A PROPOSED SYSTEM FOR A SMART GRID IMPLEMENTATION AT OKLAHOMA STATE UNIVERSITY

By

Rohit Prabhakaran Nair

Bachelor of Engineering in Electrical Engineering

University of Pune

Pune, Maharashtra, India

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Thesis Approved:

Dr. Rama Ramakumar

Thesis Adviser

Dr. Thomas Gedra

Dr. Sohum Sohoni

Dr. Mark E. Payton

Dean of the Graduate College

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TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

I.1 Current Electric Grid

It is an undeniable fact that electric power is one of the major and most important technologies that led to the rapid industrialization and globalization in the twentieth century. The electric power grid is over a century-old and is considered to be the largest and most complex interconnected physical system on earth. Due to its vastness, complexity and being inextricably linked to human development and involvement, it is termed to be an ecosystem in itself. Globally, there are more than 9,200 electric generating units with more than 1,000,000 megawatts of generating capacity and connected to more than 300,000 miles of transmission lines [1]. Life on earth is totally dependent on energy in some form or other. As a matter of fact, an abundant and sustainable supply of energy is key to solving a plethora of global problems. Furthermore, prosperity of a nation is highly dependent on its technological progress, which, in turn, depends on the availability of affordable energy in various forms. With the exponential growth in global economy and incessant population growth, there has been an increasing pressure on energy resources and the environment. Fossil fuel resources are getting depleted and coupled with a long list of geopolitical issues, prices are spiraling upwards. Global electricity usage is on the rise and there is an increasing demand for higher reliability and better quality of the electric power delivered by utilities.

It is a well-known fact that Thomas Edison and Alexander Graham Bell were the key architects of the electric power and communication systems respectively. If both were somehow transported to the 21st century, Bell would hardly be able to recognize the components of today's communications systems. On the other hand, Thomas Edison will still be able to recognize almost all the major components in today's electrical grid system. This proves the fact that the existing electrical power system needs a lot of design improvements and vital upgrades to cope up with the 21st century needs.

The current grid works well in what it is designed to do namely keeping the costs as low as possible. Also, an important aspect of the power delivery system is that it is to be consumed the moment it is generated. It is the epitome of all just-in-time delivery systems. The down side of this characteristic is that the entire delivery process would have a cascading effect and could prove catastrophic. Also, due to the digital revolution, the demand for higher quality of power is increasing at a rapid rate.

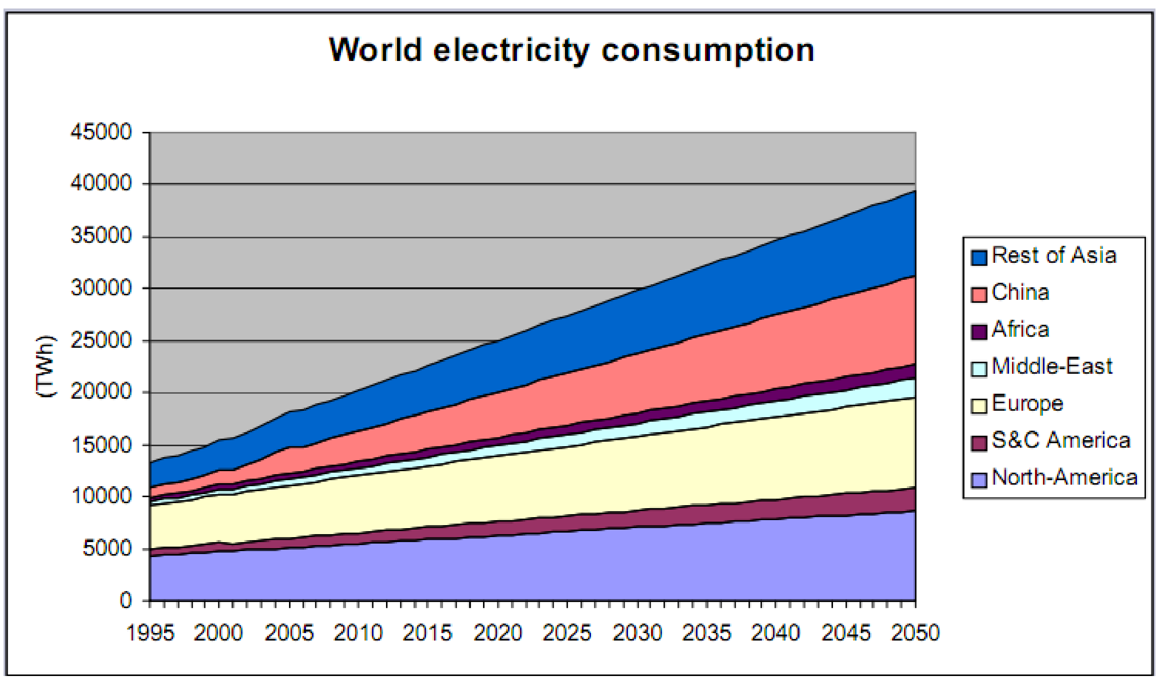

Figure I.1 World Electricity Consumption [3]

Due to population growth and increasing reliance on electricity, it is expected that global electricity supply will need to be increased by a significant amount. As seen in Figure I.1, global electricity consumption is expected to nearly double by the year 2050. More than 10,000 GW of new generation capacity is needed to fulfill this growing demand. Also, as shown in Figure I.2, fossil fuels are expected to be on a depleting trend and such a decrease in supply will lead to steep increases in prices, eventually increasing the costs of electricity worldwide. This has indeed led to a global resurgence of interest in alternate fuels and sustainable energy generation techniques and has gained considerable momentum in the past decade which still continues.

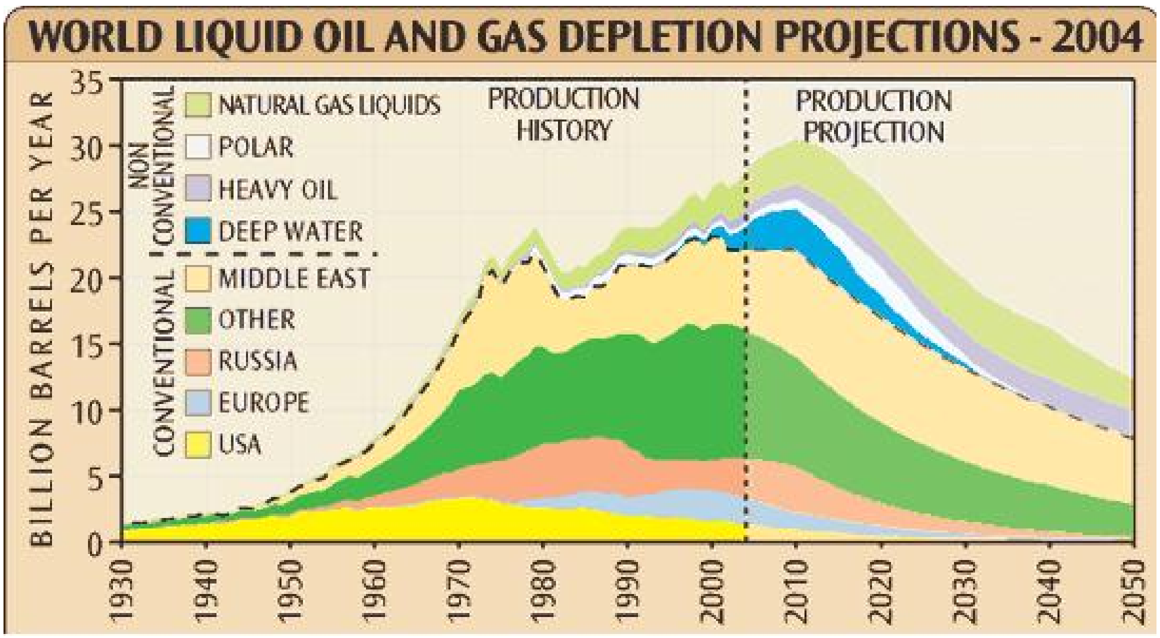

Figure I.2 World Liquid Oil & Gas Projections [4]

Due to an increasing awareness of global climate change, the Green Energy Revolution has gained considerable importance in the recent past. Renewable energy utilization is on the rise and is increasingly being integrated into existing global electric grids. Research in the fields of photovoltaic (PV) technology, Solar-thermal systems, Wind Electric Conversion Systems (WECS), fuel cells, hydrogen storage etc., has brought an altogether new dimension to the electric power industry in the past couple of decades.

I.2 Shortcomings of Current Electric Power Grid

As already mentioned, the electric power grid is over a century old by now, and many of its vital components have been operating beyond their useful life. More importantly, the aging workforce of the electric power industry which is clearly shown in Figure I.3 is of a growing concern.

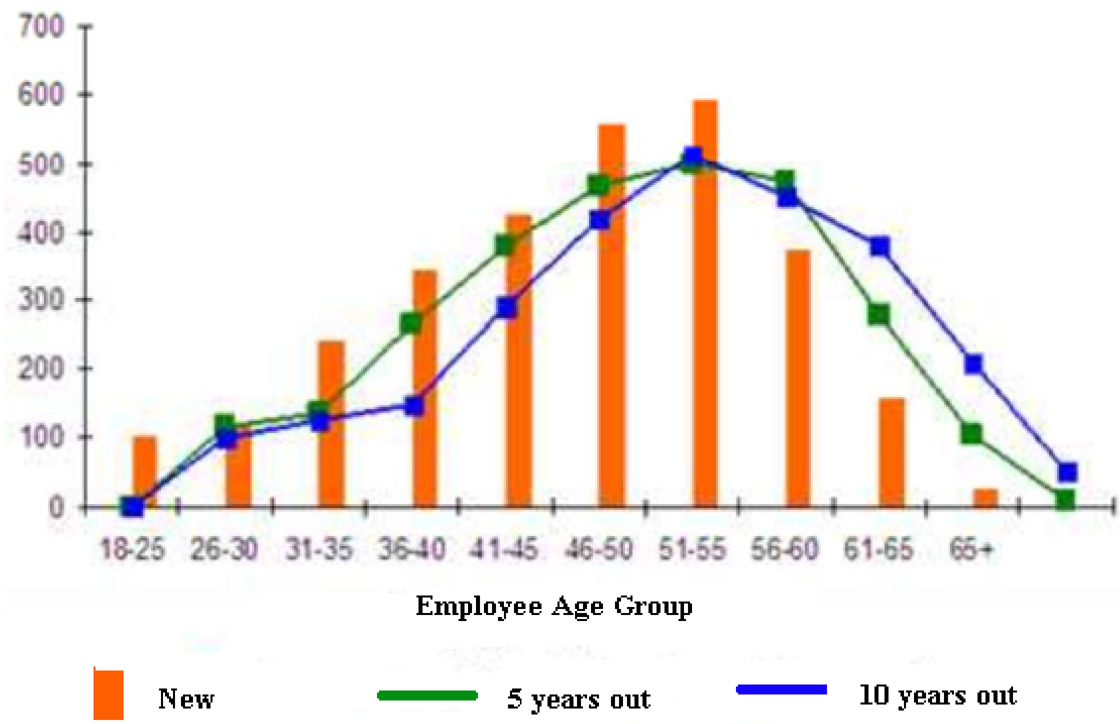

Figure I.3 Aging workforce trend (Typical Utility) Source: KEMA

Apart from this, in the U.S, it has been identified that, 70% of the transmission lines are 25 years old or older, 70% of the power transformers are more than 25 years old and 30% of the circuit breakers are more than 30 years old [5]. Further, the short-sighted bureaucratic policies of the regulators have led to a life-support level of investment in modernizing the electric grid and deepened the operational morbidity of the nation's electricity system. Automation is still at a very low level, especially on the distribution side of the electric grid system. When the current electric power system was designed, it was basically intended to serve linear loads supplied with sinusoidal voltages drawing sinusoidal currents. But, with the advent of the transistor and solid-state power electronic devices, there has been a surge in the usage of technologies that employ these on a very large scale ranging from personal computers and various other digital devices to large variable-speed drives which has made life simpler, efficient and more convenient in today's world. The down side of this is that these devices are highly sensitive to voltage variations caused by voltage sags, spikes and various orders of harmonics in the system [5]. In the absence of appropriate back up supplies, the slightest of interruptions can bring down computer servers, critical control systems, assembly lines etc that could prove to be economically catastrophic. More importantly, all these constraints are growing at a time when the pattern of electricity demand is undergoing a profound shift. On the top of these, there are growing security concerns in regard to attacks by terrorists on the current grid to paralyze the day to day businesses all across the country. Cyber sabotage on a military electric power installation has the potential to severely cripple the US military and Homeland security installations causing a dangerous ripple effect across the US.

For a very long time, the electric grid has had a singular mission namely to keep the lights on. With an aim to reduce electricity costs, long distance transportation of electricity and interconnections are employed to switch between providers to improve reliability. This has led to increased stresses on the entire network. This has also led to greater amount of congestion, exemplified by the Eastern Interconnection and the network in Southern California. Significant sums of money and resources are spent for peak power production and congestion related issues. In fact, an analysis done by the New York ISO, California ISO and the Pennsylvania New Jersey Maryland Interconnection LLC (PJM) reveal that billions of dollars are spent towards congestion and reliability related issues [Y]. Every day approximately half a million Americans experience blackouts of two hours or more, and power interruptions cost the US more than $100 Billion each year [6]. Also, the current US electric grid has been responsible for three major blackouts just in the past nine years alone, the worst of all being the Great Northeast Blackout of August 2003 that affected 50 million people and caused the US economy more than $10 Billion in damages and lost businesses [2].

The twin problems of unreliability and inefficiency in the current electric system is a product of the overall system's aging infrastructure and a severe dearth in utility industry innovation. The wide array of problems faced by the current grid compounded by increasing pressure from the customers for higher reliability and quality of power for their evolving digital society, has eventually led to the **smart grid** movement. However, this would require large investments in the energy/power sector as shown in Figure I.4, which was put forth by Lehman Brothers in 2007. As seen in this figure, significant capital investments are required for installing long transmission lines all across the country which would indeed help to integrate the renewable energy generation potential in the central and southwest parts of the country to the high density load centers in the East and the West coasts.

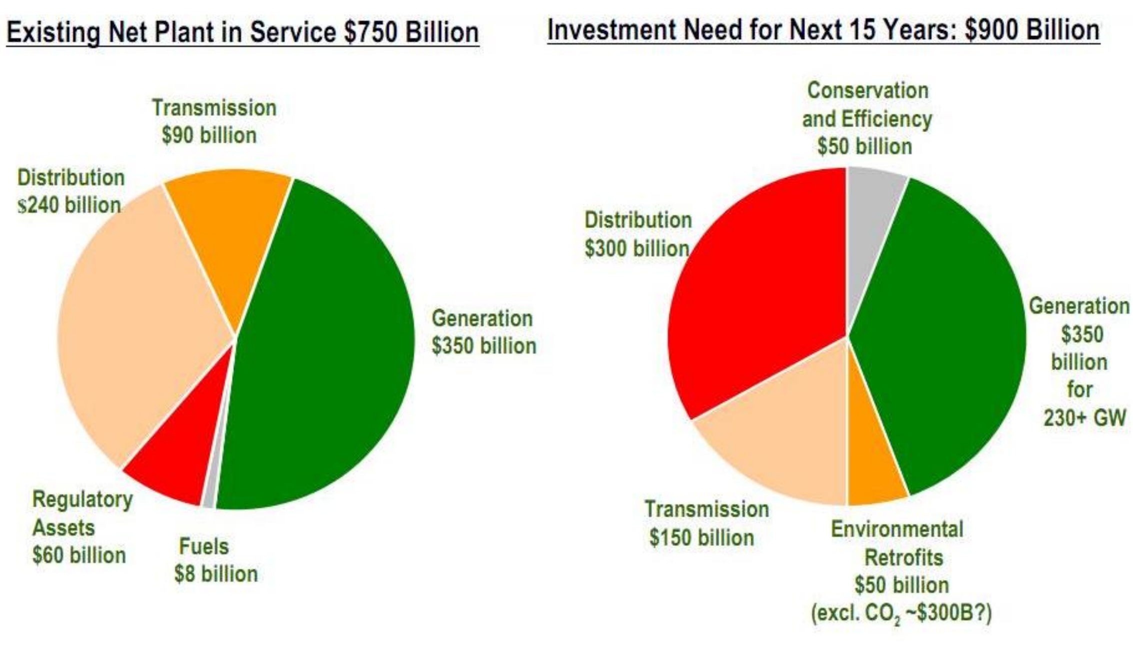

Figure I.4 Required electric capital investment Source: Lehman Brothers, 2007

Also, significant investment is required to automate the distribution system, which currently is the most fragile and outdated segment of the entire power delivery system. Energy efficiency programs, pilot projects and research and deployment of technologies associated with it will require additional investments. Such investments will definitely bring notable improvements in the overall working of the electric grid and transform it into a robust, reliable, intelligent (smart) and efficient grid.

The evolving Smart Grid is expected to provide a means to handle two-way power flows and the problem associated with intermittency of renewable energy sources. Also, shaving of the peak demand by even a small amount can save millions of dollars with the reduction in the number of required standby power plants which is very much possible in a smart grid scenario. All of this has created an exciting set of unprecedented challenges and opportunities to the current energy/power industry. They will have to deploy and utilize better ways for real-time monitoring and control of their existing facilities as well as ways for the consumers to do the same by expanded monitoring and control throughout their distribution grids all the way to the consumers' side of the meter. The use of advanced electronics, telecommunications, Internet, wireless sensor networks and information systems is imperative to achieve higher efficiency, improved power quality, enhanced reliability, lower costs, safety and security.

I.3 Objective of the Study

The concept of a Smart Grid has been the biggest and latest technological boom for the mature energy and power industry. With Billions of dollars in smart grid investments, it has been the topic of significance in an era of climate change and globalization. The effective utilization of smart grid technology for bi-directional power flow, integration of renewable energy generation sources , and improving the quality and reliability of power supply will require wireless sensors, internet and two-way communication protocols and technologies all working in unison. Further, intelligent sensing and switching technologies with higher redundancy in the power delivery sector are vital to provide effective avoidance and restoration of power failures. This focuses on the electric power network in the Stillwater campus of Oklahoma State University. Possible strategies concerning distribution automation utilizing voltage sensors, current sensors and distributed generation to transform the current grid into a Smart Grid are discussed. Different scenarios are simulated to show the benefits of implementation of such technologies in the current electric grid at the Stillwater campus of Oklahoma State University.

I.4 Organization of the Thesis

A brief outline of the chapters that follow are presented next.

Chapter II: Review of Literature

This chapter briefly summarizes the historical evolution of the concept of a smart grid and the various factors driving the smart grid movement. Various smart grid technologies and the benefits and challenges associated with it are outlined.

Chapter III: Current Grid at Oklahoma State University

This chapter presents the current scenario of the electric distribution system at the Stillwater campus of Oklahoma State University and its shortcomings. Approaches to improve its performance are discussed.

Chapter IV: Proposed techniques for a smart grid initiative at Oklahoma State University

Load flow models with and without distributed generation and other elements in the current grid at OSU are presented. Different scenarios and the potential benefits of the proposed system configurations are studied using the simulation results. Comparisons with the existing system and the improvements that would occur are presented.

Chapter V: Concluding Remarks and scope for further work

This chapter summarizes the entire study and discuses scope for further work.

CHAPTER II

REVIEW OF LITERATURE

II.1 Concept of a Smart Grid

Rapid Industrialization, urbanization and incessant infrastructure developments have led to a paradigm shift in the way electricity is generated, transmitted and consumed and it has resulted in immense stress on the age old electrical grid infrastructure. In addition, challenges due to increasing energy demand with higher quality of power and reliability are mounting. The rapid increase in penetration of nonlinear loads such as data centers, large variable-speed drives and other power electronic devices across the grid have resulted in increased reliability and power quality concerns. The concept of smart grid provides a host of solutions to many of the issues faced by the current electric grid by taking advantage of next generation technologies such as distributed generation, distribution automation, energy management systems, advanced metering infrastructure (AMI), renewable energy generation technologies, plug-in hybrid electric vehicles, two-way wireless communication and internet, to name a few.

Increased awareness of the depletion of energy consumption and environment, need for safe and steady operation of the power grid to provide high quality and reliable power supply to consumers in the digital age have thrust activities in the realm of smart grid to the forefront throughout the world [7, 8].

II.1.1 What is a Smart Grid

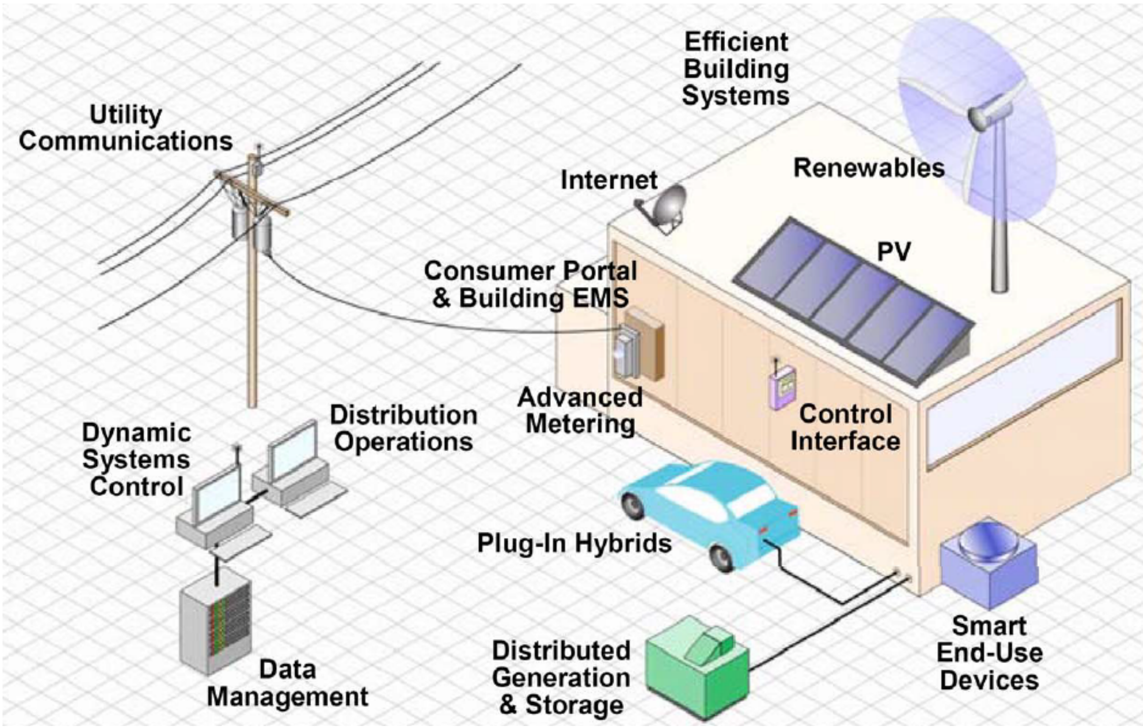

Figure II.1 Smart Grid concept (Source: EPRI)

The basic concept of a Smart Grid is to add monitoring, analysis, control, and communication capabilities to the national electrical delivery infrastructure to maximize the throughput of the system while reducing the energy consumption. The smart grid will allow utilities to move electricity around the system as efficiently and economically as possible [7].

As illustrated in Figure II.1, the smart grid can be defined as a system that employs digital information and control technologies to facilitate the deployment and integration of distributed and renewable resources, smart consumer devices, automated systems, electricity storage and peak-shaving technologies [9]. Some of the other definitions of the smart grid are:

- Convergence of information technology and communication technology with power system engineering.

- The smart grid is a broad collection of technologies that delivers an electricity network that is flexible, accessible, reliable and economic. Smart Grid facilitates the desired actions of its users and these may include distributed generation, deployment of demand management and energy storage systems or the optimal expansion and management of grid assets [10].
- A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those who do both – in order to efficiently deliver sustainable, economic and secure electricity supplies [11].
- Application of digital information technology to optimize electrical power generation, delivery and end use.
- Interaction of geographically dispersed equipment being able to perform coordinated operations through better communications and control.
- Set of advanced technologies, concepts, topologies and approaches that allow generation, transmission and distribution to be replaced by organically intelligent, fully integrated services with efficient exchange of data, services and transactions.
- Intelligent response and interaction between supply availability and demand.

With increased automation, especially in the form of sensors at distribution levels, the smart grid will significantly enhance and improve the quality and the amount of data processed by the sensors and metering infrastructure. Such an approach would not only significantly improve the efficiency, power quality and reliability of the entire system but will also lead to increased customer participation, reduction in peak demand, reduced financial losses and more importantly reduced CO_2 emissions and other environmental impacts.

II.1.2 Scope of a Smart Grid

Though a clear and concise definition of the Smart Grid is still evolving, there are several characteristics that remain common to many smart grid architectures. These characteristics clearly define the Smart Grid's potential benefits to the overall electric power system. They are:

- Anticipates and responds to system disturbances in a self-healing manner
- Incorporates information and communication technologies into every aspect of electrical generation, delivery and consumption in order to
    - Minimize environmental impacts
    - Enhance markets
    - Improve reliability and service
    - Reduce costs and improve efficiency
- The smart grid further employs digital information, distribution automation and various control strategies to facilitate deployment and integration of
    - Distributed Energy Resources
    - Renewable energy generation
    - Automated systems
    - Energy Storage systems
    - Peak shaving technologies

- Accommodates all types of generation techniques and energy storage options
- Provides higher power quality required for the 21st century digital economy
- Operates effectively and optimizes the utilization of existing and new assets.
- Operates resiliently and effectively against attacks and natural disasters.

Table II.1 shows a comparison between the traditional or the current electric grid and the proposed smart grid.

TRADITIONAL GRID	SMART GRID
Centralized Generation	Distributed Generation
No energy Storage	Energy Storage
One way Communication	Two way communication
Electromechanical	Digital
Manual Restoration	Self-healing
Failures and Blackouts	Adaptive and Islanding
Reactive Approach	Proactive Approach
Total control by Utility	Increased customer participation
Lack of real time monitoring	Extensive real time monitoring
Slow Reaction time	Extremely quick reaction time

Table II.1 Comparison of traditional grid and smart grid

It can be clearly seen that effective two-way communication in a Smart grid will help in significantly reducing the peak demand as well as the overall consumption. Further, higher penetration of renewable energy generation technologies will reduce CO_2 emissions and the associated global warming. Effective and well planned operation of the smart grid will lead to reduced operational costs, increased reliability, power quality and operating efficiency while optimizing asset utilization.

II.2 Need for a Smart Grid

II.2.1 Power Quality

In the past, power quality denoted the ability of electric utilities to provide electric power without interruption. But with higher penetration of non-linear loads, digital devices and other advanced power electronic equipment, power quality at present encompasses any deviation from a perfect sinusoidal waveform which includes Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) noise, transients, surges, sags, brown outs, black outs and any other distortions to the sinusoidal waveform. Harmonic distortions, a serious power quality issue can cause overheating of transformers, malfunctioning of equipment and even cause damage to the digital electronic control systems in operation. With increasing density of sensitive equipment on the electric grid, there is increasing pressure on the regulators to lay strict rules regarding power quality issues.

In a smart grid system, smart meters installed at end user locations have the capability to determine the THD (Total Harmonic Distortion) of the supply voltage. Such information will allow the utilities to determine the source of harmonic distortions. The location where the maximum THD is observed on the feeder can be assumed to be the source of the harmonics and remedial measures can be taken accordingly [12].

II.2.2 Increasing Renewable Energy Integration

The integration of renewable energy generation technologies is increasingly gaining importance due to concerns about global warming. At present, penetration of renewable energy generation is very low and can be handled by the current electric grid reasonable well. However, as the penetration increases, serious improvements and modifications would be needed to accommodate and integrate variable (stochastic) generation.

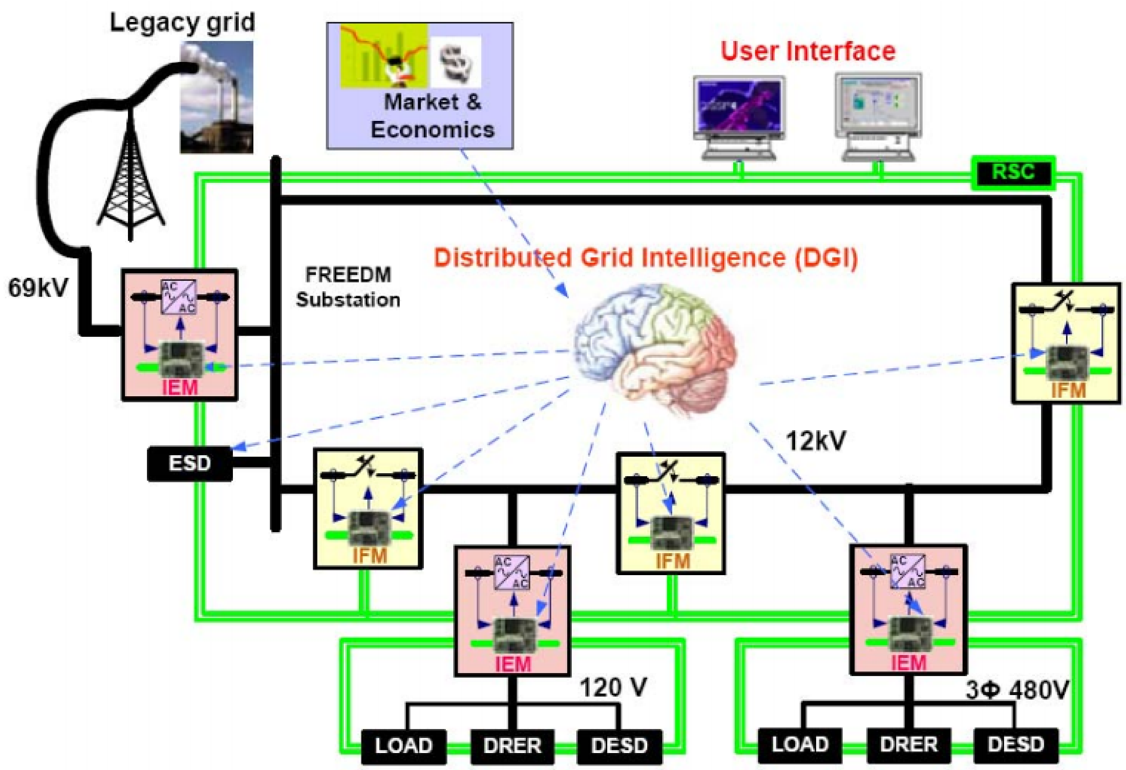

Figure II.2 Electric grid showing key elements of the FREEDM system [13]

With higher penetration levels, the electrical grid would require more fast-start and fast-ramping resources to make up for the generation shortfalls when such resources are not operating at their expected output levels [14]. Considerable amount of research is going on in this field and proposed systems such as the Future Renewable Electric Energy Delivery and Management (FREEDM) illustrated in Figure II.2 promises many of the issues. The objective is to have an efficient electric power grid integrating highly stochastic, distributed and scalable alternative generation sources and energy storage with existing power systems to facilitate a green and sustainable energy based society, mitigate the growing energy crisis and the impact of carbon emissions on the environment [13]. Thus the introduction of smart grids will not only reduce greenhouse gas emissions but also encourage increased integration of renewable sources and energy storage assets with the electric power grid.

II.2.3 Technology Development

The current electric grid severely lacks automation, especially on the distribution side of the grid. Though real-time load monitoring is used in the current system, they lack the ability to integrate information from a wide array of sources and equipment resulting in reduced situational awareness. Further, with an increase in energy efficiency programs, there is a severe shortfall in the ability to understand and act on the acquired data. Figure II.3 shows the technological evolution of the smart grid. The move to increasingly active distribution networks with stochastic generation, energy storage, and controllable and observable load is going to change the way electric power networks are planned and operated [15].

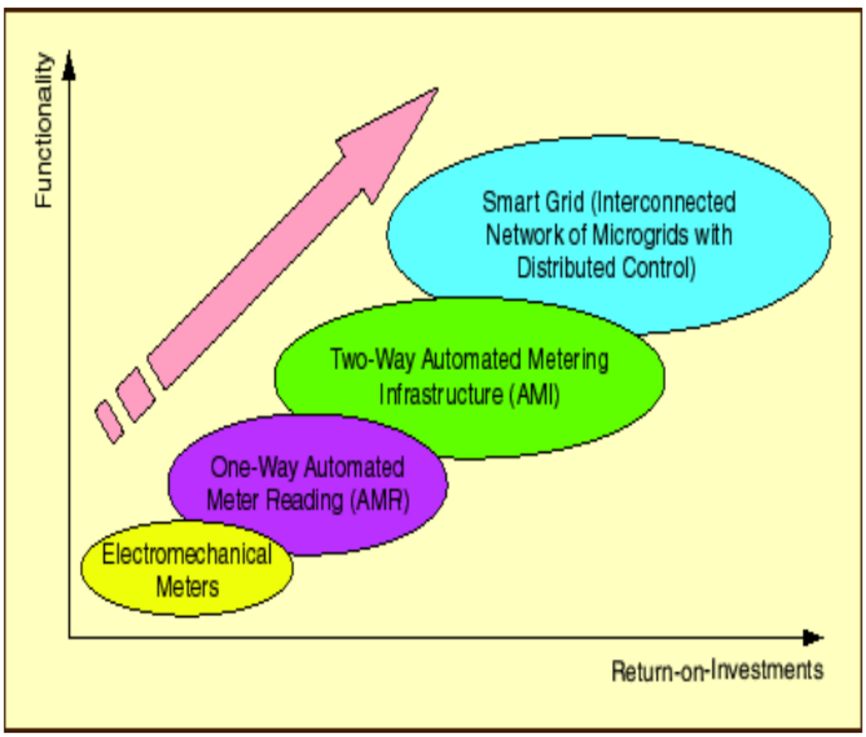

Figure II.3 Evolution of Smart Grid [16]

II.2.4 Peak Demand Reduction

As explained in the previous chapter, electricity is the epitome of the just-in-time process since electricity must be consumed the moment it is generated. Peak demand occurs during times of greatest need for electricity and prices of the same being at its highest. Due to a lack of anticipation of the time and nature of peak demand at a particular time, utility operators are forced to operate peaking plants longer than what is necessary to meet the demand and maintain availability of power. The generating units that meet the peak demand are generally expensive to operate since the fuel used in these plants are bought on the volatile “spot” market and most of the time are fossil fuels that contribute extensively to greenhouse gas emissions.

By introducing smart grids, advanced metering infrastructure, demand response and increased customer participation significant reductions of the peak demand will result. Such a smart grid implementation would help utilities drive down costs and in some cases even eliminate the use of these plants thus saving the planet from carbon emissions.

II.3 Smart Grid Technologies

II.3.1 Advanced Metering Infrastructure

The evolving smart grid is built upon distribution automation [17]. For a long time the term smart grid, especially from the vendors’ side, has been synonymous to smart metering, the advanced metering infrastructure (AMI) being the main focus of discussion involving smart grids [19]. An advanced Energy Management System (EMS) coupled with smart metering (at the end user level) as is shown in Figure II.4 would offer a variety of opportunities to reduce energy consumption and for peak shaving. The Smart Home Area Networks (HAN) would strengthen demand side programs and with advanced functionality of the advanced metering infrastructure the following additional functionalities would be realized:

- Real-time pricing/Time-of-use pricing
- Peak demand shaving
- Demand profiling
- Remote condition monitoring of sensitive equipment
- Load monitoring
- Outage detection and islanding

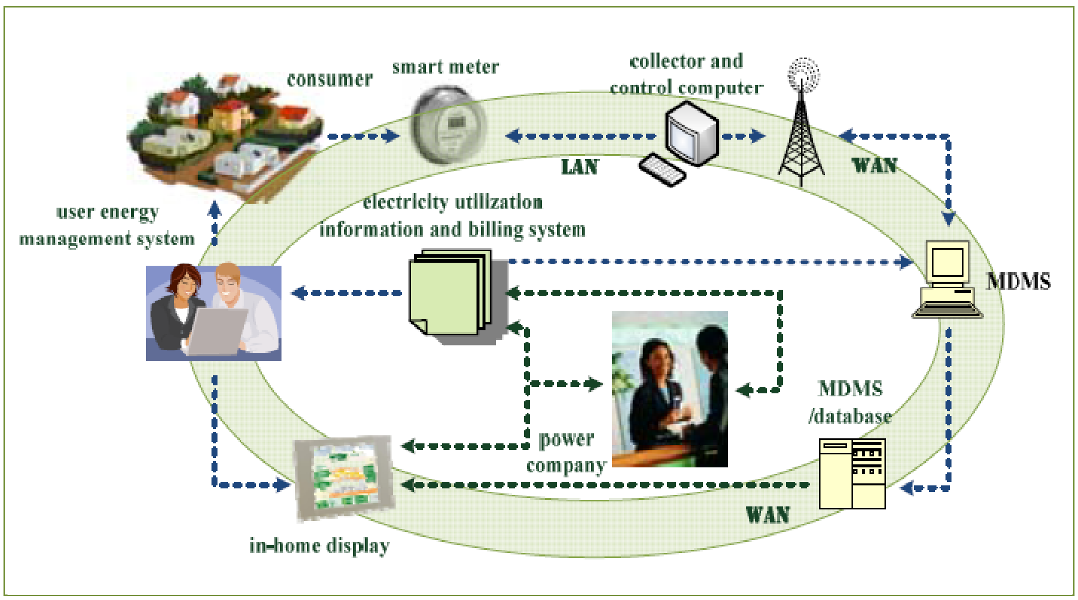

Figure II.4 AMI composition, structure and Data flow diagram [18]

Smart meters and other remote digital electronic devices that can be reached through a two-way communication network can generate massive amounts of data which need to be organized in a synthetic fashion to make them accessible to various users within the utility organization [12]. With an enhanced two-way communication technology, dynamic pricing models and load shedding techniques, load distribution management and reduction in peak demand can be achieved effectively and efficiently. It is also very important that the control center resynchronizes the pricing signals with the utility side database at regular intervals, which could otherwise jeopardize consumer's billing data and plan of action for energy conservation. Further, features such as data recording, power monitoring and tamper protection can prove vital in the long run.

II.3.2 Demand Response

Demand response (DR) is an important ingredient of the emerging Smart Grid paradigm and an important element in market design to keep the potential market power supply in check [20]. DR refers to the policy and business areas whereby electricity customers reduce or shift their electricity use during peak demand periods to 'price signals' or other type of incentives.

In recent years, DR has gained considerable interest among regulators and the government due to its economic and socio benefits. Texas being a leader in renewable energy generation, experienced a sudden, unanticipated and dramatic drop in wind power generation one afternoon in early 2008 causing a shortfall of around 1300 MW in just three hours. At this juncture, an emergency demand response program was initiated in which large industrial and commercial users restored most of the lost generation within ten minutes, acting as a buffer for this intermittent resource. This is an excellent example of smart grid principles in action [1]. Demand response technologies which primarily focus on end user technologies such as smart meters, time-of-use (TOU) pricing, and smart load controlling devices will increase customer participation providing tangible results for utilities and consumers in terms of economic benefits. The end users/building management offices may make use of the energy or demand prediction logic of smart meters to implement their peak shaving programs such as switching off some chiller loads to reduce the peak and save both electricity and money as well [21]. Thus, with more awareness and understanding of the smart grid technology and demand response programs consumers will be able to increase financial benefits and personal convenience, at the same time reducing greenhouse gas emissions.

II.3.3 Optimal Asset utilization and Operating Efficiency

One of the most important features of the smart grid is to increase the operating efficiency of the overall grid and reduce operations and maintenance costs of the electric power grid. The smart grid employs technologies that essentially make use of information including grid operating parameters and real-time data of reflecting the state of health of equipment etc, monitors equipment condition to detect the degradation in performance level, assesses its reliability to optimize its operation, even develop condition-based maintenance strategy according to fault type, and analyze its failure and maintenance characteristics to predict its life-span during its life cycle [22].

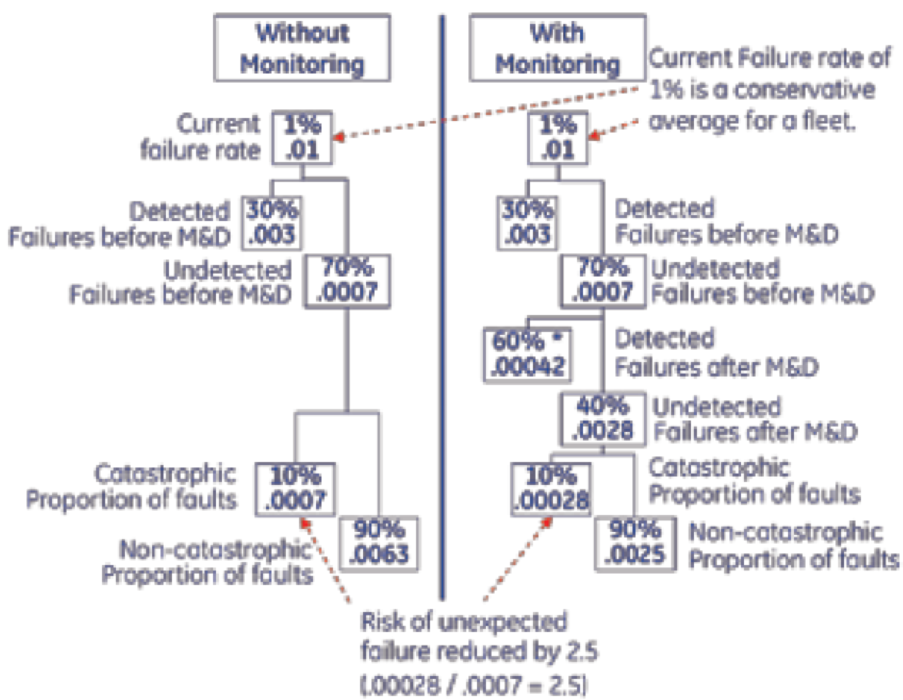

Figure II.5 Transformer reliability comparison [23]

A comparison of transformer failure rates with and without monitoring is illustrated in Figure II.5. It clearly shows that the risk of failure is around 0.7% without monitoring. With condition monitoring implemented to have a more proactive approach, the risks of catastrophic failures decreases to 0.028% which is 2.5 times less than having a reactive approach. Thus, the annual expenditure on maintenance can be reduced significantly with smart grid implementation.

II.3.4 Energy Storage

With increasing cases of blackouts, low power quality and increase in renewable energy generation, energy storage has become a major concern, leading to aggressive investments in energy storage technologies. Economic energy storage is highly desirable for peak shaving and power quality improvements. Energy storage devices enable the power system network to [24]:

- integrate renewable sources with the power system by converting them into a smoother and dispatchable format;
- provide ride through capability when the distributed generation fails to supply required energy; and
- manage the amount of power required to supply during peak power demand by storing it during off peak hours

Storage systems such as batteries (BESS), flywheels (FES), compressed air (CAES), pumped hydro (PHS), ultra capacitors (UC), super conducting magnetic energy storage (SMES), hydrogen storage etc. store energy in different forms such as electrochemical, kinetic, pressure, potential, electrostatic, electromagnetic, chemical, and thermal [25 - 29].

Lead Acid batteries are still used on a large scale due to their low cost and ruggedness but are losing popularity because of weight and power density issues. Sodium Sulfur (NAS) battery systems which are already in use at grid level by Tokyo Electric Power Company (TEPCO) since 1980's and are gaining much popularity due to their high power and energy densities, temperature stability, low cost and good safety [30]. Such storage technologies can complement the current power plants for peak shaving, emergency power supply, uninterrupted power supply and can be integrated later with various renewable energy generation resources.

Lastly, the value of energy storage technologies must be assessed with consideration to costs of installation in the short term, maintenance costs and revenue or savings provided by the energy storage in the medium term, and finally the potential long term benefits to the overall electricity infrastructure [31, 32]

II.4 Smart Grid challenges

II.4.1 Technical challenges

The smart grid is at a nascent stage of development. As such there are numerous technical challenges to be overcome [34, 41, 42].

- Merging planning and real-time analysis
- Very large system models
- Handling a large amount of AMI data
- AMI-based decision making
- Time series simulation
- DG integration and protection
- Cheap energy storage technology

Apart from the above, for effective interoperability of smart grid devices, robust standards need to be developed. Furthermore, with increased investments in the smart grid sector, a number of smart grid technologies are already being implemented in the electric power grid. In the absence of universal standards, these technologies face the danger of becoming prematurely obsolete or face its security being compromised.

Increased dependence on distributed generation, demand side resources and distribution system applications significantly increase the systems' exposure to cyber vulnerability [35]. The entire security architecture can be built on existing communication and technology infrastructures, further merging it with the electric grid to enable the Smart Grid implementation at various levels in the electric power system. Furthermore, a robust framework for conformity testing and certification of smart grid devices and systems need to be established to ensure interoperability and cyber security [33].

II.4.2 Business & Financial challenges

The business case for a smart grid needs to be established for successfully deploying the smart grid plans in real world. In its most general terms, a business case provides the basic rationale for investment in projects for business change. In the smart grid arena, the entities looking into building business cases are primarily network operators and possibly electricity retailers and newly emerging players such as generation and demand aggregators [36]. The initial capital cost of a full-fledged smart grid deployment would be significantly high and justifying it with site-proven benefits is the biggest business challenge facing the utility industry. Furthermore, consumers are skeptical about the cost benefits of such an investment as the cost benefits appear to be small compared to the investment made. Also, at the macro policy level, the power industry needs to meet the requirements of resource-saving and environment-friendly society, adapt to climate change and confirm with sustainable environment [37]. Further, sharing the cost of common infrastructure across the benefits derived from various applications will provide a more realistic cost / benefit ratio for each application in an integrated system for full roll out beyond the pilot stage [38, 39].

With so much investments put into the smart grid scenario, it is important for the utilities to recover their investment costs. Mostly smart grid is associated with costs savings at the consumer end, but it is also vital to note that on a broader perspective smart grids can lead to potential savings by increasing the reliability of the electric power grid. For example, with the implementation of wide-area measurement systems (WAMS) and phasor measurement units

(PMUs), the 2003 great northeast blackout could have been avoided saving the U.S. an approximately $10 Billion in economic damages.

Lastly, there is a need to address consumer concerns regarding plug-in hybrid electric vehicles (PHEVs) in terms of pricing, costs benefits, technical specifications and reliability. The plug in hybrid vehicles which will play an important role in future smart grid networks are currently very expensive and considered as a luxury rather than a way to save money and reduce carbon emissions. At present, the cost of converting a hybrid vehicle to a plug in hybrid electric vehicle is high and also there is very little infrastructure in the form of charging infrastructure to support this new technology. Also, PHEV's have still not gained universal acceptance as a contributor to reduced greenhouse gas emissions, since the fossil fuel base load plants are the ones powering these vehicles. All these issues in the PHEV sector need to be resolved to achieve universal acceptance of its technology and thus economic and environmental benefits.

II.4.3 Regulation challenges

With investments for smart grid deployment in the form of advanced metering infrastructure estimated to be around $27 Billion, and the Brattle Group's estimation of around $1.5 Trillion to update the grid by 2030 (Chupka et al. 2008) it is obvious that the cost factor and the regulation to permit the recovery of such investments are the biggest challenges the smart grid movement faces. Though the Smart grid is seen as a collection of technologies that enable an entirely new way of operating power systems, the utilities and regulators often view it as a collection of new kinds of transmission and distribution investments, each yielding unfamiliar new products and service streams. The utilities, regulators, and other stakeholders will have to evaluate these investments by measuring their value to customers, their impact on utility rates, and how customers and generators who use the new capabilities are charged for their use [40].

Today, with increased expectations from the smart grid, regulatory agencies face a monumental task of making sure the investements made in this sector do not prove futile. With a limited talent pool in this sector and increasing requirement for human resources, the regulators need to take up this challenge with determination and perseverance to transform the current grid into a smart grid.

CHAPTER III

CURRENT ELECTRIC GRID AT OKLAHOMA STATE UNIVERSITY

III.1 Overview

III.1.1 Design of Distribution Network

Distribution networks are the most complicated, most reliable, and also the most economical means for distributing power [43]. As is commonly done, at Oklahoma State University, the distribution system is broken down into three parts namely, the distribution substation, distribution primary and distribution secondary. Voltage level is reduced at the on-campus substation for distribution to various buildings and other electrical installations in the Stillwater campus. OG&E is the primary power supplier for the university. In addition, the university has an on-campus power plant which has an 8 MW generating capacity using natural gas as fuel. Due to its small generating capacity, it is limited to power only 18 buildings out of the more than 80 building located on campus. It is found that the total cost of generating power and transmitting it is higher than purchasing the same amount of power from the utility. Due to such an economic constraint, the on-campus power plant keeps the generation of power at a bare minimum and the chiller plants are used more frequently for heating purposes all across the campus. But during peak load conditions, especially in summer, the on-campus power plant does help in meeting the peak demand.

Figure III.1 shows one of the six segments of the current distribution system at the Stillwater campus of Oklahoma State University. It serves 13 buildings out of which 4 of them are considered as critical loads due to the density of sensitive equipment in them and the amount of research work being conducted in these buildings. These critical loads are more sensitive to power outages and voltage fluctuations. The protection systems used all across the university's distribution grid are fuses manufactured by S&C. The on-campus power plant is not connected to the grid shown in Figure III.1, thus lowering the redundancy of the overall distribution system under consideration. Also, the number of distribution lines across the university campus is significantly large and all the distribution across the campus is done using underground cables.

As illustrated in Figure III.1, buses are represented as nodes. It is known that there are different types of buses, an understanding of which would be very beneficial for this study.

The different types of buses are basically distinguished depending on their actual, practical operating constraints. The two major types of buses and which are of particular interest in distribution systems are load buses and generator buses. Load buses are referred to as PQ buses since, at the load bus an assumption is made that the power consumption data are provided by the end user. Thus both real power and reactive power are specified for every load bus. In Figure III.1, there are 13 load buses namely; Bus 9, Bus 10, Bus 14, Bus 15, Bus 18, Bus 19, Bus 22, Bus 23, Bus 31, Bus 32, Bus 35, Bus 36 and Bus 37.

In principle, at the generator buses P and Q can be specified. However, problems would arise with this. The first has to do with balancing the power needs of the system, and the second with the actual operational control of generators. As a result, it turns out to be convenient to specify P for all but one generator connected to the slack bus, and to use the generator bus voltage, V, instead of the reactive power Q as the second variable. Generator buses are therefore called PV buses [44].

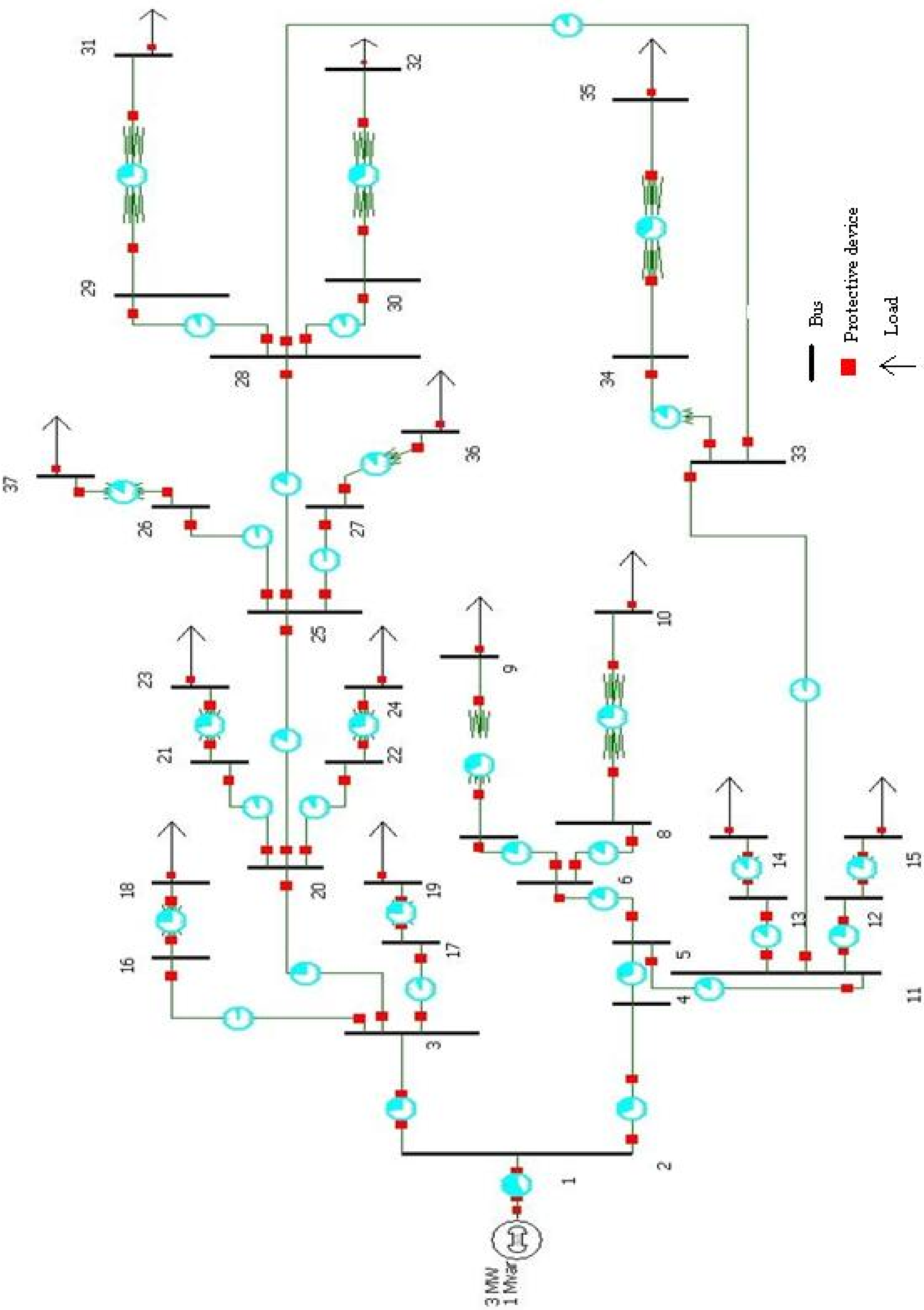

Figure III.1 A segment of the current distribution system layout at Oklahoma State University

Table III.1 summarizes the known and unknown variables for the various types of buses used in load flow studies.

Type of Bus	Given Variables	Unknown Variables (Calculated)
LOAD BUS	Real Power (P) Reactive Power (Q)	Voltage Magnitude (V) Voltage Angle (θ)
GENERATOR BUS	Real Power (P) Voltage Magnitude (V)	Reactive Power (Q) Voltage Angle (θ)
SLACK BUS	Voltage Magnitude (V) Voltage Angle (θ)	Real Power (P) Reactive Power (Q)

Table III.1 Types of buses and associated variables in load flow study

Using Power World Student v.13 software, load flow model for the current distribution system at Oklahoma State University was developed for one segment. With the load data, bus voltages and distribution line parameters as known values in the load flow analysis of the system under consideration, variation of bus voltages under changing load conditions or outages can be calculated. In addition, currents through the different lines can be calculated by the application of ohms law to each individual link. Also, it is important to know that all the currents at an instant are to be determined in order to compute the overall line losses in the system. Depending on the user's choice of programming the software, the basic output variables such as currents for all the lines can be stated in amperes, or it is even possible to express the flow in each and every link in terms of the real (Megawatts) and reactive power (MVAr) values.

III.1.2 Distribution Substation

Distribution substation design has been somewhat standardized by the electric utility industry based on past experiences. A typical substation may include the following equipments: (*i*) power transformers, (*ii*) circuit breakers, (*iii*) disconnecting switches, (*iv*) station buses and insulators, (*v*) current limiting reactors, (*vi*) shunt reactors, (*vii*) current transformers, (*viii*) potential transformers, (*ix*) capacitor voltage transformers, (*x*) coupling capacitors, (*xi*) series capacitors, (*xii*) shunt capacitors, (*xiii*) grounding system, (*xiv*) lightning arrestors/or gaps, (*xv*) line traps, (*xvi*) protective relays, (*xvii*) station batteries, (*xviii*) other apparatus [45].

There are two distribution substations on campus, one rated at 14.4 KV and the other at 24 KV. These substations feed the entire distribution system at Oklahoma State University, Stillwater campus.

III.1.3. Distribution Feeders

The majority of the distribution feeders at Oklahoma State University are either radial or loop feeder type. It is a known fact that radial feeder designs are most widely used at distribution levels all across North America due to its reduced costs and ease of planning, design, operation and analysis. But the biggest drawback of a radial system is that it provides a single electrical path from the substation to the end user. On the other hand, the loop system such as the one illustrated in Figure III.1 has two separate electrical paths to feeding the loads. The network feeder systems which are an improvement over the loop feeder systems have multiple paths to feed the load. The loop and the network feeders systems help in exponentially increasing the redundancy of the entire network. Figure III.2 illustrates the different types of distribution system designs.

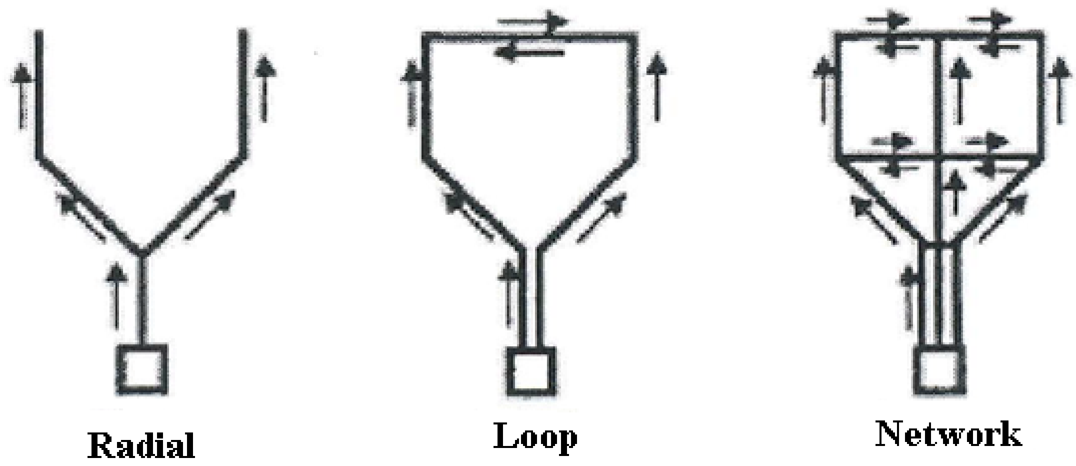

Figure III.2 Simplified illustration of the concepts behind three types of power distribution configurations [5]

As seen in the Figure III.2, the loop system exactly matches the current OSU distribution system under consideration and shown in Fig III.1. The feedback loop in the current system is connected from Bus 28 to Bus 33. In terms of complexity, a loop feeder system is only slightly more complicated than a radial system – power usually flows out from both sides towards the middle, and in all cases can take only one of two routes. Voltage drop, sizing and protection engineering are only slightly more complicated than for radial systems [43].

III.2. Challenges

With a vast main campus consisting of around 80 buildings, it is a monumental task for the utilities department to keep the lights ON every single minute of the year. The university does have an on-campus power plant with a capability to generate 8 MW of electricity using natural gas. Although OSU receives most of its electrical power from OG&E, the OSU power plant acts as a system buffer and back up supply. All distribution is done using underground cables for aesthetic purposes and as such faces problems such as shifting terrain leading to cracking of underground banks, water seepage and higher installation and maintenance costs.

As illustrated in Figure III.1, though redundancy is provided by means of a feedback loop connected from Bus 28 to Bus 33, the S&C switches and the protection devices being fuses, a considerable amount of time is lost in restoring power during power outages. Furthermore, a fault on Bus 1 would lead to a complete blackout causing significant financial losses to the university. One critical problem with the current distribution system illustrated in Figure III.1 is that during times of outages, its own feedback loop has to take care of re-routing power since the on campus power plant is not connected to this loop. This operation leads to disturbance of voltage levels at all buses. As discussed earlier, the loads connected to buses 10, 35, 31 and 32 are treated as critical loads. These buildings thus consist of a high density of electronic and sensitive equipment. Hence, it becomes extremely essential to provide enough redundancy in the electric grid connecting these loads to avoid any kind of outages. Also, it is preferred to have the voltage levels at other buses maintained above 0.99 p.u.

Though there have not been any major campus blackouts in the past few years, the electrical system needs to be upgraded since it is plagued with various challenges that need to be addressed. They are:

- Significant load growth
- Not much reliance on distribution automation
- No uniformity in distribution voltage levels
- Control center operation not extended to the building level
- Less investment on power system upgrade schemes

III.3 Load Flow Study

Load flow or power flow studies are by far the most important calculations in power system engineering, since it calculates the network performance under normal as well as during times of faults, disturbances or outages. Load flow calculations allow the designer to ensure that the current in the various branches of a network do not exceed their safe working limits or reach an otherwise unsuitable value [46]. It is more importantly used in expansion planning studies and by using optimal power flow technique the most economical operation of the current system. The results acquired from load flow studies are very helpful in designing appropriate protection schemes too. With input data provided such as the distribution system connection diagram, load data in the form of real and reactive power, transmission line parameters and transformer parameters, the condition and operation of any current system or proposed system can be studied and analyzed using load flow studies. A load flow analysis can provide the following information [47]:

a) Voltages at each bus;
b) Phase angle for each bus;
c) Power flow in each line (Megawatts and Megavars);
d) Megawatt and megavar loss in each line;
e) Direction of reactive power flow;
f) Required transformer capacities;
g) Transformer losses;
h) Generator and tie capacities;
i) Transmission line megavolt ampere capacity requirements;
j) Effects of transformer tap selection;
k) Line protective relay settings;
l) Area megawatt and megavar losses;
m) Total system megawatt and megavar losses;
n) Power factor of equipment and lines.

Further, multiple load flow studies can used to obtain the following information:

a) Optimum system operation;

b) Balanced reactive flows;

c) Effect of future loads (load growth);

d) Effect of new lines;

A load flow study on a segment of the current distribution system at Oklahoma State University is performed and all of the above results can be obtained as required. The entire system comprises of 37 Buses and load data, distribution line parameters and bus voltages are used as input data to conduct the study. The following load data are used in the study.

Load name	Real Power (MW)	Reactive Power (MVAr)	Apparent Power (MVA)
Building 1	0.45	0.22	0.5
Building 2	0.36	0.19	0.4
Building 3	0.27	0.11	0.3
Building 4	0.45	0.3	0.54
Building 5	0.04	0.1	0.04
Building 6	0.1	0.06	0.11
Building 7	0.1	0.03	0.1
Building 8	0.18	0.09	0.2
Building 9	0.11	0.05	0.12
Building 10	0.14	0.06	0.15
Building 11	0.15	0.05	0.16
Building 12	0.02	0.02	0.03
Building 13	0.07	0.03	0.08

Table III.2 Load data of a segment of the current OSU Distribution system

CHAPTER IV

PROPOSED TECHNIQUES FOR SMART GRID INITIATIVE AT OKLAHOMA STATE UNIVERSITY

IV.1 Incorporating Distributed Generation

Distributed generation, or DG, includes the application of small generators often in close proximity to loads, typically ranging in capacity from 15 to 10,000 kW, scattered throughout a power system, to provide the electric power needed by electrical consumers. As ordinarily applied, the term *distributed generation* includes all use of small electric power generators, whether located in the utility system, at the site of a utility customer, or at an isolated site not connected to the power grid [48]. The service availability of a well-designed electric distribution system is generally of the order of 99.96%. It becomes increasingly difficult and economically less feasible to increase the availability above 99.96% which would also require expensive equipment with several levels of redundancy. A high quality DG unit has a service availability of about 95%(including time out of service for both scheduled maintenance and unexpected failures and repairs). The best units have availabilities in the range of 98%. Thus, it takes redundancy, sometimes up to 100% additional capacity, to assure that DG power will always be there. Distributed generation is tailorable in both cost and reliability to a degree that the electric utility often cannot match [49, 51].

A micro grid system that includes distributed generation is one of the many ways to help the existing distribution system at the Stillwater campus of Oklahoma State University to increase its system redundancy, efficiency and improve the voltage profile of the network. A possible connection of distributed generation with the current system is illustrated in Figure IV.1. This action will result in an improved and more robust system as compared to the existing one shown in Figure III.1.

Implementation of distribution automation devices in the system such as advanced voltage and current sensors with integrated wireless communication technology will significantly reduce the outage time and also aid in maintaining a database for the various parameters of the complete system under consideration. The important item for the sensor assembly is the need for a communication interface with a communication network to transport the data to a repository and management system. The accumulated data have to be tagged with circuit information before reaching their final destination which is the data management system [50]. A large number of advanced voltage and current sensors can be deployed by connecting them to feeders and their loads. Such a scenario would prove to be economically unjustified and thus it is important to have such sensors installed near critical loads only. As illustrated in Figure IV.1, sensors are installed on feeders connecting to bus 10, bus 31, bus32 and bus 35, which, as mentioned before, are the ones feeding critical loads. With this, critical loads connected to the network are protected from outages and voltage disturbances and at the same time this is a more economically viable option.

Apart from the above, such an automated distributed generation configuration will also help the electric power grid at OSU with various other benefits such as:

- Emergency Power supply – With increasing outages and faults at OSU due to increased stresses on the distribution system, emergency power supply is a key requirement for critical loads. This can be achieved by distributed generation integrated with the current electric grid at OSU.
- Power quality benefits – There is a steady increase in the power quality requirement across the university campus and is expected to increase further in the future. DG and distribution automation can be very useful in improving the quality of power distributed across the university.
- Increase in operating reserve – With more penetration of DG into the current distribution system at OSU, an increase in the overall operating reserve can be achieved.
- Economic benefits from peak demand reduction – With DG along with aggressive energy efficiency programs, peak demand can be reduced thus financial losses to both OSU and OG&E.

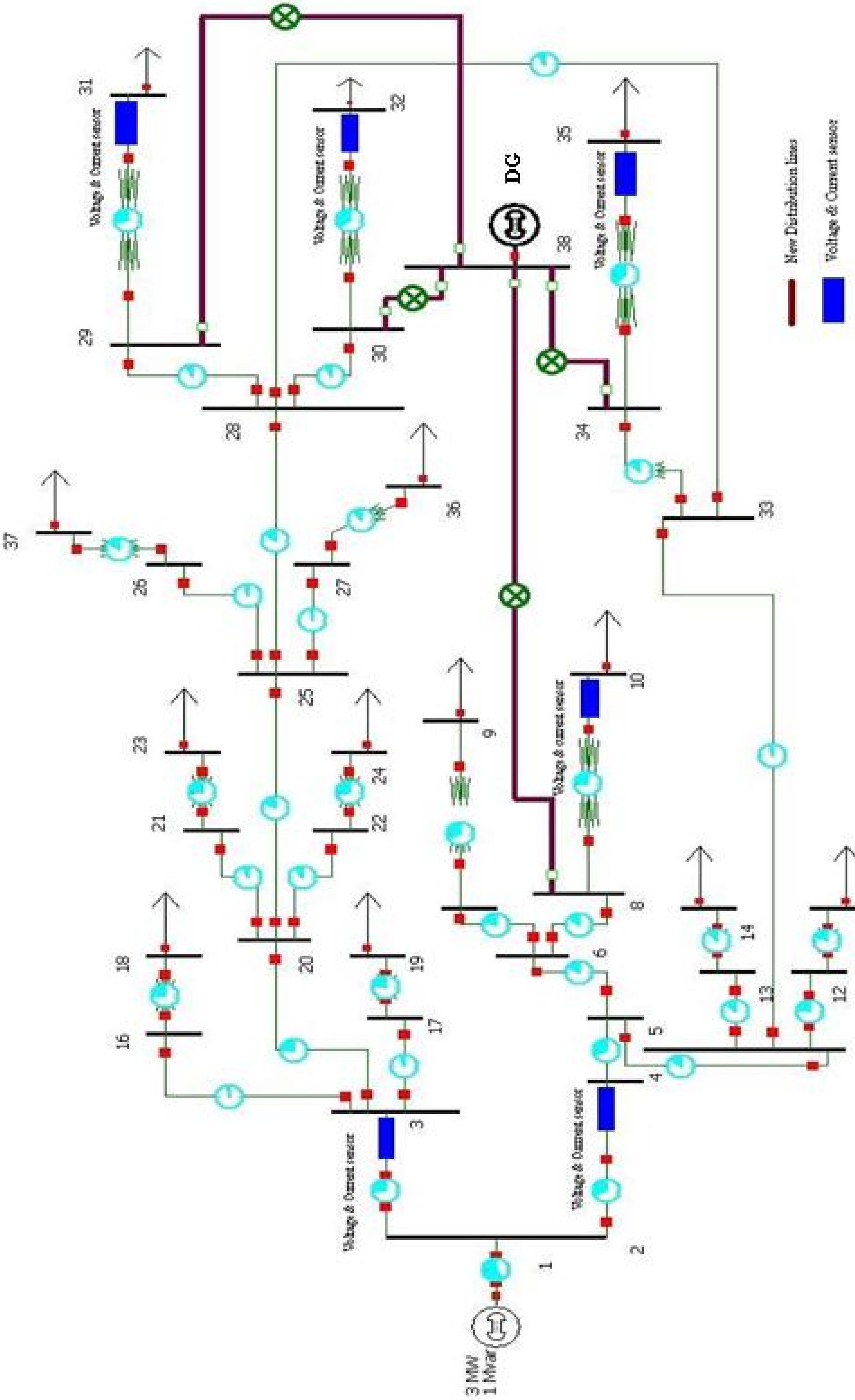

Figure IV.1 A segment of the current electric grid at OSU with Distributed Generation and added distribution lines

IV.2 Discussion of Simulation Results

One of the six segments in the existing distribution system at the Stillwater campus of Oklahoma State University is modified by adding a 300 kW DG with additional distribution lines connecting the DG to buses near critical loads as shown in Figure IV.1. Load flow analysis of this system is run considering various scenarios. Scenario 1 and scenario 3 consider an upstream in-line fault on the distribution lines which connects bus 4 and bus 3 respectively. Scenario 2 and scenario 4 consider downstream in-line faults near bus 34 and bus 30 which connect the critical loads through a step-down transformer. The charts presented for various scenarios represent the p.u. voltage values at all busses. Further, the bar graphs represent the percentage increase in p.u. voltage at all buses for the respective scenarios.

As illustrated in Figure IV.1, voltage and current sensors are placed near critical load buses namely bus 10, bus 31, bus 32 and bus 35. The operational sequence of these sensors for the various scenarios are clearly presented in the operational logic diagrams shown in figures IV.3, IV.7, IV.11 and IV.15.

The in-line faults considered in the study is a 3-phase balanced fault. Also, the line data used in this study and the load flow results for all scenarios are presented in the appendix.

IV.2.1 Scenario 1

As shown in Figure IV.2, for scenario 1, an in-line fault is considered between bus 2 and bus 4. Such faults occur on a more frequent basis, the worst being a 3 phase balanced fault. This would cause the protective device on the respective feeder to come into effect and accordingly take appropriate corrective action. In case of the OSU distribution system, fuses are used as protective devices which, in case of a fault, would cause it to open thus avoiding a cascading effect and preventing the fault from propagating upstream. With the newly proposed system consisting of distributed generation and automated voltage and current sensors connected at critical load points, a complete blackout scenario can be avoided. But it is highly important and essential that the operation of the proposed system takes place in a planned way as shown in the operational logic diagram shown in Figure IV.3. This would improve the overall voltage level at all buses and provide effective redundancy to the overall system. More importantly, it would help in safeguarding the critical loads from an outage situation. It is important to note that in this study, the DG is always in the ON state.

With the use of advanced voltage and current sensors in the proposed system, it is important to arrange a predetermined set point for each. If the voltage or current in the circuit goes below or above the set value respectively, the sensors would automatically take corrective action. The voltage and current set points in this case would be 0.994 p.u. and 400 Amp respectively. As in this scenario, when an in-line fault occurs between bus 2 and bus 4, it is observed that the voltage levels at various buses decreases significantly as illustrated in Figure IV.4. During such an instance, the voltage sensors at bus 4, bus10 and bus 35 which continuously compare the bus voltage with the reference values will activate as the voltage at the corresponding bus is observed to go below the predetermined value. When such a scenario exceeds a certain time duration (which needs to be considered to avoid corrective operation of voltage sensor during a voltage flicker or voltage sag), the voltage sensors will automatically send a signal via the communication line to the central station, leading to the switching ON of the line connecting bus 34 and bus 38 and distribution line connecting bus 38 and bus 8. Such a coordinated operation needs to be performed in this case, as it is observed that the voltage levels at both buses 10 and 35 drop below the predetermined set point.

On the other hand, the protective device (fuse) connected between bus 2 and bus 4 will operate due to the rise in current above the allowable limit. If an automated protective device is considered to be in use instead of the fuse, the current sensors located at bus 35 and bus 10 which continuously compares the current through the circuit to the reference will send a signal to the protective device to operate during such an overcurrent fault situation. Also, at the same instant, a signal is sent to the control station to activate the distribution line connecting the DG to the affected buses. Since OSU uses fuses as protective devices in its distribution system, an overcurrent condition would lead to the opening of the circuit. For restoration of power, it thus becomes mandatory to replace the fuse in the circuit which, further requires physical plant services personnel to go to the fault location and take corrective measures. Once the cause of the fault is identified and fixed, the line can be restored and if the voltage and current sensed by the sensors are within limits, the distribution line connecting the DG and the critical buses switches off automatically.

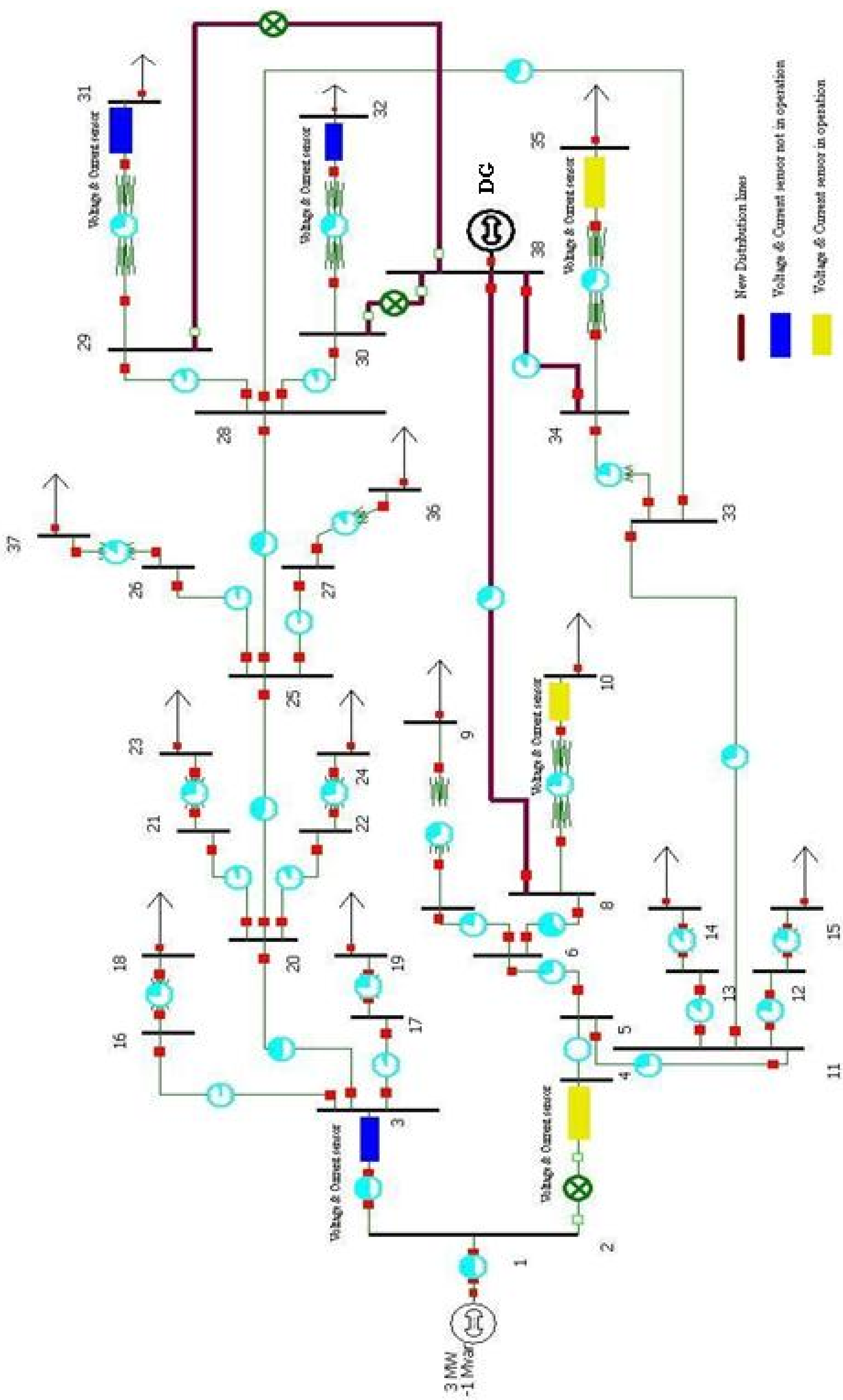

Figure IV.2 A segment of the current OSU Electric Grid with Distributed Generation & with in-line fault between Bus 2 and Bus 4

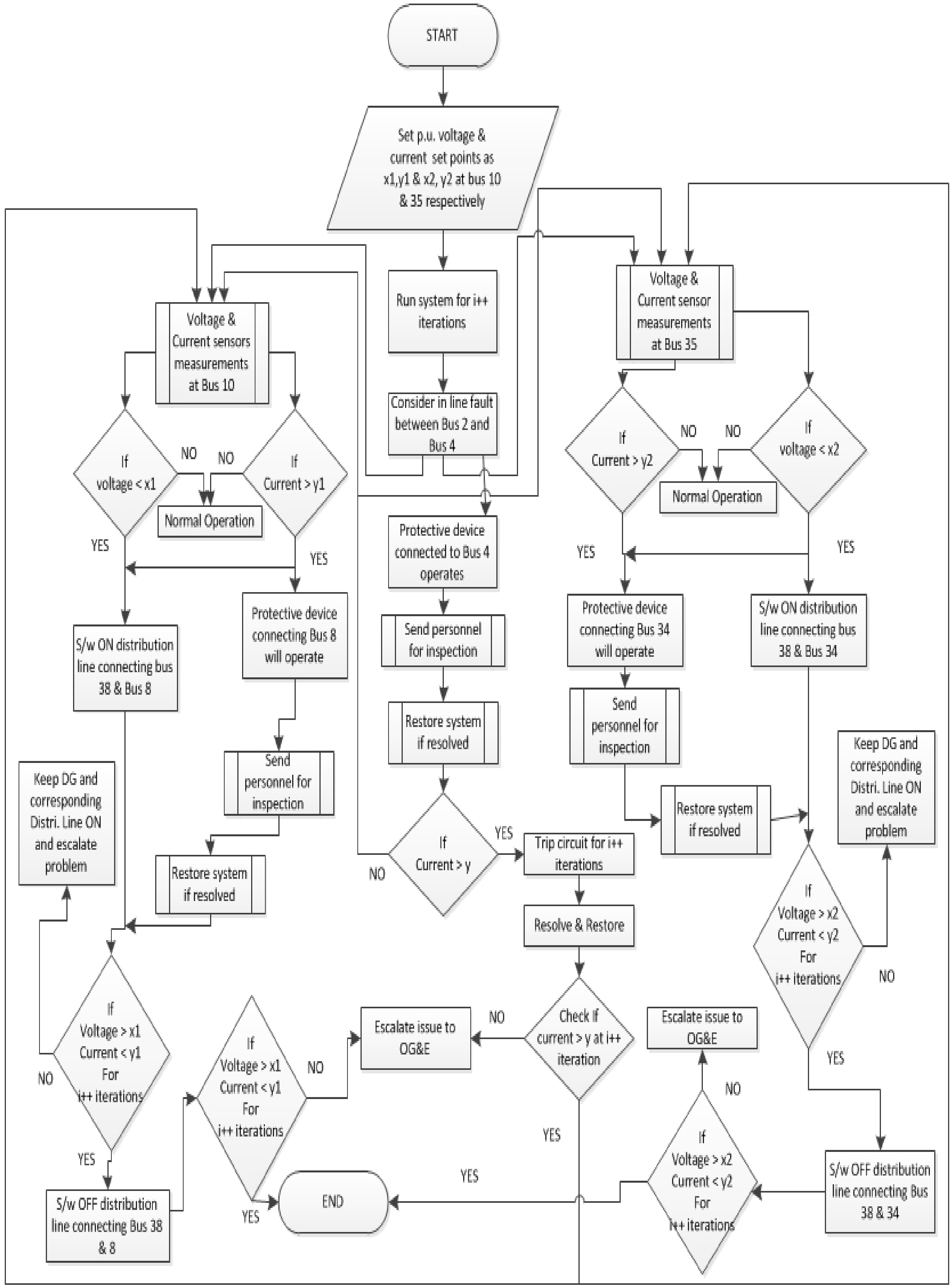

Figure IV.3 Operational logic for in-line fault between Bus 2 and Bus 4

As shown in Figure IV.4 and Figure IV.5, a well-planned and coordinated operation of the proposed scheme results in significant improvement in the bus voltage levels at various nodes in the grid and more importantly at the buses connected to the critical loads.

Even if there are multiple in-line faults in the distribution lines connecting to buses 8, 34 and 4, the voltage and current sensors will act according to the same operational logic as shown in Figure IV.3. If the voltage and current values at the buses under measurements are out of preset limits, the operation of re-routing power using DG will again come into effect.

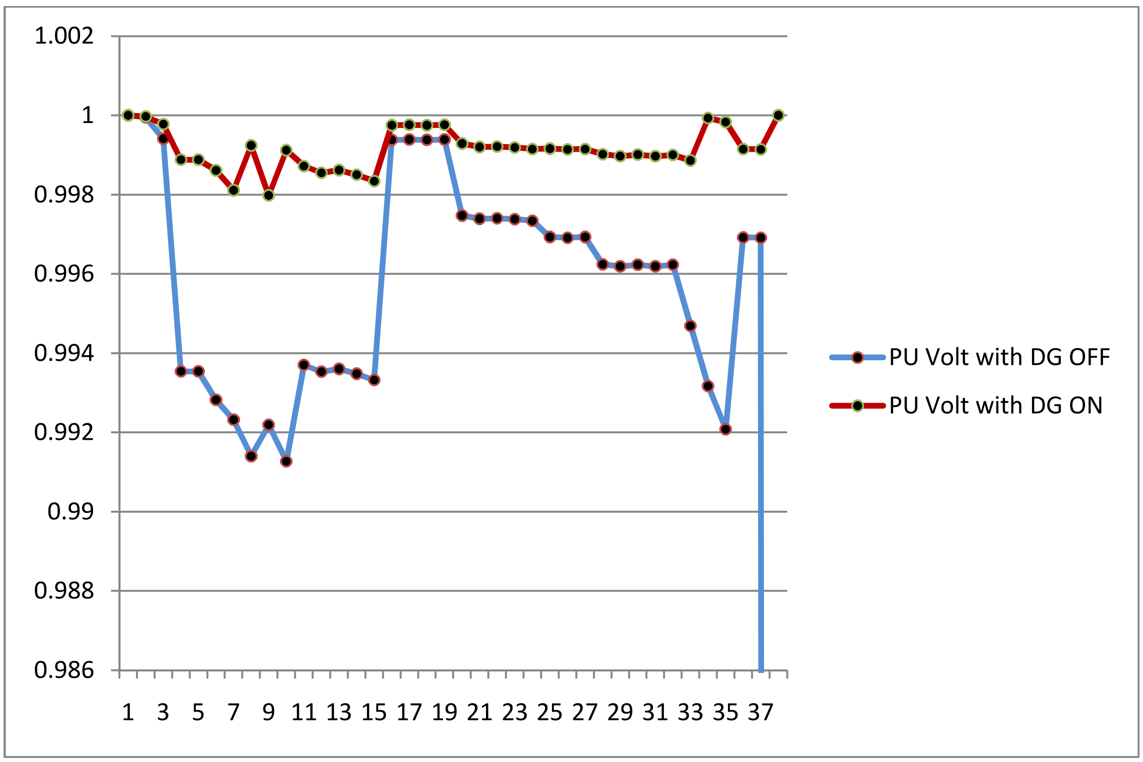

Figure IV.4 p.u. voltage at all buses during in-line fault occurrence between Bus 2 and Bus 4

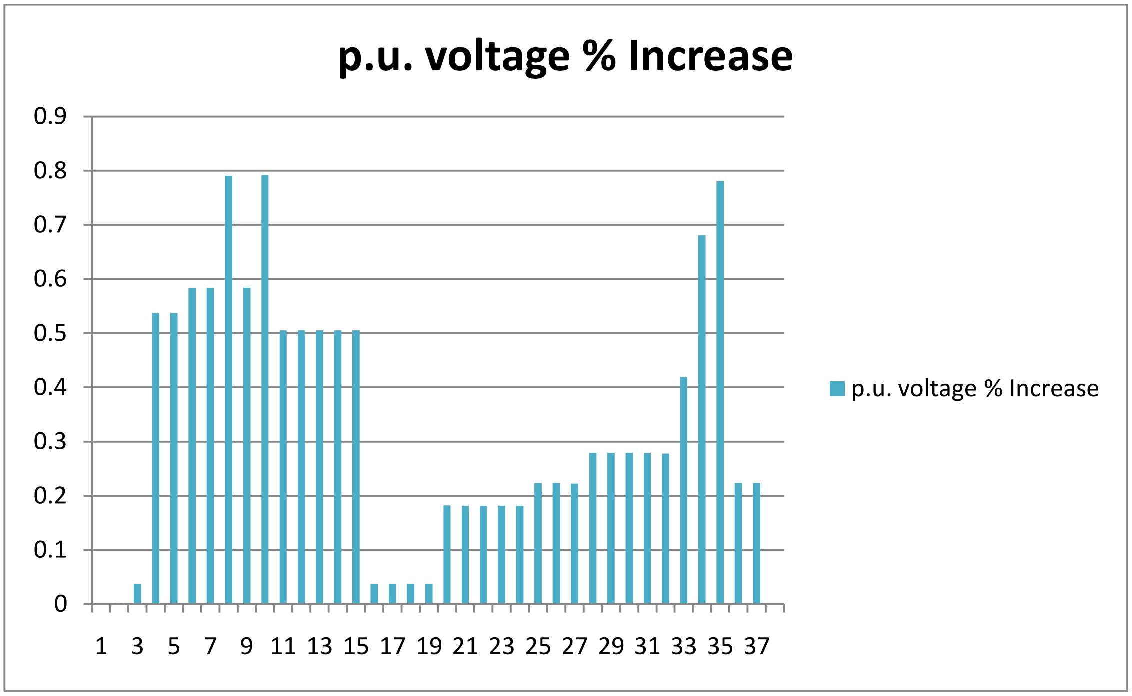

Figure IV.5 p.u. voltage percentage increase with DG in system and in-line fault between Bus 2 and Bus 4

IV.2.2 Scenario 2

As illustrated in Figure IV.6, an in-line fault is considered between bus 33 and bus 34. This is a downstream fault and thus less severe as compared to the previous case in which an upstream fault was considered. But, since a critical load is connected to bus 35, an outage at bus 34 will prove to be catastrophic. The load connected to bus 35 being a research building, loss of power to this load would lead to significant financial loss.

With the proposed system, such a scenario is eliminated due to the re-routing of power provided by the DG connected to bus 34. The entire operation of the proposed system would take place as illustrated in the operational logic diagram shown in Figure IV.7. When an in-line fault occurs between buses 33 and 34, the voltage level at bus 35 drops to zero and thus triggers the voltage sensor installed on the same bus. During an occurrence of such a fault, the voltage sensor sends a signal to the central station prompting to switch on the line connecting bus 34 to bus 38 at which the DG is installed. At the same time, the fuse which operated due to the fault current is replaced and the line is restored back to normalcy.

Once that done, the voltage and current sensors again compare the voltages and currents at bus 35. If observed to be within acceptable limits, such a scenario would further make the sensors to send a command signal to switch off the line connecting the DG and bus 34. As clearly illustrated in Figure IV.8 and Figure IV.9, the voltage levels at bus 34 and bus 35 are restored. Thus the well-coordinated operation of the proposed scheme effectively avoids an outage at the critical load bus 35.

In short, such a type of network operation makes sure that, there is no outage at critical buses and also the voltage levels at all other buses are maintained within acceptable limits. The immediate re-routing of power avoids any kind of outage time thus making the entire distribution network under consideration more redundant, efficient and cost effective.

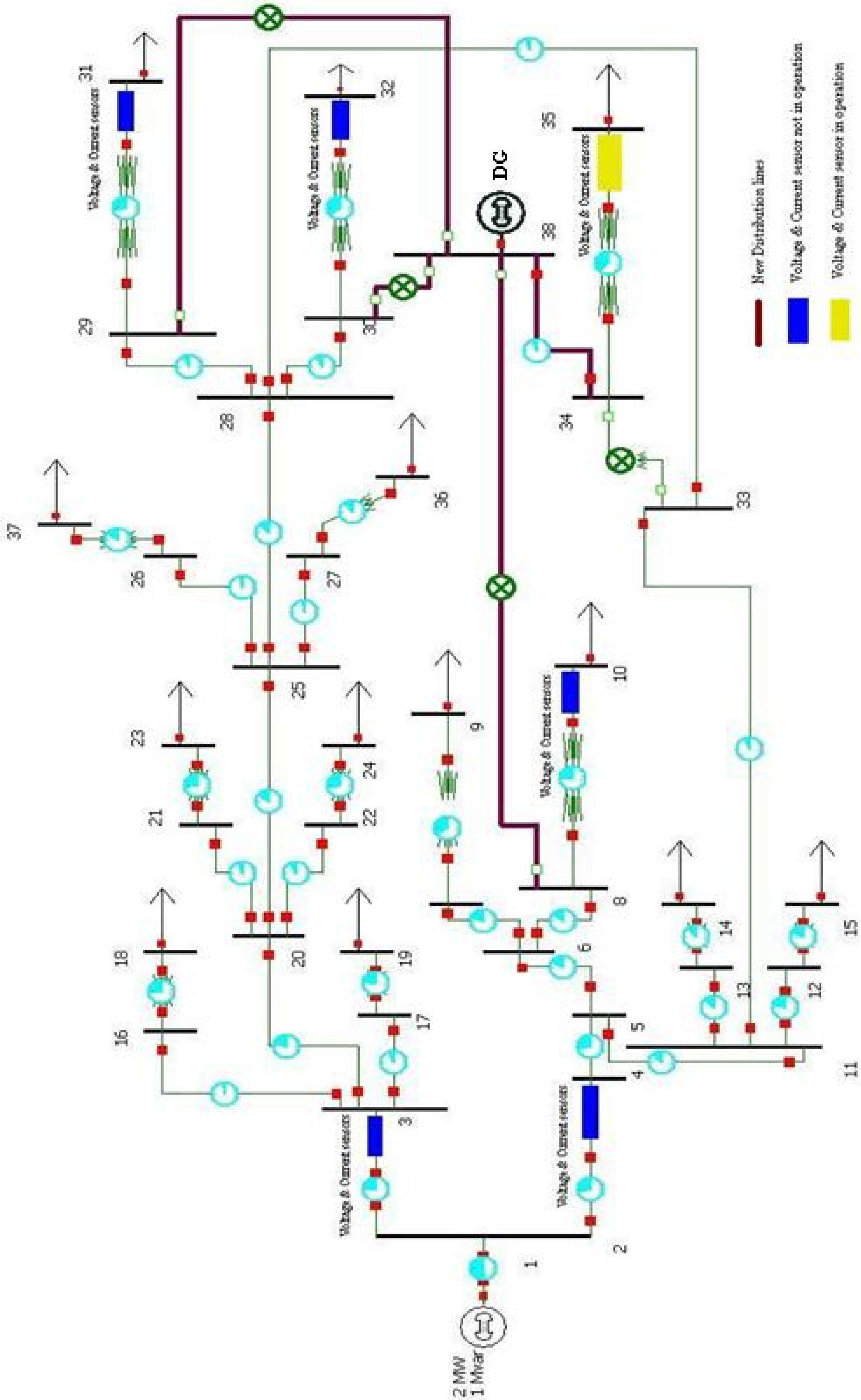

Figure IV.6 A segment of the current OSU Electric Grid with Distributed Generation and in-line fault between Bus 33 and Bus 34

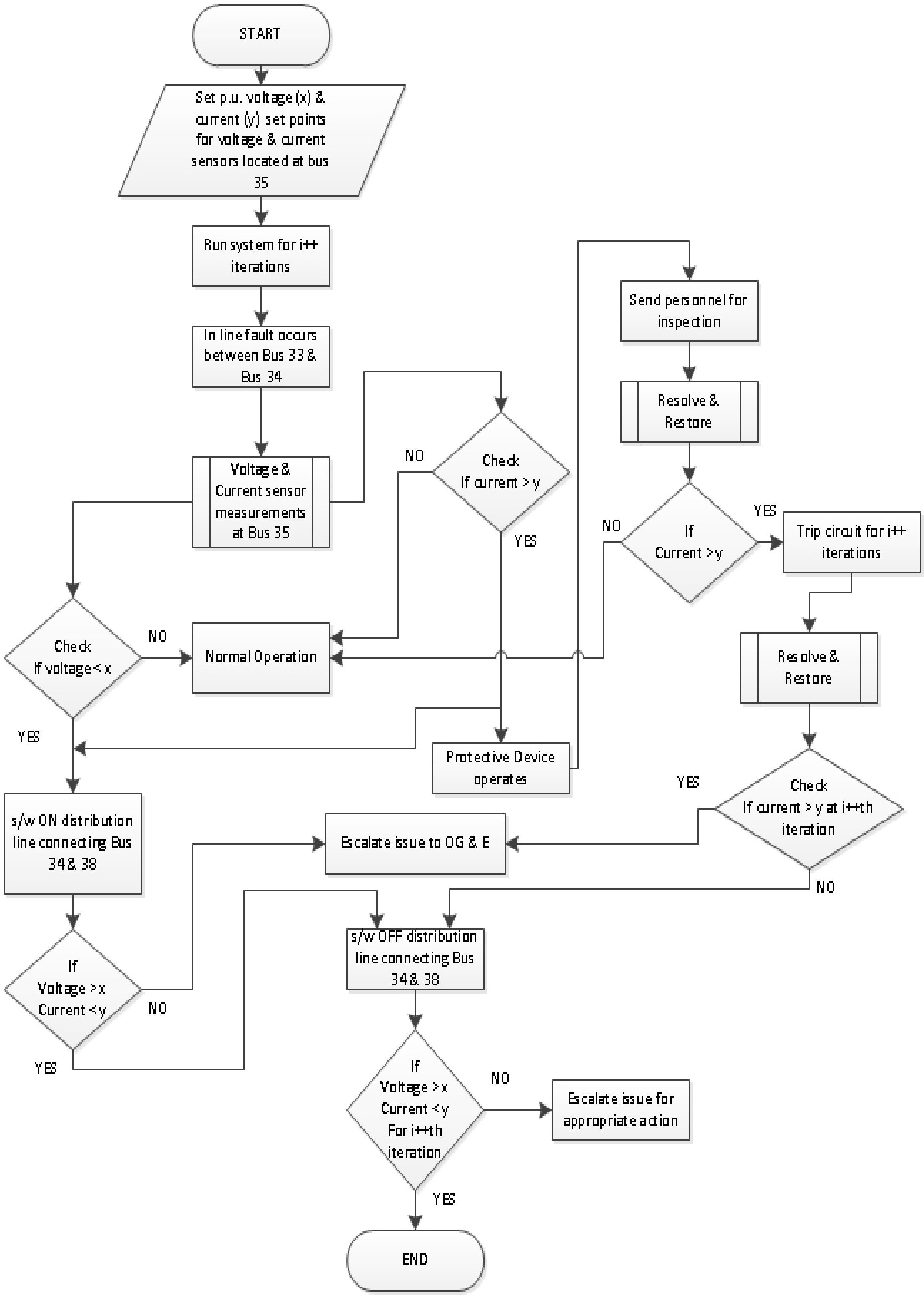

Figure IV.7 Operational logic for in-line fault between Bus 33 and Bus 34

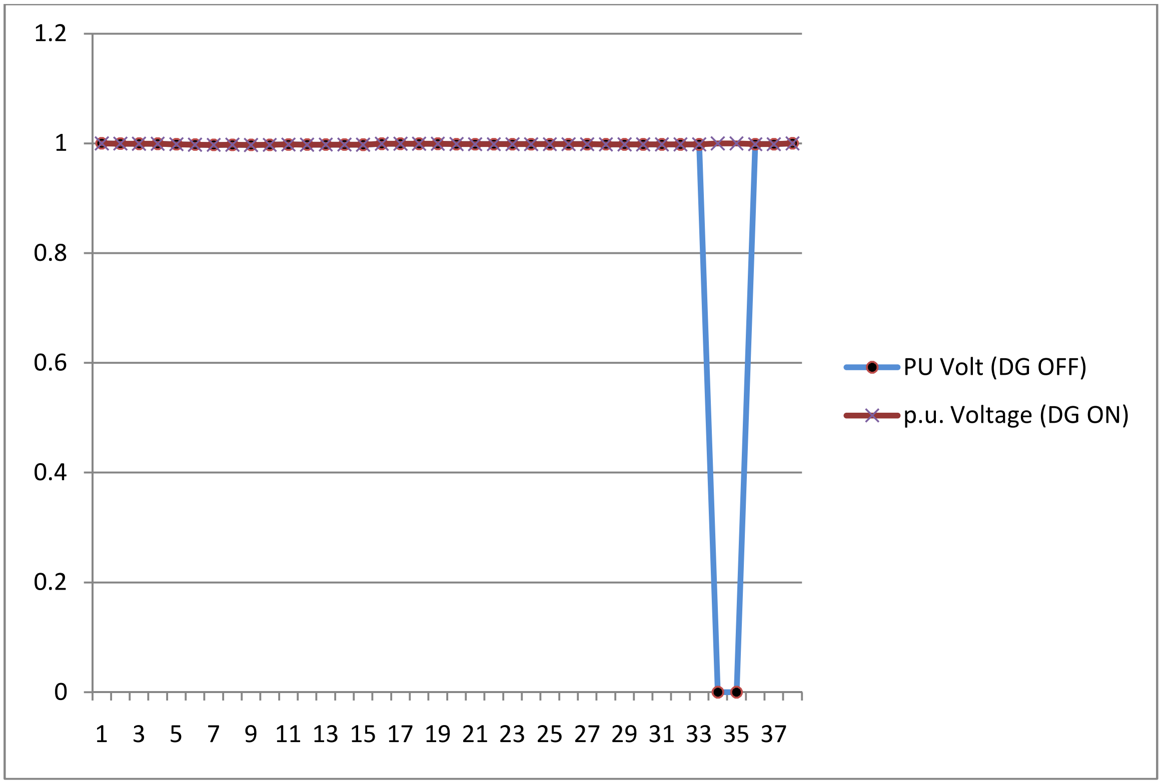

Figure IV.8 p.u. voltage at all buses during in-line fault occurrence between Bus 33 and Bus 34

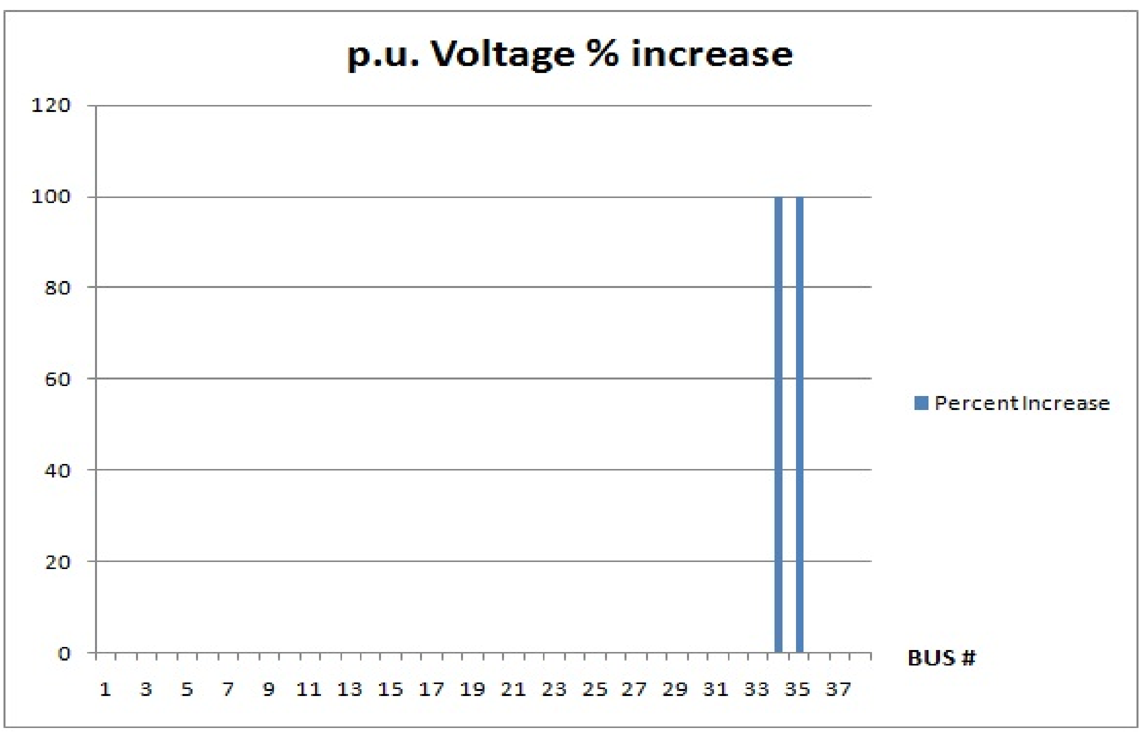

Figure IV.9 p.u. voltage percentage increase with DG in system and in-line fault between Bus 33 and Bus 34

IV.2.3 Scenario 3

This case is similar to scenario 1, where the occurrence of an in-line fault between bus 2 and bus 4 was considered. In this scenario, as shown in Figure IV.10, the occurrence of an upstream in-line fault is assumed to be between bus 2 and bus 3. It is observed that due to the opening of the fuse connected in the line between bus 2 and bus 3, the voltage levels at various buses in the system are affected significantly. It is observed that there is no outage created at any bus due to the feedback loop provided which initiates re-routing of power during such an upstream fault scenario. But since drop in voltage levels at the critical buses are of particular concern, the proposed system will provide a much more effective way of handling such faults or outage situations. During such an upstream fault scenario, the operation of the proposed system would work according to the proposed operational logic diagram shown in Figure IV.11.

For this case, the variation of the voltages at buses 10, 31 and 32 are clearly shown in Figure IV.12. As illustrated, the voltage levels at a number of buses fall sharply due to the outage at bus 3. More importantly, there is a sharp decrease in the voltage level at the critical load buses, namely bus 31 and bus 32. Since, these buses are serving critical loads; such a situation could prove far worse especially during peak load conditions. Again, in such a fault condition, the voltage sensors at bus 31 and bus 32 will measure the bus voltages against the reference voltage. As observed in this operation, the voltages at the critical buses are observed to drop below the reference level which in this case is 0.994 p.u.; thus triggering the voltage sensor which would then send a signal to switch on the distribution line connecting the DG. On the other hand, due to the sudden rise of current, the protective device connected to bus 3 operates isolating the fault from the rest of the system. Since the protective device in the system under consideration is a fuse, repairmen are sent to the fault location to resolve the problem and restore the system.

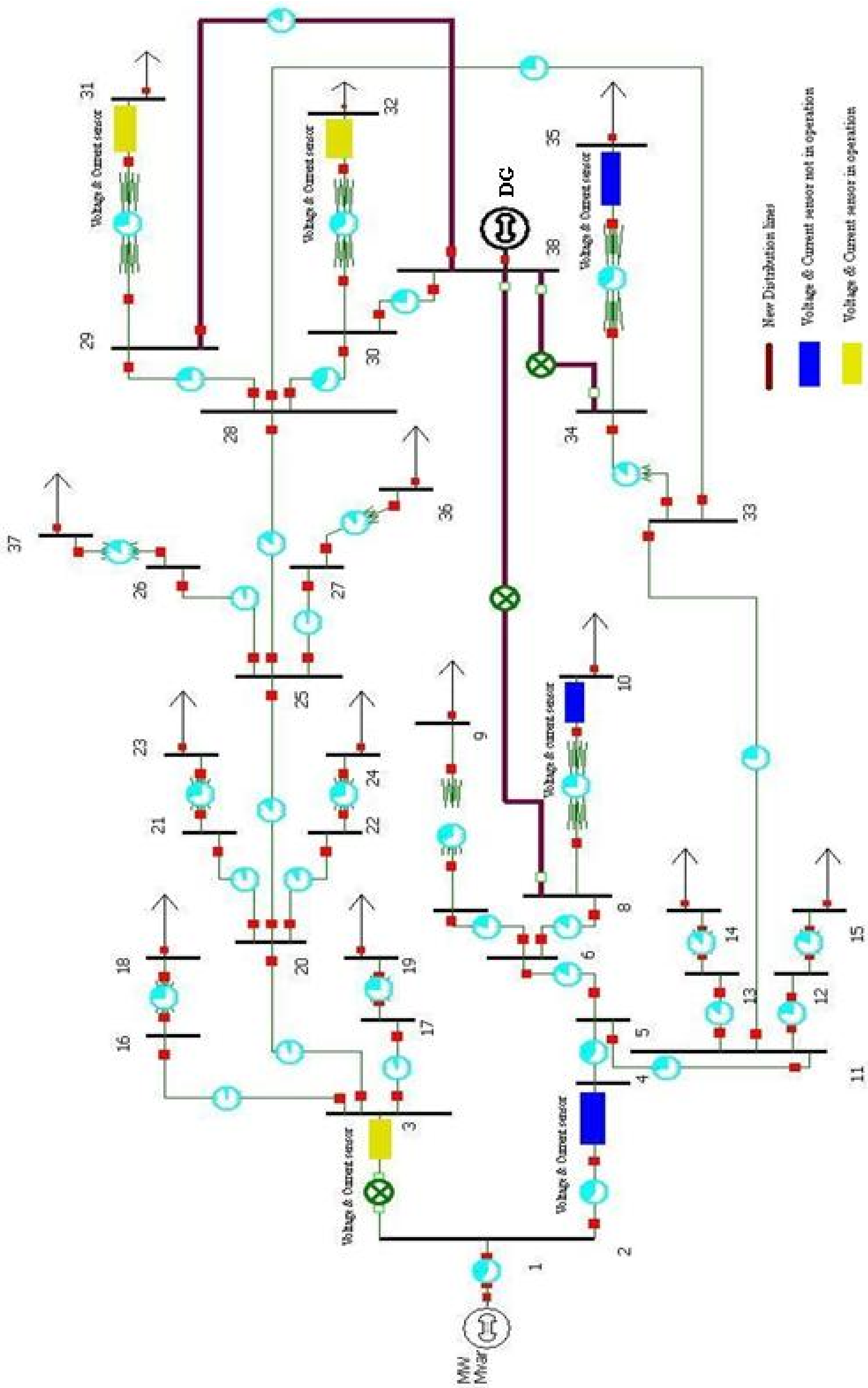

Figure IV.10 A segment of the current OSU Electric Grid with Distributed Generation & with in-line fault between Bus 2 and Bus 3

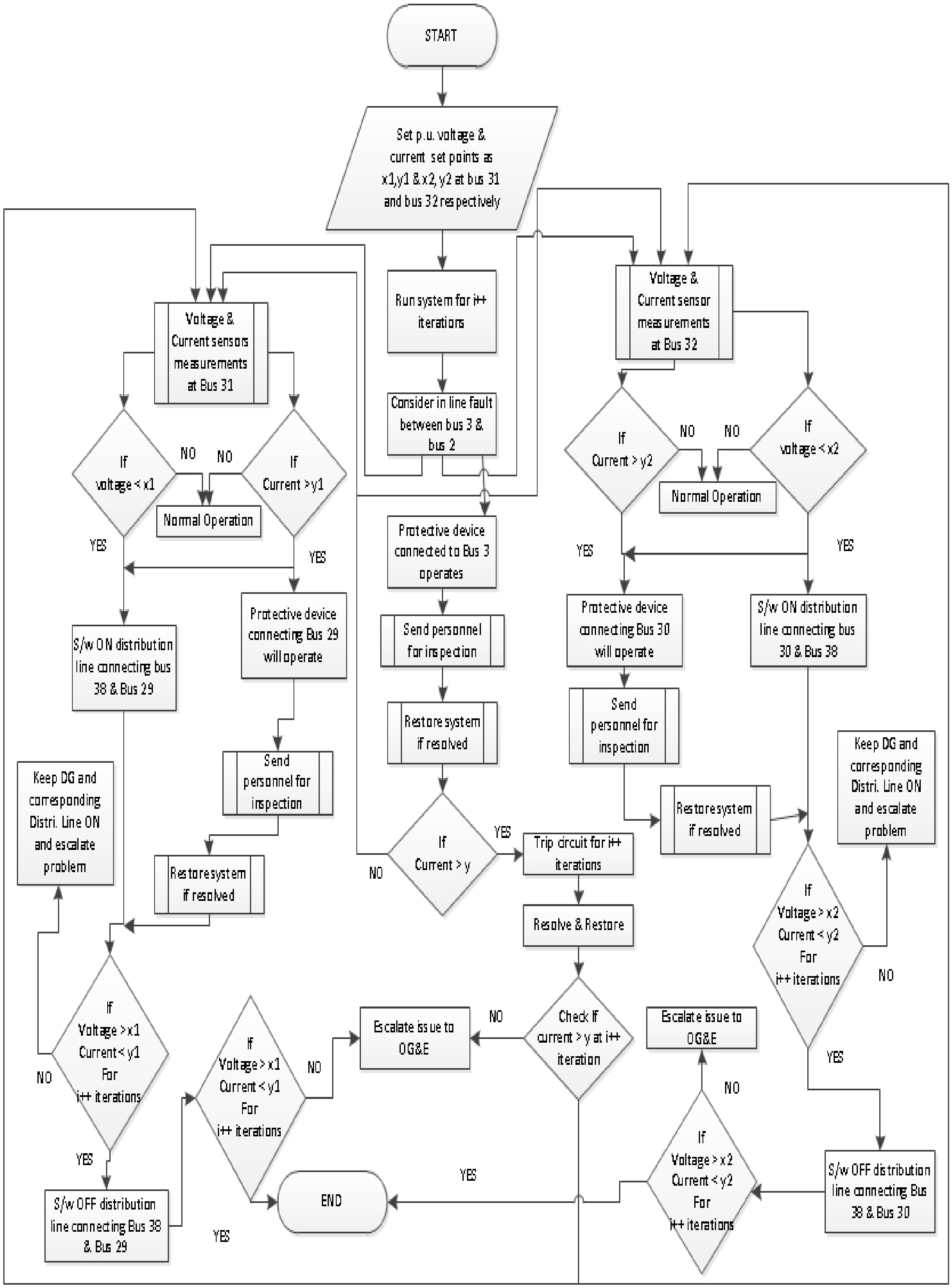

Figure IV.11 Operational logic for in-line fault between Bus 2 and Bus 3

The current sensors placed at critical buses 31 and 32 continuously keep monitoring the current through the line connected to them. A worst case scenario can occur when an upstream in-line fault occurs on the distribution line connecting bus 3 and at the same instant a downstream in-line fault occurs on the distribution lines connecting either or both buses 31 and 32. Such a scenario can be effectively resolved by the proposed scheme at the Stillwater campus of Oklahoma State University. In such a scenario, power is effectively re-routed without causing an outage of the critical loads and at the same time improving the voltage profile at all buses.

Figure IV.12 clearly shows the negative impact of an in-line fault between bus 2 and bus 3 on the voltage profiles at all buses. As illustrated in Figure IV.12 and Figure IV 13, a well-coordinated operation of the proposed system as per the operational logic diagram shown in Figure IV.11 effectively improves the voltage levels at all buses. Also, Figure IV.13 shows the percentage increase in the p.u. bus voltages due to the DG operation in such a scenario. It is clearly observed that there is a significant increase in the p.u. voltage level at the critical buses in addition to improvement in the voltage profile at other buses.

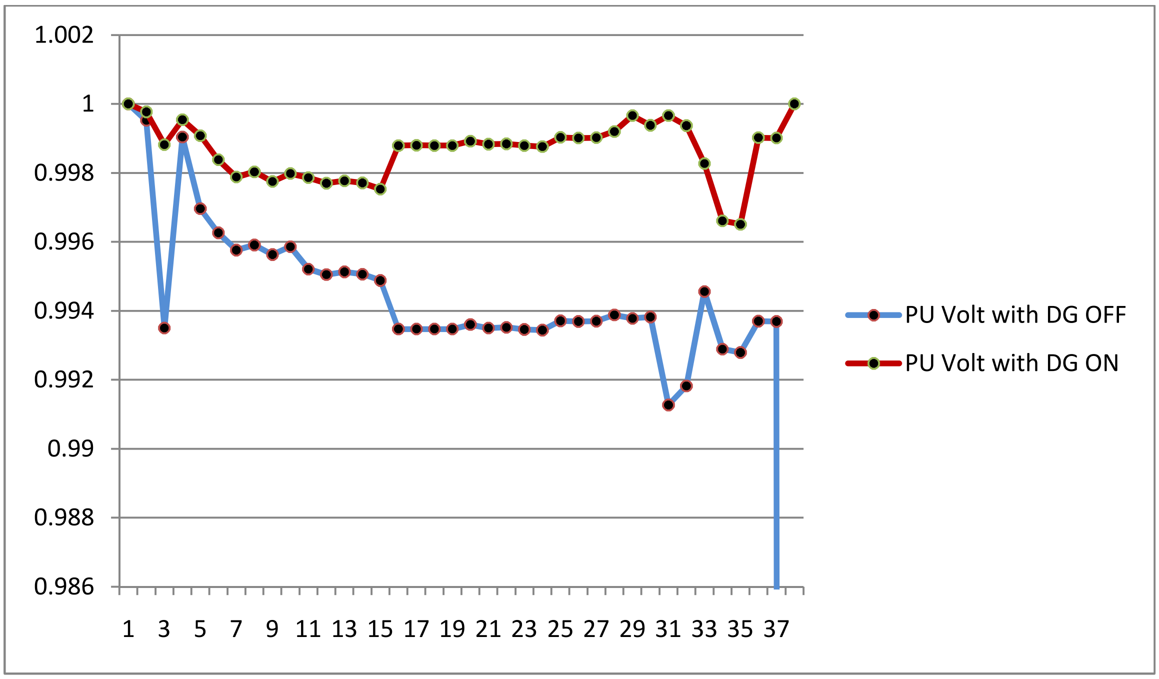

Figure IV.12 p.u. voltage at all buses during in-line fault occurrence between Bus 2 and Bus 3

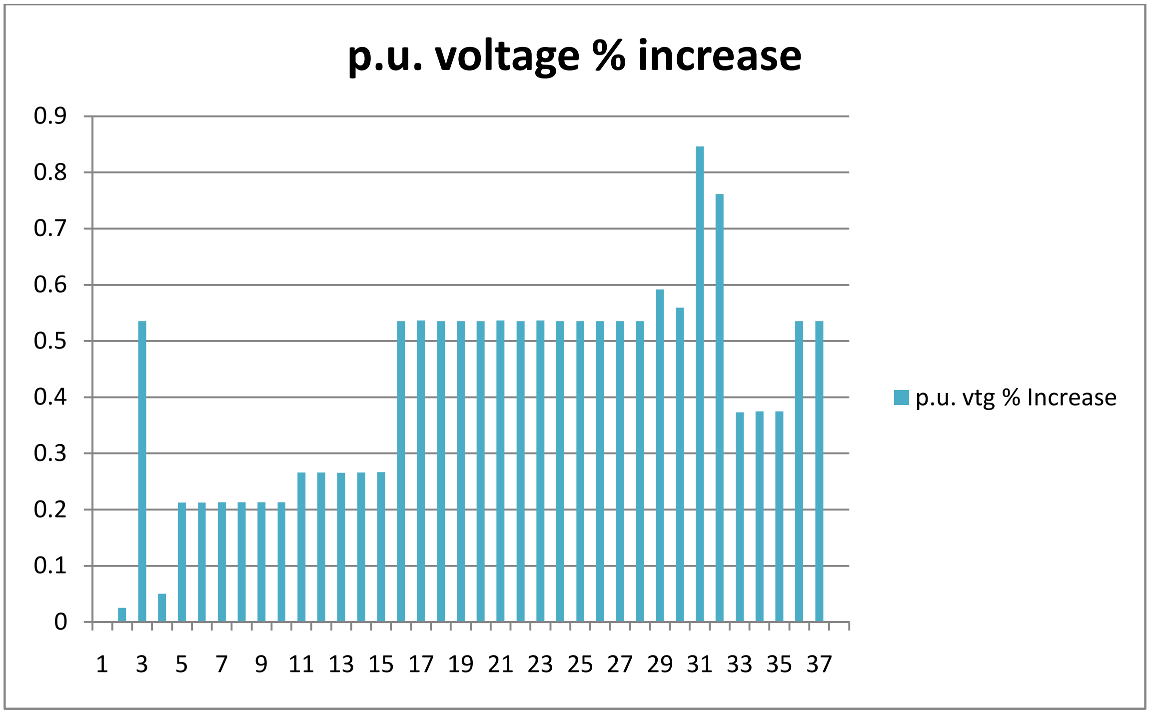

Figure IV.13 p.u. voltage percentage increase with DG in system and in-line fault connecting Bus 2 and Bus 3

IV.2.4 Scenario 4

As illustrated in Figure IV.14, a downstream in-line fault between bus 28 and bus 30 is considered. This is similar to scenario 2, wherein the fault was considered between bus 33 and bus 34. Again, such a downstream fault is less harmful unless a critical load is connected to the bus affected by the fault. In case of the OSU distribution system under consideration, such a scenario is of significant importance as the critical load is connected to Bus 32 which is severely affected during such a downstream fault scenario.

The voltage and current set points in this case would be same as in all previous scenarios i.e. 0.994 p.u and 400 amps respectively. Due to the high current in the circuit during fault condition, the protective device connected to bus 30 operates and avoids a cascading effect preventing the fault penetrating upstream which would further disrupt operation of the overall system.

The operation of the proposed system during such an in-line fault scenario takes place according to the operational logic diagram illustrated in Figure IV.15. The voltage sensor which is placed at bus 32 will come into effect and will measure the voltage level against the predetermined voltage set point. As shown in Figure IV.16, due to the in-line fault in the line connecting bus 28 and 30, the voltage falls sharply at bus 30 and 32, which would cause an outage at load connected to bus 32. This is an undesirable situation, as the load connected at bus 32 is considered to be a critical load.

The swift operation of the proposed system with voltage and current sensors installed at bus 32 will increase the redundancy and efficiency of the system. This is further achieved by re-routing power to the load through the DG connected to bus 30. It is also important to note that the duration of the drop in voltage during a fault condition should be above 1 minute to avoid false operation of the system during times of transients, voltage sags or voltage flickers.

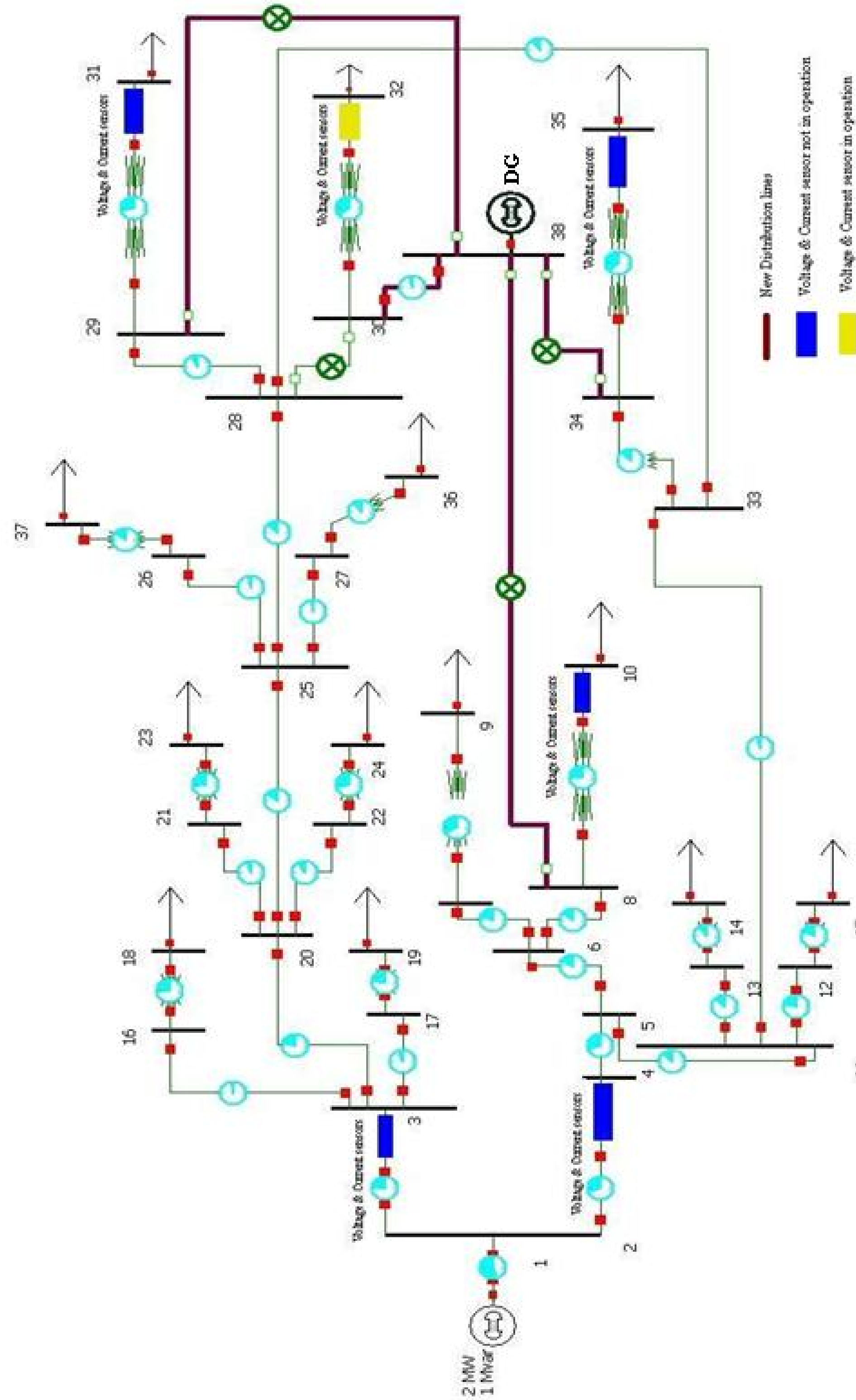

Figure IV.14 A segment of the current OSU Electric Grid with Distributed Generation & with in-line fault between Bus 28 and Bus 30

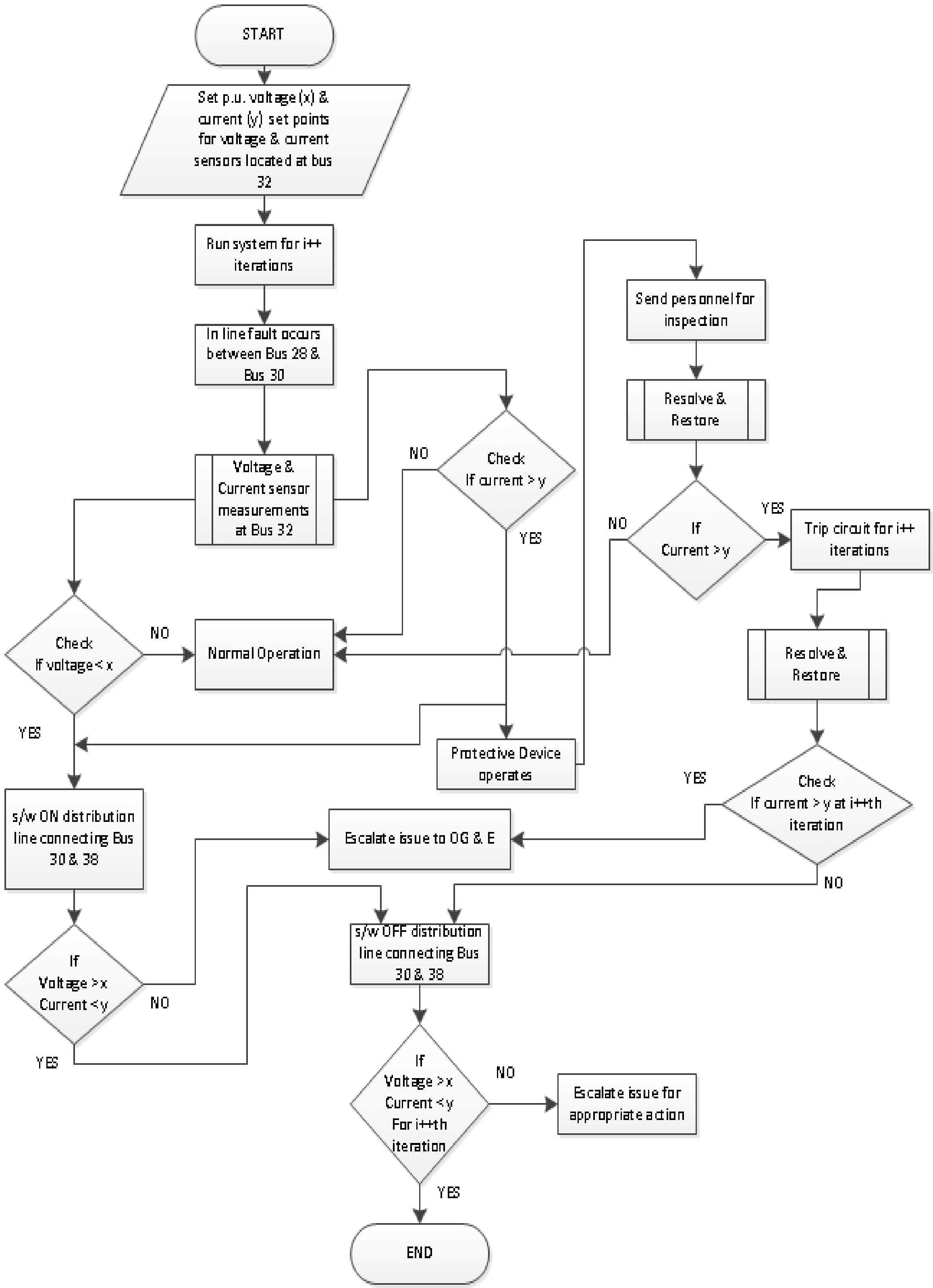

Figure IV.15 Operational logic for in-line fault between Bus 28 and Bus 30

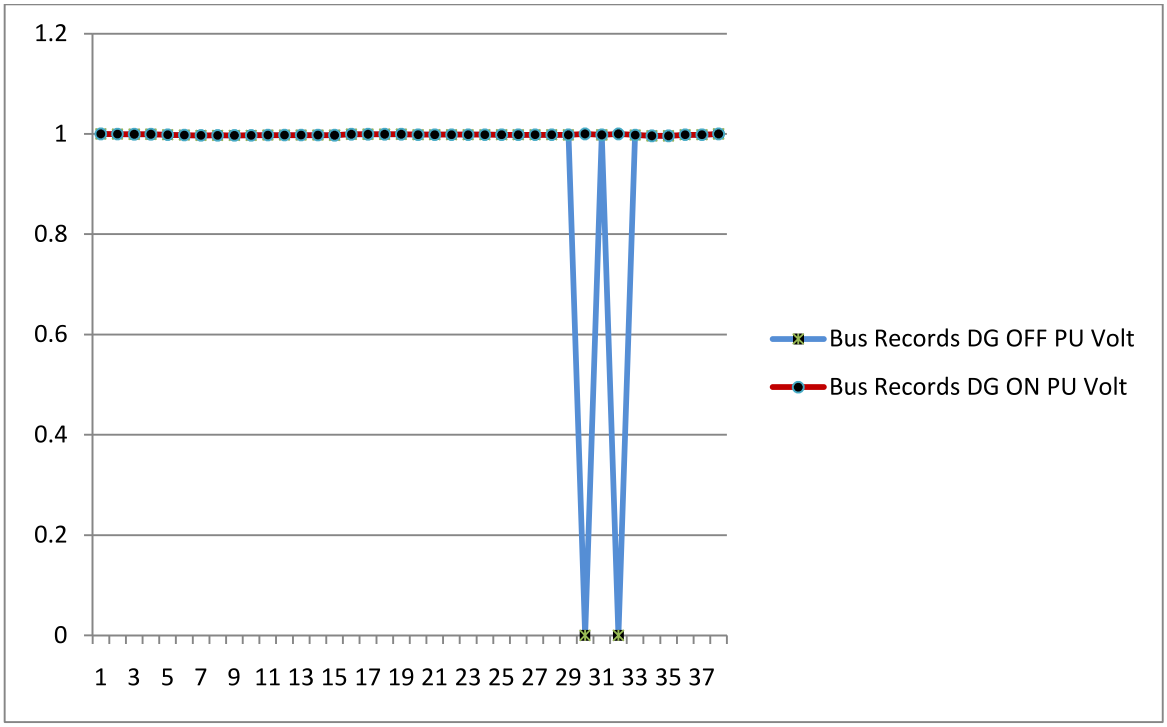

Figure IV.16 p.u. voltages at all buses during in-line fault occurrence between Bus 28 and Bus 30

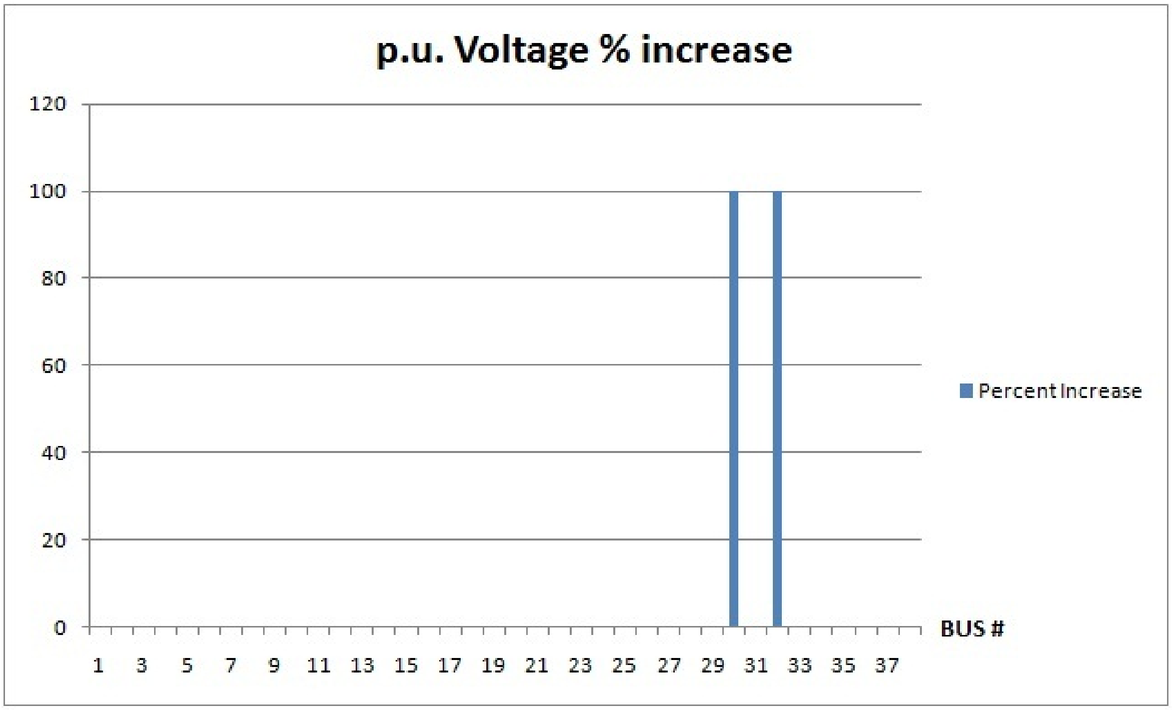

Figure IV.17 p.u. voltage percentage increase with DG in system and in-line fault between Bus 28 and Bus 30

CHAPTER V

SUMMARY AND CONCLUDING REMARKS

The transition towards a smart grid from the current electric grid at Oklahoma State University will be one of the most important decisions to meet its electric reliability, economy, efficiency and sustainability goals. The proposed smart microgrid system with distributed generation and distribution automation employing advanced voltage and current sensors will help in saving money and add value to both OG&E and to the university campus. The various scenarios presented in this study indicate that the overall operation of a segment of the distribution system at Oklahoma State University can be improved by implementing the proposed suggestions. It clearly shows that the most effective action to providing reliable and higher quality power to the university campus is by re-routing of its feeds during times of power outages or severe voltage fluctuations. Also, for taking full advantage of the proposed system for increasing the reliability and efficiency of the current distribution grid, it is important that all manual switches and fuses be replaced by automatic protection and automatic switching devices which can respond to digital signals generated by a computer with a capability to re-route power at signs of trouble without any interruptions. With a well-designed microgrid system involving distributed generation and advanced voltage and current sensors embedded in distribution automation, it would not only help the university in providing stable voltage and improved reliability but also help in shaving its demand during peak periods.

Currently, at the Stillwater campus of Oklahoma State University, during times of power outages electricity supply is restored manually which involves cost of sending maintenance personnel out to take corrective action and restore power. In this study, research buildings are considered as critical loads such as the ones connected to buses 10, 31, 32 and 35 as illustrated in Figure IV.1. Power outages in these buildings will have a pronounced effect in the form of lost faculty and staff productivity, loss of critical academic experiments and reduced life of equipment. As discussed under the various scenarios, the results clearly present the advantages of having distributed generation and additional distribution lines connecting buses 8, 34, 29 and 30 (See Figures IV.5, IV.9, IV.13, IV.17) which feed the critical loads through a step-down transformer. A well-coordinated and efficient operation of the proposed system as per the operational logic discussed under various scenarios will ensure that these critical loads are not affected by power outages or severe voltage fluctuations. The proposed system which comprises of distributed generation with additional distribution lines and advanced voltage and current sensors connects these critical buildings to a power loop which has the capacity to isolate faults and re-route power, thus increasing the overall reliability of the system and at the same time reducing the losses associated with power outages. The distributed generation considered in this study can be in the form of a gas turbine unit or solar power and/or wind energy conversion systems with suitable energy storage, fuel cells or batteries. Further research will be required to identify which specific technology or combination of technologies will be the optimum DG strategy to be implemented as part of the proposed system. Also, similar studies need to be undertaken on all segments of the distribution system at OSU Stillwater, to arrive at a comprehensive networked microgrid system that would benefit all segments of the distribution system.

The electric grid at the Stillwater campus of Oklahoma State University has a robust architecture upon which a smart grid can be installled. Developing a micro grid, encouraging renewable energy generation technologies, installing smart meters, developing impenetrable security and communication infrastructures and implementing full automation in the current grid would benefit the university in terms of availability, reliability, efficiency, higher power quality, security and reduced financial losses. Detailed economic and social benefits need to be further analyzed to justify the cost of implementing smart grid technologies on campus. Further, dynamic simulations and optimization studies of the current and proposed electric distribution systems at Oklahoma State University need to be carried out to identify projects and activities with highest potential for improvement. Addressing the cost savings and other benefits of such an implementation to concerned personnel is vital to initiate actions.

The entire process of developing a smart grid on a national scale will require concerted efforts from the government, utilities and consumers, the end result of which would be compelling. Considerable research work and financial support are still needed to make the Smart Grid an ubiquitous entity in the power sector. At Oklahoma State University, both OG&E and the university must embrace the concept of Smart Grid and start working coherently at the consumer, distribution and transmission levels.

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APPPENDIX A

Load Records

Load Records				
Load Name	Status	MW	Mvar	MVA
Building 1	Closed	0.45	0.22	0.5
Building 2	Closed	0.36	0.19	0.41
Building 3	Closed	0.27	0.11	0.3
Building 4	Closed	0.45	0.3	0.54
Building 5	Closed	0.04	0.01	0.04
Building 6	Closed	0.1	0.06	0.11
Building 7	Closed	0.1	0.03	0.1
Building 8	Closed	0.18	0.09	0.2
Building 9	Closed	0.11	0.05	0.12
Building 10	Closed	0.14	0.06	0.15
Building 11	Closed	0.15	0.05	0.16
Building 12	Closed	0.02	0.02	0.03
Building 13	Closed	0.07	0.03	0.08

APPENDIX B

Current Distribution System

Bus Records (Without outage)				Bus Records (With outage on Bus 4)			
Number	Nom kV	PU Volt	Volt (kV)	Number	Nom kV	PU Volt	Volt (kV)
1	12.47	1	12.47	1	12.47	1	12.47
2	12.47	0.99996	12.469	2	12.47	0.99996	12.469
3	12.47	0.99977	12.467	3	12.47	0.9995	12.464
4	12.47	0.99993	12.469	4	12.47	0.99467	12.404
5	12.47	0.99884	12.455	5	12.47	0.99466	12.403
6	12.47	0.99882	12.455	6	12.47	0.99465	12.403
7	12.47	0.99877	12.455	7	12.47	0.9946	12.403
8	12.47	0.99879	12.455	8	12.47	0.99462	12.403
9	0.48	0.99864	0.479	9	0.48	0.99447	0.477
10	0.48	0.99874	0.479	10	0.48	0.99457	0.477
11	12.47	0.99871	12.454	11	12.47	0.99479	12.405
12	12.47	0.99855	12.452	12	12.47	0.99463	12.403
13	12.47	0.99863	12.453	13	12.47	0.9947	12.404
14	0.48	0.99856	0.479	14	0.48	0.99464	0.477
15	0.48	0.99838	0.479	15	0.48	0.99446	0.477
16	12.47	0.99974	12.467	16	12.47	0.99947	12.463
17	12.47	0.99975	12.467	17	12.47	0.99948	12.463
18	0.21	0.99974	0.208	18	0.21	0.99947	0.208
19	0.48	0.99975	0.48	19	0.48	0.99948	0.48
20	12.47	0.99919	12.46	20	12.47	0.9979	12.444
21	12.47	0.9991	12.459	21	12.47	0.99781	12.443
22	12.47	0.99911	12.459	22	12.47	0.99782	12.443
23	0.21	0.99909	0.208	23	0.21	0.9978	0.208
24	0.21	0.99905	0.208	24	0.21	0.99776	0.208
25	12.47	0.99906	12.458	25	12.47	0.99745	12.438
26	12.47	0.99904	12.458	26	12.47	0.99744	12.438
27	12.47	0.99906	12.458	27	12.47	0.99745	12.438
28	12.47	0.99892	12.457	28	12.47	0.99689	12.431
29	12.47	0.99888	12.456	29	12.47	0.99684	12.431
30	12.47	0.99892	12.457	30	12.47	0.99688	12.431
31	0.21	0.99888	0.208	31	0.21	0.99684	0.207
32	0.48	0.99892	0.479	32	0.48	0.99688	0.479
33	12.47	0.99876	12.455	33	12.47	0.99565	12.416
34	12.47	0.99866	12.453	34	12.47	0.99555	12.415
35	0.21	0.99864	0.208	35	0.21	0.99552	0.207
36	0.21	0.99906	0.208	36	0.21	0.99745	0.207
37	0.21	0.99904	0.21	37	0.21	0.99743	0.209

APPENDIX C

Scenario I

Bus Records with in line fault between Bus 2 and Bus 4								
	With outage and DG OFF				With Outage and DG ON			
Number	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Nom kV	PU Volt	Volt (kV)	Angle (Deg)
1	12.47	1	Volt (kV)	0	12.47	1	12.47	0
2	12.47	0.99995	12.47	0	12.47	0.99997	12.47	0
3	12.47	0.99941	12.469	-0.02	12.47	0.99978	12.467	-0.03
4	12.47	0.99354	12.463	-0.18	12.47	0.99888	12.456	-0.35
5	12.47	0.99354	12.39	-0.18	12.47	0.99888	12.456	-0.35
6	12.47	0.99282	12.39	-0.17	12.47	0.99861	12.453	-0.42
7	12.47	0.99232	12.381	-0.17	12.47	0.99811	12.446	-0.42
8	12.47	0.9914	12.374	-0.17	12.47	0.99924	12.461	-0.49
9	0.48	0.99219	12.375	-0.19	0.48	0.99798	0.479	-0.43
10	0.48	0.99127	0.476	-0.18	0.48	0.99912	0.48	-0.5
11	12.47	0.9937	0.476	-0.18	12.47	0.99872	12.454	-0.34
12	12.47	0.99353	12.391	-0.18	12.47	0.99855	12.452	-0.34
13	12.47	0.9936	12.389	-0.18	12.47	0.99862	12.453	-0.34
14	0.48	0.99348	12.39	-0.19	0.48	0.9985	0.479	-0.35
15	0.48	0.99332	0.477	-0.19	0.48	0.99834	0.479	-0.35
16	12.47	0.99938	0.477	-0.02	12.47	0.99975	12.467	-0.03
17	12.47	0.99939	12.462	-0.02	12.47	0.99976	12.467	-0.03
18	0.21	0.99938	12.462	-0.02	0.21	0.99975	0.208	-0.03
19	0.48	0.99939	0.208	-0.02	0.48	0.99976	0.48	-0.03
20	12.47	0.99747	0.48	-0.08	12.47	0.99929	12.461	-0.14
21	12.47	0.99739	12.438	-0.08	12.47	0.9992	12.46	-0.14
22	12.47	0.9974	12.437	-0.08	12.47	0.99921	12.46	-0.14
23	0.21	0.99738	12.438	-0.08	0.21	0.99919	0.208	-0.14
24	0.21	0.99734	0.207	-0.09	0.21	0.99915	0.208	-0.14
25	12.47	0.99693	0.207	-0.1	12.47	0.99916	12.46	-0.17
26	12.47	0.99691	12.432	-0.1	12.47	0.99914	12.459	-0.17
27	12.47	0.99693	12.432	-0.1	12.47	0.99915	12.459	-0.17
28	12.47	0.99624	12.432	-0.12	12.47	0.99902	12.458	-0.2
29	12.47	0.99619	12.423	-0.12	12.47	0.99897	12.457	-0.2
30	12.47	0.99623	12.423	-0.12	12.47	0.99901	12.458	-0.2
31	0.21	0.99619	12.423	-0.12	0.21	0.99897	0.208	-0.2
32	0.48	0.99623	0.207	-0.12	0.48	0.999	0.48	-0.2
33	12.47	0.99469	0.478	-0.16	12.47	0.99886	12.456	-0.29
34	12.47	0.99317	12.404	-0.25	12.47	0.99993	12.469	-0.5
35	0.21	0.99208	12.385	-0.26	0.21	0.99983	0.208	-0.51
36	0.21	0.99692	0.207	-0.1	0.21	0.99915	0.208	-0.17
37	0.21	0.99691	0.207	-0.1	0.21	0.99914	0.21	-0.17

APPENDIX D

Scenario II

Bus Records with in line fault occurrence between Bus 33 and Bus 34			
Number	PU Volt (DG OFF)	Nom kV	PU Volt (DG ON)
1	1	12.47	1
2	0.99957	12.47	0.99957
3	0.99934	12.47	0.99934
4	0.99934	12.47	0.99934
5	0.99839	12.47	0.99839
6	0.99769	12.47	0.99769
7	0.99719	12.47	0.99719
8	0.99734	12.47	0.99734
9	0.99706	0.48	0.99706
10	0.99729	0.48	0.99729
11	0.99787	12.47	0.99787
12	0.99772	12.47	0.99772
13	0.99779	12.47	0.99779
14	0.99773	0.48	0.99773
15	0.99754	0.48	0.99754
16	0.99931	12.47	0.99931
17	0.99932	12.47	0.99932
18	0.99931	0.21	0.99931
19	0.99932	0.48	0.99932
20	0.99858	12.47	0.99858
21	0.99849	12.47	0.99849
22	0.9985	12.47	0.9985
23	0.99845	0.21	0.99845
24	0.99843	0.21	0.99843
25	0.99843	12.47	0.99843
26	0.99841	12.47	0.99841
27	0.99842	12.47	0.99842
28	0.99825	12.47	0.99825
29	0.99814	12.47	0.99814
30	0.99818	12.47	0.99818
31	0.99814	0.21	0.99814
32	0.99818	0.48	0.99818
33	0.99803	12.47	0.99803
34	0	12.47	0.99987
35	0	0.21	0.99977
36	0.99842	0.21	0.99842
37	0.99841	0.21	0.99841
38	1	12.47	1

APPENDIX E

Scenario III

Bus Records with in line fault between Bus 2 and Bus 3					
		With Outage and DG OFF		With Outage and DG ON	
Number	Nom kV	PU Volt	Angle (Deg)	PU Volt	Angle (Deg)
1	12.47	1	0	1	0
2	12.47	0.99952	0	0.99977	-0.02
3	12.47	0.9935	-0.07	0.99882	-0.36
4	12.47	0.99904	-0.01	0.99954	-0.04
5	12.47	0.99696	-0.07	0.99908	-0.16
6	12.47	0.99626	-0.07	0.99838	-0.15
7	12.47	0.99576	-0.07	0.99788	-0.15
8	12.47	0.99591	-0.07	0.99803	-0.16
9	0.48	0.99563	-0.08	0.99775	-0.17
10	0.48	0.99586	-0.09	0.99798	-0.17
11	12.47	0.99521	-0.03	0.99786	-0.23
12	12.47	0.99505	-0.03	0.9977	-0.23
13	12.47	0.99513	-0.03	0.99777	-0.23
14	0.48	0.99506	-0.04	0.99771	-0.24
15	0.48	0.99488	-0.05	0.99753	-0.24
16	12.47	0.99347	-0.07	0.99879	-0.36
17	12.47	0.99347	-0.07	0.9988	-0.36
18	0.21	0.99347	-0.07	0.99879	-0.36
19	0.48	0.99347	-0.07	0.99879	-0.36
20	12.47	0.9936	-0.07	0.99892	-0.36
21	12.47	0.9935	-0.07	0.99883	-0.35
22	12.47	0.99352	-0.07	0.99884	-0.35
23	0.21	0.99346	-0.07	0.99879	-0.36
24	0.21	0.99344	-0.07	0.99876	-0.36
25	12.47	0.99371	-0.07	0.99903	-0.35
26	12.47	0.99369	-0.07	0.99901	-0.35
27	12.47	0.9937	-0.07	0.99902	-0.35
28	12.47	0.99388	-0.06	0.9992	-0.35
29	12.47	0.99127	-0.06	0.99966	-0.37
30	12.47	0.99182	-0.06	0.99938	-0.37
31	0.21	0.99277	-0.06	0.99966	-0.37
32	0.48	0.99221	-0.06	0.99937	-0.37
33	12.47	0.99456	-0.04	0.99827	-0.28
34	12.47	0.99289	-0.15	0.99661	-0.39
35	0.21	0.99279	-0.16	0.99651	-0.4
36	0.21	0.9937	-0.07	0.99902	-0.35
37	0.21	0.99369	-0.07	0.99901	-0.35
38	12.47	0	0	1	-0.39

APPENDIX F

Scenario IV

Number	Bus Records with in line fault between Bus 28 and Bus 30			
	Nom kV	PU Volt (DG OFF)	Nom kV	PU Volt (DG ON)
1	12.47	1	12.47	1
2	12.47	0.99955	12.47	0.99955
3	12.47	0.99932	12.47	0.99932
4	12.47	0.9993	12.47	0.9993
5	12.47	0.99829	12.47	0.99829
6	12.47	0.9976	12.47	0.9976
7	12.47	0.99709	12.47	0.99709
8	12.47	0.99724	12.47	0.99724
9	0.48	0.99696	0.48	0.99696
10	0.48	0.9972	0.48	0.9972
11	12.47	0.9977	12.47	0.9977
12	12.47	0.99754	12.47	0.99754
13	12.47	0.99762	12.47	0.99762
14	0.48	0.99755	0.48	0.99755
15	0.48	0.99737	0.48	0.99737
16	12.47	0.99929	12.47	0.99929
17	12.47	0.99929	12.47	0.99929
18	0.21	0.99929	0.21	0.99929
19	0.48	0.99929	0.48	0.99929
20	12.47	0.99853	12.47	0.99853
21	12.47	0.99844	12.47	0.99844
22	12.47	0.99845	12.47	0.99845
23	0.21	0.9984	0.21	0.9984
24	0.21	0.99838	0.21	0.99838
25	12.47	0.99837	12.47	0.99837
26	12.47	0.99835	12.47	0.99835
27	12.47	0.99837	12.47	0.99837
28	12.47	0.99818	12.47	0.99818
29	12.47	0.99808	12.47	0.99808
30	12.47	0	12.47	0.99992
31	0.21	0.99807	0.21	0.99807
32	0.48	0	0.48	0.99992
33	12.47	0.99781	12.47	0.99781
34	12.47	0.99615	12.47	0.99615
35	0.21	0.99605	0.21	0.99605
36	0.21	0.99837	0.21	0.99837
37	0.21	0.99835	0.21	0.99835
38	12.47	1	12.47	1

APPENDIX G

Line and Transformer Records

Line Records					
From Number	To Number	Xfrmr	MW From	Mvar From	MVA From
1	2	No	2.4	1.1	2.7
2	3	No	1	0.5	1.1
2	4	No	1.5	0.7	1.6
3	16	No	0	0	0
3	17	No	0.1	0.1	0.1
3	20	No	0.8	0.4	0.9
4	5	No	1.5	0.7	1.6
5	6	No	0.8	0.3	0.9
5	11	No	0.7	0.3	0.8
6	7	No	0.5	0.2	0.5
6	8	No	0.4	0.1	0.4
7	9	Yes	0.4	0.2	0.5
8	10	Yes	0.4	0.1	0.4
11	12	No	0.5	0.3	0.5
11	13	No	0.3	0.1	0.3
11	33	No	-0.1	-0.1	0.1
12	15	Yes	0.4	0.3	0.5
13	14	Yes	0.3	0.1	0.3
16	18	Yes	0	0	0
17	19	Yes	0.1	0.1	0.1
20	21	No	0.1	0	0.1
20	22	No	0.2	0.1	0.2
20	25	No	0.5	0.3	0.6
21	23	Yes	0.1	0	0.1
22	24	Yes	0.2	0.1	0.2
25	26	No	0.1	0	0.1
25	27	No	0	0	0
25	28	No	0.5	0.2	0.5
26	37	Yes	0.1	0	0.1
27	36	Yes	0	0	0
28	29	No	0.1	0.1	0.1
28	30	No	0.1	0.1	0.2
33	28	No	-0.2	-0.1	0.2
29	31	Yes	0.1	0.1	0.1
30	32	Yes	0.1	0.1	0.2
33	34	No	0.2	0.1	0.2
34	35	Yes	0.2	0.1	0.2

VITA

Rohit Prabhakaran Nair

Candidate for the Degree of

Master of Science

Thesis: A PROPOSED SYSTEM FOR A SMART GRID IMPLEMENTATION AT OKLAHOMA STATE UNIVERSITY

Major Field: Electrical Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Electrical Engineering at Oklahoma State University, Stillwater, Oklahoma in July, 2011.

Completed the requirements for the Bachelor of Science in Electrical Engineering at University of Pune, Nashik, India in 2009.

Experience:

Graduate Research Assistant at Engineering Energy Laboratory, School of Electrical and Computer Engineering, Oklahoma State University from May 2010 to May 2011.

Name: Rohit Prabhakaran Nair Date of Degree: July, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: A PROPOSED SYSTEM FOR A SMART GRID IMPLEMENTATION AT OKLAHOMA STATE UNIVERSITY

Pages in Study: 73 Candidate for the Degree of Master of Science

Major Field: Electrical Engineering

Scope and Method of Study: The purpose of the study was to consider a possible system design for a smart grid implementation on a segment of the current distribution system at the Stillwater campus of Oklahoma State University. The proposed system includes a DG with additional distribution lines connecting the DG to buses near critical loads. In addition, voltage and current sensors are placed at critical load buses of the distribution system. The proposed system under consideration comprises of 41 buses. Load data, distribution line parameters and bus voltages are used as input to conduct the load flow study. Different scenarios are proposed and discussed with corresponding simulation results and operational logic diagrams illustrating the implementation of the proposed system.

Findings and Conclusions: All simulations are performed using Power World v.13 software. The results discussed under various scenarios clearly present the advantages of having distributed generation, current and voltage sensors at strategic points and additional distribution lines connected to critical loads. In addition, a well-coordinated and efficient operation of the proposed system as per the operational logic discussed under various scenarios will ensure that the critical loads are not affected by power outages or severe voltage fluctuations. Re-routing of power during times of power outages and severe voltage fluctuations at critical loads increases the overall reliability of the system and at the same time reduces the losses associated with power outages. The proposed system discussed here can provide a strong foundation in setting up a smart grid initiative at Oklahoma State University, Stillwater.

ADVISER'S APPROVAL: Dr. Ramakumar