_C	13.200	BUS-6_C	13.200	1.0	1.1
BUS-6_A	13.200	BUS-6	13.200	12.3	18.6
BUS-6_B	13.200	BUS-6_C	13.200	1.6	2.0
BUS-22	69.000	BUS-1	13.200	6.0	119.4
Total System Losses				166.5	359.6

Voltage Drop Report

From Bus		To Bus		Drop
Name	Base kV	Name	Base kV	%
BUS-1	13.200	BUS-2	13.200	0.6%
BUS-2	13.200	BUS-3	13.200	0.6%
BUS-2_A	13.200	BUS-3_A	13.200	-0.2%
BUS-2_A	13.200	BUS-2_B	13.200	0.2%
BUS-2_B	13.200	BUS-3_B	13.200	0.1%
BUS-2_C	13.200	BUS-3_C	13.200	-0.0%
BUS-3	13.200	BUS-4	13.200	0.6%
BUS-3_A	13.200	BUS-4_A	13.200	-0.3%
BUS-3_B	13.200	BUS-4_B	13.200	0.1%
BUS-3_C	13.200	BUS-4_C	13.200	-0.0%
BUS-4	13.200	BUS-5	13.200	0.5%
BUS-4_A	13.200	BUS-5_A	13.200	-0.3%
BUS-4_B	13.200	BUS-5_B	13.200	0.3%
BUS-4_C	13.200	BUS-5_C	13.200	-0.1%
BUS-5	13.200	BUS-6	13.200	0.5%
BUS-5_A	13.200	BUS-6_A	13.200	-0.4%
BUS-5_B	13.200	BUS-6_B	13.200	0.2%
BUS-5_C	13.200	BUS-6_C	13.200	-0.1%
BUS-6_A	13.200	BUS-6	13.200	-0.4%
BUS-6_B	13.200	BUS-6_C	13.200	0.2%
BUS-22	69.000	BUS-1	13.200	0.3%

Table-A3: Power flow summary reports (For Scenario-2)

Mismatch Report

Iteration	MW Mismatch		MVAR Mismatch	
Number	Bus Name	pu	Bus Name	pu
0	BUS-2_C	0.00102	BUS-2_C	0.00076
1	BUS-2	0.00013	BUS-2_C	0.00010
2	BUS-2_C	0.00015	BUS-2_C	0.00009
3	BUS-2_C	0.00012	BUS-2_C	0.00007
4	BUS-2_C	0.00010	BUS-2_C	0.00005
5	BUS-2_C	0.00008	BUS-2_C	0.00004
6	BUS-2_C	0.00006	BUS-2_C	0.00003
7	BUS-2_C	0.00005	BUS-2_C	0.00003
8	BUS-2_C	0.00004	BUS-2_C	0.00002
9	BUS-2_C	0.00003	BUS-2_C	0.00002
10	BUS-2_C	0.00002	BUS-2_C	0.00001
11	BUS-6_A	0.00005	BUS-2_C	0.00004
12	BUS-2_C	0.00001	BUS-2	0.00000
13	BUS-2_C	0.00000	BUS-2	0.00000

Generator Summary Report

Generator			Scheduled			Limits		Solution							
Name	Type	Rated kVA	kW	kVAR	Vpu	kVAR Min	kVAR Max	kW	kVAR	kVA	Pf	V pu	Deg	Eq'pu	Deg
UTIL-1	Sw				1.000			4562	1198	4717	0.967	1.000	0.00	1.000	0.00

Load Summary Report

Bus		Solution						
Name	Base kV	kV	Vpu	Deg	kW	kVar	kVA	Pf
BUS-1	13.200	13.271	1.005	-1.46	0	0	0	0.000
BUS-2	13.200	13.190	0.999	-1.80	220	136	259	0.850
BUS-2_A	13.200	12.733	0.965	-4.48	220	136	259	0.850
BUS-2_B	13.200	12.713	0.963	-4.72	220	136	259	0.850
BUS-2_C	13.200	12.570	0.952	-5.67	220	-45	225	-0.980
BUS-3	13.200	13.114	0.993	-2.14	220	136	259	0.850
BUS-3_A	13.200	12.759	0.967	-4.23	220	136	259	0.850
BUS-3_B	13.200	12.699	0.962	-4.96	220	136	259	0.850
BUS-3_C	13.200	12.572	0.952	-5.65	220	136	259	0.850
BUS-4	13.200	13.045	0.988	-2.46	220	136	259	0.850
BUS-4_A	13.200	12.791	0.969	-3.96	220	136	259	0.850
BUS-4_B	13.200	12.691	0.961	-5.18	220	-1389	1406	-0.156
BUS-4_C	13.200	12.581	0.953	-5.61	220	-45	225	-0.979
BUS-5	13.200	12.982	0.983	-2.78	220	136	259	0.850
BUS-5_A	13.200	12.829	0.972	-3.68	220	136	259	0.850
BUS-5_B	13.200	12.657	0.959	-5.29	220	136	259	0.850
BUS-5_C	13.200	12.591	0.954	-5.55	220	136	259	0.850
BUS-6	13.200	12.925	0.979	-3.09	220	136	259	0.850
BUS-6_A	13.200	12.874	0.975	-3.39	220	136	259	0.850
BUS-6_B	13.200	12.629	0.957	-5.39	220	136	259	0.850
BUS-6_C	13.200	12.607	0.955	-5.48	220	136	259	0.850
BUS-22	69.000	69.000	1.000	0.00	0	0	0	0.000

Table-A3: Power flow summary reports (For Scenario-2)-Continued

System Summary Report

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Total	kW	kVAR	kVA	PF
Generation in System	4562	1198	4717	0.967
Load in System	4400	2728	5177	0.850
Shunt Load in System	-0	-1888		
Losses in System	162	358	-	-
Check of Balance	-0	0		

Transformer Tap Report

Transformer	Connection		Base kV		Tap kV		LTC Description							
Name	From Bus Name	To Bus Name	From	To	From	To	Type	LTC	LTC Type	Control Side	LTC Side	Control Value pu	Limits Min kV	Limits Max kV
TX-1	BUS-22	BUS-1	69.000	13.200	70.825	13.728	2Wnd	Yes	kV	To	From	1.000	0.100	1500.000

Line Overload Report

Overload Threshold = 10.00 %

Line				Load			
From Bus Name	To Bus Name	Branch Name	Rated Amps	Load Amps	Loaded%	OverLoaded%	Comment
BUS-1	BUS-2	X-1	460.0	203.6	44.3%	-55.7%	
BUS-2	BUS-3	X-2	460.0	192.9	41.9%	-58.1%	
BUS-2_A	BUS-3_A	X-2_A	460.0	111.9	24.3%	-75.7%	
BUS-2_A	BUS-2_B	X-15	460.0	103.2	22.4%	-77.6%	
BUS-2_B	BUS-3_B	X-2_B	460.0	95.2	20.7%	-79.3%	
BUS-2_C	BUS-3_C	X-2_C	460.0	10.3	2.2%	-97.8%	
BUS-3	BUS-4	X-3	460.0	182.3	39.6%	-60.4%	
BUS-3_A	BUS-4_A	X-3_A	460.0	121.2	26.3%	-73.7%	
BUS-3_B	BUS-4_B	X-3_B	460.0	88.1	19.1%	-80.9%	
BUS-3_C	BUS-4_C	X-3_C	460.0	20.6	4.5%	-95.5%	
BUS-4	BUS-5	X-4	460.0	171.7	37.3%	-62.7%	
BUS-4_A	BUS-5_A	X-4_A	460.0	130.8	28.4%	-71.6%	
BUS-4_B	BUS-5_B	X-4_B	460.0	75.6	16.4%	-83.6%	
BUS-4_C	BUS-5_C	X-4_C	460.0	30.4	6.6%	-93.4%	
BUS-5	BUS-6	X-5	460.0	161.2	35.1%	-64.9%	
BUS-5_A	BUS-6_A	X-5_A	460.0	140.7	30.6%	-69.4%	
BUS-5_B	BUS-6_B	X-5_B	460.0	64.0	13.9%	-86.1%	
BUS-5_C	BUS-6_C	X-5_C	460.0	41.2	9.0%	-91.0%	
BUS-6_A	BUS-6	X-14	460.0	150.9	32.8%	-67.2%	
BUS-6_B	BUS-6_C	X-16	460.0	52.5	11.4%	-88.6%	

Transformer Overload Report

Overload Threshold = 10.00 %

Transformer				Load			
Name	From Bus Name	To Bus Name	Rated Amps	Load Amps	Loaded%	OverLoaded%	Comment
TX-1	BUS-22	BUS-1	125.5	39.5	31.4%	-68.6%	

Table-A3: Power flow summary reports (For Scenario-2)-Continued

Branch Losses Report

From Bus		To Bus		Losses	
Name	Base kV	Name	Base kV	kW	kVAR
BUS-1	13.200	BUS-2	13.200	21.7	33.3
BUS-2	13.200	BUS-3	13.200	19.5	29.8
BUS-2_A	13.200	BUS-3_A	13.200	6.6	9.7
BUS-2_A	13.200	BUS-2_B	13.200	5.6	8.2
BUS-2_B	13.200	BUS-3_B	13.200	4.8	6.9
BUS-2_C	13.200	BUS-3_C	13.200	0.1	-0.3
BUS-3	13.200	BUS-4	13.200	17.4	26.6
BUS-3_A	13.200	BUS-4_A	13.200	7.7	11.5
BUS-3_B	13.200	BUS-4_B	13.200	4.1	5.9
BUS-3_C	13.200	BUS-4_C	13.200	0.2	-0.1
BUS-4	13.200	BUS-5	13.200	15.5	23.5
BUS-4_A	13.200	BUS-5_A	13.200	9.0	13.5
BUS-4_B	13.200	BUS-5_B	13.200	3.0	4.2
BUS-4_C	13.200	BUS-5_C	13.200	0.5	0.3
BUS-5	13.200	BUS-6	13.200	13.6	20.7
BUS-5_A	13.200	BUS-6_A	13.200	10.4	15.7
BUS-5_B	13.200	BUS-6_B	13.200	2.1	2.9
BUS-5_C	13.200	BUS-6_C	13.200	0.9	0.9
BUS-6_A	13.200	BUS-6	13.200	11.9	18.1
BUS-6_B	13.200	BUS-6_C	13.200	1.4	1.8
BUS-22	69.000	BUS-1	13.200	6.3	124.9
Total System Losses				162.3	357.9

Voltage Drop Report

From Bus		To Bus		Drop
Name	Base kV	Name	Base kV	%
BUS-1	13.200	BUS-2	13.200	0.6%
BUS-2	13.200	BUS-3	13.200	0.6%
BUS-2_A	13.200	BUS-3_A	13.200	-0.2%
BUS-2_A	13.200	BUS-2_B	13.200	0.2%
BUS-2_B	13.200	BUS-3_B	13.200	0.1%
BUS-2_C	13.200	BUS-3_C	13.200	-0.0%
BUS-3	13.200	BUS-4	13.200	0.5%
BUS-3_A	13.200	BUS-4_A	13.200	-0.2%
BUS-3_B	13.200	BUS-4_B	13.200	0.1%
BUS-3_C	13.200	BUS-4_C	13.200	-0.1%
BUS-4	13.200	BUS-5	13.200	0.5%
BUS-4_A	13.200	BUS-5_A	13.200	-0.3%
BUS-4_B	13.200	BUS-5_B	13.200	0.3%
BUS-4_C	13.200	BUS-5_C	13.200	-0.1%
BUS-5	13.200	BUS-6	13.200	0.4%
BUS-5_A	13.200	BUS-6_A	13.200	-0.3%
BUS-5_B	13.200	BUS-6_B	13.200	0.2%
BUS-5_C	13.200	BUS-6_C	13.200	-0.1%
BUS-6_A	13.200	BUS-6	13.200	-0.4%
BUS-6_B	13.200	BUS-6_C	13.200	0.2%
BUS-22	69.000	BUS-1	13.200	-0.5%

References

ACT, V.Challenge AND opportunity: Charting A new energy future.

Albadi, M. H., & El-Saadany, E. (2008). A summary of demand response in electricity markets. *Electric Power Systems Research, 78*(11), 1989-1996.

Balijepalli, V. M., Pradhan, V., Khaparde, S., & Shereef, R. (2011). Review of demand response under smart grid paradigm. Paper presented at the *Innovative Smart Grid Technologies-India (ISGT India), 2011 IEEE PES,* 236-243.

Chiu, W., Sun, H., & Poor, H. (2012). Demand-side energy Storage management in smart grid. *IEEE Third International Conference on Smart Grid Communications*.

De Steese, J., Merrick, S., & Kennedy, B. (1990). Estimating methodology for a large regional application of conservation voltage reduction. *Power Systems, IEEE Transactions On, 5*(3), 862-870.

Ellens, W., Berry, A., & West, S. (2012). A quantification of the energy savings by conservation voltage reduction. Paper presented at the *Power System Technology (POWERCON), 2012 IEEE International Conference On,* 1-6.

Ertem, S., & Baghzouz, Y. (1989). Simulation of induction machinery for power system studies. *Energy Conversion, IEEE Transactions On, 4*(1), 88-94.

Federal Energy Regulatory Commission. (2010). National action plan on demand response. *Docket no.AD09-10,*

Frost, Sullivan. (2003). Unit shipment forecasts and business care analysis for electric utilities

Goldman, C. A., Kintner-Meyer, M., & Heffner, G. (2002). Do" enabling technologies" affect customer performance in price-responsive load programs?

Kennedy, B., & Fletcher, R. (1991). Conservation voltage reduction (CVR) at snohomish county PUD. *Power Systems, IEEE Transactions On, 6*(3), 986-998.

Kirshner, D., & Giorsetto, P. (1984). Statistical test of energy saving due to voltage reduction. *Power Apparatus and Systems, IEEE Transactions On,* (6), 1205-1210.

Kundur, P., Balu, N. J., & Lauby, M. G. (1994). *Power system stability and control* McGraw-hill New York.

Lefebvre, S., Gaba, G., Ba, A., Asber, D., Ricard, A., Perreault, C., & Chartrand, D. (2008). Measuring the efficiency of voltage reduction at hydro-québec distribution. Paper presented at the *Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE,* 1-7.

Nejad, M. F., Saberian, A., Hizam, H., Radzi, M., Amran, M., Kadir, A., & Abidin, M. Z. (2013). Application of smart power grid in developing countries. Paper presented at the *Power Engineering and Optimization Conference (PEOCO), 2013 IEEE 7th International,* 427-431.

Office of Energy. (2010). Demand Management. Government of Western Australia n.d web.

Preiss, R., & Warnock, V. (1978). Impact of voltage reduction on energy and demand. *Power Apparatus and Systems, IEEE Transactions On,* (5), 1665-1671.

Price, W., Casper, S., Nwankpa, C., Bradish, R., Chiang, H., Concordia, C., . . . Wu, G. (1995). Bibliography on load models for power flow and dynamic performance simulation. *IEEE Power Engineering Review, 15*(2), 70.

Price, W., Chiang, H., Clark, H., Concordia, C., Lee, D., Hsu, J., . . . Mansour, Y. (1993). Load representation for dynamic performance analysis. *IEEE Transactions on Power Systems (Institute of Electrical and Electronics Engineers);(United States), 8*(2)

Price, W. W., Wirgau, K. A., Murdoch, A., Mitsche, J. V., Vaahedi, E., & El-Kady, M. (1988). Load modeling for power flow and transient stability computer studies. *Power Systems, IEEE Transactions On, 3*(1), 180-187.

Sabir, S., & Lee, D. (1982). Dynamic load models derived from date acquired during system transients. *Power Apparatus and Systems, IEEE Transactions On,* (9), 3365-3372.

Schweppe, F. C. (1982). *Frequency Adaptive, Power-Energy Re-Scheduler,*

Singh, R., Tuffner, F., Fuller, J., & Schneider, K. (2011). Effects of distributed energy resources on conservation voltage reduction (CVR). Paper presented at the *Power and Energy Society General Meeting, 2011 IEEE,* 1-7.

Sinitsyn, N. A., Kundu, S., & Backhaus, S. (2013). Safe protocols for generating power pulses with heterogeneous populations of thermostatically controlled loads. *Energy Conversion and Management, 67*, 297-308.

Sonderegger, R. C. (1978). Dynamic models of house heating based on equivalent thermal parameters.

Torriti, J., Hassan, M. G., & Leach, M. (2010). Demand response experience in europe: Policies, programmes and implementation. *Energy, 35*(4), 1575-1583.

U.S Department of Energy. (2012). Smart Grid/Department of Energy.

Warnock, V., & Kirkpatrick, T. (1986). Impact of voltage reduction on energy and demand: Phase II. *Power Systems, IEEE Transactions On, 1*(2), 92-95.

Willis, H. L. (2010). *Power distribution planning reference book* CRC press.

Wilson, N., Wagner, B., & Colborne, W. (1985). Equivalent thermal parameters for an occupied gas-heated house. *ASHRAE Trans.;(United States), 91*(CONF-850606-)

Wilson, T. (2002). Energy conservation with voltage reduction-fact or fantasy. Paper presented at the *Rural Electric Power Conference, 2002. 2002 IEEE,* C3-C3_6.

Date: May 2014

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