OPTIMAL POWER FLOW SOLUTION TO VOLTAGE COLLAPSE IN A DEREGULATED ELECTRICITY MARKET

A THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES OF THE UNIVERSITY OF LAGOS IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY IN ELECTRICAL AND ELECTRONICS ENGINEERING

BY

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A Thesis submitted in Fulfilment of the Requirements for the Degree of Doctor of Philosophy (Ph. D) in the Department of Electrical And Electronics Engineering, School of Postgraduate Studies, University of Lagos, Lagos, Nigeria.

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CERTIFICATION

This is to certify that the Thesis:

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DEDICATION

To God, the Father, the Son and the Holy Spirit
for
Love, Life, Favour and Inspiration.

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Oluseyi, Peter Olabisi

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LIST OF ACRONYMS

AI	Artificial Intelligence
ANN	Artificial Neural Network
APA	Adaptive Pareto Algorithm
AREA	Adaptive Representation Evolutionary Algorithm
CM	Congestion Management
DISCO	Distribution Company
US$	U.S. Dollar
US$/MWh	U.S. Dollar per Mega watts hour
EA	Evolutionary Algorithm
EC	Evolutionary Computation
ELC	Expected Load Curtailed
EENS	Energy Expected Not Supplied
EMS	Energy Management Service
ENLC	Expected Number of Loads Curtailed
EPS	Electric Power System
EPSR	Electric Power Sector Reform
ES	Evolutionary Strategy
FACTS	Flexible AC Transmission System
FERC	Federal Energy Regulatory Commission
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
GA	Genetic Algorithm
GENCO	Generating Company
GP	Genetic Programming
IEAR	Interrupted Energy Assessment Rate
IEEE	Institution of Electrical and electronics Engineers
IPP	Independent Power Producers
ISO	Independent System Operator
KT	Kuhn- Tucker

L-index	Line index
LMP	Locational Marginal Price
LOLP	Loss of Load Probability
MATLAB	Mathematical Laboratory
MCS	Minimal Cut Set
MOEA	Multi-Objective Evolutionary Algorithm
MTTF	Mean-Time-To-Failure
MTTR	Mean-Time-To-Repair
MW	Mega watts
MWh	Mega watts hour
NESI	Nigerian Electric Supply Industry
N	Nigerian Naira (Nigerian currency)
N/MWh	Nigerian Naira per Mega watts hour
NIPP	National Integrated Power Project
NLP	Non-Linear programming
Ofgem	Office of Gas and Electricity Market
OPF	Optimal Power Flow
PDF	Probability Density Function
PESA	Pareto-Envelope Based Selection Algorithm
PHCN	Power Holding Company of Nigeria
PJM	Pennsylvania-New-Jersey Market
PSO	Particle Swarm Optimization
SMD	Standard Market Design
SPEA	Strength Pareto Evolutionary Algorithm
SSI	System Security Index
SVC	Synchronous Var Compensator
TCN	Transmission Company of Nigeria
TCPS	Thyristor-Controlled Phase Shifter
TCSC	Thyristor-Controlled Series Compensator
TP	Transmission Provider
TRANSYSCO	Transmission Company
TSP	Transmission Service Provider

Var	Volt Ampere reactive
VCI	Voltage Collapse Index
VIU	Vertically Integrated Utility

ABSTRACT

The thesis addresses the fundamental means of overcoming the challenge posed by voltage collapse to the success of electricity market unbundling. As regards the record available from the recent deregulation and unbundling of the Generation and Distribution segment of the electric power system, it has become evidently necessary to investigate the best and optimal operating conditions under which the transmission system is expected to perform with respect to the high level of transactions expected to always take place on both sides of the latter. Moreover, it is quite devastating to note that voltage collapse has remained one of the unresolved riddles that are currently plaguing the power system operation and performance under the recent electricity deregulation and restructuring regime.

There is a number of techniques for overcoming the voltage collapse phenomenon, one of them is the transmission expansion programme (TEP). But due to the developing economy's limited financial resources to engage in extensive transmission network's expansion, thus this method is not recommended for the achievement of a stable electricity supply. Hence, in this thesis, the idea of operating the existing network with special reinforcement of the physical structure by the Flexible Alternating Current Transmission System (FACTS) devices becomes a very attractive option to ameliorate the occurrence of voltage collapse. The resulting network is then subjected to multi-objective optimization approach using the improved Strength Pareto Evolutionary Algorithm (SPEA-2) to achieve the optimal operating features of the reinforced network.

Consequent upon this, the valuable contribution of the FACTS devices to the reinforcement of the network against collapse is evaluated by predicting availability and unavailability of the composite power system using the concept of Fault Tree Analysis (FTA).

In an attempt to showcase the influence of the method developed in this research work, simulation results are presented for both the IEEE-30 bus and Nigeria-26 bus systems. In the results exhibited, the IEEE-30 bus system depicts a standard system while it is studied in comparison with the Nigeria-26 bus system. The results portray Nigeria-26 bus system as a network in need of serious investment in dynamic compensating devices.

CHAPTER ONE

1.0 INTRODUCTION

Electricity is generally considered the cleanest form of energy supply. Thus, electricity industry is the fastest growing industry because of its significance to both comfort and technological development of a nation. It also serves as an index for measuring the economic development and *per capita* income of nations. The last two decades have witnessed a great deal of fascinating improvement in the electricity industry's efficiency through the introduction of deregulation, restructuring and privatization of the industry. This is as a result of similar experience that was recorded in both aviation and communication industries. In contrast to the operating principles guiding the latter, electricity industry is quite more complicated in the sense that even though both aviation and communication services do not suffer from short duration of expiry of the service, the same is not possible in the case of electricity. In other words, electricity must be consumed immediately it is produced due to the fact that it cannot be stored in large quantity for a long time. Thus, the amount that can be consumed is generated at every point in time.

Under the traditional vertically integrated utility (VIU) regime, this challenge is handled without jeopardizing the system and market operation. This is because this utility is under the dictate of a monopolistic authority which, in essence, performed all functions from generation to retail sale of electricity. With the advent of deregulation, this duty is becoming a major area of interest to the market operators as well as the system operators simply because of the introduction of competition to the market which makes it very obvious that electricity supply industry can no longer be treated just based on only the principles of engineering without any consideration for the modelling of the system economics. Thus, this study on the optimal power flow solution to voltage collapse in a deregulated electricity market explores these two fields so as to prepare the emerging electricity market in the developing economies for the obvious challenges of the industry.

1.1 BACKGROUND OF THE STUDY

It is on record in the Holy Bible (Genesis chapter 1 verse 3) that when the world began, there was a declaration for light to precede every other creation, which underscores the importance of *'light'* to human existence and growth. Thenceforth, human civilization has been technologically linked to the ability to harness, utilize and control this *'light'*. Prior to 1800, most of the companies generated enough electricity to take care of their immediate environment since there was no transmission system beyond the very vicinity of the generators (Gross, 1981, Kirchmayer, 1958). According to this account, it was later that the industry became linked together so as to ensure that when there is less generation from a particular locality it would not result in the lack of electricity supply to the load in such a location. Thus, the various generators were linked together through the transmission circuits which now developed into a network that feeds the various distribution centres (Awosope, 1982).

From the work of Awosope (1982), the generators are sparsely distributed over a vast geographical area (most of which are located near the source of fuel) and are interconnected to adequately account for the system reliability but most of the time, the system suffers great setback from a transmission network that is a weak link between the generation and load centres as represented by the transmission (Awosope, 2003). In this vein, it becomes necessary that the electric power industry should be categorized into three main sections namely: generation, transmission and distribution. All of these sections are important which make them a great influence on the provision of adequate and value-added electricity service. Due to this observation, the various governments are now embarking on researches into feasible methods of supplying the service without incurring much financial burden. Thus, it was in Chile that this effort first paid off when in 1982 the country tried out the idea of deregulation of the power system. This accounted for the reduction of system losses from 21% to 8% of the total generated power. It was this particular testimony that has led to the phenomenal interest in the deregulation of the power system in many developing countries(Arango *et al.,*, 2006). Nevertheless, it is necessary to state that deregulation has different players whose duty is to ensure the market's effectiveness is guaranteed by engaging the market in pure competition.

In many of the deregulated electricity markets, the electric power industry is streamlined along the well defined functional structures (Lo and Yuen, 2001). Here, the generation and distribution sections are open to competition while, in most cases, the transmission section of the power system remains a monopoly. In this regard, the electricity industries of many nations are basically addressed according to this categorization as the Generating Companies (GENCOs), Transmission System Company (TRANSYSCO) and the Distribution Companies (DISCOs). Among these three companies, the TRANSYSCO (because of its strategic position in the electricity industry and consequently linking its several loads to generators) is carefully guided by a set of system operation rules. It is so, in order to make it accessible to the entire market participants without any constraints or political/economic favouritism towards any of the market players/participants. Meanwhile, it is noteworthy to state that the GENCOs and DISCOs are naturally equipped to explore market principles and rules to their respective benefits.

In the new electricity market dispensation, it becomes obvious that electricity is traded like any other commodity in the marketplace. There are several forms of market structures and mechanisms namely: the pool, bilateral, multilateral markets and so on which have become operational in different countries of the world (Oricha *et al.*,, 2007). But in all these markets, there is an establishment of the independent umpire to regulate the activities of the various sellers and buyers of electricity in the industry so as to maintain the system against violation of the system operation constraints. The agency that performs this duty is known as the independent system operators (ISOs). It bears various names in different countries, for instance, in the United States of America (USA) it is referred to as Federal Energy Regulatory Commission (FERC), while the United Kingdom (UK) names it the Office of Gas and Electricity Markets (Ofgem). Whereas, in Nigeria this duty is under the supervision of an umpire known as the Nigerian Electricity Regulatory Commission (NERC). It is the responsibility of this commission to monitor the market as a non-partisan professional body in such a way as to ensure that the rules guiding operation and marketing are not in any way infringed to the disadvantage of the market participants as well as the system stability.

In several countries, this has led to the seceding of government's role in the electricity industry as the decision makers to the private participants whereby the privatized electricity utility companies become accountable to the investors and/or shareholders while the government performs oversight activities in the industry. For instance, in the UK, a full competition is experienced in the Scottish electricity market where all the sectors are liberalized for the investors/private owners to be encouraged to invest at any point (Woo *et al.*,, 2003). But in some other nations, though there is an organized competition in the generation and marketing of electricity (Gross, 1981, Perez and Ramos, 2008), the transmission and distribution activities remain under regulation. This approach is adopted by the deregulation and restructuring programmes in England and Wales, Spain, Norway, Argentina, Australia, and Alberta (Canada); ensures reliance on electric load forecast (Woo *et al.*,, 2003). But the competition has opened a number of fresh challenges to the industry which range from congestion management (a factor of voltage collapse) to degradation of quality of service and thus eventual threats to the power system security and reliability (Awosope, 1982).

For the record (Woo *et al.*,, 2003), there have been several system collapse incidents caused by voltage insecurity that have been reported in various countries such as USA (Austria, 2004), Japan, France, Belgium and of course Nigeria (Woo *et al.*,, 2003, Onohaebi and Apeh, 2007, Onohaebi, 2009). It is envisaged that under the liberalization of the electricity industry, there is a great tendency that the transmission network may be further endangered by the activities of the market forces; which could result in increasingly and heavily loaded transmission system as an evidence of several activities of both the system and market operators.

In other words, voltage insecurity is becoming an emerging area of challenge to the power system planning and operation in a deregulated market. This menace has its influences on both the price and quality of electricity service. Hence for a reliable and secured electricity supply services, these issues have to be tackled in such a way that the benefits of power system deregulation are not traded off in exchange for a reliable and qualitative electric power system. In the case of transmission congestion, the two major methods of confronting this challenge are mainly installation of compensating devices at specific locations along the network and construction of new transmission lines where there are no difficulties in obtaining right-of-way and fund to achieve interconnected loop network (Omoigui and Ojo, 2007). It is on this note that several researchers have observed it as an active area of research that can be explored to address the various problems of which some are itemized in this work. Though this issue of congestion has always been encountered in the vertically integrated utility (VIU), it was much easier to cope with it. In the case of the latter, it is possible to place the engineering interest over investment/market forces' interest. But in the new deregulated market in which the electric power system has metamorphosed to a restructured and liberalized market environment, it becomes very challenging to maintain the engineering interest over economic interest such as the return on investment (Caroin *et al.*,, 2007).

From the foregoing, the transmission system is largely addressed as a monopolistic channel of power flow from the competitive generators to equally competitive distributors, thereby creating a great deal of manoeuvrability of the system reactive power support (Rabiee *et al.*,, 2009). It is pertinent to note that the system operators (including the transmission providers (TP)) are vested with the responsibility of coordinating the activities of the electricity industry to meet the load demand through the available generated supply without any deficit; whereas surplus is encouraged as the spinning reserve (Oricha *et al.*,, 2007).

In developing economies, the power systems are radially connected with an attendant long span transmission lines which are susceptible to voltage instability (Komolafe and Ojo, 2007). Furthermore, it has been revealed that the problems related to this challenge have resulted in a number of power system failures in various countries (Tuan *et al.*,, 2005). Hence these failures are the major concerns in power system operation and planning today. The transmission system has thus experienced operation that is very hazardously close to its maximum capacity. This leads to such considerations as prospect of increase in the number of generation units as well as transmission expansion to alleviate the dangers of system congestion(Prada *et al.*,, 2005). According to some researchers, many of these collapse syndromes can be linked to inadequate reactive power content in the system(Pama and Ramdan, 2009, Prada and Souza, 1998). Hence any form of improvement on the voltage profile of this system will directly lead to a commensurate improvement in the reactive power value (El-Sadek, 1988, Gao *et al.*,, 1992, Glavisch and Alvarado, 1998, Zambroni, 2000).

The general belief is that outages due to the above mentioned factor can be corrected by effective planning and operation of the system under deregulation. Several researchers have helped in developing techniques to ensure that the quality and quantity of service provided are reliable and efficient in meeting the load demand (Larsen, 2004, Lu *et al.*,, 2007, Niimura and Nakashima, 2003, Tuan *et al.*,, 2005). Some of these techniques predict the voltage collapse ahead of time while several others are in support of correcting the anomaly. This includes the P-V curves (Pama and Ramdan, 2009), Q-V curves (Overbye *et al.*,, 1994), modal analysis (Gao *et al.*,, 1992), and minimum value decomposition (Ekwue *et al.*,, 1999, Maranino *et al.*,, 1994). Others are Thevenin/load impedance indicator, energy functions (Gross, 1981, de Souza *et al.*,, 1997) while several other research activities on this issue are reported in IEEE voltage stability working group report (Schlueter, 1998, Gross, 1981).

It could be concluded that since the electricity markets in industrialized nations have commenced deregulation more than twenty years ago, the industry has witnessed several metamorphoses in terms of system operation(Schweitzer *et al.*,, 1997, Veit *et al.*,, 2009). However, there are several unresolved cases of transmission security and reliability problems which have led to loss of revenue. In developing economies, the issue of system reliability is an area of great challenge due to lack of virile and adequate transportation infrastructure for the generated electricity (Schweitzer *et al.*,, 1997, Nagayama, 2009, Veit *et al.*,, 2009).

1.2 STATEMENT OF THE PROBLEM

Electricity is an important index for measuring national development and technological advancement. The nation’s *per capita* consumption of electricity is useful for predicting the future economic and technological development of such a nation. In many developing nations, preference has not been given to adequate provision of infrastructural facilities for the expected electrical load growth which has resulted in long duration of loss of electricity service. Consequently, this trend has greatly affected both the quality of life and level of technological development of these nations. Due to apparent poor developmental plan, the upgrading of electricity infrastructures in the developing economies has left the transmission network grossly over-utilized because of the menace of high transmission network losses (Jamasb, 2006). Many researchers have linked this problem to several factors such as the inability to replace the old power equipment with new and more efficient facilities as well as poor revenue generation (on the part of the industry) which makes the utility to lack the strength for financial self-sustenance. Similarly, the politics of electricity has further endangered the industry in the hand of several governments with chequered policies. The latter have not helped the industry out of the current predicament from low service quality, low revenue collection, poor service coverage, etc.

It should also be noted that the upward improvement in literacy level in the developing economies has also brought about tremendous growth in electricity consumption pattern. But it is quite unfortunate that several of these developing nations were not planned with the conception of the practical electricity forecasting in mind. This particularly has led to high energy demand not supplied (EDNS) because of the fact that the available facilities of the electricity supply industry cannot meet the electrical load demand. This has led to civil unrest in a pocket of these nations and even made many of the populace to rely on captive generators (with its attendant green house emission) (Awosope, 2003).

Lately, following the experience of Chile and the UK as the pioneers of the electricity industry deregulation, many countries have embarked on a process of liberalization of their respective electricity sectors (Castro-Rodriguez *et al.*,, 2009). In most markets, the electricity industry is deregulated with the restructuring of the erstwhile vertically integrated utility to make way for the generation and distribution segments to be owned by private investors which operate in competition. The transmission sector, on the other hand, is run in such a way as to make it impartial to all players in the industry. This has resulted in effective and efficient system and market operation in the industry. With the success attributed to this deregulation exercise in Chile, several developing economies are currently in the midst of drastic transformation from the monopolistic, state-owned producers to a market regime built on competition in order to achieve cost-efficient electricity production and low electricity price (Lise *et al.*,, 2008).

1.3 AIM AND OBJECTIVES OF THE STUDY

The main aim of the work is to study the challenges of voltage collapse in the existing deregulated electricity market and subsequently design a model for the electricity market that could be used to reduce the voltage collapse in the developing nations.

The objectives of the work are articulated in three-fold as follows:

1. To develop an Optimal Power Flow (OPF) model for the system availability and reliability assessment of the composite power system under deregulated environment.

2. To investigate the weak buses in the network and take the advantage of the features of the FACTS devices to assist in improving the voltage profile at these buses.

3. To model an electricity market structure for the electricity supply industry with the capability to reduce the advent of voltage collapse.

1.4 RESEARCH QUESTIONS

In the course of this study, the following questions shall be addressed:

1. How can optimal power flow methodology help at improving the power system availability and reliability?

2. In an electricity market with inadequate generated power and long transmission lines, how best can the relationship between reactive power and bus voltage be explored to overcome the menace of voltage collapse?

3. Finally, what nature of electricity market structure would best fit the developing economy's electricity industry?

1.5 CONCEPTUAL FRAMEWORK OF THE STUDY

The concept developed in this work involves the implementation of real life optimization technique to utilize the power system in its best form that would ensure reduction in power losses and cost of operation as well as the improvement of the reliability of the network(Prada *et al.*,, 2005). These are conflicting parameters which have a number of constraints and thus can only be handled with the help of multi-objective optimization approach whose major feature is that it has the ability to choose out the number of objective functions those that must be optimized based on trade-off among these objectives. This approach is commonly referred to as multi-objective optimization problems which include genetic algorithm (GA), Adaptive Pareto Algorithm (APA), multi-objective evolutionary algorithm (MOEA), etc. One of the variants in this category is called the Strength Pareto Evolutionary Algorithm which was developed in 1999 (Thielle, 1999). It has been compared with a number of other techniques used in power system and found to be proficient (Abido, 2006).

In the case of the reliability and availability assessment of the reinforced transmission network involving flexible alternating current transmission system (FACTS) devices as compensating tools, the fault tree analysis is introduced as a useful tool for evaluating the failure rate of the system under the new dispensation. This failure rate predicts the availability of the system using the probability theory (Nieuwhof, 1975, Hong and Lee, 2009).

1.6 SIGNIFICANCE OF THE STUDY

The incessant power system failure to supply the load demand appropriately and adequately has been an undeniable source of low *per capita* income in the developing economies (Bajpai and Singh, 2004). This work would assist in laying a technical foundation for the success of power system deregulation in the developing economies. In these economies, the load forecast has provided the information that the electricity consumption pattern is continuously growing at an exponential function index while the electricity supply industry lacks a commensurate provision of power system infrastructures for meeting such growing load demand.

So, this work would ensure the reinforcement of the existing system by introducing the FACTS devices to the transmission network. The exercise is to influence the power flow as well as reduce losses along the transmission network by optimizing the thermal/power flow capacity of the transmission network which in essence reduces the voltage collapse.

1.7 SCOPE OF THE STUDY

In the study, the voltage profile of the selected networks namely: IEEE-30 bus and Nigeria-26 bus systems shall be evaluated. The weak buses in these networks are identified and thus the compensation devices are introduced to the network to reinforce it against collapse. Finally, the network is tested using the Fault Tree Analysis to determine the system failure which would, on the long run, determine the availability of the reinforced transmission system.

The rest of the work is structured as follows: in Chapter 2, a critical appraisal of the literature review of the electricity deregulation, optimal power flow and voltage collapse shall be discussed. This chapter links voltage collapse with the deregulation and then probes into the various methods of overcoming voltage collapse and their respective failures. So also some of the existing electricity market models are considered while a model that could best suit the developing economy is proposed keeping in view a number of factors itemized in this work. Chapter 3 gives an elaborate description of the conceptual framework on which the market is built on, materials and method used in this study. This involves modelling of power system using optimization technique whose idea is advanced from the economic dispatch approach which leads to the introduction of Fault Tree Analysis (FTA) as a means of testing for the system failure probability. Chapter 4 implements the model developed above using the IEEE-30 bus and Nigeria-26 bus systems to obtain a series of results. Additionally, these results are discussed in this chapter. Chapter 5 discusses the conclusion reached in the work. In this chapter, summary of the findings is itemized. Finally, the contributions of the thesis to the frontier of knowledge are articulated in Chapter 6. And then an outlook of future research is given.

1.8 DEFINITION OF TERMS

Adequacy: the ability of electric power system to supply aggregate electrical demand and energy requirement of the customers.

Ampere (Amp or A): the unit of electrical current.

Common cause failure: the nature of failure that its occurrence results in complete failure of the system.

Competition: the process whereby suppliers attempt to maximize profit or demanders/buyers attempt to maximize net value or benefit from electricity service.

Congestion management: the activity put in place to control the dispatch in order to avoid the violation of the transmission line flow limits.

Congestion: over-usage of a transmission line due to lack of adherence to the flow limits of the line.

Contingency: the unexpected failure or outage of a system component, such as the transmission line, generator, circuit breaker, or switch.

Current: the electrical parameter which is measured in Amperes or A.

Deregulation: this is the term used in referring to the unbundling of the power system into the functional zones for both system and marketing operation.

Dispatch: the operation and control of a power system especially with respect to determining the outputs of the system generators.

Economy of scale: this refers to reduction in unit cost as output increases due to expansion or increase in the size of facilities. It is associated with supply-side.

Economy of scope: it is similar to economy of scale but it is associated with the demand-side economy of production of two products together to reduce selling price of each of them.

Electric transmission network: the medium for the bulk transportation of electrical energy from the generator bus-bar to the load bus-bar.

Energy: the capacity to do work, i.e. energy is the power flow (MW) in a period of time (hour).

Expected Energy Not Supplied: the average value of energy demanded by the consumers which could not be supplied by the utility company. It is sometimes referred to as Energy Demanded but Not Supplied (EDNS).

Expected Load Curtailment: the number of days per annum during which load loss occurs.

Expected Number of Load curtailment (ENLC): the expected value of a random variable is the average value that would be observed for the variable if it were sampled many times (technically, an infinite number of times).

Forced outage: the removal from service of a generating units, transmission line or other facility for emergency reason or condition due to unanticipated of failure

Gaming: the process whereby a market participant exploits the market's loopholes to its advantage.

Grid: the transmission network.

Hierarchical level: a terminology in power system reliability in which the system reliability could be treated in three major levels, i.e. considering only the reliability of generating units (that is HLI), considering the combined reliability of the generating units and transmission system as an entity (i.e. HL II) and the consideration of the three functional zones as an entity, which is often referred to as HL III.

Independent system operator: non-profit system moderator which is not under the control of any of the market participants. It ensures smooth running and strict adherence to the rules guiding the system operation.

Interrupted Energy Assessment Rate (IEAR): the ratio of cost of outages to the Energy Demanded but Not Supplied

Load bus: the bus-bar to which load or demand devices are connected.

Load: an end-use device that receives power from the electric system.

Market: any context in which sales and purchase of goods and services take place. Electricity market is thus a market put in place for the sales and purchase of electricity under a number of market rules.

Market power: dominance of a market either by a particular customer (out of several customers) who creates a buyer's market or a particular company (out of many competing companies) who creates a seller's market in a competitive market.

Mean Time To Failure: the time between the breaking down and restoration of service.

Mean Time To Repair: the time between operation of equipment and its breaking down.

Monopoly: a firm that has the sole authority for the delivery of goods or service. The transmission network has the monopoly for wheeling electricity between the numerous generators and numerous distribution companies. Thus, transmission network has a monopoly in the electricity market.

Ohms (Ω): the unit for measuring the resistance to the flow of electricity current.

Operating reserve market: specialized market set up in order to meet the reserve needs of a particular electricity market.

Operating reserve requirement: a level of operating reserves measured in Megawatts. If reserves fall below this specific value then the system operator tries to increase it by purchasing more power to restore the reserve status.

Operating reserve: generation in excess of demand, scheduled to be available on short notice to ensure the reliable operation of the power system.

Optimal power flow: a program for determining the least cost dispatch of power system with respect to a number of transmission constraints.

Outage: the inability of a power facility to provide service due to its unavailability e.g. transmission line, generating units, etc. There are two types namely: forced outage and maintenance outage.

Power electronics technology: otherwise referred to as FACTS technology is the aggregate of system controllers that are connected to the transmission network to coordinate and control a specific electrical parameter in the network; this parameter could be series line impedance, shunt line impedance, current or voltage.

Power losses: the loss in power lines due to the effect of heat on the transmission wire, the negative impact of this is that less power than the generated amount reaches the load bus.

Reactive power: an alternating current power flow can be decomposed into two components namely: real and reactive powers. The reactive power flows back and forth with no net power in either direction. In the process causes the loss that results in heat generated in the transmission line.

Real power: the active power that flows from the generator unit to the load units. It is useful for heating, lighting, and driving loads.

Real-time: the evaluation carried out on an hourly or five-minute basis.

Reliability study: the study of the probability of performance of electrical facilities.

Reliability: the ability of a power system to deliver the power with voltage and other electrical parameters within their normal operating limits and rules guiding the system operation without any special consideration of any of market players.

Security limit: the power flow limit imposed on a line to protect it from exceeding the line's physical limits of operation.

System security: the ability of the electric system to withstand sudden disturbances such as sudden change of load, etc.

Thermal limit: the limit imposed on the transmission line to protect it against the possibility and likelihood of damage from heat, which causes loss of electrical energy.

Voltage collapse: the gradual or sudden degradation of the voltage level to a level that cannot perform its duty in an electrical network.

Voltage: electrical parameter normally referred to as the electrical pressure in a network that is measured in Volts.

Watts: the unit of real electric power flow.

CHAPTER TWO

2.0 LITERATURE REVIEW

The recent deregulation of electricity supply industry into the functional structures has led to considerable change in regards to the power system operation. The traditional vertically integrated utility structure is now decomposed to different functional segments or structures. In these structures, the generation sector is opened to competition from private investors while the transmission network is a monopoly whereby the transaction at the distribution segment to access electricity supply depends on the strength and capacity of the transmission network to support the latter's demand from the generation. This new development in the industry has given rise to several threats to the power system security and reliability. In order to handle this issue, the system operators in the electric energy management industry have the duty of placing the engineering consideration of the transmission network above the economic interests of the investors. This is the essence of this research, in which the study of the system security is employed as a yardstick of evaluating the system reliability under the deregulated and competitive electricity market (Verma *et al.*,, 2004).

Some of the former works in this area of interest shall be reviewed in the sections that follow with respect to deregulation, OPF and reactive power together with its influence on the transmission network and then the emphasis shall be placed on the reliability of the network.

2.1 POWER SYSTEM DEREGULATION AND OPTIMIZATION

Deregulation of the structures of electricity industry is not totally a new concept (Blumstein, 2002, Bushnell *et al.*,, 2002, Borenstein *et al.*,, 2002, Bushnell, 2003). The earlier primitive power system supply activity started from the stage of decentralization (even though it was without any serious competition) before the system was later transferred to the government's portfolio who then integrated the whole system as a unitary utility with such features as central control and coordination of the system operation, protection and planning.

The current interest of many developing countries in unbundling their respective power systems cannot be totally dissociated from the success recorded by the Chile's electricity supply industry. From records, Chile was the first country to initiate the idea of deregulation in 1982 (Arango *et al.*,, 2006, Pollitt, 2004b). The exercise culminated in the unbundling of the state-owned electricity utilities which accounted for the improvement in the quality of supply with significant improvement in its electricity sector's performance. This has led to an unprecedented reduction in its network's technical losses (i.e. wasted energy) and non-technical losses (due to power theft). In the work of Pollitt(2004b), the Chilean's network had the technical energy losses in its distribution system reduced from 10.2% in 1982 to 6.2% in 2002, while for its neighbouring Argentina, that commenced deregulation in 1992, the available report has it that the technical and non-technical losses dropped sharply from 26% in 1992 to 13% in 2002 (Pollitt, 2008, Pollitt, 2004a, Zambroni, 2000, Pollitt, 2004b).

Though most industrialized countries perceive the restructuring of electricity supply industry as a way of increasing efficiency and transferring the responsibility of production and sales of electricity from the State to private investors, this is quite different from the expectation of the developing economy for electricity industry's unbundling exercise. For example in the United Kingdom, the state-owned enterprise was split into smaller entities which transferred the ownership to the private investors. Meanwhile, the developing countries prefer to interpret 'privatization' of electricity industry as admitting the private, and in many cases, foreign investors to finance and operate the generators that were previously being procured and operated by government (Nikomborirak and Manachotphong, 2007). These investors are then rewarded from the revenues generated from the operation of the facilities in line with government policy on power system deregulation. At the end of the concession period, ownership is thus transferred to the government. In the work of Ausubel and Cramtom (2009), this arrangement is attractive to some host governments in the developing nations because it addresses the immediate challenges of power supply at the margins without upsetting the structure of the domestic utility industry (Ausubel and Cramtom, 2009).

Moreover, deregulation of the electricity industry in developing countries has encouraged newly introduced independent power producers (IPPs) to enter into the market. This arrangement has greatly enhanced power supply in the developing nations in a substantial manner. By the global account rendered by McGovern and Hicks (2004), it is on record that in 1996, IPPs accounted for 30% growth in the market for new power plants, compared with the value of less than 5% that was obtainable ten years before the deregulation exercise (Larsen, 2004, McGovern and Hicks, 2004). The World Bank's reports revealed that there are some fifty-two projects commissioned in ten developing countries with a total installed capacity of 24 GW (Albouy and Bousba, 1998). From all these achievements, it is very clear that the era of electricity supply being reserved for government's participation is no longer attractive.

Notwithstanding these glaring sets of advantages, there are a number of points being raised by power deregulation's antagonists with such explanation as the citing of the case of the California energy crisis of 2003 and its impact on other energy markets and their deregulatory/re-regulatory actions (Bushnell *et al.*,, 2002). This electricity crisis has increased concern over the security of supply in the context of liberalization but according to Joskow (2001, 2003), the crisis is independent of inherent deficiency of deregulation, but depends on the challenge originated from the nature of electricity structure adopted and the way California Independent System Operator (CAISO) implemented its power sector reforms (Joskow, 2001, Joskow, 2003). The latter is further supported by the deregulation exercise that is working effectively in Pennsylvania, while Norway and England have always presented good examples of successful deregulation. So it is not impossible to experience failure in a situation where there is a significantly ill-fortune and ineffective government responses to the problems of market policy and badly structured electricity market.

This argument has always brought about a high cost of electricity per MW due to such factors as: the peculiar nature of electricity as a non-storable commodity which exposes the market to spot pricing of the service as well as the issue of market power in which the market participants seek the price advantages. This is capable of casting aspersion on the benefits of power system deregulation which has the tendency of ensuring the violation of transmission constraints.

From the foregoing, the so called pool system is still the most widely implemented (Rudnick *et al.,*, 1997) and recognized electricity market design with a dominant open market (Ilic *et al.,*, 1998) where the transmission system as a natural monopoly to power market players is always open to all the market participants. Since it is compulsory under this scenario that both the power producers (sellers) and dealers/consumers (buyers) have to share a common transmission network for wheeling the power from the generation to consumption centres, it is going to be necessary to coordinate the network in a manner that would keep it from violating any of the network's constraints.

If the latter becomes a difficult task to actualize, then the system becomes prone to overload or congestion on the ground that the system operators are not in position to effect a number of decisions on trading in the process of service provision (Bajpai and Singh, 2004). Once the right decision from the system operator (SO) is taken, then, the task of keeping the network within the secured region is ensured (Tuan *et al.*,, 2005). This is because the contracted power transactions are carried out with the help of a reliable market structure and real-time optimization approach.

Meanwhile, without adequate action from the SO, the volume of transactions handled simultaneously by the transmission provider could lead to transmission networks congestion. Thus, it is a necessity to proffer solution to this challenge. There are several means of overcoming this challenge as itemized in the work of Momoh (1999). This solution approach ranges from economic to technical ones (Momoh *et al.*,, 1999). The technical approach to this problem includes re-dispatching of the generated power with the close observation of the security and transmission constraints, operation of transformer taps, forced outages of congested lines, load curtailment and operation of compensator devices such as reactors, capacitors, FACTS devices, to mention but a few.

Christie *et al* (2000) suggests three different means of addressing this challenge in a transmission system as follows: firstly, the point-of-connection tariff and price area congestion model commonly used in Sweden and Norway respectively. Secondly, a transaction-based model approach as exemplified in Mid-West, USA's electricity market which consists of three stages (Lai, 2002). In this case the buyer and sellers enter into bilateral trading arrangement with one another and sufficient information is made available to the transmission provider on the necessary action to be taken. The third method is based on optimal power flow (OPF) as implemented in the UK, parts of USA, in Australia and New Zealand (Tuan *et al.*,, 2005). In all these markets, it is envisaged that in the absence of scarcity of transmission capacity, the electricity market would operate as a commodity market (Wilson, 2008, Christie *et al.*,, 2000).

One of the very useful tools for the solution to this problem is the Optimal Power Flow (OPF) technique (Mansour and Abdel-Rahman, 1984, Orfanoghianni and Bacher, 2000). This means that operating the system at its 'best' index of operation to avoid insecurity and instability in the system. OPF has remained relevant for sometime now as an efficient technique for obtaining the minimum cost of generation pattern in a power system with the existing transmission and operation constraints. According to a number of informed works (Burchett *et al.*,, 1984, Burchett *et al.*,, 1982, Momoh *et al.*,, 1996), the OPF was originally intended for the solution of economic dispatch problems in power systems which was later extended to other ac and dc operations in power system analysis. When it is compared with other methods such as the continuation PF methods (Ajjarapu and Christy, 1992), it has been adjudged as a better solution approach that can easily cope with both non-convex and non-linear problems.

With the power trading transaction in place, the possibility of insufficient resources to meet the bidding schedule may lead to network congestion which is the root cause of voltage instability. Therefore, the OPF as an optimization tool for power system planning and energy management is an effective, versatile and dispensable tool deployed for this purpose in a deregulated power markets (Momoh *et al.*,, 1999, Bansal, 2005, Pandya and Joshi, 2008).

On the major causes of voltage collapse, it is quite informative to define the process as a phenomenon whereby the power system yields to the threats from disturbance which is caused by the system operating above its technically safe operating limits. This may lead to the tripping of the protective devices in the system in order to prevent inherent damage to the system devices

(Chen, 2002, Echaraven *et al.*,, 2003). In other words, an acceptable voltage level must be maintained at all buses in the system under normal condition and after a disturbance (Onohaebi, 2009). Many recent power system disruptions are characterized by a progressive decline in bus voltages which could be due to the shortage of reactive power supply along the transmission line. This condition could later degrade the voltage level until it eventually results in voltage collapse. According to some authors, this phenomenon can occur over a period of few seconds or minutes to several hours, starting with gradual decrease in system voltage (Strbac and Jenkins, 2001, Onohaebi and Apeh, 2007). There are several mechanisms of voltage collapse that can be considered but this is beyond the scope of this work.

The reactive power (VArs) is imperatively very significant for the transportation of the real power to the load ends with the support of an adequate voltage profile. So, it is essential to maintain the transmission line with a significant amount of the former in the network which ensures that the power factor of the system is maintained under normal condition of operation. Hence, it is noteworthy that the flexible Alternating Current Transmission Systems (FACTS) devices are useful source of improvement of the amount of the reactive power support in the system (Oluseyi, 1997).

Indeed, the shortage of reactive power in a network can have serious repercussions including voltage collapse and ultimately blackouts. For example, on the 23rd of September 2003, over 4 million homes and businesses in Denmark and Sweden lost power for four hours; and on the 28th of August 2003, an estimated 400,000 people were without power in London (Lehtonena and Nye, 2009). Both blackouts were attributed to voltage collapse. It is then essentially necessary to carry out the reliability assessment of the power system with the inclusion of such components as the FACTS devices in transmission network. This can further stress the importance of the introduction of reactive power support to reinforce the transmission system against collapse in deregulated markets to avoid loss of service(Onohaebi and Kuale, 2007).

In line with this, the reactive power and other ancillary services at the load ends of the power system were later introduced. So, the optimal supply of reactive power has the ability to alleviate transmission constraints and ultimately lead to wheeling of cheaper real power through the transmission line to an increasingly competitive market (Mount *et al.*,, 2004). This process of enhancing the system voltage profile using the reactive power resources is referred to as the reactive power planning. Various research works have reported that the development of the reactive power planning optimization produced an improvement in the voltage profile under the vertically integrated utility (VIU) market. This was achieved by minimizing the system losses and voltage instability (Mamandur and Chenoweth, 1981, Qiu and Shahidehpour, 1987, Deeb and Shahidehpour, 1990, Deeb and Shahidehpour, 1991, Abdul-Rahman and Shahidehpour, 1994, Venkatesh *et al.*,, 1999, Su and Lin, 2001, El-Samahy *et al.*,, 2007). Meanwhile, in a deregulated market, it is a more challenging issue. It requires the implementation of a procedure that would incorporate the economic and technical challenges of transmission system in the requisite formulation for the optimal and efficient location and allocation of the reactive power support for the power system (David and Wen, 2002).

The deregulation of the electricity market has been able to utilize the OPF tool to achieve a number of influences in power system operation and planning. This includes proper adjustment of the reactive power control variables (using the synchronous motor, transformer tap setting or reactor/compensator bank) as well as optimal operation of the transmission network (Dommel, 1974, El-Samahy *et al.*,, 2007). As a consequence of this, the transmission utility with the technical and economic activities of the various market players is subject to a capacity stress in which it is operated quite close to its practical/technical limit thus bringing about power loss along the transmission line.

It is quite necessary to state that studies have put these losses at an average of 13% of the generated energy in some developed countries (Venkatesh *et al.*,, 1999, Cañizares *et al.*,, 2004) while in Nigeria it is recorded that these losses are in the neighbourhood of 40% (Oluseyi, 1997, Onohaebi and Apeh, 2007). From this, it is one of the expected responsibilities of the system operators in the new and emerging markets to ensure that the network losses are reduced to the barest minimum (McGovern and Hicks, 2004). This is because the market operators are expectant of maximizing profit using the available technical and economic theory that could ensure safe and least cost of electricity delivery. On this note therefore, there are a number of facilities that are useful for economic delivery of electricity. These include improvement of the voltage profile, power factor and system stability. In this emerging market, the transmission providers such as the Transmission Company should be responsible for managing the integrity of the transmission grid (Akinbulire *et al.*,, 2009, Singh and David, 2000). So, it is quite a necessary assignment for this company to facilitate a responsive coordination of the entire network at all times in order to prevent inadequate supply of reactive power in the network at any point in time (Almeida and Salgado, 2000). In other words, the system experiences congestion due to unexpected market activities in which the company would need to employ the assistance of the ancillary support providers. This would ensure that the system is protected against the threats of system collapse (Exposito *et al.*,, 2000).

In the new emerging electricity market, the provision of this ancillary service shall be based on the real-time coordination of the placement of the reactive power support facilities on the network (Kazemi and Badrhzadeh, 2004) but there are many installations that have been done which have not been able to assist the network in overcoming collapse. This argument was overridden by the work of Singh and David (2000), in which there was a development of control and coordination of compensators along the transmission network to actualize effective system security. Thereafter, a number of research efforts proposed a framework for Optimal Reactive Power (ORP) planning and its spot pricing using benefit-to-cost ratio to appropriately assist in the placement and sizing of capacitors/reactors respectively (Song, 2004, Chattophadhyay *et al.*,, 2001).

The OPF concept is one of the few optimization techniques that have the ability to optimize multiple objectives at the same time (Henault and Galiana, 1991, Dommel, 1974, Alsac *et al.*,, 1990). Since voltage collapse phenomenon is due to system instability, the OPF has found a great importance in solving this problem. This has led to the development of various methodologies of overcoming the power system security problems with the set of goals including power loss minimization, economic network utilization as well as gas emission as some of the objective functions (Radziukynas and Radziukyniene, 2009, Warkad *et al.*,, 2009, Mínguez *et al.*,, 2007, del Valle, 2009).

In the late twentieth century, the OPF methodologies were basically hinged on classical mathematical programming approaches which have restricted its convergence to a local optimum. These approaches produce an unreliable solution because it can not produce a practical and representative result. A more realistic and reasonable solution to this challenge involves the application of artificial intelligence (AI) methods (Rahman, 1993). Various AI methods have been developed. They include, among others, simulated annealing (Ahmed and Sheta, 2008, Wong, 1998), evolutionary strategies/algorithms (Panda, 2009, Wong and Yuryevich, 1999) and genetic algorithms (Younes *et al.*,, 2007). The Genetic Algorithm-optimal power flow (GA-OPF) has shown great ability to overcome the limitation faced by the conventional mathematical methods in the modelling of non-convex cost functions, discrete control variables and prohibited operating regions by providing a practical means of solution (AlRashidi and El-Hawary, 2009, Farhata and El-Hawary, 2009).

Moreover, both the theoretical and applied researchers have found this area of research to be highly challenging and productive especially with respect to the recent deregulation and restructuring activities in the power industry which opens the market to a more volatile pricing policy and uncertainty of supply meeting the demand (Fang and David, 1999, Werner and Ward, 2004, Bergström, 2006). Even though voltage collapse has always occurred before the advent of deregulation (Woo *et al.*,, 2003), recent reports have shown that deregulation of the power system is capable of exposing the system to the threats of system congestion that could result in voltage collapse. It is very essential to develop a means of alleviating the menace of voltage collapse in managing the emerging deregulated power system. To perform this task is a number of optimization methods (Fang and David, 1999) which are developed as non-linear models for dispatching the transaction at the various buses using such approach as current injection. This influenced another area of research (Fernandes and Almeida, 2003) in which the weighting factors and the deviation of the vector of power contracts from the desired/proposed values are implemented for overcoming the influence voltage collapse.

It is noteworthy that it is impossible to avoid losses in power system (no matter the kind of structure and model implemented) but it is possible to reduce it because if this loss is substantial, it could lead to different payments for services rendered to different buses within the system and this is not expected in a developing economy. This fact was corroborated by Stoft (2002) with a statement that a generator injecting power into the system at a particular bus can cause substantially different losses and congestion in comparison to a similar injection at another bus/ location. In the proposed deregulated environment, it is impossible for the market players to invest in new transmission system since transmission investment is not open to competition (Wua *et al.,*, 2006). But if the investment in transmission network does not keep pace with the increasing demand for electricity (as it has been experienced in developing nations such as Nigeria (Megbowon and Popoola, 2009)), the nation is bound to face electric power system supply inadequacy and thus would result in economic and unreliability problems. So the OPF solution approach could be introduced to this kind of electricity market with the tendency to improve the voltage profile of the network.

The first set of the optimization techniques ever used in power system was based on the mathematical programming approach which includes such methods as nonlinear programming (NLP) (Wei *et al.,*, 2003, Liu *et al.,*, 2002, Lo and Yuen, 2001, Wei *et al.,*, 1998, Wu *et al.,*, 1993, Wu *et al.,*, 1994), quadratic programming (Lo and Meng, 2004, Tong and Lin, 2005, Grudinin, 1998, Granelli and Montagna, 2000) and linear programming (Stott and Marinho, 1979). Some of these techniques have a number of shortcomings (Akinbulire *et al.,*, 2007). Most of these shortcomings are addressed using the heuristic or metaheuristic approach. These methods include expert systems (ES), artificial neural network (ANN) and genetic algorithm (GA). Fuzzy logic emerged recently in the field of power systems as a set of better alternatives to the mathematical optimization approach. From the list above, various optimization techniques have been applied to solve power system problems as early as 1958 (McCarthy, 1958). Review on various power system problems have been presented by several scholars (Kothari, 1988, Sen and Kothari, 1998, Ahmad and Kothari, 1998, Momoh *et al.,*, 1999, Sachdev *et al.,*, 1977, Happ, 1977, Quintana *et al.,*, 2000, Rahman, 1993, Henault and Galiana, 1991) and IEEE committee (Report, 1980).

This heuristic technique includes other methods such as simulated annealing, fuzzy logic, genetic algorithm (GA), evolutionary algorithm (EA), evolutionary strategy (ES), artificial neural network (ANN), etc. These methods have found great implementation in power system. For example, the simulated annealing (SA) is a stochastic algorithm aimed at minimizing numerical functions of a large number of variables, and it allows random upward jumps at judicious rates to provide possible escapes from local energy wells. As a result, it converges asymptotically to the global optimal solution with probability of one. This methodology has been useful in determining the appropriate location for the installation of Volt-Ampere reactive (VAR) provider, the types and sizes of VAR providers to be installed, and the settings of VAR resources at different loading conditions (Hsiao *et al.*,, 1993). In order to speed up the solution algorithm, a slight modification of the fast decoupled load flow is incorporated into the solution algorithm. In a further development, the VAR planning problem was formulated as a constrained, multi-objective and non-differentiable optimization problem and it provided a two-stage solution algorithm based on the extended simulated annealing technique and the ε –constraint method (Hsiao *et al.*,, 1994). However, only the new configuration (VAR installation) is checked with the load flow, and existing resources such as generators and regulating transformers are not fully explored. In addition, the SA takes much CPU time to find the global optimum (Jwo *et al.*,, 1995). In another development, the proposition of the genetic-based algorithms for solving the optimal capacitor placement problem was considered(Ajjarapu and Albanna, 1991). This work was exhaustively concluded that the genetic algorithms (GAs) offer greater robustness than any other methods before it (Warkad *et al*, 2009).

Until recently, the heuristic method has been a single objective optimization solution but with the prevalent circumstance around the effective operation of power system deregulation, the methods have since evolved into multi-objective optimization solutions. This led the researchers to consider multi-objective approach which is loosely referred to as the multi-objective evolutionary algorithm (MOEA) approach. In this case, several conflicting real-life goals are placed in the same optimization set in which the introduction of a series of constraints lead to the evaluation of choice of the best solution for a specific application. This includes Non-dominated Sorted Genetic Algorithm (NSGA), Pareto Archive Evolutionary Strategy (PAES), Niche Pareto Genetic Algorithm (NPGA), and Strength Pareto Evolutionary Algorithm (SPEA) (Abido, 2006). They have been applied to economic and environmental dispatch problem and could be extended to solve the power transmission system challenges. In comparison with other variants of MOEA, it has not found extensive implementation in power system.

2.2 INFLUENCE OF REACTIVE POWER PLANNING ON VOLTAGE COLLAPSE

The voltage profile of a power system is closely related to the reactive power flow in the system. This could be explained using a 2-node system in which a deficiency in reactive power at a bus is low, the transmission line between the two-node is expected to draw more reactive power from the other node and in so doing reduces the voltage magnitude at the latter node. Before the advent of power system deregulation, the issue of reactive power planning was handled by the central dispatch but under the deregulated market, the study became more popular and inadvertently unavoidable apparently due to the economic loss that accompanies its deficiency in the network. It is on this note that the optimization approach was introduced to the market.

The solution to the reactive power planning optimization problem has undergone major changes over the years, each with its peculiar mathematical and computational characteristics. A survey of reactive power planning methods with a number of them based on the optimization techniques has been carried out (Zhang *et al.*,, 2007). This is in line with the initial work on the OPF idea which was introduced in 1968 by its pioneers. This has since brought a great deal of improvement to the concept of energy management system as a good and veritable tool for application in the deregulated environment (Lai, 2002, Malley and Liu, 2002, Dommel and Tinney, 1968). This includes such tools as Newton's sequential linear or quadratic methods (Momoh *et al.*,, 1994, Almeida *et al.*,, 1984, Zhang *et al.*,, 2000).

Moreover, the OPF is an intelligent load-flow tool (Farag *et al.*,, 1995, Chao *et al.*,, 2007, Almeida *et al.*,, 1984). It is designed to find an alternating current (a.c.) power solution which optimizes the performance functions such as fuel cost or network losses while at the same time enforcing the loading limits imposed by the system equipment such as voltage and transmission loading limits (Zhang *et al.*,, 2000). The method exploited the mathematical structure of the non-linear power- flow equation in conjunction with the optimization techniques to present an efficient solution to the power system security problem. In essence, the primary goal of OPF is to minimize the cost of meeting load demand for a power system while maintaining the security of the system i.e. keeping all the devices in power system within their desired operational range (Aghaei *et al.*,, 2009). Its second goal is the determination of marginal cost which aids in the pricing of the ancillary services (such as voltage support) through MVAr support and provision of spinning reserve (Weber, 1997, Sauer *et al.*,, 2001, Caroin *et al.*,, 2007). Other features include minimizing power losses, active and reactive power optimization improvement of the system performance, minimizing fuel and energy costs, minimizing load shedding and optimizing power exchange with other systems (U.S. Department of Energy, 2003).

The optimal approach that has found implementation in power system includes such methods as the Non-linear Programming (NLP) which deals with the problems involving non-linear objective and/or constraint functions. This method can be grouped into three categories namely: the Generalized Reduced Gradient (Yu *et al.,*, 1986), Newton's Approach, and the Successive Quadratic Programming (Bazaraa *et al.,*, 1993). In the case of linear programming (LP) formulation in power system analysis, it involves a process of linearization of objective function as well as constraints with non-negative variables. This LP-based algorithm is suitable for both loss minimization and investment cost minimization (Iba *et al.,*, 1988). The linearized objective function consists of two parts: one represents the effect of reductions in power losses, and the other represents investment costs of new capacitor or reactor banks. An optimization approach based on a recursive mixed-integer programming technique using an approximation method was presented in Aoki et al (1988). A decomposition technique can be employed to decompose the problem into a continuous problem and an integer problem(Aoki *et al.,*, 1988). However, such a procedure makes the algorithms rather complex (Jwoa *et al.,*, 1999).

The traditional methods of voltage stability investigation have relied on static analysis using the conventional power flow model (Prada and Souza, 1998). This analysis has been practically viable because of the view that the voltage collapse is a relatively slow process because it is being primarily considered as a small signal phenomenon (Barquin *et al.,*, 1995). The various analytical tools classified under steady-state analysis mode have been able to address the otherwise dynamic phenomenon of voltage collapse(Berizzi *et al.,*, 1996, de Souza *et al.,*, 1997, Deeb and Shahidehpour, 1990, Irrisari *et al.,*, 1997, de Souza, 2000). These include such tools as the P-V curve(Berizzi *et al.,*, 1996), Q-V curve, eigenvalue, singular value, sensitivity and energy based methods which were proposed Berizzi *et al*, (1996), de Souza *et al*, (1997) and Irrisari *et al*, (1997).

This analysis of the voltage stability is not restricted to only the static voltage stability computation but also the dynamic voltage stability. It becomes necessary therefore to engage a corrective action any time the need arises to analyze the system so as to save the latter from an impending voltage collapse (Huang and Zhu, 1999, Schlueter, 1998, Gao *et al.*,, 1996). It is quite important to state that due to the attractive properties of the static computation especially its simplicity and ease of performing a number of calculations on the real-time power system under voltage stability analysis, it is quite appealing to engage these services for the analysis of system stability under a deregulated environment. The dynamic computation approach as a method of solution is encumbered with a number of challenges in a deregulated market (this ranges from its complexity and inability to respond fast to calculation under the real-time scenario) even though it is more accurate but has not been so appealing to the system operators.

This has led to a number of research works on the reactive power control techniques (Zhang *et al.*,, 2007). Majority of the works suggested transformer tap and switchable source of reactive power at load nodes. In the earlier work, a method for calculating transformer tap position and generator terminal voltage was presented to reduce the reactive power flow in the lines. This has led to the improvement of the weak bus voltage magnitude to the desired value (Shoults and Chen, 1976). In another approach, the linearized model was developed for reactive power control using simple method while in another development the losses were minimised by adjusting taps and generator voltages (Fernandes and Almeida, 2003). In a separate work presented earlier than the latter, the dual LP was implemented for minimizing the losses by adjusting tap positions and generator voltages as well as switchable reactive power which was used (Mamandur and Chenoweth, 1981). There was also a presentation on the Reduce gradient and Fletcher method for finding the optimal generator terminal voltage magnitude, tap position and setting of

switchable VA sources to reduce the transmission losses and improve voltage profile without disturbing the system security(Deeb and Shahidehpour, 1991, de Souza *et al.*,, 1997).
The reactive power allocation in the scope of electricity markets varies from country to country. In some countries, it is mandatory to provide non-paid ancillary service while in others, it is mandatory to pay for it; in yet another it is subjected to auction mechanism. Whenever the topic is dwelling on reactive power planning, it is highly important to address two issues namely: the cost and geographical location of the reactive components with respect to the voltage profile improvements. Such equipment includes synchronous condensers, capacitors and inductors, Flexible AC Transmission System (FACTS) devices like Static Var compensators (SVC) and Static synchronous Compensators (STATCOM) (Mehta *et al.*,, 1992).

The FACTS devices are controllers based on solid state power electronics technologies (Hingorani, 1988), whose two main objectives are to increase the transmission capacity and to control the power flow over designated transmission routes. The controllers are classified into four categories. They include Series Controllers, Shunt Controllers, Combined series-series Controllers, Combined series-shunt Controllers (Alves *et al.*,, 2008). In line with this, the installation of the SVC in a power system provides such services as transient stability improvement, power system oscillation damping, reactive power compensation, power transfer capacity increase and line loss minimization, maintenance of voltage regulation, reduction of voltage flicker, etc (Houari *et al.*,, 2007). All these properties ensure that the system is quite controlled using these devices to ensure voltage stability.

It is necessary to mention a number of recorded voltage collapse incidences around the world as follows: South Zealand, Denmark in March 1979, Southern part of Nordel (Norway and Denmark) in December 1983, Czechoslovakia in July 1985, England in May 1986 (Kazemi and

Badrhzadeh, 2004) and US in August 2003 (Attia *et al.*,, 2006, Austria, 2004). Each of these events occurred due to different reasons. Consequently many discussions on the nature of the voltage collapse have been indexed (Berizzi *et al.*,, 1996). However, voltage collapse is not restricted to a particular market force though under the deregulated market in which imperfect models are implemented. Similarly, it may not be correct to wholly declare that market model could not affect the occurrence of voltage collapse (Bajpai and Singh, 2004).

Since it has been established that voltage collapse is a situation in which voltage instability leads to loss of service in a significant part of the system, it is imperative therefore to ensure that an appropriate approach is employed to overcome the occurrence of voltage collapse through effective planning (Echaraven *et al.*,, 2003). It is an event that occurs when electric power system does not have adequate reactive support to maintain voltage stability within the predetermined range of values (Zhang *et al.*,, 2007). It may result in outage of the system elements which eventually lead to the interruption in service to customers (El-Sadek, 1988, Ellithy *et al.*,, 2002).

In a nutshell, voltage collapse is a phenomenon by which voltage instability leads to fluctuation in voltage magnitude (and probably angle) in a significant way that its effect results in loss of service to some segments of the electric power network (Prada *et al.*,, 2005). It is often a catastrophic and sudden phenomenon with severe effects on some network areas or the entire grid. Such a system thus becomes unstable during a period of disturbance (e.g. increase in load or other system change) with an unprecedented and fast response with respect to voltage drop which could drift downwards while operators and automatic system control fail to improve the voltage level. It is pertinent to note that the voltage decay may take few seconds to several minutes (Raoufi and Kalantar, 2009).

The introduction of FACTS devices to assist in maintaining the voltage profile within a specific range in a deregulated environment has assisted in improving the power flow capacity of the transmission line. Thus, in order to evaluate the significance of these devices on the entire power system, it is essential therefore to study the reliability of the composite network before and after the installation of the reactive support devices (Billinton and Allan, 1984).

The study of reliability assessment of power system has witnessed a great deal of works since 1950s but comparing the latter statement with the recent advancement in the deregulated environment, it can be mildly stated that there are still much research works to be done in this area (Billinton and Kumar, 1990, Billinton *et al.*,, 1973, Hong and Lee, 2009).

Due to the kind of records available (Daia *et al.*,, 2001) on the issue of voltage profile after deregulation, it becomes a serious challenge to the power system operators and researchers that a newly emerging deregulated market must be properly modelled bearing in mind the experience of the maturing power system deregulated markets in order to overcome the inadequacies noticed in the maturing markets. This informed the introduction of a mathematical modelling that would not stop at resolving the technical issues but also incorporate a number of economic issues so that there could be a veritable and honest solution to the voltage collapse phenomenon in a deregulated environment (Prada and Souza, 1998, Stoft, 2002, Maranino *et al.*,, 1994).

In order to actualize this, the assessment of the composite power system reliability under a deregulated market is expected to be analyzed. Hence it becomes necessary to search for a credible solution approach to this peculiar subject matter which, on the long run, led to the introduction of fault tree analysis (FTA) technique (Yuge and Yanagi, 2008, Volkanovski *et al.*,, 2009, Hong and Lee, 2009) which has been in use in such places where zero tolerance mistakes are demanded such as in aeroplane industry, nuclear plant industry, and such other places. It is becoming increasingly a popular approach for evaluating the system reliability and failure occurrence in electricity industry, as a means of innovation which has been a credible way to secure this industry against loss of service under very unpredictable market participants. This method of system reliability analysis was developed in 1961 by H.A. Watson (Bell Telephone Laboratories) (NUREG, 1981, Chung *et al.,*, 2004, Yuhua and Datao, 2005).

There are a few contributions towards the implementation of the fault-tree analysis in power engineering system stability studies. The most prominent among them is the work of McCalley and Fu (1999), where it was recommended that the fault-tree analysis can be used to assess the reliability of a special protection system (SPS) but this was suggested for a small scale system. Then, an improvement over this was developed in which the fault-tree analysis was implemented to study the reliability of a transmission system protection in larger power system (Schweitzer *et al.,*, 1997, McCalley and Fu, 1999). In other words, the system reliability of the transmission protection was discussed by considering only six components and two hardware operations. The approach for enhancing the reliability related to the transmission protection was based on an empirical trial-and-error procedure. Thus, the implementation of this approach in this research is a way of projecting another area of application of the FTA in power system, in which case it is implemented in a reinforced system to evaluate the influence of the FACTS devices on the power system reliability.

2.3 OPTIMAL POWER FLOW SOLUTION IN A DEREGULATED ENVIRONMENT

The change in paradigm in electricity market is producing a new era in electricity supply industry based on the liberalization of the market with its attendant massive entrance of participants to the generation and distribution segments of the electrical power industry. This is having its toll on the system stability and availability. The goal of OPF tools is to ensure a good control and coordination of the system variables to allow for a better and more efficient system planning and operation. The OPF has achieved a great deal in vertically integrated utility (Momoh *et al.*,, 1999). As a useful tool in power system planning, the electricity supply industry in a competitive environment has enjoyed the benefits of the OPF in its capability to adequately maximize the transmission network against overload. It is believed that the tool has the tendency of solving a number of complex power system problems which is capable of influencing the network investment. This has assisted in efficient management and utilization of the transmission network. So it is interesting to note that the OPF is capable of handling a number of cases in power system planning ranging from optimizing the system in preventive or corrective mode against certain system undesirable occurrences such as uncertainty in load demand to optimization of a set of contingencies, transmission line thermal limits and so on (Momoh *et al.*,, 1999).

Based on this, the OPF is utilized as an incentive for optimal energy resources management in competitive electricity market. This is because of the fact that the bulk power transmission brought with it a number of challenges to power system deregulation which includes the effective management of the transmission network in such a manner that all the competitors would have a fair share of the network capacity. This is a great challenge because of the fact that the engineering theory guiding the transmission network, i.e. the Kirchoff's Laws are not adequately entrenched in the business contracts guiding the administration of the transmission network as a monopolistic entity in the electricity market.

In a restructured electricity market, the OPF thus performs a number of responsibilities namely; optimal utilization of the resources for successful price-based competition, effective mathematical manipulation of the feature of the power transmission segment as an open access network to the advantage of the system security and reliability, as well as creation of market for the ancillary services such as the reactive power, black-start capability (for power plant with capacity self-start after system collapse), frequency regulating service, spinning reserve service, etc.

The OPF is a non-linear programming problem that needs the use of optimal control parameter setting to actualize a minimized desired objective function, subject to a number of system constraints. With diverse objective functions that require several level of optimization, the desired result is orchestrated by maximizing such goals while the undesired ones are minimized. This has resulted in such an achievement as cost minimization, power loss minimization, transmission flow maximization, etc all performed at the same time in a multi-objective optimization environment (Rosehart and Aguado, 2002).

The phenomenal challenge of power system deregulation has made the OPF a useful tool (Venkatesh *et al.*,, 2003). This is evidently observed in the stressed power system which is characterized by line overloads and low voltages at the buses. One of the practical ways of managing the system operation is by engaging the OPF tools for efficient operation of the network (Venkatesh *et al.*,, 2003). As suggested by Venkatesh *et al* , (1999, 2003), the method is able to manage the system voltage collapse activities so that the reactive power needed to support a transmission system real power flow is enhanced by the OPF by transferring the requisite reactive power from the sources to the load centres to avert voltage collapse by maximizing the voltage margin of the transmission network during overload (Venkatesh *et al.*,, 1999). The fuzzy model has been used to achieve such a goal as minimization of cost of generation, transmission loss and voltage stability margin.

In the aspect of electricity pricing, the OPF has been greatly utilized to achieve appropriate pricing of the electricity commodity, e.g. the economic dispatch of the network which operates the least expensive generators in the network in order to achieve low cost of production. There is a scenario in a deregulated environment whereby during the transmission system overload, the Locational Marginal Pricing (LMP) approach is used to discourage load growth at specific buses. This is done by sending signals (for the reduction of electricity supply) to specified buses by reducing the price at such buses which discourages the competitive generators from posting electricity to such locations (Alvarado, 2005). In a very critical environment, the transmission network is further supported by placing premium on the price of the reactive power as well as the operating reserves of the network so as to ensure that voltage collapse is averted. Thus, the OPF is a great tool at determining the prices of operating the power transmission network in the sense that if the optimal operating price of the generators supplying a transmission network is known it is very easy in a transparent competitive electricity market to determine the cost of system operation. This is quite useful in converting a congested network to an uncongested network with the assistance of the price signals.

The issue of reactive power planning and dispatch as a means of overcoming system collapse is gaining a lot of attention with several researches in this area. In a deregulated electricity market, the reactive power dispatch is a necessity for short-term real-time decision taking in allocating it in such a way as to ensure that the system operation is not endangered under the current operating condition. The OPF helps the ISO to choose a criterion that best suits the competitive market structure (El-Samahy *et al.*,, 2007). The dispatch is done on time basis which means that the reactive power market is decoupled from the real power. This gives the ISO the opportunity of maintaining an efficient coordination of the system security in such a way that the operating time frame for the auctioning of the real power is not the same as that of the reactive power (Singh *et al.*,, 2009).

The system is prone to voltage collapse once the reactive power is inadequate. Unlike the real power market, the reactive power cannot travel a long distance over the transmission lines, so it is only made available locally at the designated buses or somewhere adjacent to the designated bus. Thus, its procurement is based on the bilateral contracts between the ISO and the generators. Some of the methods used in supplying the reactive power support include installation of synchronous generators whose service is either paid for as it is in New York ISO and UK or as in Sweden the reactive power supply is mandatory without any financial compensation (Singh *et al.*,, 2009). The newest method of improving the reactive power support in a transmission network is by engaging the power electronics devices that are useful in boosting or reducing the reactive power in the system for an effective maintenance of a profitable system voltage profile (Kamarposhti and Alinezhad, 2009). Many research works have involved such devices generally referred to as Flexible Alternating Current Transmission Systems (FACTS) devices. A typical FACTS consists of Thyristor-Controlled Series Compensator (TCSC), Thyristor Controlled Phase Shifter (TCPS), Static Synchronous Compensator (STATCOM), Synchronous Var Compensator (SVC), etc (Komolafe and Ojo, 2007, Kazemi and Badrhzadeh, 2004).

The solution methodology for harnessing the benefits of this market (in order to ensure effective energy management that would not result in voltage collapse) has been designed by a number of researchers and practitioners in this market (Kodsi, 2005, Hague, 2000). Most of the works have made the security of the system their source of inspiration but the issue of the system availability by studying the reliability of the system under deregulation with the support of the system with power flow controllers like the FACTS devices, has not been thoroughly exhausted (Verma *et al.*,, 2004). Also, majority of the solution approaches have not considered the myriad of challenges that the electricity markets face in developing economies such as inadequate generation, rapid growth of electrical load due to a number of reasons ranging from sophistication in electricity consumption to improvement in wages (Awosope, 2003).

2.4 RESTRUCTURING OF ELECTRICITY SUPPLY INDUSTRY IN A DEVELOPING ECONOMY

According to Sioshansi (2006), the restructuring of the electricity market started in Chile in 1982 and followed by Britain in 1989. From these two countries' gains from the reforms in electricity industry, many parts of the world have been enjoined to implement it (Sioshansi, 2006). The underlining purposes of restructuring vary from country to country. The aligning principles are correlated by the respective nation's level of industrialization and urbanization (Bahce and Taymaz, 2008). The electricity consumption *per capita* of many of the less developed countries (LDC) is on an average of 1500kWh which is far below the World Bank or Organization of Economic Co-operation and Development (OECD) average of 7300kWh whereby most of their electricity consumption is on domestic rather than industrial (Bahce and Taymaz, 2008). This has been able to explain the reason behind the low and slow state of .industrial self-reliance in these countries. Many of these countries are encouraged by the international organizations like the World Bank to liberalize the electricity industries so as to reduce their respective poverty level. This has led these international financial institutions to involve themselves in such projects as the installation of generating stations to improve the electricity supply in some of these countries.

Many of these countries have since gone ahead to open the generators to competition in which case several generators are allowed to negotiate with the ISO for transportation of the generated power over the transmission network that is still monopolistic in operation. This suggests that the generators are bound to invest in only efficient technologies so that the cost of electricity generation can be kept low. The transmission network also would have to share its limited available capacity among the various generators at a price. This price would ensure that whichever generator easily overloads the network would be allowed to pay for its activity based on the violation of the minimum required level of overloading that can be tolerated from each of the generators. There is no flat rate for this but it is based on the economy of scale. Thus, the scope of each generator is dealt with according to its respective merit of operation.

The distribution segment is another portion of the electricity industry that has been viewed with great concern in the sense that many practitioners are afraid of opening it to competition (Reiter and Cook, 1999), but it is only competitive distributional network that can promote the virtues and benefits of system deregulation. This ensures not only a static efficiency but dynamic efficiency at reducing the influence of the potential market power as some of the large generators may probably want to take undue advantage of the market. The foregoing idea is further defeated by ensuring that every consumer has the right to switch to any supplier of choice because of price incentives. This eventually encourages the generators to lower the price of electricity by engaging the most efficient means of generating electricity (Bahce and Taymaz, 2008).

In many developing economies, the government is responsible for the operation and management of power plants and construction and financing of future infrastructural development (Sioshansi, 2006). Typically there are no independent regulators. This results in a number of shortcomings ranging from risks in the investment being borne by the taxpayers, with or without accountability, which translates to little or no pressure on the market operators to improve customers service or technological innovation. A great problem that has also been identified among these developing countries is that the government lacks sufficient resources to adequately finance and invest in the electricity infrastructure which has resulted in chronic power shortages and poor service reliability as evident in India, China, the Philippines and Nigeria, to provide few examples.

Whereas in advanced economies, the regulated monopoly is practised in which private sectors operate a significant part of the infrastructures. For example, in the US and Hong Kong, there are private companies running 100% of the electricity infrastructure, while in Korea and France provision is made for a single company to virtually own and operate the infrastructure. In the case of South Africa, it is a single company that owns and operates 90% of the infrastructure (Sioshansi, 2006). Since it is a regulated monopoly, there is an independent regulator that ensures that best practices are implemented, especially in terms of pricing of electricity and congestion management.

The regulated monopoly model of electricity suffers from a number of setbacks as follows: no customer choice, investment's risk of the industry is borne by the ratepayers, no or slim price subsidies and sub-optimal regulations.

2.5 MOTIVATION FOR RESTRUCTURING OF ELECTRICITY SUPPLY INDUSTRY

The force behind electricity market deregulation is different from countries to countries with different factors motivating different countries into electricity market deregulation. In this respect, the study carried out on 66 countries articulated the following findings (Pollitt, 1999):

1. Inefficiency of dominant players is a common reason behind most of the market liberalization.
2. Challenges of political economics contributed a great deal in the sense that the politicians are not ready to play the role of laying off the over-bloated staff, but with the transfer of ownership to the private investors, the uneconomic staff population is quickly shed and uneconomic contracts are discarded forthwith.
3. The issue of public debt was a very obvious reason behind the case of reform in Victoria, Australia, in which case, the sale of heavily indebted state-owned asset brought relief to the government of the time.
4. Inadequate investment in electricity infrastructure has encouraged private partnership investment in the utility. This is very common in the developing economies and this has led to the provision of credit facilities by the international financial institutions to ensure that power supply is adequate in such nations. This has been attracting foreign investors as recorded in Orissa State in India and Serbia (Sioshansi, 2006, Jednak *et al.*,, 2009).
5. Incidence of cumbersome/ bureaucratic bottleneck in decision making has led to poor management of the electric power system and market operations(Jednak *et al.*,, 2009). In many of the centralized electricity markets, the issues of real-time load forecasting, financing, operation, maintenance and coordination of network (especially in geographically expansive land mass as a country) are becoming too complicated. Thus, the best solution to this challenge is to unbundled the system to avoid inefficiency and slow control of the network. This is the case in a number of nations such as Iran, India and China.

2.6 FEATURES OF COMPETITIVE ELECTRICITY MARKETS

The main purpose of deregulation and reforms in electricity markets is to institute efficiency in the operation of the electricity industry with the following items being the major components of competitive electricity markets (Joskow, 2003, Joskow, 2006):

1. Open access to all players for electricity generation.
2. Unbundling of vertically integrated utilities to remove government financial assistance to the industry.
3. Creation of wholesale electricity market that is open and transparent for investment.
4. Creation of articulate and effective independent grid operator with the task to manage the transmission system against congestion ensure system reliability and involve in healthy market operations.
5. Creation of forward market in which electricity could be sold before its production; this ensures perfect planning ahead of execution of the contracts. This is good for risk management (because it assures the market of income).
6. Unbundling of the prices for the sake of transparency and to avoid cross subsidization (i.e to ensure that profit from one sector is not used to cover losses from another).

2.7 MODELS OF THE EMERGING ELECTRICITY MARKETS

Deregulated electricity market is still maturing all over the world and this has given the prospective countries that opportunity to make the choice of model with reference to the aspiration of the nation's electricity and energy policy. From the reports of the deficiencies already encountered by the maturing nations, it is important for the emerging nations to choose their respective models carefully (Amobi, 2007, Yoon and Ilic, 2002, Sioshansi, 2006, Delmas, 1999, Jednak *et al.,*, 2009). In any way, there are several models that are available ranging from the highly successful to the less successful markets which serve as the litmus test for any emerging market. For instance, Swedish model is tailored to give the municipality owned company a prominent role in the distribution of energy while the privately owned company generators are meant to supply a fraction of the electricity need along with the municipality companies. In England and Wales, the electricity sector took a metamorphosis from mandatory pool model to the present state (by going through nothing less than three stages).

European models consist of such models as the wholesale market model otherwise known as the freedom of investment and trade model, the retail competition or customer's choice model and the regulated network access. But the energy-only electricity market models have enjoyed great patronage among nations having been adopted in the original (defunct) California design, in Nordpool, the Australian Victoria pool (although with an *ex post* Value of Lost Load, or VOLL) and in the recent British NETA design. There is the need to ensure that the low income earners and rural dwellers are not alienated by the type of model that would be adopted since this would help the climate change campaign. So the model would generate a pricing scheme that the government would have to subsidize or rather the rich urban dwellers would be made to bear this percentage in order to encourage electricity usage in the rural areas.

In the meantime, the transmission provider (TP) has duty to perform, particularly during the initial stage and medium stage of deregulation in which case the TP is expected to oversee the market activities as the link between the generators and load/demand. The major models considered include: multilateral transaction, mandatory system operator, purchasing agency and the voluntary system operator models (Yoon and Ilic, 2002, Oricha *et al.*,, 2007).

2.7.1 Multilateral transaction model

This is based on bilateral transaction among the market players. This model consists of three stages of transaction shown in the figure 2.1. The individual buyers and sellers initialize the procedure by making available their respective bids and offers through a bilateral transaction. The transmission service provider (TSP) receives the various market operators' volumetric and monetary request which is then processed in real-time along with the physical network constraints. If the proposed transaction violates any of the system constraints, then the market players are once again advised to prioritize their respective offers and bids for reprocessing by using the loading vector approach. The advantage of this is that force of supply and demand dictates the activities in this market. It is specifically implemented in the USA by Midwest ISO. The model makes a special provision for both future contracts and forward markets as it is the case in Nord Pool and the USA (David and Wen, 2002).

2.7.2 Wholesale competitive model

This is a model in which there is no central dispatch authority and it is illustrated as shown in Figure 2.2. The distribution companies are responsible for the buying of electricity directly from the generating companies which by implication means that the operation of the spot market and the transmission network are the sole functions being coordinated in this market. This thus means that the centre does not coordinate the pricing of the commodity. Hence the wholesale price is determined by the market forces of supply and demand. It is noteworthy to state that the retail price of electricity is the only regulated entity. This is a means of protecting the small consumers from exploitative pricing mechanism in this kind of market (Oricha, *et al.,* 2007).

2.7.3 The mandatory system model

The TSP developed here is based on the existing practices of tight power pools. In which case the TSP is the major overseer of the market whereby it economically and functionally bundles the energy and transmission trades even though the system still remains a deregulated one. It is very common in spot market practices with elastic demand .The TSP simultaneously dispatches generators and allocates transmission capacity using the knowledge provided by the Optimal Power Flow (OPF) program in order to evaluate the most economical mix of the generators. Figure 2.3 gives a detailed explanation of this. This is explored in Australia where a body of non-profit making entity accumulates the function of the market and system operator with 7-day half-hourly bids up to ten incremental prices without any fixed price (Yoon and Ilic, 2002).

2.7.4 Purchasing Agency

The model is supervised by an agency which buys the power in wholesale from the independent power producers (IPPs). In other words; the utility that produced the power does not have ownership over the generated capacity. There is a great danger here in that the agent makes it look as if the model is a regulated model which could affect the price rates .It can then be said that this model is not a thorough free market. Figure 2.4 explains the market model. Example of this model is found in Central and Eastern Europe. A typical example is Hungary. In most cases, the market operators and the system operators have distinct and separate duties and responsibilities (Oricha *et al.*, 2007).

2.7.5 The voluntary system operator model

This is a model that supports multi-tiered structure that minimizes the TSP's influence on profits by the market players while the issue of system reliability is not jeopardized .In this particular model, the bilateral and centralized market based trading arrangement is favoured which then means that the spot pricing must be the electricity market proper transaction mode. This has helped the customers in making choice of generators while the generator is better equipped to cope with direct activities with both the system operators and market operators. The California market is a very good example of this model shown in Figure 2.5. In this case, the trading arrangement is organized in such a simple way that there is provision for the hourly-based price-volume bid on a day ahead basis. Also Spain is a good example where market and system operators are separate. The challenge is that the model could be subjected to inappropriate sharp practices if care is not taken to track the volume of electricity by using pre-paid meters(David and Wen, 2002).

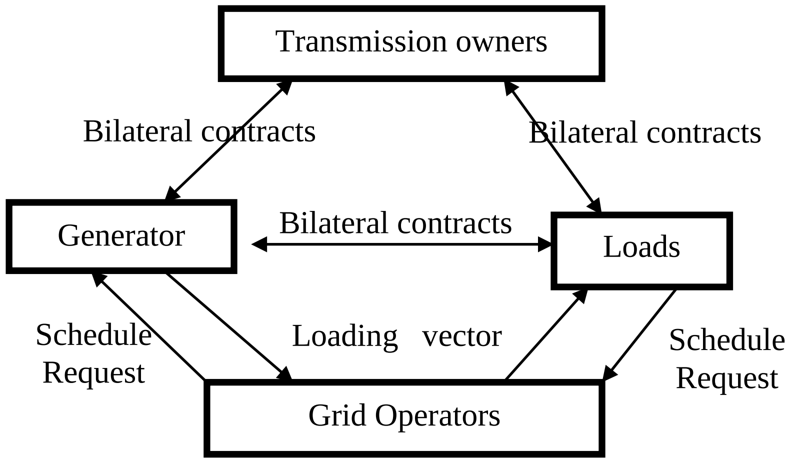


Figure 2.1: Multilateral transaction model

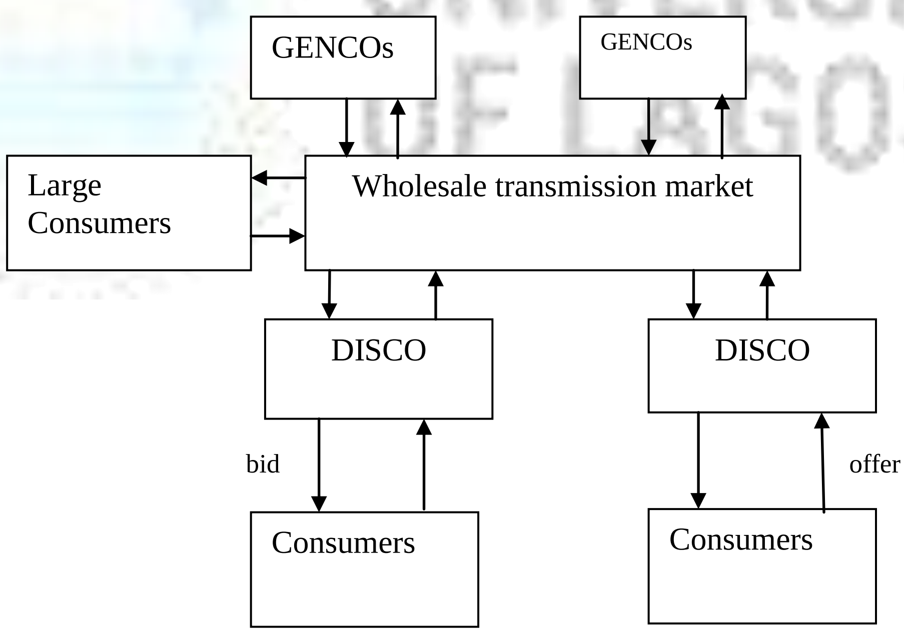


Figure 2.2: wholesale competition model (Oricha *et al.*,, 2007)

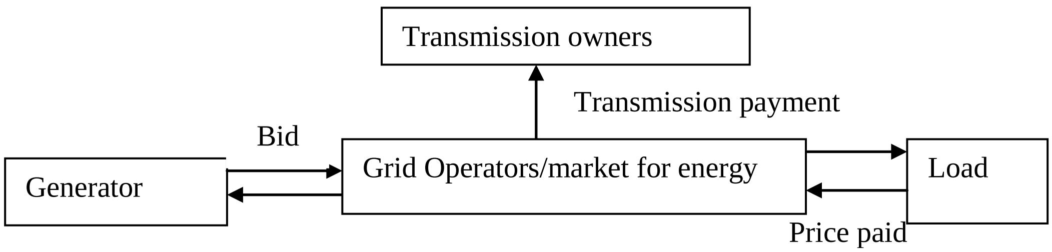


Figure 2.3: Mandatory system operator model

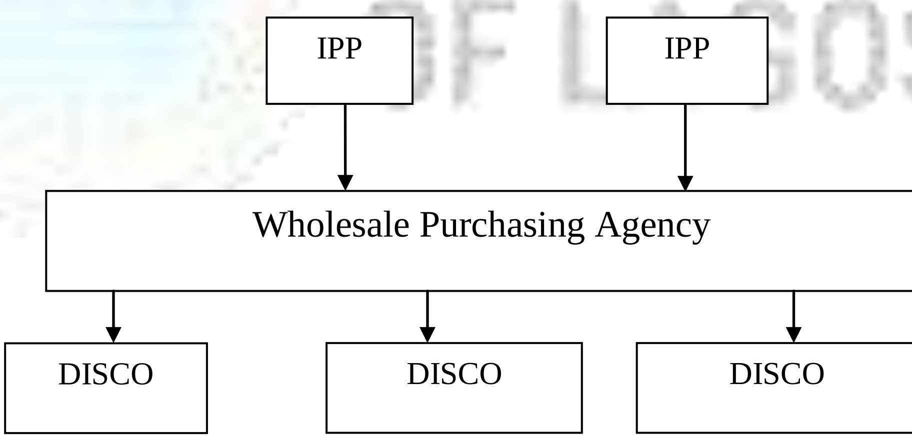


Figure 2.4: Purchasing Agency Model

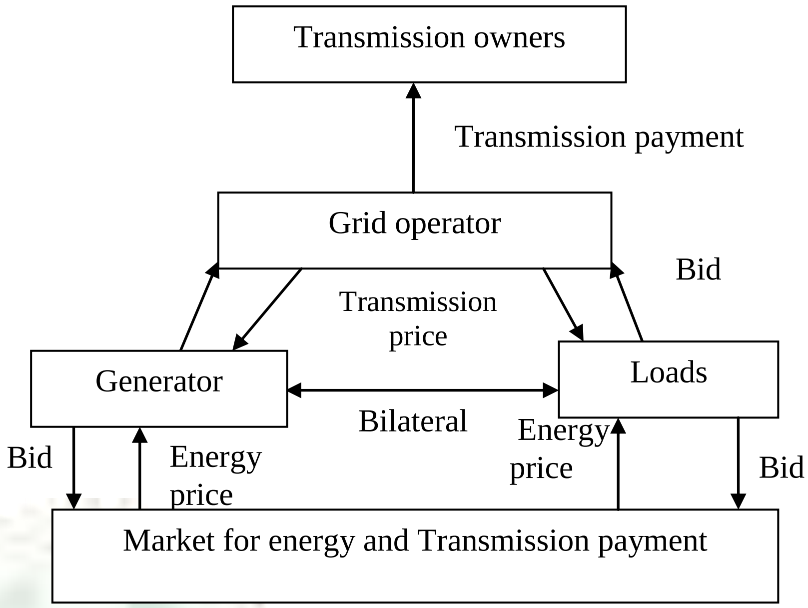


Figure 2.5: Voluntary system operator model

CHAPTER THREE

3.0 METHODOLOGY

This research work will consider the voltage security in a deregulated environment with the assistance of a well designed market structure and installation of the FACTS device for improving the power system security against voltage collapse. The resulting reinforced composite power system would be subjected to reliability assessment by using the Fault Tree Analysis approach to determine the composite system failure rate.

3.1 THEORETICAL FRAMEWORK

There is a necessity for the development of an electricity market model for the developing economy with respect to the available information in the previous chapter.

3.1.1 ATTRIBUTES OF WELL-DESIGNED DEREGULATED ELECTRICITY MARKETS

Electricity market reform can only succeed in the developing economies when the annual growth rate in electricity consumption is approximately 7.5%, if the market model can address the following itemized points (Lee and Ahn, 2006):

(i) Improve the efficiency of electricity supply by transiting the industry from a monopolistic market to a competitive one.

(ii) Guarantee cheap and stable electricity supply in the long run.

(iii) Increase the industry's social welfare benefits by expanding the customers' choice in the use of electricity.

(iv) Attract enough investment from the mostly foreign investors as well as local ones.

Thus, to achieve the above it is of great necessity for a well-designed market to possess the following qualities:

1. ***Self- sustenance:*** this is very important since the governments in the developing countries are no longer ready to fund electricity supply. The well-designed electricity market therefore is expected to be able to sustain both its risk and assets in order to remain relevant. Though the generators are well prepared for this particular assignment/task, it is doubtful if the same could be attested to the transmission network's financial standing. Thus, in a well-designed market, the transmission network would be able to sustain its basic task if the funds that accrue to it for wheeling the power to the load centres could be retired to it in form of transmission rent and congestion pay rate.

2. ***Efficiency:*** it is also the expectation of the market to ensure that the energy management is effective, which means both the system and market efficiency is significant to the electricity market. In the case of the system efficiency, the system must display a characteristic efficiency in terms of utilization of capital, labour, technology and fuel. This kind of efficiency has to do with perfect and correct mix of generation, reliable transmission and distribution networks to ensure power supply at all time at every place. On the other hand, the market efficiency is basically hinged on transparency in market participants' transactions, effective competition at all levels (except transmission network), and accountable usage of transmission facilities. This objective is better managed by the power system optimization approach.

3. ***Resilience:*** since electricity market is quite complex, then it is expected that a well-designed market must be structured in such a way as to survive the undesirable and

unpredictable shift in market paradigm due to such occurrences as weather condition, loss of generation or transmission line, etc.

4. ***Absence of abusive market power:*** it is necessary to ensure that the market players are much disciplined in order to avoid abuse of their respective power market to the disadvantage of the system and market operation. This is very important to avoid the reoccurrence of the California market experience of Years 2000/2001. It is suggested that the dominant position of an entity in the electricity market to own substantive generators in the system should be discouraged so as to achieve a credible and smooth-running market system (Badgdadioglu and Odyakmaz, 2009).

5. ***Customer service:*** Even though government is no longer in charge of the electricity supply in a deregulated market, it does not remove the over-sight duty of the latter to the citizens. Hence to achieve this, power to make choice should be made available to the customers so as to encourage improvement of service among the service providers. This is very important in the developing economies so as to protect the low income earners as well as the rural dwellers (Brunekreeft *et al.*,, 2005).

From the foregoing, it is necessary for the developing and dynamic economy to desist from fashioning the electricity market structure after the order of the developed economy like the UK because of the peculiar regulatory challenge that is bound to arise due to adaptation of policy. This is further buttressed by Badgdadioglu and Odyakmaz (2009) who observed that many of the developing economies are faced with inadequate electricity generation as against sufficient generation in the UK's electricity supply industry. Thus, this makes the demand for *ex-ante* regulation and day ahead balancing of demand and supply forecast an essential in the deregulated environment. In other words, a great commitment to market reforms framework becomes an important index for boosting the efficiency of market structure in the developing economy. Appreciation of the local challenges in generation, transmission and sales of electricity should be accommodated in the market structure that is to be adopted.

3.1.2 RESTRUCTURING THE ELECTRICITY SECTOR

Only very few published accounts are on electricity reform in developing economies and much fewer on the kind of markets in Africa (Sebitosi and Okou, 2010, Turkson and Wohlgemuth, 2001). Hence the work of Pineau (2008) still gives the best account of electricity reform in West Africa while that of Bowen *et al* (1999) presented the South Africa power pool. There are several challenges to the success of efficient power system reforms in many developing countries. For example in the West Africa, these range from lack of commitment to privatization in Senegal to inability to cope after a few years after liberalization as it was the case in Mali which later retrieved the power sector from a private foreign investor. The World Bank has been promoting the issue of competition in electricity market but political issues have also brought about a number of barriers to this reform (Bowen *et al.,*, 1999). For example in Nigeria, the market structure is still vertically integrated after more than five years of instituting the Electric Power Sector Act in 2005 which is supposed to oversee the restructuring of the power system. Only few of the countries in the West Africa sub-region have been able to entrench the Independent Power producers (IPPs) in their electricity generating policy; this includes Burkina Faso, Cote d'Ivoire, Ghana, Senegal and, to some extent, Nigeria (Pineau, 2008).

As at 2003, the total installed electricity generating capacities of West Africa amounted to 9.8GW which constituted 57.8% of thermal power stations and 42.2% of hydro-electric plants

(Gnausounou *et al.*,, 2007),. The total electricity production was 31TWh; the major producers are Nigeria, Ghana and Cote d' Ivoire with their respective capacities put at 15.6, 5.4 and 5.1TWh. Total electricity consumption was 28.4TWh with Nigeria (14.5TWh), Ghana (5.1TWh), Cote d' Ivoire (3.4TWh) and Senegal (1.2TWh) as the main consumers. The majority of electricity market in the region is vertically integrated monopolies with government control over the utility being very apparent except for a handful of countries such as the ESKOM in the Republic of South Africa, Companie Ivorienne d'Electricitie in Cote d'Ivoire and Electricity Company of Ghana which are run by private investors. This explains the reasons behind ineffective electricity market in Cameroon where 93% of SONEL (electricity utility company) is state-owned or Nigeria's PHCN which is a state monopoly in its operation. Because there is no adequate investment in the sector, the room for expansion and improvement is constrained by government participation in the electricity market activities.

For example in the West Africa, only 40% of the population has access to electricity. The main problem of Nigeria stems from the fact that the power generation system operates significantly below the installed capacity due to vandalism and old age of the facilities (Tyler, 2002). So, in February 2006 the country electricity demand was 7600MW, while the actual generation was only 3600MW. Only part of the electricity demand is satisfied by the grid which means that a significant share of the consumption is achieved through self-production using the captive generation. For example, according to Tyler (2002), the companies in Nigeria use their own power-generating units in two-thirds of time and they use electricity from the public utility for only one-third of the time. This portrays that the available data of the electricity consumption mainly signifies the available supply rather than effective and absolute level of electricity demand (Tyler, 2002) . This is a great challenge to the planners.

3.1.2.1 Nigerian Electricity Market Model

Nigeria is an emerging electricity market with a great market potential by the virtue of the fact that only 40% of its more than 120 million population have access to electricity. Therefore it requires huge investment and uncommon engineering understanding of the country's socio-economic structure to provide adequate and constant supply of electricity for the entire population. In other words, the market is large and dynamic but the facilities need improvement in order to deliver sufficient amount of electricity to the populace. As at now, the government is building a number of generating units especially around the oil- rich Delta region of the country (where gas is available) while the existing supply is mainly from three hydro stations in the Northern part of the country and about six gas/steam turbine stations in the Southern part. The total installed capacities of these generators are not enough to meet the need of the country at the best of times .This is further decimated by the age of most of these units as well as the lack of funds for proper maintenance and overhaul.

The essence of this work is to consider the peculiar nature of Nigeria's electricity market in order to propose a particular model to the nation. With respect to the demographic information available and the high demand of electricity by the citizens, the 48 million out of the total population of about 120 million that are being served with an average of 3500-Megawatts daily portrays a high level of under-production of an essential service like electricity. Hence every sub-sector of the electricity supply industry in Nigeria needs improvement on its facilities.

The transmission network in Nigeria consists of two variants namely 330-kV and 132-kV each spanning a total distance of 5000km and 4000km respectively. These are supported by 23 substations (330/132-kV) and 91 substations of 132/33kV.Many cases of system collapse have been recorded due to both technical and non-technical losses such as very poor voltage profile, overload and weak distribution system, old and obsolete power system equipment, vandalism of transmission line and poor metering and billing system. In the case of the distribution there are also two types of lines namely the 33kV and 11kV. The former covers a distance of about 23,753 km while the latter is networked across the whole cities and towns in the country covering about 19,226km.There are 1790 distribution transformers and 680 injection stations. But all these have been totally neglected with the kind of feeder pillars that are used in some parts of the nation's cities without fuses but ungraded current carrying conductors, which are installed by the rule of the thumb.

The Nigerian Electricity Supply Industry (NESI) is currently undergoing progressive though slow-pace transformation from vertically integrated monopoly based utility to a disaggregated and liberalized industry. At the concluding end of this transition of the electricity industry to competitive regime, the transmission line is expected to be left as an entity while the existing generating stations are unbundled into six (6) companies named after their respective locations. In continuation of this, the distribution sub-sector becomes 11 companies named after the area being served by the individual companies (Gazette, 2005). Several other agencies were established for easy running of the affairs such as the Nigerian Electricity Regulatory Commission, NERC, which serves as a regulatory body to monitor and oversee the activities of the market players. Rural Electrification Agency is saddled with the responsibility to expand the accessibility to electricity in the rural areas. Power Consumer Assistance Fund Agency (PCAFA) was also established and funded by the government to subsidize the tariff for the underprivileged consumers.

The system has suffered great imbalance due to the fact that the power demand in 2005 was put at 6,000MW which is forecasted to be 10,000MW by 2010. This outstrips the installed capacity of total supply hence the need to make the market attractive for investor to bring in competition that is highly needed. To attain the electricity demand target, the government has recently made it a compulsory venture for the oil producing companies within the country to generate a specific volume of electricity for the National grid. Likewise a quota of gas from these companies is expected to be supplied to the newly built National Integrated Power Projects (NIPP) across the country as its feed for generating electricity.

It would have been much easier for the operation of deregulation but the financial return to the investors is very low which results in the lack of excitement at investing in the industry by the private investors. In other words, the pricing of the electricity in Nigeria is below what could sustain the market players. But in 2008 the regulatory body, the Nigerian Electricity Regulatory Commission (NERC), instituted the Multi Year Tariff Order (MYTO) which is a schedule of tariffs to be paid each year from July 1, 2008 to June 30, 2013. This tariff path set was developed using the historical and forecast data. This is an attempt towards encouraging investors to participate fully in the market.

From the foregoing, it is important to observe the necessary criteria for laying a good structure for an emerging deregulated electricity market in Nigeria. This will equip the market with an effective and efficient operation that has the ability to deliver similar results with respect to the testimonies that are prevalent in other fully deregulated electricity markets around the world.

3.1.2.2 A Model for Nigerian Electricity Supply Industry (NESI)

As earlier explained, Nigeria electricity market is a peculiar and special case study for the electricity market model experts in that the system has a number of local challenges which must be handled with great caution in order not to jeopardize the restructuring process that is going on. The bottleneck can be linked to the inadequate funding of the utility and non-implementation of the load forecast reports prepared by the planning engineers over the years. The tariff charged is under the supervision of the Government hence it is impossible for the utility to implement its own tariff structure that could have adequately made the market a self-sustaining sector. Hence a three-phase structure instituted by the Government representative in the current Nigeria's electricity market may not totally produce a superior solution to the market needs for stable and efficient power supply if a number of facilities and man power are not entrenched in the sector.

Hence a conglomerate of bilateral market model where the consumers can choose as well as the wholesale market is suggested. This looks quite close to the model in figure 2.5 but there is a little amendment to this, which includes a proper bilateral market between the big customers and the generators. Also whenever a particular producer is not able to meet its bid it can negotiate with the neighbouring generator to assist with some volume of electricity for it to meet the demand (its bid) from its clients. Hence, it is better to suggest a hybrid of agency and bilateral market (voluntary) model for the Nigeria's electricity market. This would enable the system to run an efficient industry that would have enough revenue to address the issue of volumetric production and pricing approach. There are several big companies (especially the oil companies) which have the opportunity to generate electricity for running their businesses hence surplus of the generation could be sold to the distribution company (DISCO) in their areas. This concept is as shown in figure 3.1.

The volume of electricity produced is coordinated by the independent system operators (which need to be well defined by the Nigerian Electricity Regulatory Commission). This shall be assisted by the Transmission Company of Nigeria (TCN) as the transmission service provider, which is expected to act as the system and market operators. The pricing approach is expected to be monitored by the independent market experts who will supply a trend of billing at intervals of three to five years as specified by MYTO.

Even though the electricity market is a volatile business environment that depends greatly on time-of-use as well as price in a third world emerging deregulated power market, the Government would still have to insist that price spiking should not be billed on the poor especially those in rural areas to forestall the possibility of impacting negatively on climate change. This could be encouraged by including Rural Electrification Agency (REA) in the model to source for the sustenance fund for electricity supply to the rural poor. This could be in form of a policy statement that would encourage the conglomerates to assist in the rural areas with a number of tax-relief based on their achievement at carrying out effective and efficient electricity supply to this group at a reduced price. This set of transactions could be bilateral without exerting more pressure on the frail transmission network. In this way, the system collapse would be reduced with the efficient implementation of the programme developed in this work.

Meanwhile, bilateral market as an electric power market concept is a process in which the suppliers and the consumers independently arrange electricity marketing trades within themselves without the input of the ISO. This is done in such a way that the power market players (as separate entities) set their respective amount of generation and consumption with corresponding financial terms without any recourse to or interference from the independent system operator (ISO). According to Akinbulire (2007), this market structure enhances economic efficiency but it runs the risk of violating the transmission network operation constraints due to little or no coordination and thus absence of regulation of the market activities (Akinbulire *et al.*,, 2009). This particular challenge is overcome by assuming that the generation is near the load centre which suggests that the transmission network would be involved in the power exchange.

In the subsequent chapter, the methodology for solving the voltage collapse in this electricity market structure is developed. It is worthy of note that the available transmission capacity and forecast load are used in the proposed method as a means of improving the network capacity. In the eventuality that more load centres are linked with the transmission network, it is the belief of this work that the proposed solution would assist the network against collapse.

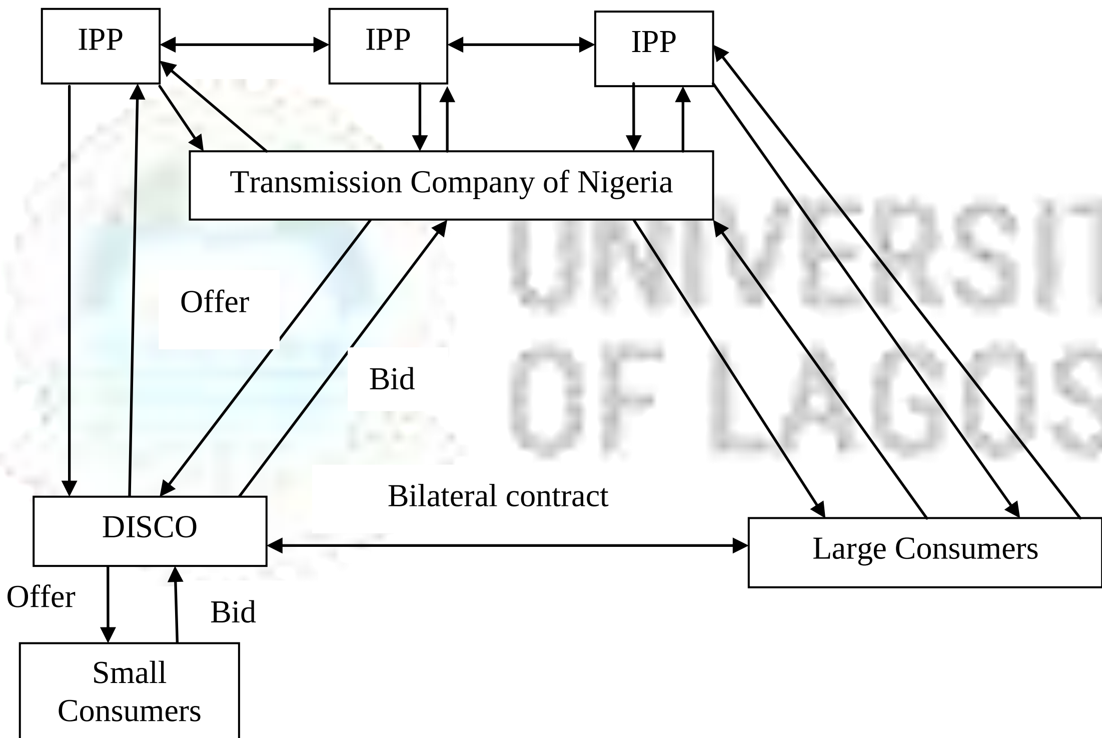


Figure 3.1: Hybrid electricity market model proposed for Nigeria

3.2 MATERIALS AND METHOD

The materials for the facilitation of this research are as follows:

1. The IEEE-30 bus system and Nigeria-26 bus system power networks are used as the test cases.

2. Existing data on IEEE-30 bus system were obtained from the webpage of the Institute of Electrical and Electronics Engineers (IEEE) Power Engineering Society.

3. Data collection on the Nigeria's power transmission system's voltage collapse occurrences and power failures was based on PHCN logbooks report (National Control Centre, 2008).

These materials were used for solving the power system problems by implementing the transmission section of the market model shown in Figure 3.1, using the following methodology:

1. Development of optimization model for the alleviation of the voltage collapse in an existing power system by maximizing and/or minimizing a number of electrical parameters using the multi-objective optimization approach. This is achieved by modelling of the FACTS devices into the electric power transmission network in order to improve the magnitude of the reactive power at specific buses in the network. This reduces the propensity of voltage collapse in the electric power network.

2. Reliability studies of the existing and modified composite power system to evaluate the advantages of the FACTS devices in attaining the system adequacy (Verma *et al*, 2004). This is then subjected to multi-objective optimization technique as part of the contributions of this work to knowledge.

3. Simulation of various optimized models in order to examine their respective influences on the transmission network of both standard IEEE-30 bus system and Nigeria-26 bus grid using an improved Strength Pareto Evolutionary Algorithm (SPEA-2) with MATLAB software (Abido, 2006).

3.2.1 FORMULATION OF OPTIMAL POWER FLOW METHODOLOGY

A power system optimization problem is a mathematical model in which the objective is to minimize undesirable electric power system parameters such as cost, power loss, congestion, reactive power or maximize desirable ones like the profit, social benefits, quality, efficiency, reliability indices, etc. This mathematical arrangement is naturally subjected to a number of physical and economic constraints such as the gas emission, costs, bus voltage limits, tap setting limits, etc.

This approach had been in use for several decades especially for the analysis of the economic dispatch/operation of the generators in vertically integrated utility regime. Recently it finds applications in the deregulated market due to its great influence in economic operation of the available resources for the benefit of the market participants. According to the work on the recent development in electricity supply industry, the deregulation scheme challenges the old method of power business approach in that the power supplier is no longer necessarily the agency that is saddled with the responsibility of selling electricity to the customers(Oluseyi *et al.*,, 2009). In which case, the seller rather than produce electricity is now buying shares from the generation company. Retail wheeling represents a group of distribution agencies which are allowed access to the transmission network for the transportation of the purchased energy through the transmission system which is a monopoly market entity (Yong and Lasetter, 1999).

Conventionally, optimal operation of power system network has been based on economic criterion. Economic Load dispatch is normally used by most power utility companies for the purpose of energy management service (EMS). However with the contending issue of power quality for improved voltage profile, the necessity is laid on the system operator to consider additional objective in OPF formulations. From the technical perspective of operating the power system, one of the major sources of voltage instability has always been inadequacy of reactive power support in the system. A lot of work has been done on optimal reactive power dispatch as a sub-problem in OPF. This has been useful for studying the voltage profile as well as account for the transmission loss in the power system (Yong and Lasetter, 1999). The procedure for this is by redistributing the reactive power in the network using the installation of capacitor component(s). But there are few literatures on the cost of investing in the installed capacitor. A work in this direction would encourage the utility in establishing the social benefit of this installation in this era of little or lack of Government financial assistance, due to restructuring of the industry.

In order to meet the increasing complexity of the power system in a regime of system deregulation, it was essential to introduce the risk of security limit evaluation. Because the ability to avoid security limit violations is among the highest precautionary measures usually adopted for maintaining the transmission system security within a very safe region of operation (Bakare *et al.*,, 2001, Raoufi and Kalantar, 2009, Warkad *et al.*,, 2009).

To really appreciate this work, it is very important at this juncture to introduce the generalized transmission line model (Lynn, 2004, Saadat, 2004). In which case, it is considered that the line parameters are uniformly distributed and the line is modelled as a 2-port, 4-terminal network shown in figure 3.2 (Chung *et al.*,, 2004, Dai *et al.*,, 2000) .

$$V_s = AV_r + BI_r \tag{3.1}$$

$$I_s = CV_r + DI_r \tag{3.2}$$

The ABCD constants of a line of length l, having a series impedance of $z\Omega / km$ and shunt admittance of yS / km are given by :

$$A = D = \cosh(\gamma l) \quad ; \quad B = Z_c \sinh(\gamma l) \; ; \quad C = \sinh(\gamma l) / Z_c \; ; \; where \;\; \gamma = \sqrt{zy} \;\; and \;\; Z_c = \sqrt{\frac{z}{y}} \tag{3.3}$$

The apparent power extracted from the sending-end bus (P_s and Q_s) and injected to the receiving-end bus (P_r and Q_r) of the line can be written as:

$$P_s = C_1 \cos(\beta - \alpha) - C_2 \cos(\beta + \delta) \tag{3.4}$$

$$Q_s = C_1 \sin(\beta - \alpha) - C_2 \sin(\beta + \delta) \tag{3.5}$$

$$P_r = C_2 \cos(\beta - \delta) - C_3 \cos(\beta - \alpha) \tag{3.6}$$

$$Q_r = C_2 \sin(\beta - \delta) - C_3 \sin(\beta - \alpha) \tag{3.7}$$

$$where \;\; C_1 = \frac{A}{B} V_s^2 \; ; \; C_2 = \frac{1}{B} V_s V_r \;\; ; \; C_3 = \frac{A}{B} V_r^2 \;\; ; \; \overline{A} = A\angle\alpha \;\; , \; \overline{B} = B\angle\beta \;\; and \; \overline{V}_r = V_r\angle 0$$

Note that the sending-end bus (s) is later referred to as the bus i, while the receiving-end bus is defined as the bus j (Saadat, 2004).

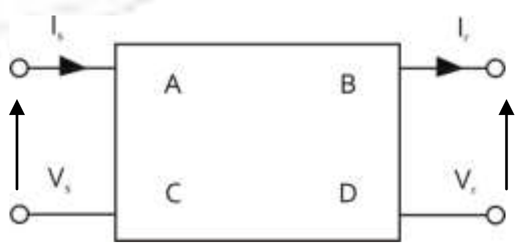


Figure 3.2: 2-port, 4-terminal network of the power system

Thus, the real and reactive power flows between the buses *i* and *j* can be written as stated below (Lynn, 2004):

$$P_{gi} = V_i^2 g_{ij} - V_i V_j g_{ij} Cos(\delta_i - \delta_j) - V_i V_j b_{ij} Sin(\delta_i - \delta_j) \tag{3.8}$$

$Q_{gi} = - V_i^2 b_{ij} - V_i V_j g_{ij} Sin(\delta_i - \delta_j) - V_i V_j b_{ij} Cos(\delta_i - \delta_j)$ (3.9)

$P_{dj} = V_j^2 g_{ji} - V_j V_i g_{ji} Cos(\delta_j - \delta_i) - V_j V_i b_{ji} Sin(\delta_j - \delta_i)$ (3.10)

$Q_{dj} = - V_j^2 b_{ji} - V_j V_i g_{ji} Sin(\delta_j - \delta_i) - V_j V_i b_{ji} Cos(\delta_j - \delta_i)$ (3.11)

Where Q_{gi} and P_{gi} are the generator real and reactive powers; P_{dj} and Q_{dj} are the load real and reactive powers while g_{ij} and b_{ij} are the transfer conductance and susceptance respectively of the line from bus i to bus j.

Therefore, the multiple objective functions of both technical and economic goals can now be stated as follows:

$$f(x,u,z) = \begin{cases} \min\_(P_{loss}) \\ \min\_(L_j) \\ \min\_(\cos ts) \end{cases} \quad (3.12)$$

where, P_{Loss} : active power loss, L_j : voltage collapse index

and

costs: cost of overcoming losses due to transmission congestion.

Each of these objective functions is derived as follows:

(a) Power loss

This could be developed in line with equations (3.8- 3.11) hence the power loss is

$$P_{loss} = \sum g_{ij} \left[(V_i^2 + V_j^2 - 2V_i V_j Cos\delta_{ij}) \right] \quad (3.13)$$

(b) Voltage collapse index

In a similar development (Kessel and Glavitsch, 1986, Moghavveni and Faruque, 1999, Subramani *et al.*,, 2009), there has been a number of mathematical designs to overcome voltage collapse, this includes stability index of the transmission line as well as that of the busbars. But the interest of this research is in that of the stability index of each of the load busbars in the power system, this is obtained as follows:

$$L_j = \left| \frac{S_j^*}{Y_{jj} V_j^2} \right| \tag{3.14a}$$

where S_j^* : injected apparent power, Y_{jj}: self admittance at the load bus while V_j: complex voltage at load bus j

At any load bus of a stable power system, the voltage collapse factor is

$$L_j \leq 1 \tag{3.14b}$$

Voltage collapse is possible once the eq (3.14b) exceeds 1 for any load bus whose voltage is compared with the global voltage indicator, L, which could be deduced from eq (3.14a). This results in the following expression:

$$L_j = L^{\max} \tag{3.14c}$$

where $L^{\max}$ is,

$$L^{\max} = \left| 1 - \sum_{gi=1}^{Gi} Y_{ji}^{+} \frac{|V_{gi}|}{|V_{dj}|} \right| \tag{3.14d}$$

$\boldsymbol{Y_{ji}^{+}}$ is a submatrix of a hybrid matrice Y shown below.

$$Y = \begin{vmatrix} Y_{ii}^{+} & Y_{ji}^{+} \\ Y_{ij}^{+} & Y_{jj}^{+} \end{vmatrix} \tag{3.14e}$$

In this direction, the voltage collapse index for an effective and dynamic electricity market is defined as

$$L = \max_{j \subset dj} \left| 1 - \sum_{gi=1}^{Gi} Y_{ij} \frac{|V_{gi}|}{|V_{dj}|} \right| \tag{3.14}$$

where $Y_{jj} = \dfrac{1}{Z_{jj}}; S_j^* = S_j + S_j^{corr}$

$$S_j^{corr} = \sum_{\substack{i \in d\ j \\ i \neq j}} \frac{Z_{ij}^*}{Z_{jj}^*} x \frac{S_i}{V_i} x V_j \tag{3.15}$$

dj is the set of load buses and Gi: total number of generator units in the network.

(c) costs

The cost of overcoming transmission congestion depends on the cost of reactive power support implemented under a contingency scenario for a particular system under deregulation. This could be modelled using the concept previously developed (Daia *et al.*,, 2001). In which case, it is possible to establish that the theory of opportunity cost addresses the issue of employment of MW and MVAr quantities in a power system (Koutsoyiannis, 2003). Thus, the MVA rating of generator could possibly be varied in favour of the components of power (i.e. real or reactive power) that is deficient in the transmission network. In other words, the system is operated to produce more of either the MW or MVAr. So in such a case the system requires the injection of more reactive power quantity to avoid system collapse then the cost implication of such activity could be determined as follows (Dai *et al.*,, 2000, Chung *et al.*,, 2004).

$$C_{gi}^q = \tau_{gi}[C_{gi}^p(S_{gi}^{\max}) - C_{gi}^p\sqrt{(S_{gi}^2 - Q_{gi}^2)}] = \tau_{gi}[C_{gi}^p(S_{gi}^{\max}) - C_{gi}^p(P_{gi}^{\max})] \tag{3.16}$$

where $S_{gi}^{\max}$: the maximum apparent power of generator, gi

C_{gi}^{p}: the active power cost which is earlier modelled in the form of economic dispatch (Saadat, 2001).

τ_{gi}: the assumed maximum profit rate for active generator at the generator bus, gi.

C_{gi}^{q}: the reactive power cost.

Note that the opportunity cost of choosing which of the power components to be produced is based on the real-time power balance equation using the demand-supply-balance equation and evaluation.

It follows from the above that in order to keep the demand/load-bus voltage profile away from collapse point, a fixed amount of MVAr must be drawn from (or injected to) the line .It is on this account that it is suggested that a separate specialized private investors could own this reactive compensator which the investor could install at selected buses (since unlike the active power, the reactive power production is a localized service) (Daia *et al.*,, 2001). Thus, the cost of purchasing the transmission system conditioner installed at the selected buses in the power system could be evaluated with regards to the quantity consumed by the load bus to alleviate any form of voltage collapse. The price charge of which is assumed to be proportional to the amount of the reactive power output purchased to avoid voltage collapse is defined as:

$$C_{cj}(Q_{cj}) = r_j Q_{cd} \tag{3.17}$$

Where r_j and Q_{cj} are reactive power cost or depreciation rate and amount purchased, respectively, at the demand bus located at bus j; the amount purchased is based on system operating condition and voltage stability margin requirement. Thus, the depreciation rate of the capacitor at the load bus j can thus be calculated as (Chung, *et al*, 2004):

$$r_j = \frac{\text{investment cost}}{\text{Operating hours}} \tag{3.18}$$

Thus, the total cost of maintaining the system voltage stability in a steady-state condition is obtained from the combined action of equations (3.16) and (3.17):

$$Costs = \sum C_{gi}^{q}(Q_{gi}) + \sum C_{cj}(Q_{cj}) \tag{3.19}$$

Thus, the reactive power planning is then subjected to both equality and inequality constraints. These are as follows:

The equality constraints consist of the load-flow equation i.e.

$$P_i - V_i \sum_{j=N_g+1}^{N} V_j (g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}) = 0 \tag{3.20}$$

$$Q_i - V_i \sum_{j=N_g+1}^{N} V_j (g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}) = 0 \tag{3.21}$$

Then the system operating constraints which include the operating limits of the generator voltage, reactive power generated by the compensators, transformer tap setting range, and others are state variables as the load bus voltage and reactive power generation of the generator and line flow limits.

Inequality constraints represent the system operating constraints namely;

$$V_{i,\min} \le |V_i| \le V_{i,\max} \tag{3.22}$$

$$Q_{gi,\min} \le Q_{gi} \le Q_{gi,\max} \tag{3.23}$$

$$Q_{cj,\min} \le Q_{cj} \le Q_{cj,\max} \tag{3.24}$$

where N_{gi} *and* $N - N_g$ are the total numbers of generator and load buses in the system respectively ; P_j and Q_j are the specified active and reactive power demands at load bus j ;

$Y_{ij} \angle \theta_{ij}$ the element of the magnitude and angular displacement of the admittance matrix;

$V_i = V_i \angle \delta_i$ the magnitude and angular displacement of the bus voltage at bus i; $V_{i,\min}$ and $V_{i,\max}$ the lower and upper limits of bus voltage; $Q_{gi,\min}$ and $Q_{gi,\max}$ the lower and upper limits of reactive power output of the generator; similarly $Q_{cj,min}$ and $Q_{cj,max}$ are the lower and upper limits of reactive power output of the capacitor for compensation.

Transformer constraints: The transformer settings are bounded as follows:

$$T_{i,min} \leq T_i \leq T_{i,max} \tag{3.25}$$

where i=1,...NT, where NT: number of transformers

Load bus voltage: these include the constraints of voltages at the load buses V_j, as follows:

$$V_{j,min} \leq V_j \leq V_{j,max} \qquad j = N_g+1,...N \tag{3.26}$$

Line flow limit of the power system transmission line is yet another constraint which can be denoted as

$$S_{l,\max} \geq |S_l| \tag{3.27}$$

This leads to the evaluation of the voltage at each of load buses designated as j which is defined as

$$V_j^{index} = \sqrt{\sum_{j=1}^{N}(V_j - V_j^{ref})^2} \tag{3.28}$$

In other words, the voltage collapse index limit as one of the constraints to be satisfied is denoted as

$$L^{\max} \geq L_j \tag{3.29}$$

where $j = N_g + 1, \ldots, N$ (which is the number of load buses).

L_j: collapse index which is computed for all load buses while the maximum value of all the indices is used for validating a weak bus in the power transmission network to which the necessary corrective action would be taken in order to reduce the influence of voltage collapse.

Thus, equations (3.13, 3.14 and 3.19) are substituted into equation (3.12) to evaluate the optimization of the network operation with respect to the constraints itemized in equations (3.20 to 3.29).

3.2.2 INTRODUCTION OF FACTS DEVICES TO A TRANSMISSION NETWORK

As power transfer grows, the system becomes increasingly more complex in a deregulated market hence to operate such as network, self-commutated semiconductor devices in form of power electronics devices are introduced to the network. This ensures that the system security is maintained without any form of violation of the operating limits (Oluseyi, 1997). The power-injected model is a good model for a FACTS controller because it will handle them well in a load–flow computation problem. Since this method will not destroy the existing impedance matrix *z*, it would be easy to implement in the load–flow programs. In fact, the injected power model is convenient and sufficient for a power system with a FACTS controller. Mathematical models of the FACTS controller are developed mainly to perform steady-state research. The Thyristor-Controlled Series Compensator (TCSC), Thyristor-Controlled Phase Shifter (TCPS), Synchronous Var Compensator (SVC) and Unified Power Flow Compensator (UPFC) are modelled using the power injection method (Mehta *et al.*,, 1992). Furthermore, the TCSC, TCPS, SVC and UPFC mathematical models are integrated into the model of the transmission line.

3.2.2.1 Modelling of Thyristor-Controlled Series Capacitor (TCSC)

For this static application, FACTS device is modelled by Power Injection Model (PIM). In the injection model (which describes the FACTS as a device that injects a certain amount of active and reactive powers to a node) the FACTS device is represented as PQ elements. The advantage of PIM is that it does not destroy the symmetrical characteristic of the admittance matrix and allows efficient and convenient integration of TCSC devices into existing power system analytical tools (see figure 3.3).

Hence the effect of the TCSC on the network is evidently observed as a controllable reactance inserted in the related transmission line, whereby the voltages and angles at the buses i and j are V_i, δ_i and V_j, δ_j respectively.

Thus, the real and reactive power flows between the buses i and j can be written as the real and reactive power flows between the buses i and j as stated below. With recourse to power flow equations stated above, the transmission transfer functions with the compensator installed are

$$g_{ij}'' = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2} \tag{3.30}$$

and

$$b_{ij}'' = -\frac{x_{ij} - x_c}{r_{ij}^2 + (x_{ij} - x_c)^2} \tag{3.31}$$

From equations 3.8 to 3.11, the injected power to the weak bus can be evaluated as

$$P_{inj}^{t\,csc} = g_{ii}''V_i^2 + \left(g_{ij}''\cos\delta_{ij} + b_{ij}''\sin\delta_{ij}\right)V_iV_j \tag{3.32}$$

$$Q_{inj}^{t\,csc} = -b_{ii}''V_i^2 + \left(g_{ij}''\sin\delta_{ij} - b_{ij}''\cos\delta_{ij}\right)V_iV_j \tag{3.33}$$

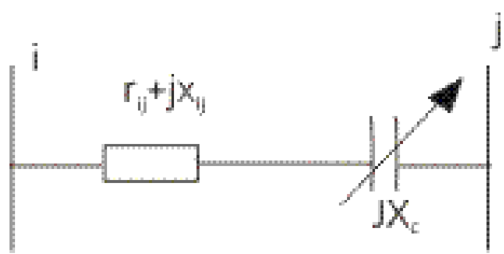


Figure 3.3: Equivalent circuit diagram of TCSC

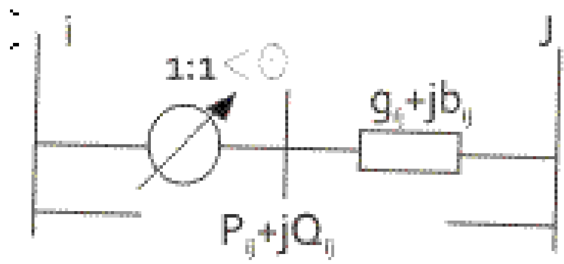


Figure 3.4: Equivalent circuit diagram of TCPS

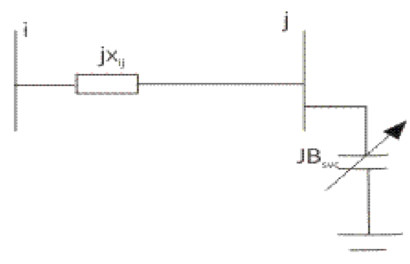


Figure 3.5: Equivalent circuit diagram of SVC

The model of a transmission line with TCSC connected between the buses i and j is as shown in figure 3.3; the change in the line flow is due to the series reactance, jX_{tcsc}. The constraint on the network with the TCSC device is determined from the system maximum loadability as

$$X_{tcsc,j}^{\min} \le X_{tcsc} \le X_{tcsc,j}^{\max} \tag{3.34}$$

where $j = 1, \ldots, \eta_{tcsc}$

In equation (3.34), the value of X_{tcsc} for effective operation is within the range of $-0.7X_{ij}$ and $0.2X_{ij}$, where X_{ij} is the reactance of the transmission line $i - j$.

3.2.2.2 Modelling of Thyristor-Controlled Phase Shifter (TCPS)

In this case, the TCPS is modelled by a phase shifting transformer which has a control variable as the phase value, i.e φ, as shown in Figure 3.4. Thus, the power-flow equation of the line could be written with reference to equations (3.8 to 3.11) as follows:

$$P_{ij} = \frac{V_i^2 g_{ij}}{Cos^2\phi} - \frac{V_i V_j}{Cos\phi}\left[g_{ij} Cos(\delta_i - \delta_j + \phi) + b_{ij} Sin(\delta_i - \delta_j + \phi)\right] \tag{3.35}$$

$$Q_{ij} = -\frac{V_i^2 b_{ij}}{Cos^2\phi} - \frac{V_i V_j}{Cos\phi}\left[g_{ij} Sin(\delta_i - \delta_j + \phi) - b_{ij} Cos(\delta_i - \delta_j + \phi)\right] \tag{3.36}$$

$$P_{ji} = V_j^2 g_{ji} - \frac{V_j V_i}{Cos\phi}\left[g_{ij} Cos(\delta_i - \delta_j + \phi) - b_{ij} Sin(\delta_i - \delta_j + \phi)\right] \tag{3.37}$$

$$Q_{ji} = -V_j^2 b_{ji} + \frac{V_i V_j}{Cos\phi}\left[g_{ij} Sin(\delta_i - \delta_j + \phi) + b_{ij} Cos(\delta_i - \delta_j + \phi)\right] \tag{3.38}$$

where the $\delta_{ij} = \delta_i - \delta_j$; similarly, P_{ij} and Q_{ij} are real and reactive power flows between the buses *j* and *i*.

Following from equations (3.32) to (3.38), the equations governing the activities of the power electronic device are written as follows:

$$P_{iC} = -g_{ij} V_i^2 \tan^2\phi - V_i V_j \tan\phi\left[b_{ij_j} \cos(\delta_i - \delta_j) + g_{ij} \sin(\delta_i - \delta_j)\right] \tag{3.39}$$

$$Q_{iC} = b_{ij} V_i^2 \tan^2\phi + V_i V_j \tan\phi\left[g_{ij} \cos(\delta_i - \delta_j) + b_{ij} \sin(\delta_i - \delta_j)\right] \tag{3.40}$$

$$P_{jC} = -V_i V_j \tan\phi\left[g_{ij} \sin(\delta_i - \delta_j) + b_{ij} \cos(\delta_i - \delta_j)\right] \tag{3.41}$$

$$Q_{iC} = -V_i V_j \tan\phi\left[g_{ij} \cos(\delta_i - \delta_j) - b_{ij} \sin(\delta_i - \delta_j)\right] \tag{3.42}$$

In other words, from equations 3.35 to 3.42, the voltage angle between the buses *i* and *j* can be regulated by TCPS. This is illustrated by modelling the TCPS along with a transmission line as expressed in equation (3.43). Thus, the injected real and reactive powers at buses i and *j*, *in* which case, the phase shifter is regarded as the compensating device can be incorporated into equations (3.4 to 3.11) to describe the influence of TCPS on the electrical transmission network. Hence the range of values for which the TCPS can operate efficiently is often defined as:

$$\phi_{tcps,j}^{\min} \leq \phi_{tcps} \leq \phi_{tcps,j}^{\max} \tag{3.43}$$

where $j = 1, \ldots, \eta_{tcps}$ are the load buses with TCPS.

The working range of the TCPS is between -5° and $+5^{\circ}$ (Song, 2004).

3.2.2.3 Modelling of the Static Var Compensator (SVC)

The SVC is an important component of voltage control in power system, whereby its primary purpose is usually to control voltages at weak points in a network. It is always connected as shown in figure 3.5.

Thus, the reactive power output of the SVC can be computed as

$$Q_{SVC} = \frac{V_j (V_j - V_{ref})}{X_{sl}} \tag{3.44}$$

where V_j: the nodal voltage magnitude

V_{ref} : reference voltage magnitude

X_{sl}: slope reactance in per unit (p.u.) which equals the slope of voltage control characteristics.

Equation (3.44) is valid as long as the reactive power output of the SVC, Q_{svc}, is within the operating limits set by available inductive and capacitive susceptances (i.e. B_{ind} and B_{cap}) which are otherwise defined as follows:

$$Q_{ind} = B_{ind} V_{ref}^2 \tag{3.45}$$

$$Q_{cap} = B_{cap} V_{ref}^2 \tag{3.46}$$

In the Optimal Reactive Power (ORP) planning formulation, the SVC has been considered as a reactive power source with the above stated reactive power limits which are in close relationship with the equation below .i.e.

$$B_{svc_j}^{\min} \leq B_{svc_j} \leq B_{svc_j}^{\max} \tag{3.47}$$

where $j = 1,\ldots,\eta_{svc}$ are the load buses with SVC device.

The practical working range of the reactive power sourced from the SVC is normally between $-100M\,V$ar and $+100M\,V$ar.

From the foregoing, it is evidently clear that the reactive power is tightly related to the bus voltages throughout the power network. This is the essence of introducing the FACTS devices so as to facilitate an improvement of the system voltage profile by controlling the system reactive power flow. This is highly promising because it ensures that the system operates under a better quality of power supply to the load centre without necessarily overloading any of the lines.

In order to appreciate this new development, the expression for the cost of investment in reactive power component is introduced into the power loss equation to obtain the price of reactive power support needed to alleviate voltage collapse as:

$$C(Q) = KP_{loss}(Q) \tag{3.48}$$

where $$P_{loss}(Q) = RI_x(Q^{'})I_x(Q) \tag{3.49}$$

and $$I_x(Q^{'}) = \frac{Q^{'}}{\sqrt{3}V_L \sin\varphi} \tag{3.50}$$

$$I_x(Q) = \frac{Q}{\sqrt{3}V \sin\varphi_L} \tag{3.51}$$

Substituting equations (3.50 and 3.51) into equation (3.49), we have

$$P_{loss}(Q) = R\left(\frac{Q^{'}}{\sqrt{3}V_L \sin\varphi}\right)\left(\frac{Q}{\sqrt{3}V_L \sin\varphi}\right) \quad (3.52)$$

$$= R\left(\frac{Q^{'}}{3V_L^2 \sin^2\varphi} Q\right) \quad (3.53)$$

In a transmission line model, the resistance of the line could be expressed as a function of the length as

$$R = rl \quad (3.54)$$

where r : per phase resistance per unit length

and l : the line length

Substituting equations (3.53) and (3.54) into equation (3.48) results in the cost of the reactive power employed for the loss of service reduction which is defined as

$$C(Q) = C_K \frac{rlQ^{'}}{3V_{ref}^2 \sin^2\varphi} Q \quad (3.55)$$

Since the power system loss reduction is one of the principal ways of achieving the delivery of electricity to load centre with minimal losses incurred; hence from equation (3.55), C_K which is defined as the cost due to losses and released capacity [US$/(Kw-year)], is defined as

$$\text{Cost of loss reduction, } C_K = \frac{12C_p}{\cos\varphi} + 8760F_{loss}C_e \quad (3.56)$$

In essence, $\frac{12C_p}{\cos\phi}$ is the annual cost saved due to the released capacity (Baskaran and Palanisamy 2006). The released capacity factor is determined by dividing the actual output with the maximum possible output of power system component. This released capacity factor is assessed using a cost function, otherwise known as the capacity charge C_p (in US$/KVA-month) which is related to the fixed cost of the network. $\cos\phi$ is the power factor and C_e is energy charge in US$.

F_{loss} is the Loss factor which is expressed as the average power factor over a given period of time and is used in the energy industry to express losses in the transmission system from heat, incomplete combustion of fuels and inefficiencies in the system (Baskaran and Palanisamy 2006) .

In equations (3.48) and (3.49), this loss is calculated over a period of a whole year of 365 days to give 8760 hours while Q is the reactive power before the compensation. In order to minimize the losses, it could be established that the reduction in energy losses yields an increase in the maximum power metered during the entire year. Thus, saving could be simply translated as the difference between the cost before compensation and cost after compensation.

The reactive power, Q that initially flows would surely be affected by compensation in bus j, to the new value as $Q^{'}$ which obviously results in the expression that:

$$Q_{ij} \succ Q_{ij}^{'} \tag{3.57}$$

Thus, the benefit to be obtained annually from compensated network is expressed as

$$\beta = \sum_{i=1}^{N_g} \sum_{j=N_g+1}^{N} C_{ij}^{L} (Q_{ij} - Q_{ij}^{'}) \tag{3.58}$$

Thus, equation (3.55) can be rewritten with respect to the contribution of the compensators towards the reduction of losses in the system. This gives the new value of cost of loss of service reduction as:

$$C^{'}(Q) = C_K \frac{r_{ij} l_{ij} Q_{ij}}{3V_L^2 \sin^2 \varphi} Q_{ij}^{'} \tag{3.59}$$

This is the cost of compensators per unit in US$/kVAr.

The investment cost is taken as the overall cost of purchasing and installing the compensator banks which are selected using merit order of their respective capacity **a**, which is multiplied by a binary decision variable $X(j,a)$ with respect to their respective placement.

$$C_{inv} = \sum_{j=1}^{N} \sum_{a=11}^{d} C_{ij}^{L}(a) X\left(j, a\right) \qquad (3.60)$$

So the placement is formulated as

$$K_{inv} = \frac{(1+B)^{n_{facts}} B}{(1+B)^{n_{facts}} - 1} \qquad (3.61)$$

where B is the refundable investment rate expressed as a percentage

n^{facts} : life expectancy of the FACTS devices

k_{inv} : investment cost factor.

This device is operated as ranked. Thus, the ranking of the compensators is very significant to their performance in the network. This is the reason for introducing the ranking coefficients (Raoufi and Kalantar, 2009).

Using these coefficients, some compensators are considered ‘important’ while some are considered ‘less important’ at a particular point in time. The important compensators have small ranking coefficients while the less important ones have large ranking values.

Using the elementary statistical approach, the compensators’ mean ranking coefficient is written as:

$$\overline{C}_{rank} = \frac{1}{n} \sum_{j=N_g+1}^{N} C_{rankj} \qquad (3.62)$$

where n: number of load buses at which there are compensators

C_{rank_i} : Coefficient of compensator ranking

j: the load bus number

The variance of equation (3.62) could be obtained

$$\mu_j^{k+1} = \mu_j^{k} + \alpha(C_{rank_j} - \overline{C}_{rank}) \qquad j \in N \notin N_g \qquad (3.63)$$

where α : weighting factor

The weighting factor is either reduced or increased according to the severity or otherwise of voltage violation in the power system operation. In other words, for the implementation of the compensator with less severity, then small ranking of value $\alpha \succ 0$ is needed while for a severe portion of the transmission network then the more compensators is deployed which means that it will be represented by a small weighting factor i.e. $\alpha \prec 0$.

At the important compensator nodes, there is high tendency for the voltage profile to be very high. Thus, the voltage margin is improved by increasing the reactive power generation at this bus while the reactive power generations at the other compensated buses is regulated. This can be achieved by relaxing equation (3.59).

Using the penalty term obtained in equation (3.63) for this purpose, then the cost of generating reactive power at each compensated bus is obtained as:

$$C_j = \sum_{j \notin N_g} C^{'}(Q) + \sum_{j \notin N_g} (\mu_j Q^{'}_{ij}) \tag{3.64}$$

where $\mu_j = \mu_j^{k+1}$

For a j[th] bus which is a load bus, equation (3.65) can be subjected to further constraints to ensure a full scale exercise of the convergence of the solution as (Jacoby, *et al*, 1972)

$\mu_j \prec 0$; for the deployment of the compensator at a more critical bus (3.65)

$\mu_j \succ 0$; for the deployment of the compensator at less critical bus (3.66)

In the case of equation 3.64, the penalty term is deducted from the objective function while for the latter (i.e. equation 3.65), it is added to it to achieve a proper reactive power dispatch at any critical bus or location.

The optimization is then performed for the scenario where the FACTS devices are now implemented in the place of the less dynamic capacitor compensator that was treated in section 3.2. All the constraints deployed in section 3.2 are still valid in the current section but with an extension to the number of goals which is now including equations (3.58), (3.59) and (3.60) while that of the number of constraints now includes equations (3.32) to (3.47), (3.57), (3.64), (3.65) and (3.66).

3.2.3 RELIABILITY STUDY OF THE COMPOSITE POWER SYSTEM

One of the main duties of an electricity supply industry is to provide a reliable and uninterrupted power supply to its customers; this is even more necessary in a deregulated market. And in order to achieve this goal, electricity utility companies have tried in several ways to assess the reliability of the various electric power equipment components to ensure their respective level of dependability in the eventuality of occurrence of disturbance.

According to Billinton and Kumar (1990), the basic technique for this assessment is approached from the applications of the relevant adequacy indices to the various segments of the composite power system. These segments are streamlined along the functional zones of the electric power system namely generation, distribution and transmission. For the sake of reliability studies, there are three main hierarchical levels which are the functional boundaries normally implemented in the power system reliability studies. These are the Hierarchical level I (HLI) which is concerned only with the generation facilities, HLII for the study of both generation and bulk transmission while HLIII involves all the three functional zones in its study.

For this current work, the study shall be limited to HLII, in which case the composite power system reliability assessment involves such components as generating units, transmission lines, transformers, switching elements. The extension to previous works on system reliability in a deregulated regime is the introduction of system security measures such as the FACTS devices which are then modelled in line with the other components in other to establish a more robust system in line with the expectation of a deregulated market (Billinton and Fotuhi-Firuzabad, 1996).

The transmission system adequacy indices of a composite power system can best be expressed by revisiting the system and load point indices. In this case, it is interesting to examine a number of adequacy indices that would assist in making design decisions in a deregulated environment a meaningful assignment that would, on the long run, facilitate a secured system operation. The analysis of the system using the load point indices approach may present a more sincere result of the system adequacy based on the fact that the deregulated market is owned at different load buses by different power system distribution administrators. On this note, it is arguably correct to state that in a deregulated environment, the open transmission access is a serious area of power system engineering design challenge. This is tackled in such a way as to preserve the system from voltage collapse with special regard to the influence of FACTS devices in the network. Thus, it is equally important to evaluate the degree of reliability contributed to the improvement of the power system transmission operation by this power electronics tools.

Thus, this work shall not only involve the comprehensive study of the adequacy indices of the system load points but would also investigate the possibilities of improving the voltage profile by performing optimization on these indices with respect to the relevant system and economic constraints. The beauty of this is in keeping with the obvious strength of the OPF to proffer a kind of solutions that would be very much adaptable to any system. So the relevant system indices are the load point indices, load curtailment and voltage violation indices (Prada, 1999).

This analysis is performed using a very simple but powerful probability model(Ross, 2007). The most commonly used indices are probability of system failure, frequency of failure and expected duration of failure. These indices can be calculated for a specific period of the season or a period of time (say, annual). In order to supply a load demand, three factors are taken into account namely: plant availability, bus load variation and system contingencies. The bus load demand is generally modelled by normal distribution while the plant distribution could be modelled by the general discrete distribution while in the case of contingencies, two main factors are considered in its modelling, these are namely: the violation of transmission line capacity and voltage violation (Billinton and Kumar, 1990).

Using conditional probability approach(Billinton and Allan, 1984, Billinton *et al.*,, 1973), the probability of power system failure is measurably defined as the Probability of failure, h, is conditionally based on the probability that the load bus fails, u, happening.

$$p(h/u) = \frac{p(h \cap u)}{p(u)} \tag{3.67}$$

i.e. $$p(h \cap u) = p(h).p(h/u) \tag{3.68}$$

where $P(h \mid u)$ is a conditional probability that h occurs if u has occurred.

Assume the load is independent of the contingencies, then the probability of failure at the load bus j, is

$$p_{jf} = \sum_{f} p(\hbar_f)(p_{gf} + p_{lf} - p_{gf}.p_{lf}) \tag{3.69}$$

where

$\hbar_f$: a stress state in the transmission network (line and transformers)

$p(\hbar_f)$: probability of existence of state $\hbar_f$

p_{gf} : probability of the generation capacity outage exceeding the reserved capacity

p_{lf} : probability of the transmission line that links the generator bus to the load bus fails.

But the generation schedule used in the load flow analysis is not modified to include the outage of individual units. Hence it is assumed that the generation units are considered along with the transmission line and transformers in order to determine the outage condition. This is in line with the statement that the bus voltages and line loadings are subject to the generation schedule.

So the expression in equation 3.68 is modified as:

The probability that bus j fails to supply load, $p_{jf} = \sum_f p(\hbar_f).p_{lf}$ (3.70)

So that the frequency of occurrence of failure is $\hat{\lambda}_{jf} = \sum_f \hat{\lambda}(\hbar_f).p_{lf}$ (3.71)

where $\hat{\lambda}_f$: frequency of occurrence of failure.

The reliability evaluation of a transmission system is further simplified by considering the loss of load probability which is commonly related to the summation of entire generation capacities available from various units in the power system network. Thus, from the daily distribution of the probability and frequency of occurrence of failure as typified in equations 3.70 and 3.71, it is easy to evaluate the state of health of the power system in any circumstance. This is often defined as the probability of the failure to be able to serve the expected peak load over a specified period of time. The technique includes the evaluation of the expected load at various load points; this is usually characterized by the upper limit capacity of the individual generation unit and the long-term probability of being in service (i.e. availability).

It can be simplified by the help of mathematical expression in order to arrive at the probability of loss of load expectation (LOLE) at a specific load bus as:

$$P_{LOLE} = \sum_L n_L A_G \quad \text{hours/period} \tag{3.72}$$

where

n_L: number of occurrences of voltage violations that result in negative margin for load level.

A_G: cumulative probability of the outage states of the generation units that result in negative margin for load level at a specific load bus.

Thus, equation (3.72) indirectly suggests the expected number of voltage violations in a power system. This would result in load curtailment in a power system so as to maintain high system availability

The expected load curtailed (i.e. expected energy demanded but not supplied) at the load buses with respect to the probability of loss expectation in order to prevent voltage collapse due to system congestion is thus obtained as

$$p_{EENS} = \sum_f L_{jf} \lambda_f = \sum_f L_{jf}\, p_f .8760 \quad \text{[MWh]} \tag{3.73}$$

where

λ_f : frequency of occurrence of system failure

L_{jf} : total load curtailed at a load bus to avoid system congestion that could lead to system failure

p_f : probability that failure would occur at a particular load bus due to market activities.

3.2.3.1 Application of the Optimization Technique to the system adequacy study

The only documented work available in this area made use of the DC load flow technique to achieve the reliability assessment of the composite power system (Verma *et al*, 2004). In the current research work, there is further addition to this, which is by extending the DC load-flow approach to incorporate an AC power flow formulation. In this case, every possible failure-causing event is taken into account in such a way that the solution obtained has a considerable efficiency for any size of power system especially the small and medium sized systems. The objective functions take into account the significant impact of the common cause failure (CCF) on the power system.

The objective functions are:

$$F1 = \max \sum_{j=N_g+1}^{N} A_j \tag{3.74}$$

$$F2 = \min p(EENS) = P_{\_curtailed,j} \text{ x } p(\text{outage exists})_j \text{ x } 8760 \quad [\text{MWh}] \tag{3.75}$$

$$F3 = \text{Min Cost\_outage} = 0.003P_{j\_curtail}^{2} + 0.3051P_{j\_curtail} + 127.38 \quad [\text{US\$/MWh}] \tag{3.76}$$

where A_j : measure of availability of load bus j

$P_{\_curtailed,j}$: power curtailed at load bus j to alleviate voltage violation due to congestion

P (outage exists)$_j$: probability that load bus j is out of service over a period of time, say 1 year.

Cost_outage: financial burden that voltage collapse placed on market players in US$/MWh

Subject to the following power-flow equations:

$$P_i - V_i \sum_{j=N_g+1}^{N} V_j (g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}) = 0 \tag{3.77}$$

$$Q_i - V_i \sum_{j=N_g+1}^{N} V_j (g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}) = 0 \tag{3.78}$$

$$Q_{jc} = \sum_{i=1}^{N_g} V_i \sum_{j=N_g+1} V_j (g_{ij}^{'} \sin \delta_{ij}^{'} - b_{ij}^{'} \cos \delta_{ij}^{'}) = 0 \quad (3.79)$$

$$V_{i,\min} \leq |V_i| \leq V_{i,\max} \quad (3.80)$$

$$Q_{gi,\min} \leq Q_{gi} \leq Q_{gi,\max} \quad (3.81)$$

$$Q_{cj,\min} \leq Q_{cj} \leq Q_{cj,\max} \quad (3.82)$$

$$0 \leq X_{cj} \leq X_{cj,\max} \quad (3.83)$$

$$T_{j,\min} \leq T_j \leq T_{j,\max} \quad (3.84)$$

$$I_{l,\max}^{2} \geq I_l^2 \quad (3.85)$$

$$P_{\_curtal,j} \leq P_{demand} \quad (3.86)$$

$$P_{\_curtailed,j,\min} \leq P_{\_curtailed,j} \leq P_{curtailed,j,\max} \quad (3.87)$$

$$\gamma_{\min} \leq \gamma \leq \gamma_{\max} \quad (3.88)$$

$$\gamma_{\min}^{c} \leq \gamma^{c} \leq \gamma_{\max}^{c} \quad (3.89)$$

where $$\gamma_{\min}^{c} = \gamma = Y_{ij} = |Y_{ij}| \cos(\theta_{ij} + \delta_i - \delta_j) - j|Y_{ij}| \sin(\theta_{ij} + \delta_i - \delta_j) \quad (3.90)$$

$$\gamma_{\max}^{c} = \frac{\gamma}{1 - k^{\max}}, \quad (3.91)$$

where $$0 \leq k^{\max} \leq 0.995 \quad (3.92)$$

Such that the limit of the compensation from the FACTS devices is determined by

$$0 \leq X_{comp} \leq k^{\max} \frac{1}{\gamma} \quad (3.93)$$

Thus, the line reactance of the specific transmission line with the compensating device is obtained as

$$x_{ij}^{c} = x_{comp} = \frac{1}{\gamma} - \frac{1}{\gamma^{c}} \quad (3.94)$$

In other words, the new value of the transmission line susceptance could be derived from eqs (3.93) and (3.94) (Verma *et al.*,, 2004)

$$\gamma_{ij}^{c} = \gamma^{c} = \frac{1}{1/\gamma - x_{comp}} \tag{3.95}$$

The equations with a subscript ij are sets of equations that correspond to the analysis of those lines where compensators have been included. Equation (3.78) is the equation whereby the compensators are not included while in equation (3.79) the influence of the compensator is expected to reflect in the system operation.

where $$g_{ij}^{c} = g_{ij} - \gamma_{ij}^{c} \cos \delta_{ij}^{c} \tag{3.96}$$

$$b_{ij}^{c} = b_{ij} - \gamma_{ij}^{c} \sin \delta_{ij}^{c} \tag{3.97}$$

Equations (3.96) and (3.97) are line conductance and susceptance, but since the voltage collapse is evidently affected by the latter so then the equation (3.97) is of great interest to market designers while equation (3.96) can be reduced to such a value that shows no significant difference between its value before and after compensation.

The solution approach adopted for the optimization model described in the last section is handled using the knowledge of fault tree analysis (FTA) as a means of obtaining the system availability from the failure probability of the various conditions under which the system can be found culpable of voltage collapse and then the implementation of the optimization technique (Wanga *et al.*,, 2008).

3.2.3.2 Fault tree analysis (FTA) model

There are two main failure analysis methodologies available for the assessment of the system reliability. These are Failure Mode Effects and Criticality Analysis (FMECA) and Fault Tree

Analysis (FTA). While the former is an effective technique for safety and risk analysis, the latter is more conversant and convenient for safety analysis. This is due to the fact that it is a deductive methodology for determining potential cause of accidents or system failure as well as estimating future probability. This method is useful for determining the causes of undesired event referred to as the top event. It then proceeds downward as it dissects the system in increasing detail to determine the root cause of a potentially significant economic loss (Hajeeh and Chauduri, 2000). It is efficient because of its ability to give both qualitative and quantitative details of the system under consideration using the logic gates interrelationship between events to arrive at the top event (failure)(Omidiora *et al.*,, 2007).

3.2.3.2.1 Introduction to Fault tree analysis

Since it is common knowledge in system reliability studies that it is impossible to completely correct any mistake made in the design of system reliability, then it is necessary to carry out a thorough synthesis before engaging in the analysis of parameters involved in the system reliability study. In this vein, the Fault tree analysis (FTA) as failure event determining tool has been outstanding in this area.

Fault tree analysis (FTA) is a failure analysis tool with a special ability to analyze the undesired state using the combination of logic gates as a series of lower-level events. This analysis method is a peculiar design for a particularly single failure-of-interest analysis and it is specifically used in the modelling of only that part of the system which is of interest to the system operators, hence its influences on the system is evaluated using the probability of the failure of that specific engineering component (Yuge, *et al*, 2008)

Interestingly, the FTA has enjoyed great patronage in the investigation of failure effect of various equipment failures on the overall system failure rate in the field of engineering and biology. It uses different basic Boolean logic gates to provide the path for the flow of information to the top event which serves as a veritable way of exposing various manners of system failure occurrence. This information serves a main purpose of preventing the occurrence of the fault by taking appropriate preventive actions before eventual occurrence of the failure.

In order to achieve an effective development of Fault Tree Analysis, the engineers need an in-depth knowledge of the system under analysis. Thus, the FTA as a failure probability modelling tool can be employed for tracking down only one major event at a time (Chang *et al.*,, 2002). This technique has been around as reliability assessment technique since 1970 (Bartlett *et al.*,, 2009, Contini *et al.*,, 2008). It is useful for both qualitative and quantitative assessment of system reliability. It is a self explanatory, graphical representation of various logical gate combinations of fault and accident that could result in an undesired top event such as loss of service or voltage collapse (Volkanovski *et al.*,, 2009, Choi and Cho, 2007).

3.2.3.2.2 Construction of Fault tree analysis (FTA) model

There are a number of literatures on the ways to construct the FTA (Nieuwhof, 1975). The construction is better illustrated once the deep understanding of the system has been acquired. There are many ways of developing the fault tree for a specific event. Thus, there is no hard and fast rule to the construction of the model.

To conduct the FTA, it is better to choose the undesired event as the top event. Then the fault tree is constructed and quantitatively evaluated using either the Failure mode evaluation analysis (FMEA) or the probability evaluation method.

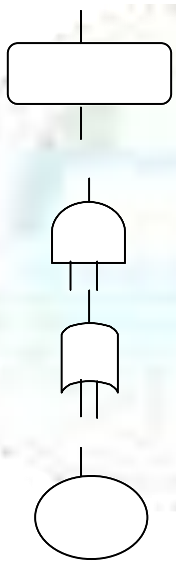
The probability evaluation method is an analytical approach used for calculating the probability of occurrence of logical interrelationship of events that cause the top event as displayed in figure 3.6. It provides the analysts with better understanding of potential sources of failures. The standard symbols, commonly used are logic gates which are displayed in figure 3.5. The AND gates denote the connection of all groups of events and conditions of the system that must occur together to create failure of the system. Whereas OR gates represents the existence of alternative ways of effecting a failure in a system (Hajeeh and Chauduri, 2000).

In the case of the current work, the FT model is implemented in evaluating the voltage collapse. In other words, the top event is the voltage collapse probability (or system failure) which is depicted in figure 3.6 below. So in line with this, the probability evaluation method shall be implemented. Though different transmission companies may have different substation structures and protection systems with different maintenance policies, since this may result in data that are not accurate, then it is necessary to work with estimated values(Suresh *et al.*,, 1996) in order to obtain system failure rate. Thus, it requires operational experience and expert judgment to handle the study (Suresh *et al.*,, 1996, Haarla *et al.*,, 2008).

The outcome expected as the top event is the voltage collapse. The analysis is performed with and without using the reactive power support device to be able to clearly identify if the investment in it can be economically and operationally justified. The analysis described here may be applied to any system. In this work, IEEE-30 bus test system and Nigeria-26 bus system are chosen as test systems, the former because of readily available data on outage rates and the later for a practical system that would be useful for the on going restructuring process in the Nigeria Electricity Supply Industry (NESI). The data used for the Nigeria's system is obtained from the supervisory control and data acquisition (SCADA) system at the National Control Centre, Oshogbo. These data cover different periods and the quality is not constant being better during some period and otherwise at other time, so there is the need for electric forecasting methodology for making provision for adequate data for the sake of the study(Hong, 2009).

3.2.3.2.3 Fault tree symbols for the construction of voltage collapse probability

There are a number of symbols that shall be introduced in the construction of the FT, hence the following are the ones employed in the modelling of the FT for voltage collapse. For larger list of symbol the reader can consult the literatures (Nieuwhof, 1975).



Rectangle: denotes a malfunction event which results from combination of fault events as an output of logic gate.

AND-gate: denotes the situation whereby the two or more input events are required to generate an output event.

OR-gate: denotes the situation whereby the output event will exist if any one event is present.

Circle: denotes a basic fault event.

Figure 3.6: Logic Gates and their interpretations

Implementing the symbols shown in figure 3.6 leads to the realization of the FT shown in figure 3.7. This is adequate for the evaluation of the comparative study of reliability of the power system against a top event, otherwise referred to as voltage collapse

The available information in figures 3.7 and 3.8 is useful in the formulation of expressions for the various probabilities of the events within the system. This forms the discussion in the next sub-section. The fault tree breaks down from the top event into lower-level events. Logic gates show the relationship between lower-level events and the top event(Hong and Lee, 2009). The OR-gate expresses the idea that any of several failures can cause the protection system to fail. Thus, the failure of any of these would make the system to fail, contrariwise, the AND-gate signifies that the occurrence of the failure of the two events entering the logic gate would result in the failure of the system (Chang *et al.*,, 2002, Omidiora *et al.*,, 2007). The probability of the top event (voltage collapse probability) is computed using the procedure shown in figure 3.7. This approach is suitable for evaluating the failure of the system because only those sequences of events that result in top event (failure) are considered.

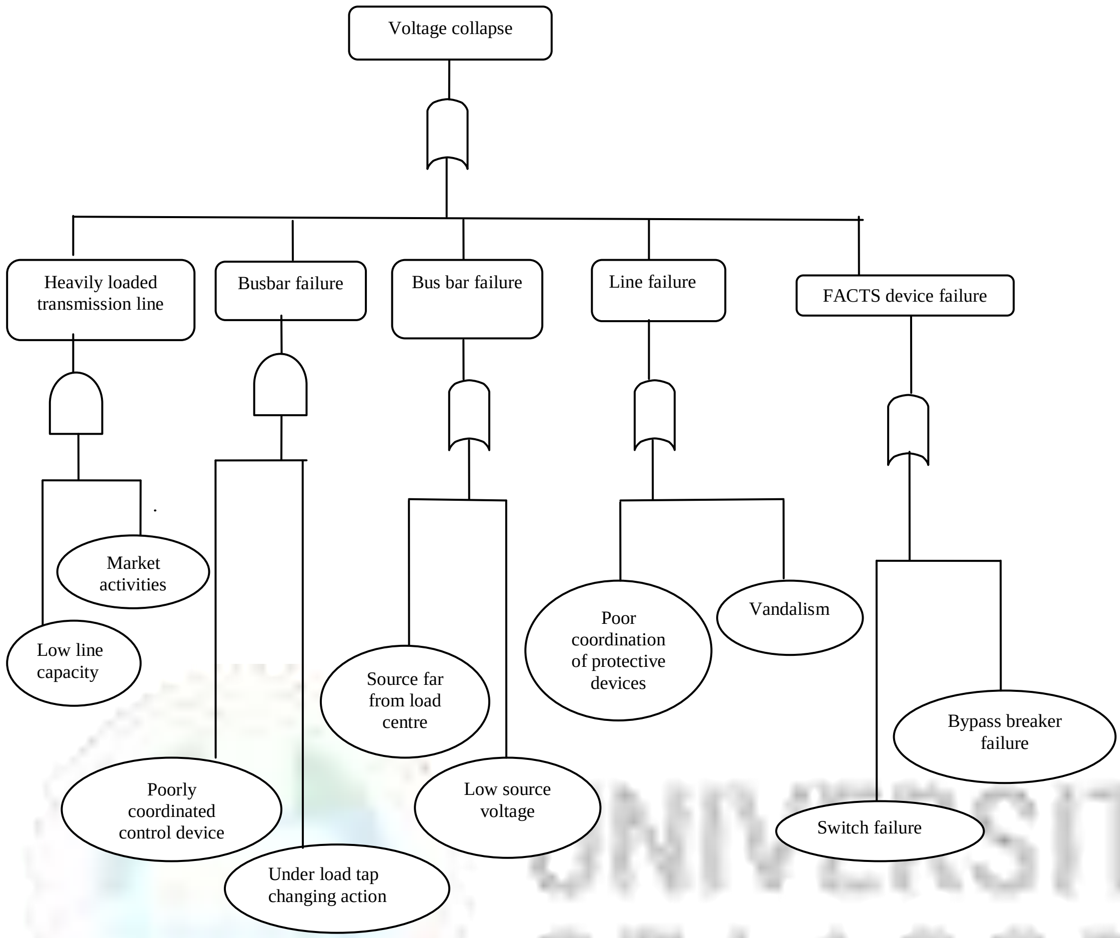


Figure 3.7: Evaluation of voltage collapse probability using Fault tree analysis (FTA)

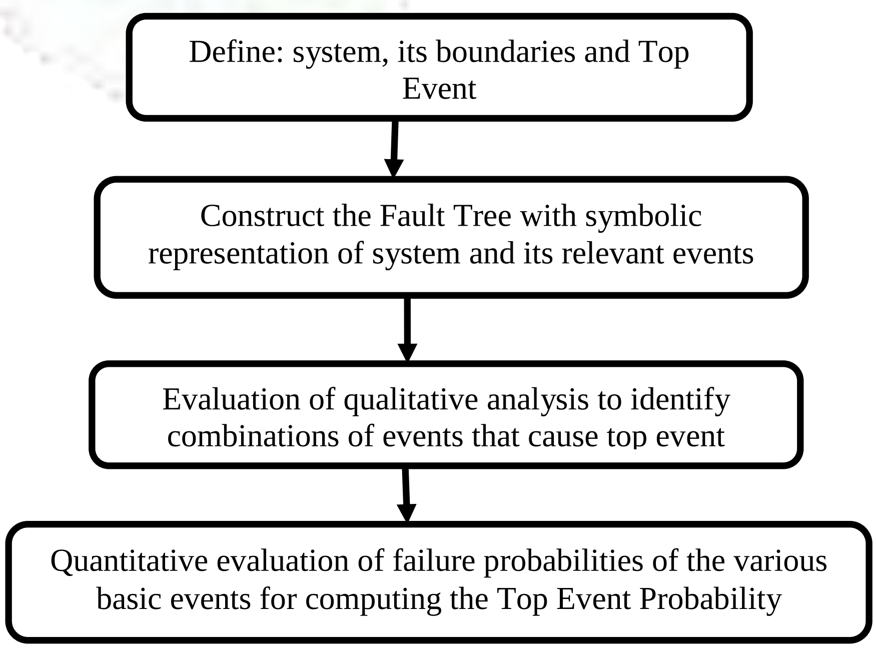


Figure 3.8: Algorithm for performing Fault Tree Analysis (FTA)

3.2.4 GENERAL APPROACH TO SYSTEM ADEQUACY MODELLING

Since the FACTS devices cannot be considered to be perfectly reliable, it then becomes necessary to evaluate the failure probability of the line when it has the FACTS devices connected to it. This is then compared with that of the original probability of the line without the influence of the FACTS devices. Thus, in order to incorporate this failure as a series of events involving the compensator, it becomes imperative to state that the probability that the compensator would fail may not necessarily result in the failure of the line, but in the other matter if the line should fail, automatically the compensator would then fail (Trivedi, 2001). In other words, the compensator is statistically dependent on the line. Thus, the system coherence can be adduced to be effective in operation. This failure could be obtained in such a way as to reflect the failure of the line along with the FACTS devices as well as the expected failure while the line is uncompensated. Perhaps, it is important to realize that the device is not assumed to be 100% reliable. Thus, the failure rate before the introduction of the FACTS devices shall be identified using subscript o, while the rate with the new technology installed on the line would be allotted subscript n (Nieuwhof, 1975).

In this analysis, all contingency states are evaluated using the adequacy assessment approach to solve the reliability studies as an important and effective means of evaluating the load point indices at the load buses whereby the contingencies are evaluated with the fore knowledge that not more than two line contingencies are allowable in a particular network(Billinton *et al.*,, 1973, Billinton and Kumar, 1990). Since the transmission continuity is the main focus in this work, it is quite necessary to evaluate the load-point frequency and average annual outage expected in case of the introduction of this new technology to the transmission network using two well known techniques that are of great value namely: loss of load method and frequency duration method.

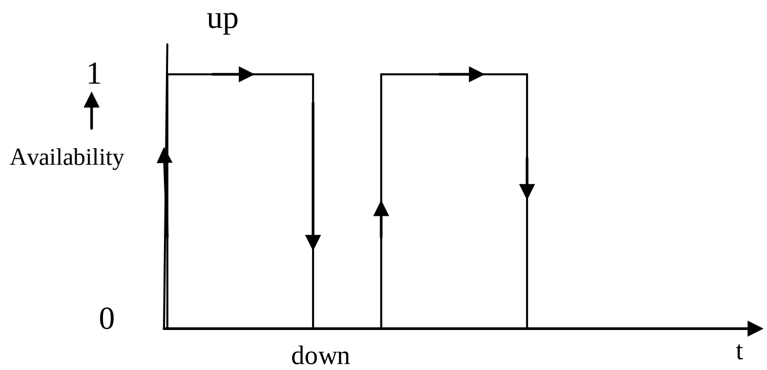


Figure 3.9.: Average history of time capacity

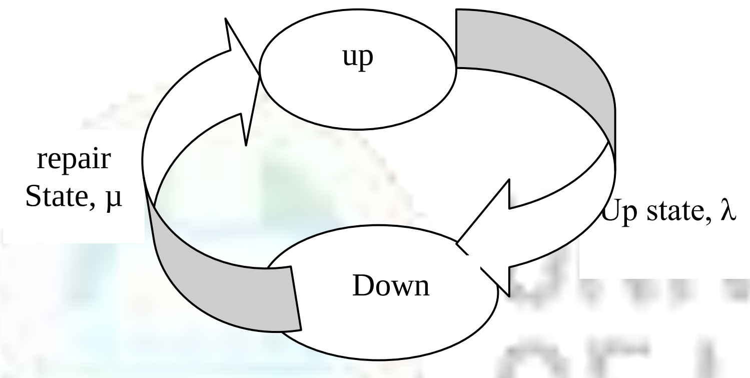


Figure 3.10: Two–state Markov Chain transition diagram for reparable plant

With the aid of the 2-state model shown in figures 3.9 and 3.10, it is possible to derive the mathematical expressions for both failure rate and repair rate as shown below.

where the failure rate is

$$\lambda = \frac{failure\_of\_the\_component}{time\_in\_the\_up\_state} \tag{3.98}$$

and the repair rate is

$$\mu = \frac{repair\_of\_the\_component}{time\_in\_the\_down\_state} \tag{3.99}$$

Thus, the availability of a given component is given by the ratio of average up time m, to average the cycle time T, Meanwhile, the cycle time is the sum of the repair time and up time. This is referred to as the system availability given as:

$$A = \frac{\overline{m}}{\overline{T}} = \frac{\overline{m}}{\overline{m} + \overline{r}} \tag{3.100}$$

where $\overline{r}$: the mean down time.

$\overline{m}$: the mean up time

Thus, the system unavailability is thus obtained as:

$$\overline{A} = 1 - A = \left(1 - \frac{\overline{m}}{\overline{m} + \overline{r}}\right) = \frac{\overline{r}}{\overline{m} + \overline{r}} \tag{3.101}$$

While the frequency of occurrence of system collapse is

$$f = \frac{1}{\overline{m} + \overline{r}} = \frac{1}{\overline{T}} \tag{3.102}$$

The subsequent expressions then translate equations 3.98 and 3.99 into:

$$\text{Failure rate, } \lambda = \frac{1}{AT} \tag{3.103}$$

where A: system availability

T: cycle time which is the reciprocal of fault frequency, f.

and Repair rate, $\mu = \frac{1}{\overline{A}T}$ (3.104)

where $\overline{A}$: system unavailability

T: cycle time which is the reciprocal of fault frequency, f.

The average up duration is easily determined from equation 3.100 for system availability or system long-term probability of success while equation 3.102 defines the system frequency of system failures. The Mean-Time-Between-Failure (MTBF) is often designated as the reciprocal of the failure rate, λ .

$$MTBF = \frac{\overline{A}}{f} = \frac{1}{\lambda} \tag{3.105a}$$

and

$$MTTR = \frac{1}{\mu} \tag{3.105b}$$

where MTBF is the Mean Time Between Failure and MTTR is Mean Time To Repair.

From this development, it is then possible to estimate the system availability with respect to time or period of occurrence of failure event as (Megbowon, 2009)

$$\text{A(t)} = \frac{MTTR}{MTTR + MBTF} = \frac{\mu(t)}{\mu(t) + \lambda(t)} \tag{3.106}$$

where MBTF is the Mean Time Between Failure and MTTR is Mean Time To Repair

3.2.5 RELIABILITY ANALYSIS MODEL

There are two major types of reliability analysis approaches normally in use. They are the Failure Mode Evaluation Analysis (FMEA) and the Probability Evaluation method (Nieuwhof, 1975). There are a number of uncertainty factors that are associated with a voltage collapse namely: contingencies, short-term system load forecast and generation dispatch. In this work, the first uncertainty is the issue that has arrested the attention of the researcher and thus considered here.

The occurrence of contingency is calculated using the outage rate defined for each contingency condition. For contingency to take place, therefore it is necessary to observe the loading margin of the system which is critically affected in such a way that the load is left unserved, in the case of very little or no margin(Billinton and Fotuhi-Firuzabad, 1996).

The original probability of failure (voltage collapse) study of the system before compensation is obtained using the appropriate ac load flow for efficient discovery of the system reliability. Here, these probabilities are calculated using equation (3.105) with outage rates of each line specified. The probabilities of critical contingencies or voltage collapse at the load buses are thus considered as follows:

Case 1: Transmission line without FACTS devices

The probability that the power system would collapse at a particular load bus is

$$\text{Prob(collapse)} = \sum \Pr ob(\tau\ ) * \Pr ob(\rho\ ) * \Pr ob(1-\tau) * \Pr ob(\Gamma) \tag{3.107}$$

The probability that the power system would not collapse at a particular load bus is

$$\text{Prob(no collapse)} = \sum_{k=1}^{n} \Pr ob(\tau\ ) * \Pr ob(1-\rho\ ) * \Pr ob(1-\tau) * \Pr ob(1-\Gamma) \tag{3.108}$$

Case 2: Transmission line with FACTS devices in operation

The probability that the power system would collapse at a particular load bus with compensation technology installed is :

$$\text{Prob(collapse)}_{comp} = \sum_{k=1}^{n} \Pr ob(\tau\ ) * \Pr ob(\varepsilon\ ) + \Pr ob(1-\tau) * \Pr ob(\omega) \tag{3.109}$$

The probability that the power system would not collapse at a particular load bus with compensation technology installed is

$$\text{Prob(no collapse)}_{comp} = \sum_{k=1}^{n} \Pr ob(\tau\ ) * \Pr ob(1-\varepsilon\ ) * \Pr ob(1-\tau) * \Pr ob(1-\omega) \tag{3.110}$$

It should be noted that the occurrence of contingencies is calculated using equation (3.107).

The terminologies of various probabilities of occurrences are defined as follows:

$$\Pr ob_o(t) : \text{Probability of contingency and outage of line ij } = \frac{\lambda_o}{\lambda_o + \mu} \tag{3.111}$$

$\Pr ob_\tau(t)$: probability of voltage collapse given contingency or outage of line ij, without compensation = $\left(\frac{\mu}{\lambda_o+\mu}\right)\left(\frac{\lambda_o}{\lambda_o+\mu}\right)$ (3.112)

$\Pr ob_{\alpha}(t)$: probability of no contingency or outage of line ij= $\left(1-\frac{\lambda_o}{\lambda_o+\mu}\right)$ (3.113)

$\Pr ob_{\sigma}(t)$: probability of contingency but no outage of line ij ,

without compensation = $\left(\frac{\mu}{\lambda_o+\mu}\right)\left(1-\frac{\lambda_o}{\lambda_o+\mu}\right)$ (3.114)

$\Pr ob_{\kappa}(t)$: probability of no voltage collapse given a contingency or outage of line ij ,

without compensation = $\left(\frac{\lambda_o}{\lambda_o+\mu}\right)^2$ (3.115)

$\Pr ob_{\varpi}(t)$: probability of no voltage collapse given no contingency or outage of line ij ,

without compensation = $\left(\frac{\lambda_o}{\lambda_o+\mu}\right)\left(1-\frac{\lambda_o}{\lambda_o+\mu}\right)$ (3.116)

$\Pr ob_{\varepsilon}(t)$: probability of voltage collapse given a contingency or outage of line ij ,with

Compensation = $\left(\frac{\mu}{\lambda_o+\mu}\right)\left(\frac{\lambda_o}{\lambda_o+\mu}\right)\left(\frac{\lambda_m}{\lambda_m+\mu}\right)$ (3.117)

$\Pr ob_{\omega}(t)$: probability of voltage collapse given no contingency or outage of line ij , with

compensation = $\left(\frac{\mu}{\lambda_o+\mu}\right)\left(1-\frac{\lambda_o}{\lambda_o+\mu}\right)\left(\frac{\lambda_m}{\lambda_o+\mu}\right)$ (3.118)

$\Pr ob_{\chi}(t)$: probability of no voltage collapse given a contingency or outage of line ij ,

with compensation = $\left(\frac{\lambda_o}{\lambda_o+\mu}\right)^2\left(\frac{\lambda_m}{\lambda_m+\mu}\right)$ (3.119)

$\Pr ob_{\beta}(t)$: probability of no voltage collapse given no contingency or outage of line ij ,

$$\text{with compensation} = \left(\frac{\lambda_o}{\lambda_o + \mu}\right)\left(1 - \frac{\lambda_o}{\lambda_o + \mu}\right)\left(\frac{\lambda_m}{\lambda_m + \mu}\right) \qquad (3.120)$$

So, the failure probability of a line ij along with the operation of the FACTS compensating devices could be obtained in the same manner by which original failure probability in the line was derived by replacing the subscript, o, with subscript, m, in the failure rate as shown. The new failure rate which is called the modified failure rate can be effectively defined (using with the method developed in an earlier work which is defined (Billinton, 1996)) as:

$$\lambda_m = \lambda_o + \lambda_{cc}(1 - R_{ss}) \qquad (3.121)$$

where R_{ss} : reliability of the switching element

λ_{cc}: probability of failure rate of common control device given by (Volkanovski *et al.*,, 2009):

$$\lambda_{cc} = \prod_{k=1}^{mcs} \lambda_{B_k} \qquad (3.122)$$

where λ_{B_k} : probability of occurrence of basic events which could eventually lead to top event

mcs: number of basic events in minimal cut set, k that can simultaneously lead to the top event (i.e. voltage collapse).

Substituting equation (3.122) in equation (3.121), we have;

$$\lambda_m = \lambda_o + \prod_{k=1}^{mcs} \lambda_{B_k} (1 - R_{ss}) \qquad (3.123)$$

Thus, the consequence of the last three equations (i.e. equations (3.121) to (3.123)) with respect to the overall system reliability is that any violation of system parameters especially the bus voltage would surely dictate the health of the system in the sense that minimum basic events of the power system is capable of jointly contributing to the loss of service resulting from voltage collapse.

The system availability can then be modelled using a transmission system which is expected to supply continuous and uninterrupted service to the load point with the assumption that there are three mutually exclusive states in which this composite transmission system can reside namely:

$p_l = \Pr ob_l$: Probability that line fails

$p_b = \Pr ob_b$: Probability that compensator breaker fails

$p_o = \Pr ob_o$: Probability that there is no failure in the system

In which case, there would be voltage collapse and hence system failure whenever the first two conditions occur. For the purpose of analysis, the model developed is a "renewable process" (i.e. Markov process) in which the stochastic processes of failure and repair are the same for each run-repair cycle as shown in figure 3.9. To ensure that this claim is actualized, the run-repair cycle must be statistically independent (the events have no influence on each other.) and the distribution of duration is stationary in time (i.e. time invariant).

With this assumption and using the binomial distribution, the total enumeration of system reliability assessment (with the knowledge of voltage collapse probability) provides the crucial information on the condition of the system with respect to the establishment of a means of identifying bad and good condition of the system(Billinton *et al.*,, 1973).

Using the three conditions of the transmission system defined above for p_l, p_b and p_o, the probability distribution is obtained as :

$$p_l + p_b + p_o = 1 \tag{3.124}$$

$$(p_l + p_b + p_o)^2 = p_l^2 + p_b^2 + p_o^2 + 2p_l p_b + 2p_l p_o + 2p_b p_o \tag{3.125}$$

where $p_l = \Pr ob_l$: probability that line fails

$p_b = \Pr ob_b$: probability that compensator breaker fails

$p_o = \Pr ob_o$:probability that there is no failure in the system

Separating equation (3.125) into the two main scenarios, we have:

The probability that the transmission system would not fail is

$$p \text{ (no failure)}= p_0^2 + 2 p_o p_b \tag{3.126}$$

Also the probability that the transmission system fails to supply the load points is:

$$p \text{ (voltage collapse)}= p_l^2 + p_b^2 + 2 p_o p_l + 2 p_l p_b \tag{3.127}$$

From equation (3.127), the top event probability can then be obtained. Hence line failure probability for a transmission network with FACTS devices is obtained as:

$$p_{l(FACTS)} = \frac{\lambda_m}{\lambda_m + \mu} \tag{3.128}$$

Equating equation (3.127) and equation (3.128) the failure mode is thus presented as

$$p(top) = p_l^2 + p_b^2 + 2 p_o p_l + 2 p_l p_b = \frac{\lambda_m}{\lambda_m + \mu} \tag{3.129}$$

i.e.

$$\lambda_m = \mu \frac{p(top)}{1 - p(top)} \tag{3.130}$$

This is instrumental in the evaluation of the failure mode in a transmission system with FACTS devices in operation.

3.2.6 ANALYSIS OF SYSTEM ADEQUACY IN A DEREGULATED POWER MARKET

The system adequacy is an important feature that needs to be enumerated in this work using the available indices already developed (Koonce *et al.*,, 2006). This is useful in order to effectively obtain and compare the expected number of loads curtailment (ENLC), expected load curtailed (EDC), expected demand not supplied (EDNS), expected energy not supplied (EENS), interrupted energy assessment rate (IEAR) for both cases listed above (i.e. with and without FACTS devices).

Thus, to obtain the overall availability of each load bus location using the system frequency of availability, it is assumed that the transmission system at any point in time is available for the trading and transfer of power amongst the various power players (GENCOs and DISCOs). Thus, the composite system is considered as a two-state continuous time Markov chain with repair time solely depending on an exponentially distributed time with rate λ before failure, which means once failed it takes an exponential time with rate μ to be repaired (Ross, 2007)

From this, the system availability can be obtained as:

Availability without compensation is $A_o(t) = \prod_{i=1}^{n} \left[\frac{\mu}{\lambda_o + \mu} + \frac{\lambda_o}{\lambda_o + \mu} e^{-(\lambda_o + \mu)t} \right]$ (3.131)

Equation (3.131) can be extended for the evaluation of the system adequacy indices for the transmission line while the FACTS devices in the network are deployed to alleviate violation of system voltage as:

$$A_m(t) = \prod_{i=1}^{n} \left[\frac{\mu_m}{\mu_m + \lambda_m} + \frac{\lambda_o}{\lambda_o + \mu} e^{-(\lambda_o + \mu)t} \right] \quad (3.132)$$

So also the unavailability of the system is:

System unavailability without compensation is $\overline{A}_i(t) = \frac{\mu}{\lambda_o + \mu} - \frac{\mu}{\lambda_o + \mu} e^{-(\lambda_o + \mu)t}$ (3.133)

i.e. $\overline{A}_o(t) = \prod_{i=1}^{n} \left[\frac{\lambda_o}{\mu_o + \lambda_o} (1 - e^{-(\lambda_o + \mu)t}) \right]$ (3.134)

so also for the system with FACTS devices, the unavailability of the modified system is:

$$\overline{A}_m(t) = \prod_{i=1}^{n}\left[\frac{\lambda_m}{\mu_m + \lambda_m}(1 - e^{-(\lambda_m+\mu)t})\right] \quad (3.135)$$

Equation (3.131) is an expression for the availability of service at the individual load bus for the actualization of equation (3.74) which is the maximization of the system availability. While equations (3.134) and (3.135) are the expressions for the unavailability of service at respective load bus, it is useful for evaluation of the failure probability at each of the buses using the quantitative analysis of the Fault Tree. It is from this that the system availability is obtained as defined in equation (3.101).

From equations (3.112), (3.113), (3.115), (3.118) and (3.119), it is possible to obtain the composite failure probability at each bus of the system as:

$$F(t) = \int_{o}^{\infty}(F_o(t)F_\tau(t)F_\sigma(t)F_\varepsilon(t)F_\omega(t))dt \quad (3.136)$$

where $F_o(t) = prob_o(t)$

$F_\tau(t) = prob_\tau(t)$

$F_\sigma(t) = prob_\sigma(t)$

$F_\varepsilon(t) = prob_\varepsilon(t)$

$F_\omega(t) = prob_\omega(t)$ and

$F(t)$: the system unavailability or failure probability for an exponential time, t for component i=1,…n.

Moreover, from the equations obtained for the expected energy not supplied (EENS) and cost of outage, i.e. equations (3.75) and (3.76) respectively, there are a number of other reliability assessment analyses that can be investigated in the power system under deregulation. This term includes the Interrupted Energy Assessment Rate (IEAR) which is capable of portraying vividly the achievement of FACTS devices.

Thus, the annualized Interrupted Energy Assessment Rate (IEAR) at bus, i , can be calculated as

$$\text{IEAR}_i = \frac{Cost\_of\_outage}{EENS} \quad \text{[N/Mwh]} \tag{3.137}$$

Recall EENS= $\sum_{f \in F} p(outage\_exist)_f * P_{curtail,j} * 8760$ [Mwh/year] (3.138)

and Cost of outage = $0.003P_{curtail,j}^2 + 0.301P_{curtail,j} + 127.38$ [N/year] (3.139)

The loading effect of the FACTS devices can be studied by using the following reliability index for obtaining the impact of the compensating device.

where $P_{curtail,j}$: Power curtailed at bus j.

$p(outage\_exist)_f$: Probability that outage encountered over a period of 1 year

F: number of failures, f, which results in voltage collapse in 1 year

$$Loading\_effect\_index = \frac{\beta_{busbar\_with\_compensation}}{\beta_{busbar\_without\_compensation}} \tag{3.140}$$

where β is the reliability index of the busbar with or without FACTS device.

3.3 MULTI-OBJECTIVE EVOLUTIONARY ALGORITHM

In a deregulated market, there is high demand for real-life handling of the market/system operation activities with several conflicting goals that must be simultaneously optimized. In order to achieve the best compromise of all the objective functions, it is proper to appeal to a versatile multi-objective optimization solution approach, among which are, the Niche Pareto Genetic Algorithm, Non-Sorting Genetic Algorithm, Strength Pareto Evolutionary Algorithm (Zitzler, 1999). According to the nomenclature, the multi-objective optimization is intended to give a number of optimal set of solutions (otherwise known as Pareto-optimal set). Among these optimal solutions, a number of trade-offs is observed in order to consider any of them to be best solution with respect to all the objective functions. In essence, it takes good judgment to pick the optimal solution from the pareto-optimal set; this is basically the solution that is non-dominated within the search space (Ziztler, 1998). Among the various algorithms, the improved strength pareto evolutionary algorithm (SPEA2) is implemented in this research work due to a number of good qualities that it possesses such as its robustness to handle several objective functions and ability to update the population set in such a manner that gives credence and opportunity to the fittest compromise to achieve the best solution.

3.3.1 STRENGTH PARETO EVOLUTIONARY ALGORITHM (SPEA)

Zitzler and Thiele (1999) developed the SPEA as a multi-objective optimization solution approach (Zitzler, 1999). This was later improved upon to attain the features earlier stated above in order to provide a better variant otherwise known as the improved SPEA (normally referred to as SPEA 2) approach (Zitzler *et al.*,, 2003). The latter technique is implemented in this work due to a number of potential weaknesses in the former SPEA such as fitness assignment which incorporates density information, density estimation and archive truncation (Zitzler *et al.*,, 2003, Zitzler, 1999).

The following should be noted in developing this algorithm (Abido, 2006):

Input: N (population size)

N (archive size)

T (maximum number of generations)

Output: A (non-dominated set)

Thus the algorithm is executed in a step-by-step approach as follows

Step 1: **Initialization**: Generate an initial population P_t and create the empty archive (external set) Po =( ); .Set t = 0.

Step 2**: Fitness assignment**: Calculate fitness values of individuals in P_t and $\overline{P}_t$.

Step 3: **Environmental selection**: Copy all non-dominated individuals in P_t and $\overline{P}_t$ to $\overline{P}_{t+1}$. If size of $\overline{P}_{t+1}$ exceeds $\overline{N}$ then reduce $\overline{P}_{t+1}$ by means of the truncation operator, otherwise if size of $\overline{P}_{t+1}$ is less than $\overline{N}$ then fill P_{t+1} with dominated individuals in Pt and $\overline{P}_t$.

Step 4: **Termination**: If $t \geq T$ or another stopping criterion is satisfied then set A to the set of decision vectors represented by the non-dominated individuals in $\overline{P}_{t+1}$. Stop.

Step 5**: Mating selection**: Perform binary tournament selection with replacement on $\overline{P}_{t+1}$ in order to fill the mating pool.

Step 6: **Variation**: Apply recombination and mutation operators to the mating pool and set P_{t+1} to the resulting population. Increment generation counter (t =t + 1) and go to Step 2.

This is succinctly illustrated in figure 3.11(Abido, 2006).

In contrast to SPEA, SPEA-2 uses a fine-grained fitness assignment strategy which incorporates density information. Furthermore, the archive size is fixed, i.e. whenever the number of non-dominated individuals is less than the predefined archive size, the archive is filled up by dominated individuals; with SPEA, the archive size may vary over time. In addition, the clustering technique, which is invoked when the non-dominated front exceeds the archive limit, has been replaced by an alternative truncation method which has similar features but does not lose boundary points(Zitzler *et al.*,, 2003, Zitzler and Thiele, 1998). Finally, another improvement to the SPEA is that only members of the archive participate in the mating selection process with regard to the SPEA-2.

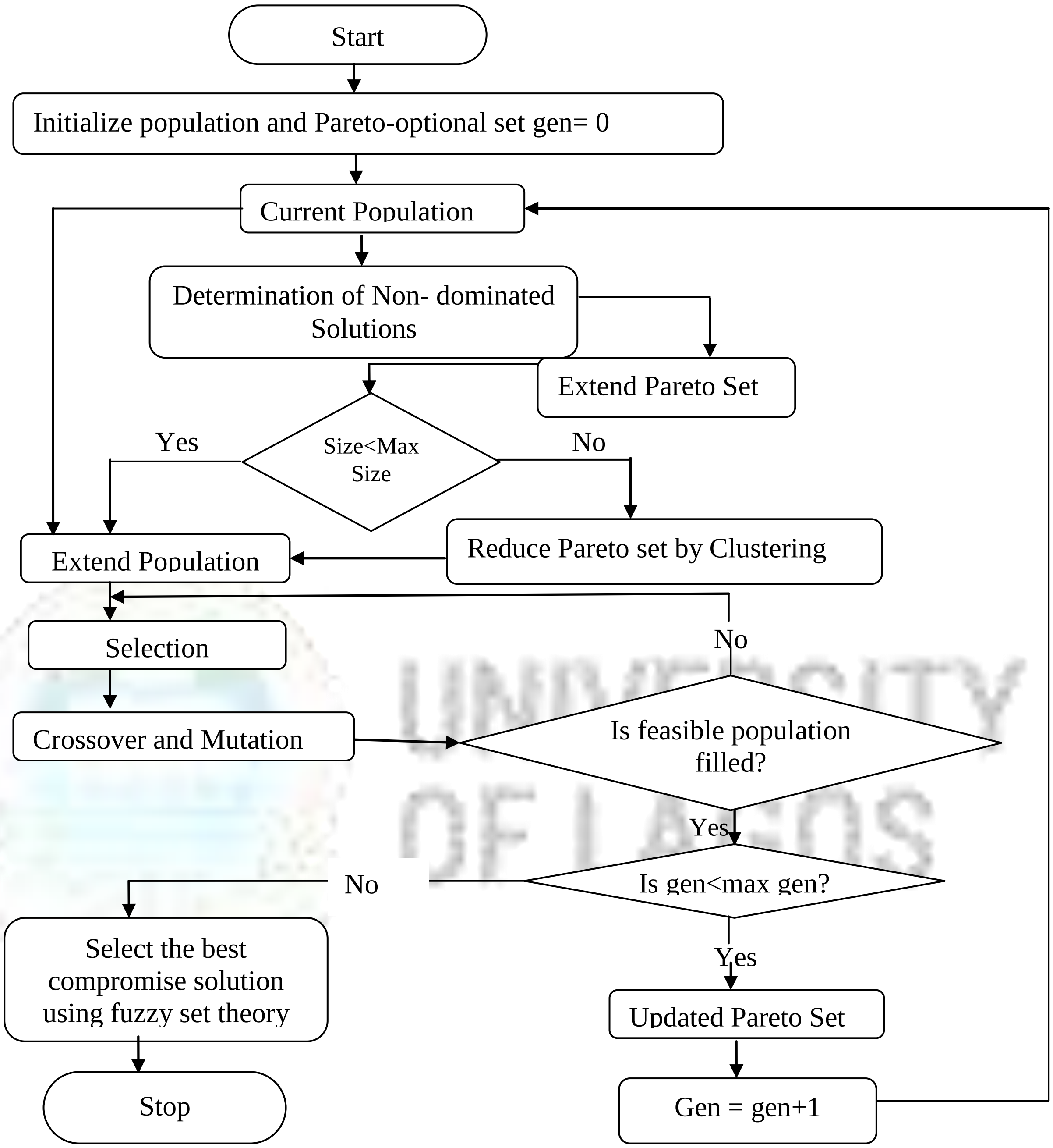


Figure 3.11: Computational flow of the SPEA

3.3.2 SETTING OF THE SOLUTION APPROACH

The technique used in this study is developed and implemented using MATLAB software package (Saadat, 2004). On all optimization runs, the population size and the maximum number of generations are selected as 200 and 500 respectively but then at some points, the convergence is achieved at the 10th generation and due to limited computer memory the population is reduced to tenth of the value stated. The maximum size of Pareto front is set as 30 solutions while the crossover and mutation probabilities are selected as 0.9 and 0.1 respectively at a tolerance of 0.0001.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 RESULTS

The results of simulations obtained by implementing the technique introduced in Chapter three are here presented for two sets of cases, that is, the standard IEEE-30 bus system and the Nigeria-26 bus system.

Table 4.1: Improved Strength Pareto Evolutionary Algorithm (SPEA-2) Parameters:

Generations	200
Archive Size	50
Population Size	250

Optimization completed in 912.86 seconds.

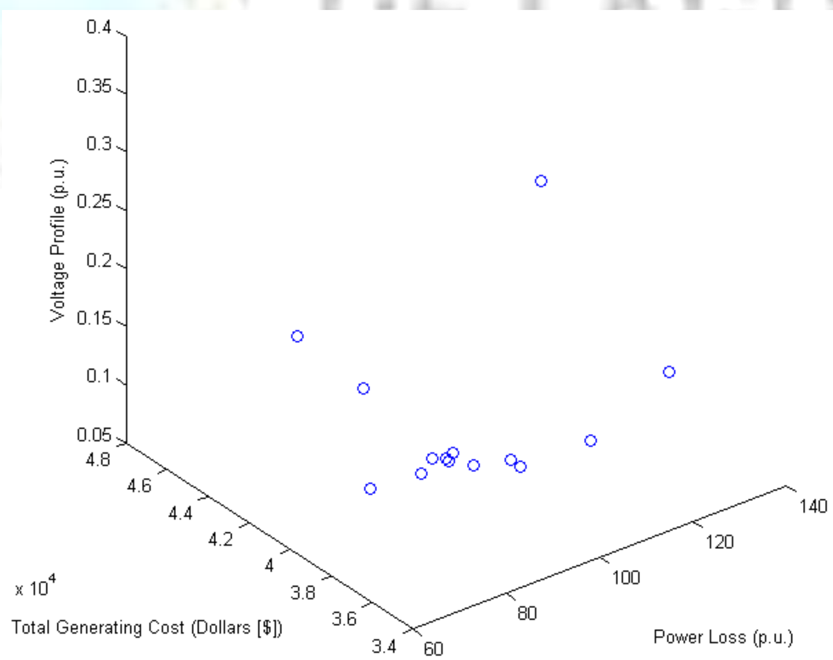


Figure 4.1: Pareto-Optimal Front for the multi-objective functions

Table 4.2: Best Solutions from the Pareto-optimal front

Parameters	Power Loss	Total Operating Cost	Voltage Profile
Best Bias [Power Loss]	63.2966	36813.06	0.13412649
Best Bias [Total Cost]	90.7342	34752.79	0.37940726
Best Bias [V. Profile]	92.9199	39784.72	0.07819776
Best Compromise	63.2966	36813.06	0.13412649

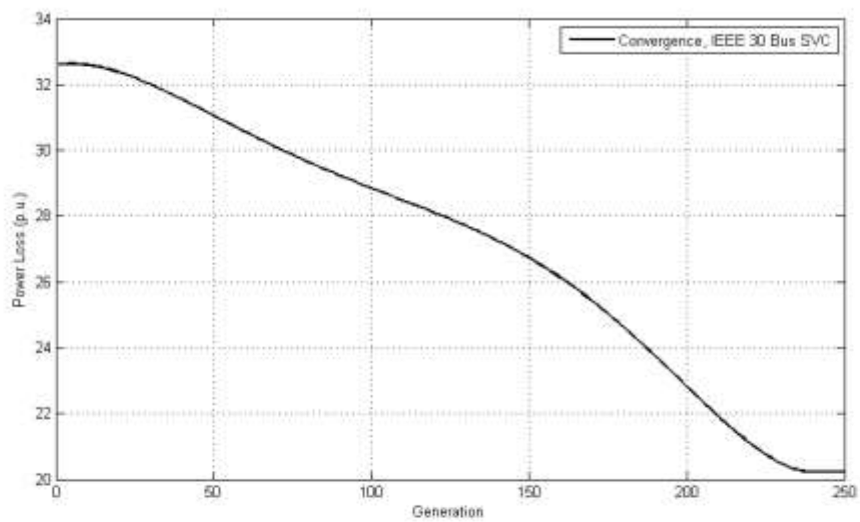


Figure 4.2: Convergence of the system with SVC

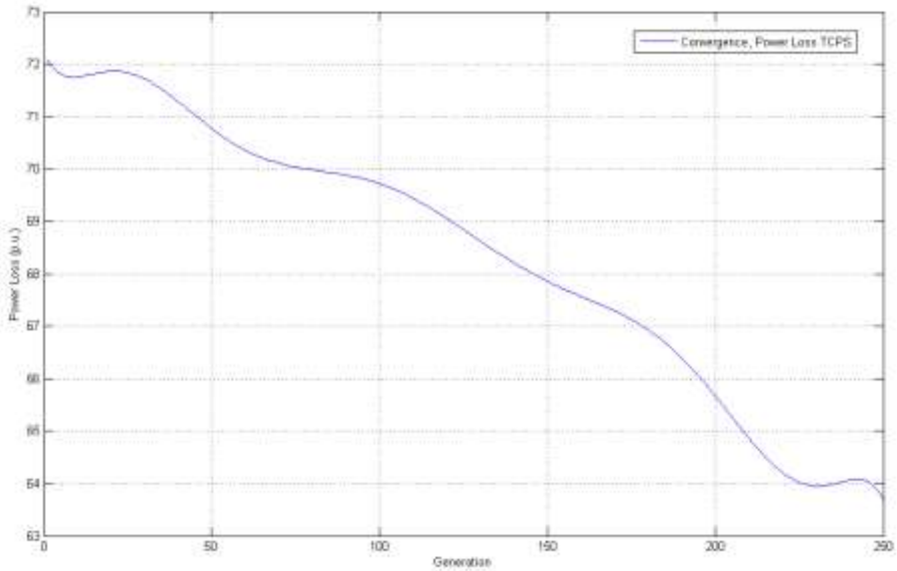


Figure 4.3: Convergence of the system with TCPS

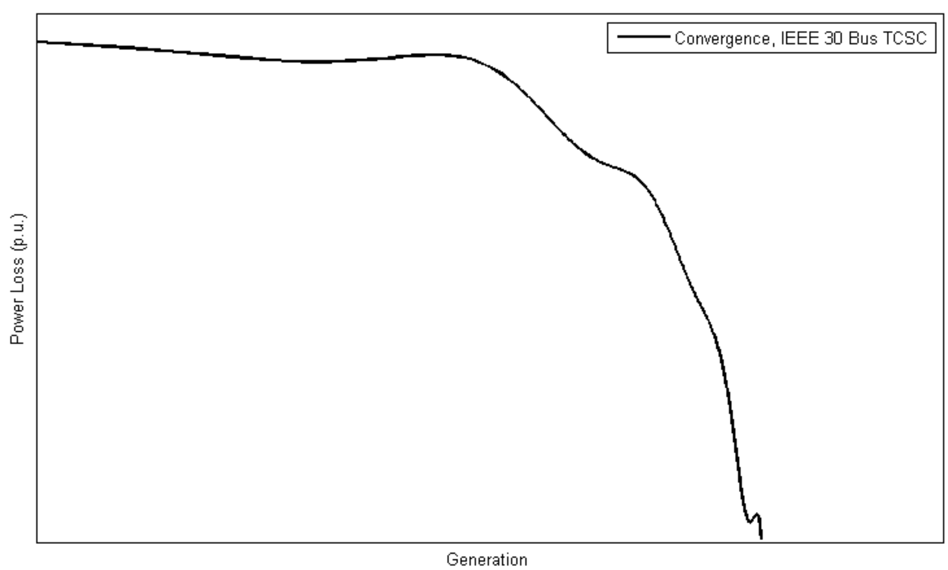


Figure 4.4: Convergence of the system with TCSC

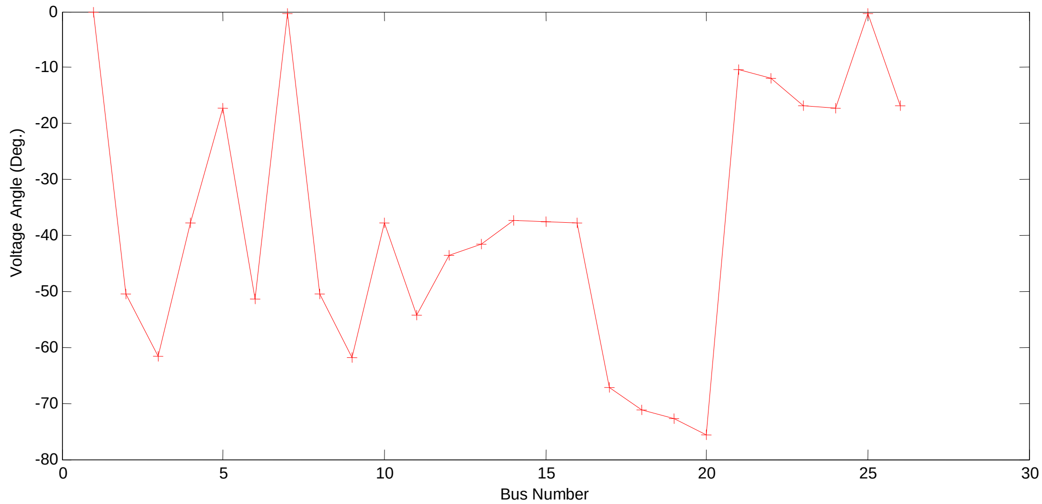


Figure 4.5: Voltage Profile of the Nigeria -26 Bus system

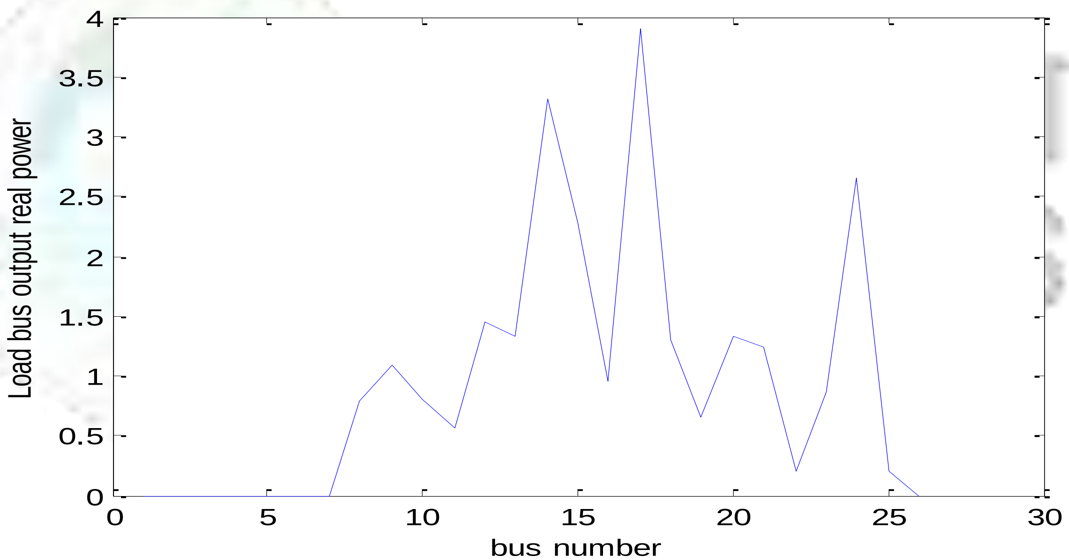


Figure 4.6: Real power measured at the load buses of the Nigeria-26 bus system

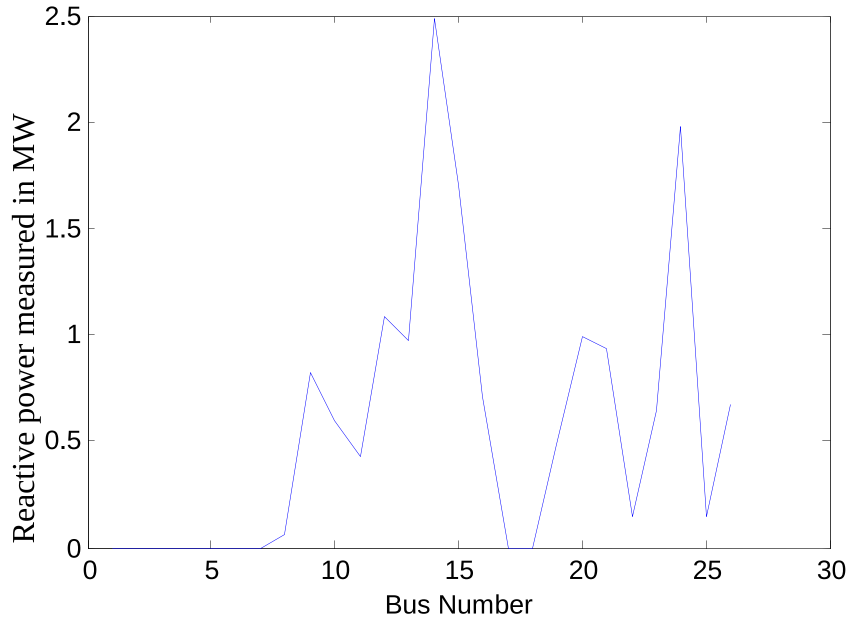


Figure 4.7: Reactive power measured at the load buses of the Nigeria-26 bus system

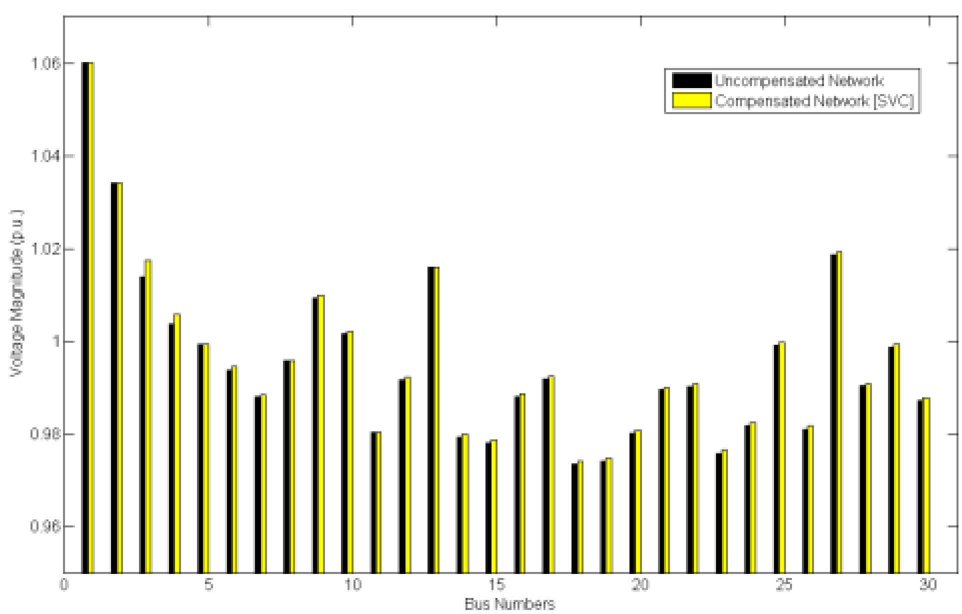


Figure 4.8: Chart of the IEEE-30 bus system with/without SVC

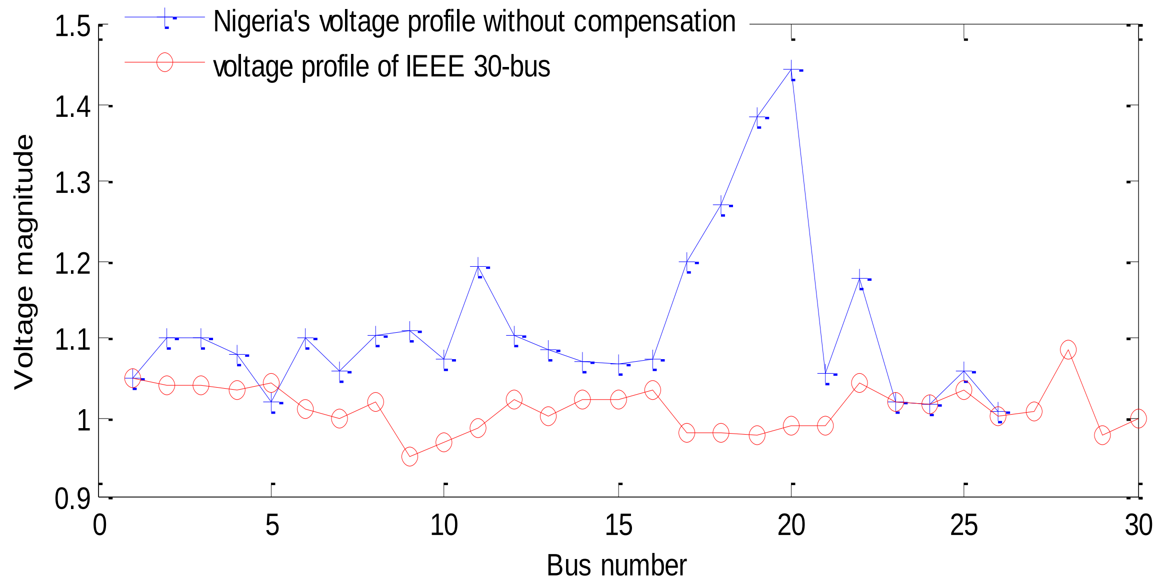


Figure 4.9: Interface of voltage profile of IEEE and Nigeria' bus system (without compensation)

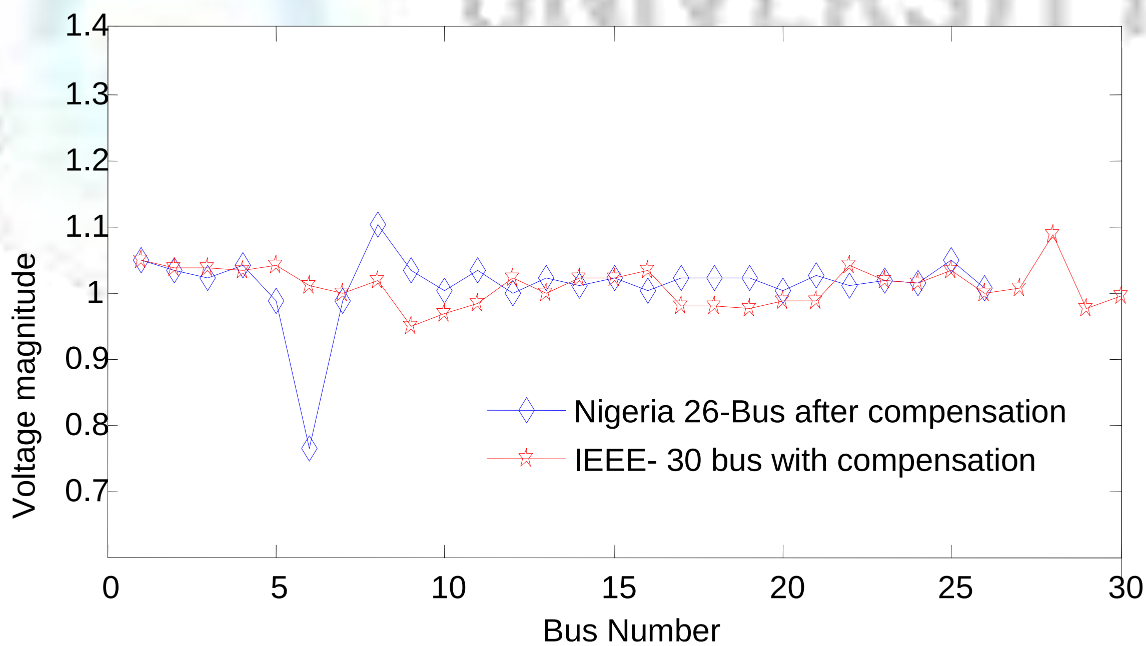


Figure 4.10: Voltage profile after introducing capacitance for compensation

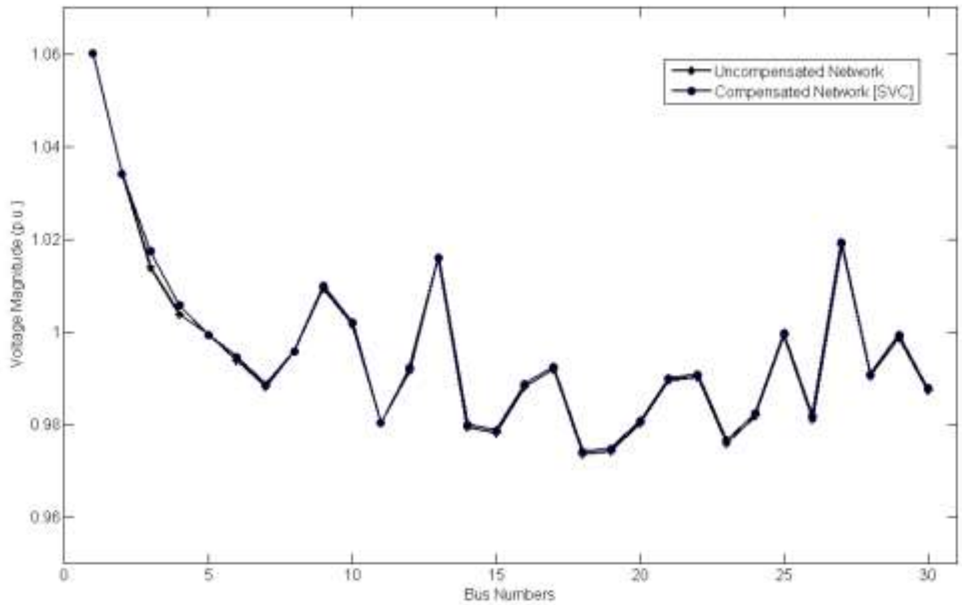


Figure 4: 11: IEEE-30 bus system with/without SVC

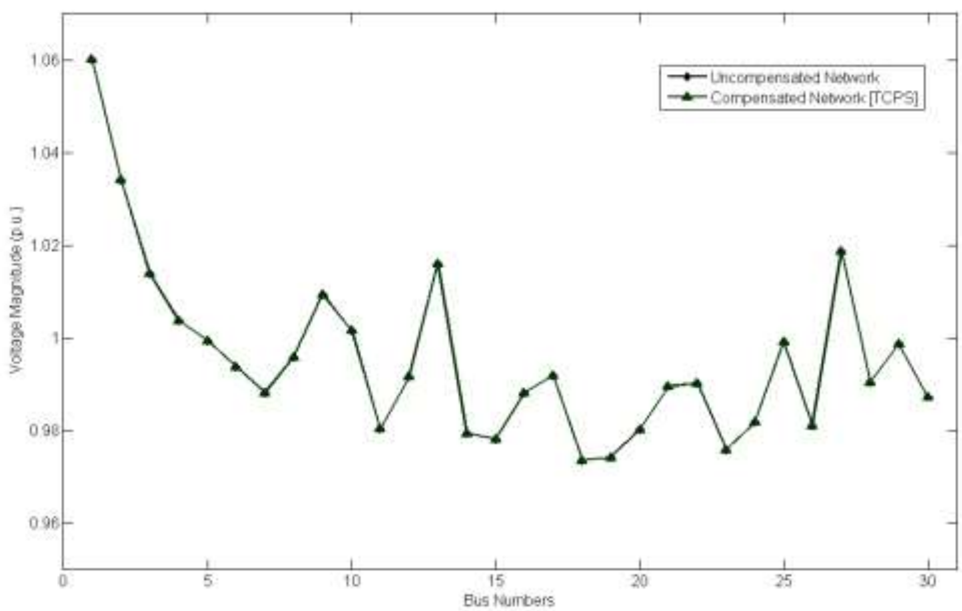


Figure 4.12: IEEE-30 bus system with/without TCPS

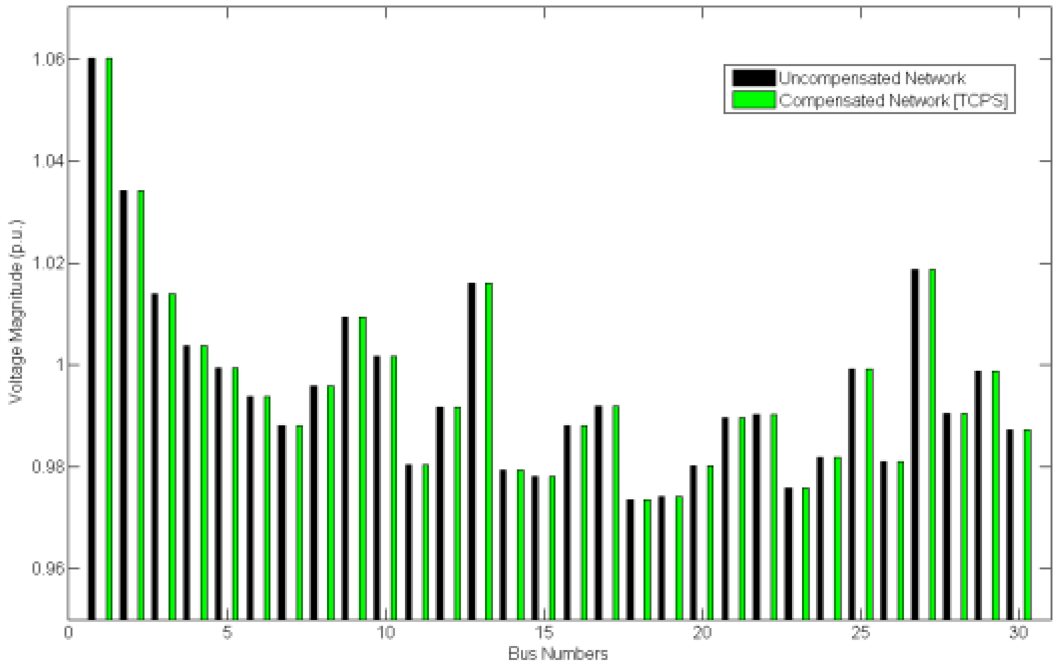


Figure 4. 13: Bar chart of the IEEE-30 bus system with/without TCPS

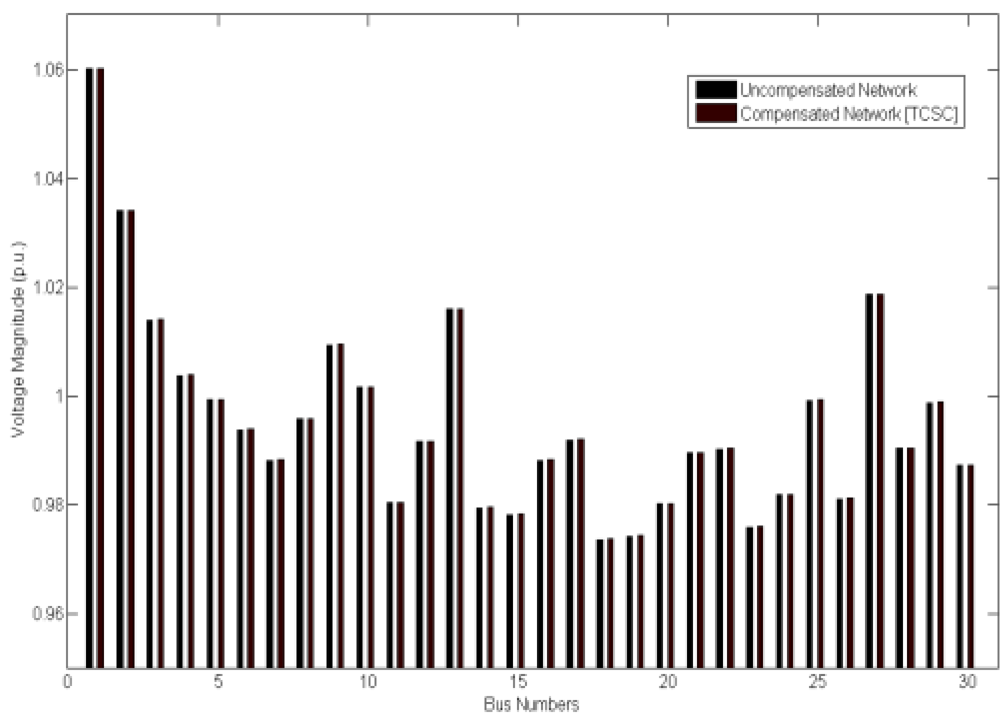


Figure 4.14: Bar chart of the IEEE-30 bus system with/without TCSC

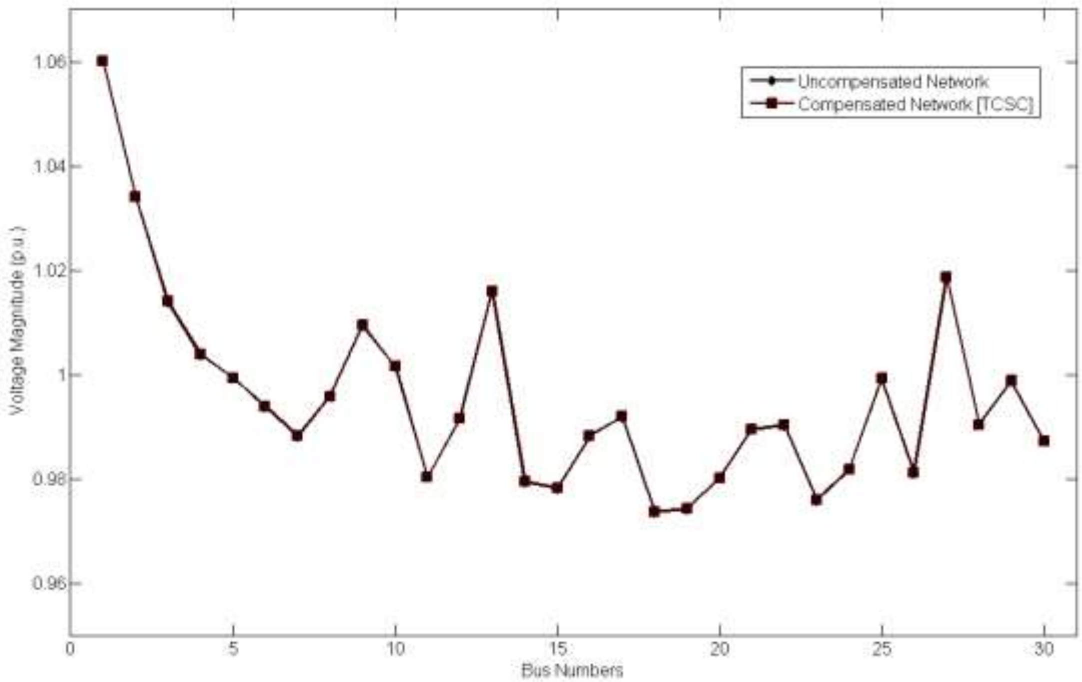


Figure 4.15: Graphical representation of the IEEE-30 bus system with/without TCSC

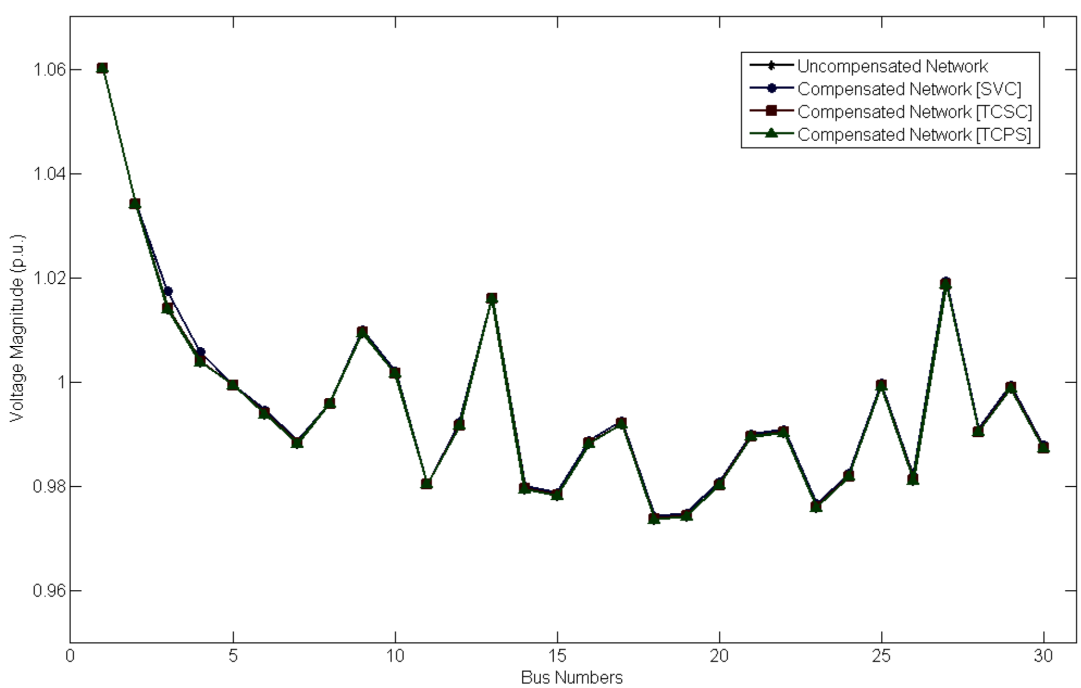


Figure 4.16: Graphical representation of the IEEE-30 bus system with /without FACTS devices/compensator-SVC, TCPS, TCSC

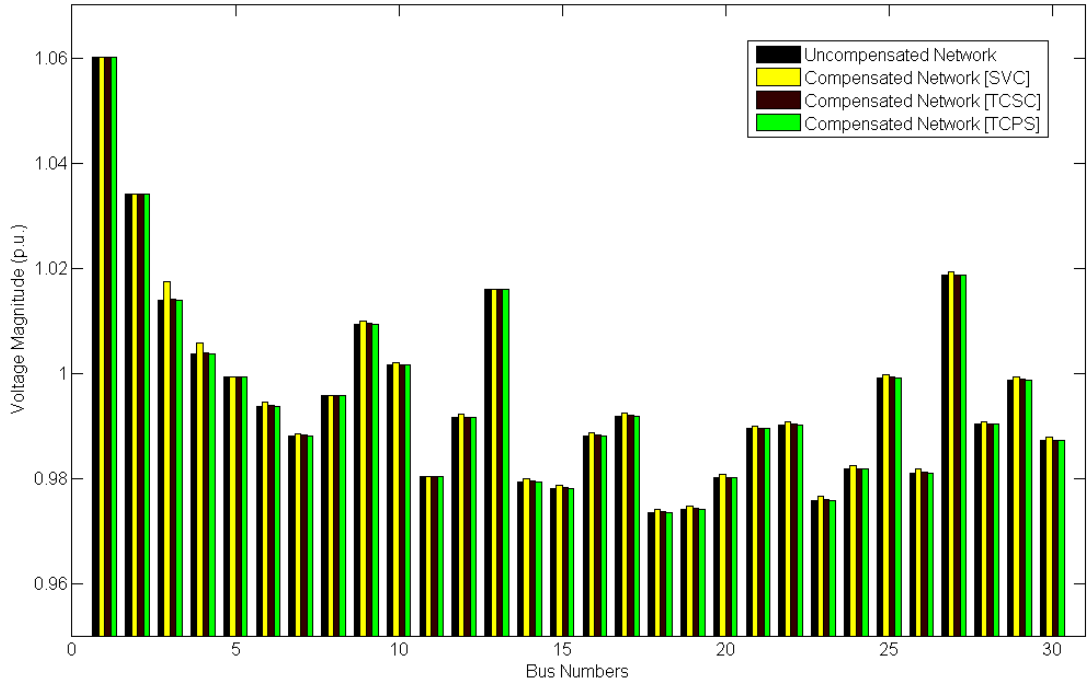


Figure 4.17: Bar chart of the IEEE-30 bus system with/without FACTS devices/compensator-SVC, TCPS,TCSC

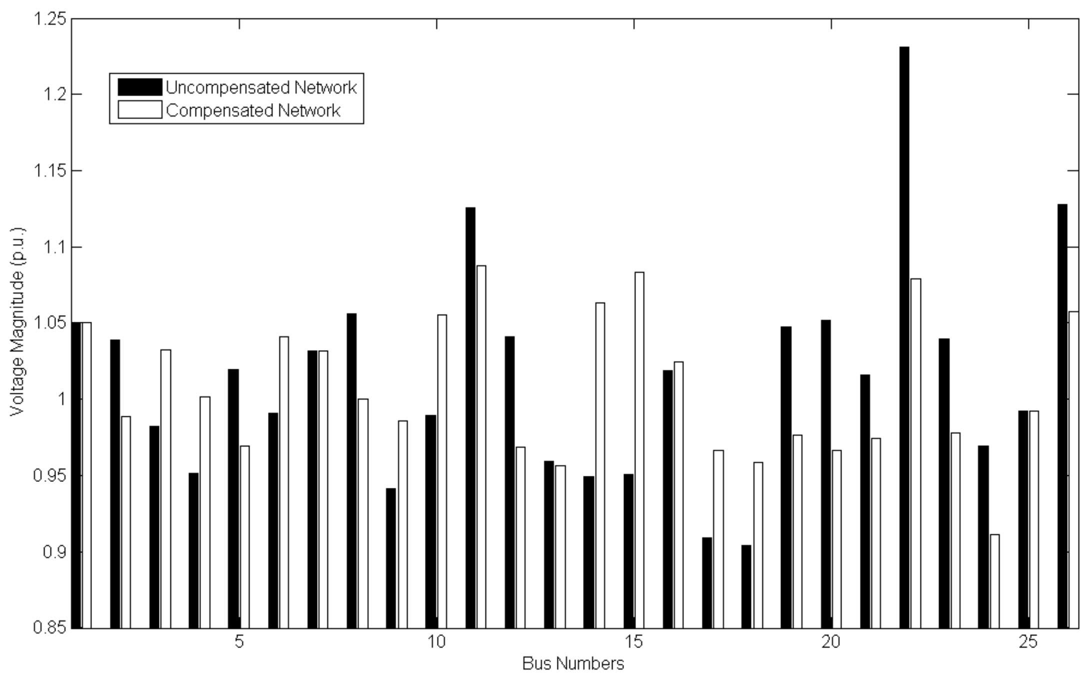


Figure 4.18: Bar chart of the Nigeria-26 bus system with/without TCSC

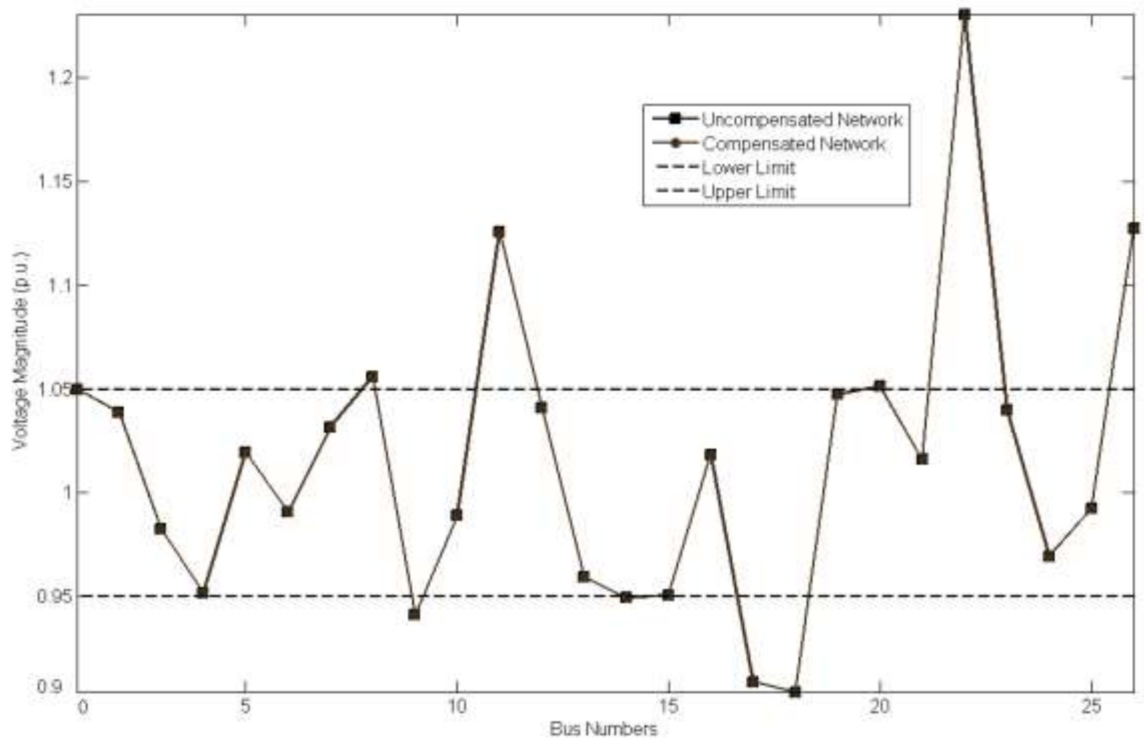


Figure 4.19: Graphical representation of voltage magnitude of Nigeria-26 bus system with /without compensator-TCPS (showing the upper and lower limits)

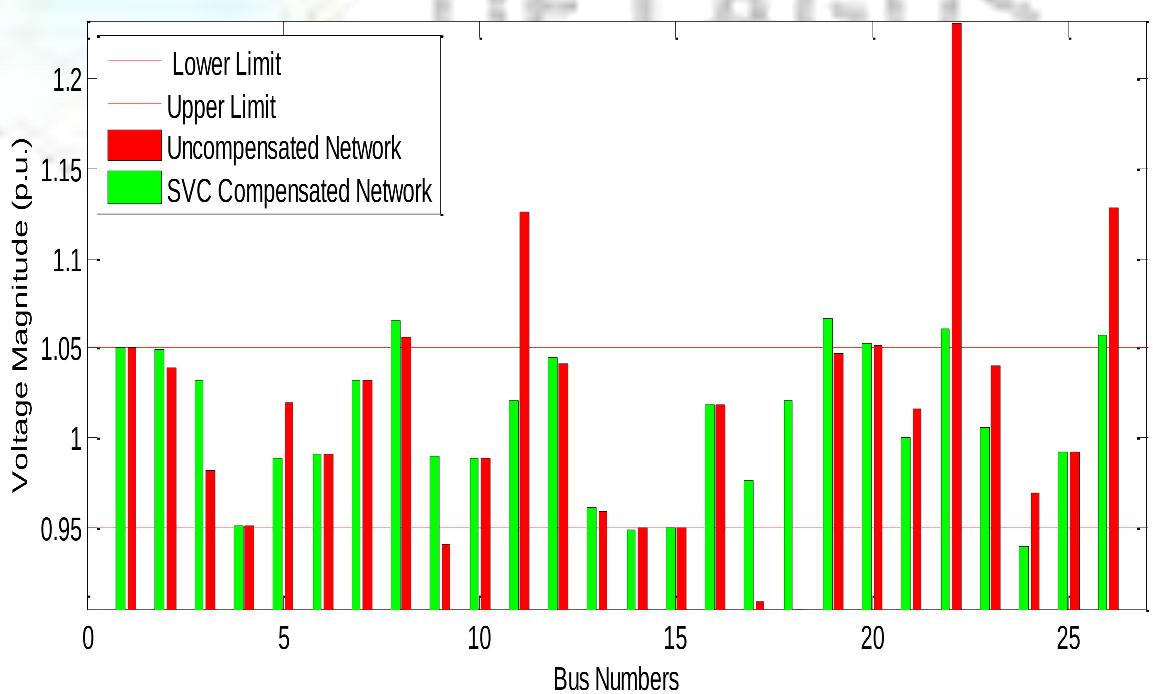


Figure 4.20: Bar chart representation of voltage magnitude of Nigeria-26 bus system with /without compensator-SVC (showing the upper and lower limits)

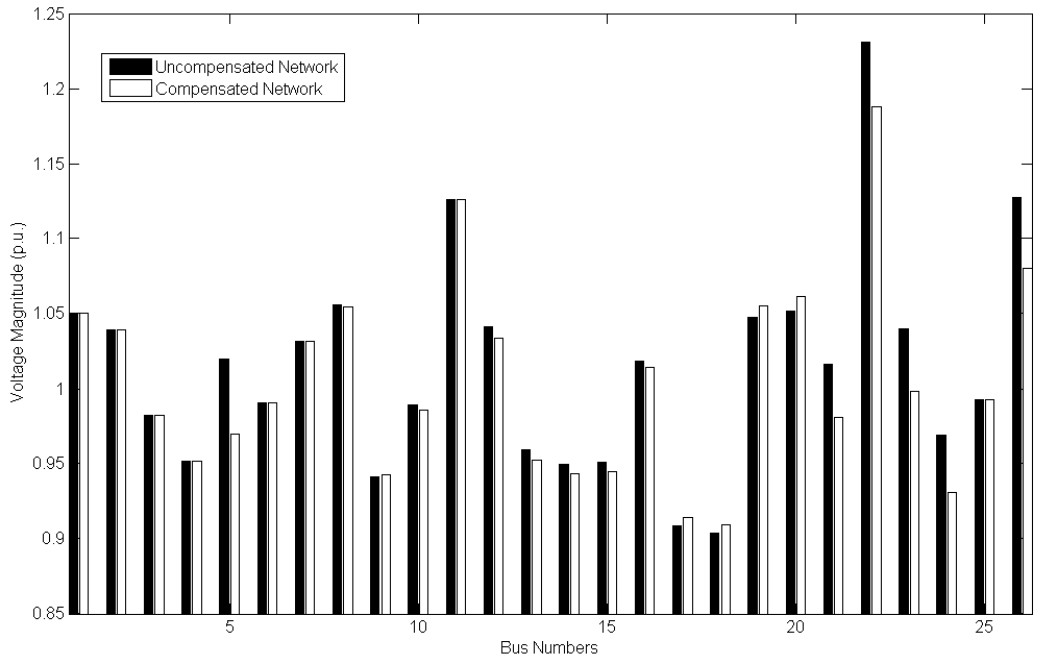


Figure 4.21: Bar chart representation of voltage magnitude of Nigeria-26 Bus system with compensator – capacitor only

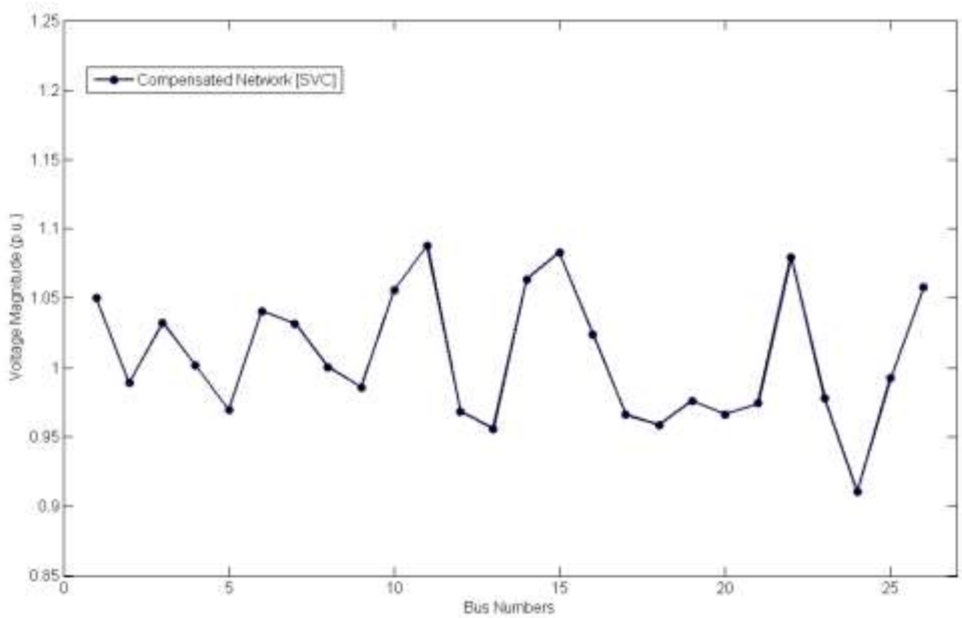


Figure 4.22: Graphical representation of voltage magnitude of Nigeria-26 Bus system with compensator – SVC only

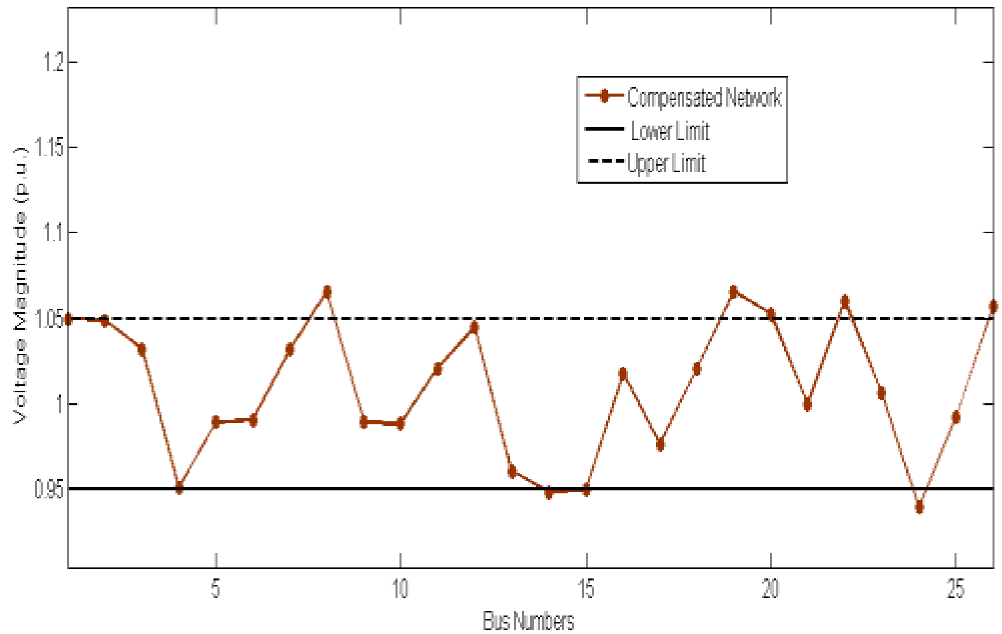


Figure 4.23: Graphical representation of voltage magnitude of Nigeria-26 Bus with compensator – SVC showing the lower and upper limit of operation

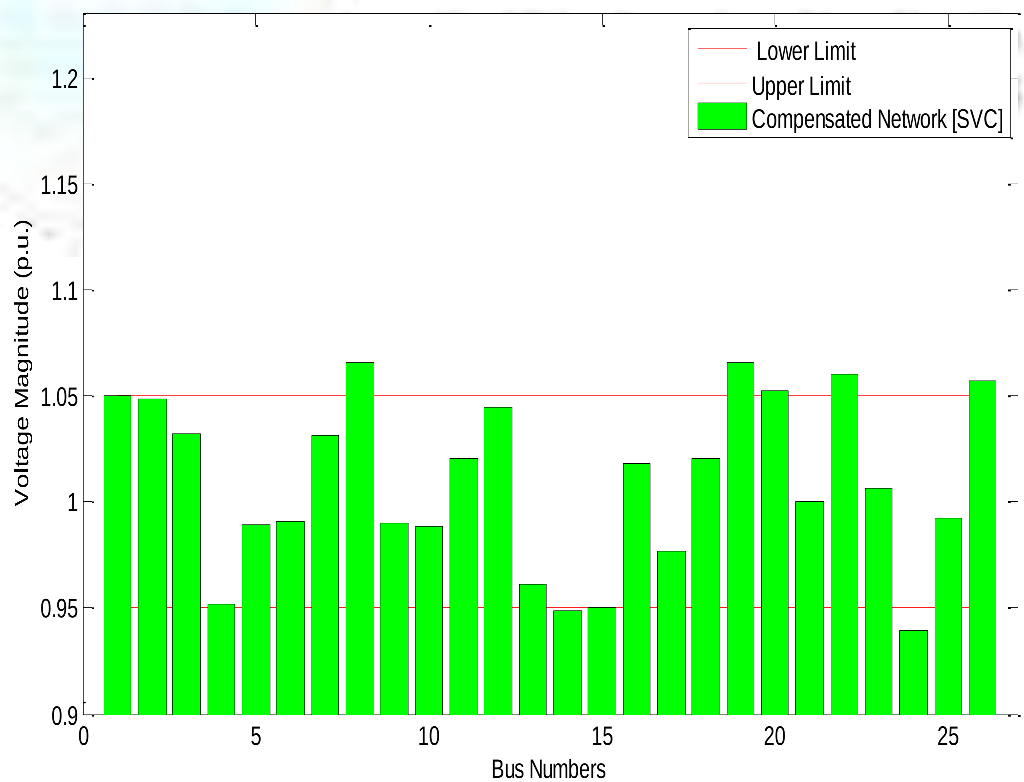


Figure 4.24: Bar Chart representation of voltage magnitude of Nigeria-26 bus with compensator –SVC showing the lower and upper limit of operation

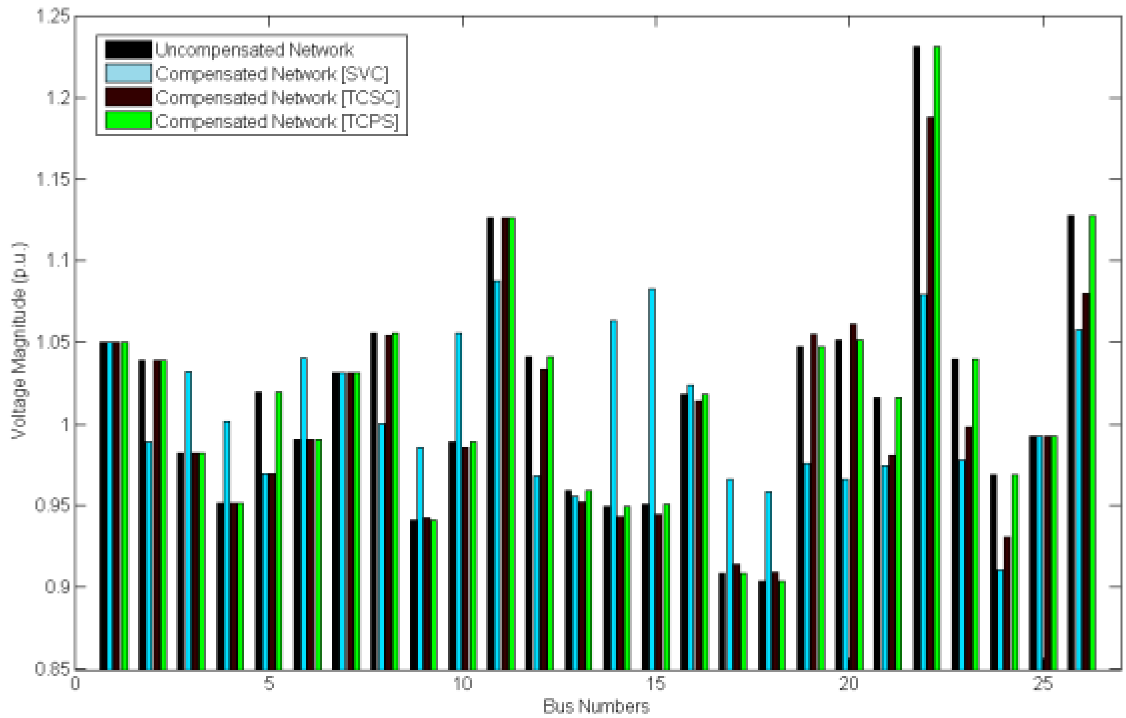


Figure 4.25: Bar chart of voltage magnitude of Nigeria-26 bus system with FACTS devices- SVC, TCPS and TCSC.

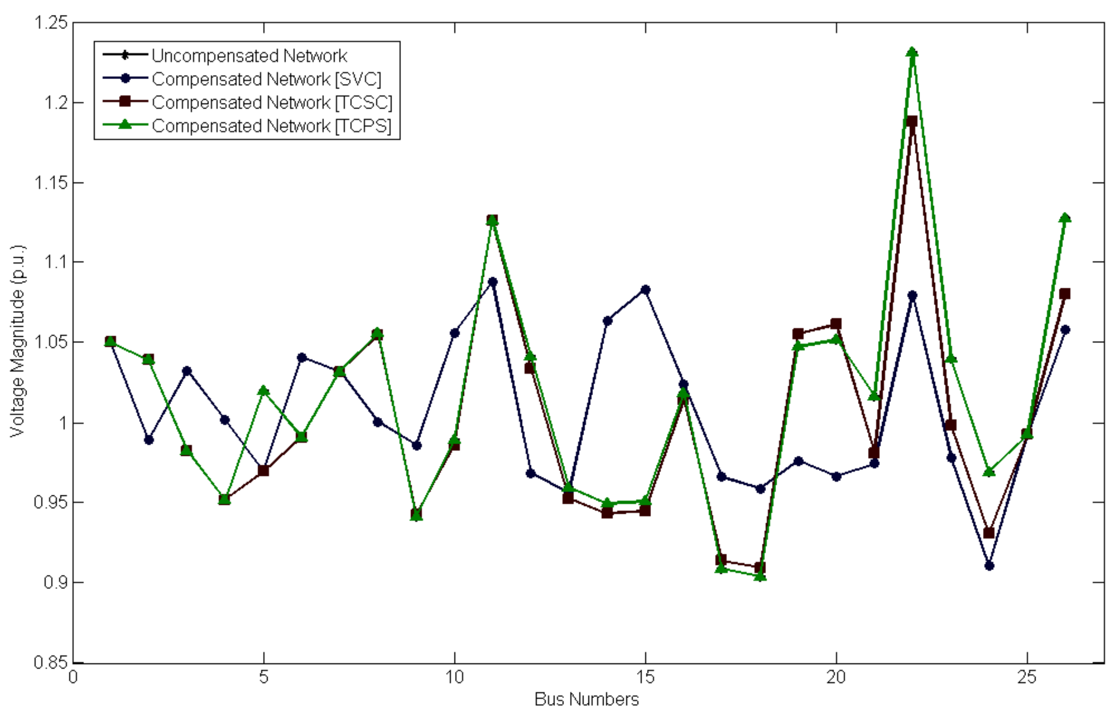


Figure 4. 26: Graphical representation of voltage magnitude of Nigeria-26 bus system with/without FACTS devices/compensator-SVC, TCPS,TCSC

Table 4.3: Load forecast for 2000 -2020

Year	Capacity Required (MW)
2000	3500
2001	5400
2002	7500
2003	9500
2004	11500
2005	14000
2006	17650
2007	21500
2008	25000
2009	28550
2010	32500
2011	36000
2012	40000
2013	44500
2014	50000
2015	54500
2016	59000
2017	64500
2018	67540
2019	72450
2020	81900

Table 4. 4: Annualized bus system adequacy indices for a system peak load 4500MW (Nigeria-26 bus system)

Bus no	Failure Probability /yr	Modified Failure probability /yr	LOLE probability /yr	Total load curtailed MW	Energy Expected Not supplied MWh	Cost of Outages X10^2 N/MWh	Availability Without FACTS devices /yr	Availability with FACTS devices /yr
1	0.005675	0.005675	0.000021	7.88	112.87	129.97	0.688356	0.888843
2	0.012372	0.012372	0.000040	89.32	167.82	178.57	0.554321	0.754462
3	0.000345	0.000345	0.000057	12.98	113.75	131.85	0.481157	0.981154
4	0.002376	0.000798	0.000013	10.65	121.74	130.97	0.44388	0.994398
5	0.001324	0.001324	0.000022	6.76	203.98	129.58	0.28765	0.887653
6	0.013425	0.013425	0.000091	5.87	85.75	129.27	0.392133	0.892173
7	0.000212	0.000212	0.000043	11.60	211.60	131.32	0.478325	0.778345
8	0.123541	0.000193	0.000011	112.98	1164.53	200.14	0.448368	0.988788
9	0.019332	0.000379	0.000091	76.98	1060.00	168.64	0.344552	0.994352
10	0.002354	0.002354	0.000042	4.87	74.56	128.94	0.339003	0.999123
11	0.067435	0.000496	0.000087	8.88	98.32	130.33	0.457973	0.997653
12	0.000112	0.000112	0.000021	7.85	89.56	129.96	0.458443	0.998453
13	0.002319	0.002319	0.000031	9.64	88.50	130.60	0.459224	0.899934
14	0.087121	0.000513	0.000022	15.09	94.98	132.67	0.551131	0.991231
15	0.088776	0.000105	0.000054	25.50	93.25	137.11	0.343349	0.993452
16	0.000334	0.000334	0.000012	10.01	55.06	130.73	0.458245	0.998276
17	0.092354	0.001009	0.000064	4.56	98.75	128.83	0.699944	0.889976
18	0.092311	0.002030	0.000076	77.05	1022.98	168.70	0.463276	0.993245
19	0.102386	0.003597	0.000038	13.81	122.09	132.17	0.497655	0.997644
20	0.000354	0.000254	0.000073	12.89	198.55	131.81	0.468344	0.998543
21	0.076854	0.001349	0.000006	55.72	203.21	153.69	0.446111	0.996754
22	0.098763	0.000263	0.000043	121.95	1465.09	209.20	0.443229	0.991342
23	0.001887	0.003245	0.000046	215.76	765.98	332.87	0.452332	0.888572
24	0.090807	0.001089	0.000033	33.87	54.56	141.16	0.465118	0.998762
25	0.000017	0.000017	0.000054	45.93	4.57	147.72	0.543354	0.897321
26	0.087945	0.003458	0.000064	64.01	5.87	159.20	0.556798	0.884532

Table 4.5: Interrupted Energy Assessment Rate at each Nigeria-26 Bus system

Bus No	Energy Expected Not supplied (MWh)	Cost of Outages x10^2 (\$/MWh)	Interrupted Energy Assessment Rate (\$/MWh)
1	112.87	129.97	1.151502
2	167.82	178.57	1.064057
3	113.75	131.85	1.159121
4	121.74	130.97	1.075817
5	203.98	129.58	0.635258
6	85.75	129.27	1.507522
7	211.60	131.32	0.620605
8	1164.53	200.14	0.171863
9	1060.00	168.64	0.159094
10	74.56	128.94	1.729345
11	98.32	130.33	1.325570
12	89.56	129.96	1.451094
13	88.50	130.60	1.475706
14	94.98	132.67	1.396820
15	93.25	137.11	1.470349
16	55.06	130.73	2.374319
17	98.75	128.83	1.304608
18	1022.98	168.70	0.164910
19	122.09	132.17	1.082562
20	198.55	131.81	0.663863
21	203.21	153.69	0.756311
22	1465.09	209.20	0.142790
23	765.98	332.87	0.434567
24	54.56	141.16	2.587243
25	4.57	147.72	32.323850
26	5.87	159.20	27.120950

Table 4.6: IEEE –RTS 30-bus system

Bus No	From Bus	To Bus	Without FACTS Probability of no collapse	With FACTS probability of no collapse	Without FACTS probability of collapse	With FACTS Probability of collapse
1	1	2	0.179115	0.792117	0.179117	0.017118
2	1	3	0.183824	0.838233	0.118382	0.008382
3	2	4	0.094578	0.745781	0.424578	0.00023
4	3	4	0.078081	0.780811	0.228081	0.001065
5	2	5	0.083008	0.830086	0.118308	0.003008
6	2	6	0.061291	0.776191	0.236191	0.001691
7	4	6	0.072313	0.723131	0.222313	0.002313
8	5	7	0.117647	0.164711	0.221647	0.001724
9	6	8	0.129776	0.999776	0.112776	0.003443
10	6	9	0.128638	0.986398	0.222638	0.000138
11	6	10	0.125846	0.981584	0.211546	0.002154
12	9	11	0.115653	0.991565	0.241653	0.000198
13	9	10	0.028540	0.872854	0.132540	0.000540
14	4	12	0.045236	0.984523	0.145236	0.001586
15	12	13	0.110406	0.981041	0.210406	0.003451
16	12	14	0.008219	0.998201	0.111219	0.000401
17	12	15	0.019164	0.871919	0.241916	0.000226
18	12	16	0.127955	0.987955	0.317955	0.000125
19	14	15	0.111742	0.991742	0.221742	0.000127
20	16	17	0.123931	0.977312	0.113931	0.000331
21	15	18	0.156256	0.886257	0.216256	0.001243
22	18	19	0.152888	0.828883	0.312888	0.000821
23	19	20	0.117217	0.742178	0.112173	0.000117
24	10	20	0.119558	0.951528	0.112558	0.000118
25	10	17	0.226885	0.968283	0.116885	0.001823
26	10	21	0.118334	0.885774	0.2218334	0.001423
27	10	22	0.198713	0.875134	0.112713	0.001232
28	21	22	0.010464	0.984643	0.232464	0.002354
29	15	23	0.002756	0.925744	0.445756	0.000006
30	22	24	0.012297	0.896594	0.226297	0.000189

Table 4.7: Probability of voltage collapse in the Nigeria-26 bus system with and without FACTS devices

Bus No	Without FACTS Probability of no collapse	With FACTS probability of no collapse	Without FACTS probability of collapse	With FACTS Probability of collapse
1	0.001231	0.447781	0.883412	0.9901487
2	0.010013	0.445166	0.779713	0.999122
3	0.010224	0.414699	0.877465	0.887354
4	0.001126	0.443212	0.754294	0.894005
5	0.000127	0.498674	0.796687	0.891127
6	0.001336	0.511288	0.864432	0.888214
7	0.000112	0.218197	0.923417	0.974563
8	0.000424	0.424487	0.849652	0.993244
9	0.000029	0.429355	0.783492	0.789965
10	0.000016	0.466553	0.866753	0.865323
11	0.000241	0.427666	0.844402	0.954321
12	0.000072	0.456272	0.833457	0.874328
13	0.000137	0.533499	0.875233	0.657655
14	0.002228	0.531082	0.876532	0.827865
15	0.001262	0.445076	0.978106	0.967863
16	0.000199	0.422554	0.9432945	0.995321
17	0.000015	0.423475	0.681222	0.855987
18	0.000014	0.323261	0.446752	0.899647
19	0.000145	0.453234	0.654845	0.981455
20	0.001704	0.565984	0.746755	0.746875
21	0.001326	0.554534	0.545395	0.995576
22	0.000145	0.523189	0.895445	0.976541
23	0.000416	0.523954	0.876156	0.799846
24	0.000977	0.452256	0.779864	0.757961
25	0.000003	0.653298	0.834768	0.843327
26	0.000021	0.530735	0.822786	0.821864

Table 4.8: Comparison of the reliability (With and Without FACTS Devices) of the Nigeria-26 Bus system at the weak buses

Loading factor	Bus 8		Bus 11		Bus 17		Bus 18		Bus 21		Bus 26	
	No FACTS	FACTS	No FACTS	FACTS	No FACTS	FACTS	No FACTS	FACTS	No FACTS	FACTS	No FACTS	FACTS
1.0	0.003241	0.003342	0.000119	0.000118	0.000129	0.001221	0.000123	0.000123	0.000111	0.000110	0.000114	0.000231
1.1	0.005121	0.005132	0.000243	0.000231	0.000143	0.001129	0.000164	0.000152	0.000182	0.000173	0.000153	0.000333
1.2	0.006341	0.005912	0.000341	0.000322	0.000196	0.001816	0.000201	0.000216	0.000254	0.000246	0.000200	0.000200
1.3	0.017823	0.008721	0.024368	0.004322	0.047653	0.002347	0.045321	0.000543	0.008739	0.003871	0.005643	0.000987
1.4	0.677219	0.135421	0.665329	0.128362	0.598732	0.098722	0.664232	0.203549	0.764232	0.254778	0.611023	0.219873
1.5	0.765321	0.342517	0.782653	0.228971	0.782345	0.241689	0.887124	0.342167	0.823450	0.288769	0.768853	0.291872
1.6	0.892617	0.342631	0.828702	0.436278	0.863542	0.397642	0.910021	0.354121	0.912351	0.342617	0.887676	0.332516
1.7	0.923664	0.445328	0.887635	0.438734	0.931476	0.407564	0.987631	0.394627	0.971234	0.400001	0.945361	0.412768
1.8	0.998224	0.456381	0.882675	0.441276	0.993281	0.421187	0.998753	0.476023	0.993421	0.435219	0.991245	0.445367

4.2 DISCUSSION OF RESULTS

Table 4.1 shows the Strength Pareto Evolutionary Algorithm's parameters employed in this work. It is as follows: the number of generations (it is from a previous generation that the next parents for current generation are chosen) is 200 while the size of archive (externally stored Pareto solutions) is 50 and the population size is 250. This leads to convergence to a Pareto-optimal front shown in Figure 4.1 from which Figure 4.2 is obtained with respect to compromise regarding the multi-objective environment in which the system is operated. The best compromise is then implemented on each of the FACTS devices as shown in figures 4.3 (for SVC), 4.3 (from TCPS), and 4.4 (for TCSC). From these results, it is obviously evident that SVC has the best convergence for the Nigeria-26 bus system.

Figure 4.5 shows the voltage profile of the Nigeria-26 bus system both in terms of angle hence it was this data that was implemented for the rest of the solution in the work. It is also very important to investigate the real and reactive powers of the system. These were displayed in figures 4.6 and 4.7. The latter later becomes very essentially linked to the voltage profile in the sense that any form of correction effected on the voltage is an indirect means of controlling the reactive power of the system. In figure 4.9, the voltage magnitude of both the IEEE-30 bus and Nigeria-26 bus systems were graphically compared on the same axes in order to evidently portray the clear difference in the two cases. And this becomes necessary in the event that Nigeria decides to exercise full deregulation of the power sector then a number of facilities must be put in place. Thus, compensation of the transmission line to avoid power loss could be performed in two ways namely; by engaging the service of either the static or the dynamic compensators.

Figure 4.10 shows the influence of the static compensator on the system. Thus it shows a good potential for curbing voltage collapse. But in a deregulated environment whereby market activities are very dynamic, it then casts a serious doubt on the ability of the Capacitors to perform excellently in this condition. Hence the dynamic compensators become very useful and necessary in the sense that they respond fast and accurately to any form of voltage fluctuation that may call for the compensation of the transmission line. This led to the activities of FACTS devices such as shown in figures 4.11 for SVC, figure 4.12 and 4.13 for TCPS and figures 4.14 and 4.15 for TCSC on the IEEE-30 bus system. The comparative influence of these three devices was show-cased in figures 4.16 and 4.17. It could be observed that the IEEE system has no need for any further compensation since both the compensated and non-compensated conditions yield the same nature of family of curves. In other words, the IEEE-30 bus system is at its optimal.

For the Nigeria-26 bus system, a number of diagrams were also produced to investigate the impact of the FACTS devices on the power system. Figure 4.18 shows the Nigerian transmission system with and without the TCSC while figure 4.19 presented the action of TCPS on the same transmission system and figure 4.20. This can be considered with other forms of compensators by looking closely at figures 4.18, 4.19 and 4.21 which show-case the pattern of the voltage profile when TCSC, TCPS and static capacitor are implemented. The influence of the SVC on the improvement of the system voltage profile is quite evident. So also figures 4.23 and 4.24 further portray the ability of this unique FACTS device by considering its appropriateness at maintaining its voltage stability features within the standard operating region along the Nigerian electric power system. In figures 4.25 and 4.26, the comparison examination of all these devices was produced showing their respective influence on the transmission network. It is evident that under deregulation, there would be unparalleled needs for the installation of the FACTS devices especially the SVC type on the critically weak buses along the power transmission lines. This becomes necessary since the system is going to be responding to several market demands and actions that could easily have a dramatic effect on the system voltage profile.

From the foregoing therefore, the Nigeria-26 bus system without any form of reinforcement against voltage collapse may not be able to cope with the challenges of power system deregulation. Thus, the transmission system may not be able to sustain the expected load demand. Then it means that the system must be reinforced with reactive support to avoid voltage collapse.

Table 4.3 shows the source of the data employed in performing the necessary calculations in this work. It is the forecast work that was believed to be the actual energy need of Nigeria without any suppressed load. The bus system adequacy indices were extracted as shown in Table 4.4 with the opinion of showing the influence by optimization to explain the availability expected of the FACTS devices. This further supports the initial judgment that the FACTS devices (the ones earlier considered in this work) improve the system adequacy and supply. Table 4.5 was obtained by extracting the EENS and Cost of outage from Table 4.4 to provide information on the Interrupted Energy Assessment Rate of the system; this clearly presents the cost of interrupting the power supply at each bus. In Table 4.6, the IEEE-30 bus system was also subjected to the same process to obtain the information which shows that the system is not seriously affected by the installation of the FACTS devices. This further shows that the existing work that dealt with DC optimization has the same bearing as this current work in that it was stated in the referred work that this is possible due to the fact that IEEE-RTS has strong transmission system compared with generation capacity and load demand. Further improvement in the transmission system does not provide much benefit in terms of the system reliability indices.

Table 4.7 evaluated the voltage collapse probability that is possible under power system deregulation and hence a means of tactically ensuring that the system adequacy is not endangered under the deregulated market is the installation of FACTS devices which adequately and evidently reduce the system probability of voltage collapse; this further supports the fact that the system reliability becomes improved under deregulation with the installation of FACTS devices. In figure 4.8, this submission was further proven with the introduction of loading effect to the system in such a way that the transmission line’s ability to be influenced was examined and it was shown that the weak buses, which later became the area of concentration, got drastic improvement in their respective system service reliability up to a particular stage with the assistance of the FACTS devices after which the improvement is not so remarkable.

A curious observation of the tables (i.e. Tables 4.4 to 4.8) evidently portrays the kind of information required by the system operators in line with the power system reliability improvement of the composite system, considering the influence of the SVC. In a nutshell, it was quite obvious that the reliability of IEEE-30 bus system was neither assisted nor degraded by the installation of any of the FACTS devices. But this cannot be said of the Nigeria-26 bus system, especially with reference to the SVC. There are a number of observations that can be drawn from this study.

CHAPTER FIVE

5.0 CONCLUSION

From this research work, a number of discoveries were made from which the following concluding remark is drawn.

5.1 SUMMARY OF FINDINGS

The following information has been obtained from this research work:

- The reduction of voltage collapse using the Static Var Compensator (SVC) as a compensating element and improvement in transmission capacity.

- The reliability assessment of the reinforced transmission network shows that the installation of FACTS devices ensures improved system availability.

- Development of hybrid electricity market model for developing economy which has the tendency to ameliorate the influence of voltage collapse encourages supply of rural loads at the least cost. In other words, the Transmission Company, during a period of very massive electricity trading and transactions that may threaten the healthy operation of the power system, is expected to engage the OPF technique for the benefit of managing the system against any form of collapse.

5.2 CONCLUSION

This work is a report of the influence of the flexible AC Transmission systems (FACTS) on the improvement of the operating capacity of a transmission line in order to overcome the menace of voltage collapse in a deregulated electricity market. The assessment of the system reliability with the installation of this device is predicted. A hybrid electricity market model is developed with an established optimization methodology using an improved Strength Pareto Evolutionary Algorithm (SPEA-2) methodology.

This approach proffers a preventive solution ahead of voltage collapse using flexible alternating current transmission system (FACTS) devices as means of improving the transmission line capacity for power flow. This is very essential in a deregulated environment where the system is subject to market principles that could lead to network congestion. It is an important development, especially for the developing economy where it is possible to achieve additional MW flow using the existing transmission line due to dearth of fund for the construction of new right-of-way.

The system reliability assessment is performed by introducing the fault tree analysis (FTA) for the evaluation of the system failure rate expected from the electricity market activities. In comparing the power system transmission network with and without the FACTS devices, the system availability is predicted to be higher for the system that is reinforced with the FACTS devices. This suggests that the FACTS device assists the transmission system to improve the power flow and ensure an improvement in the up-time of the transmission system for the provision of electricity service.

This scenario has been able to give a definite statement on the ability of the FACTS devices to assist the network in attaining secured system in which voltage collapse could be ameliorated. This is obviously more cost effective than construction of new right-of-way. The optimal reactive support for the composite system has been the main solution approach to voltage collapse in this work, other meaning such as spinning reserve and introduction of distributed generation are suggested for further research as a means of ameliorating voltage collapse in a deregulated electricity market.

CHAPTER SIX

6.0 CONTRIBUTIONS TO KNOWLEDGE

This research work has presented new approach for power system optimization analysis in a deregulated power system industry considering the influence of the FACTS devices on the transmission flow capacity of a line and its reinforcement against voltage collapse through analysis. The major contributions of the work are as follows:

(i) Implementation of fault tree method in the analysis of optimal power system reliability assessment as an extension of the alternating current (AC) optimal power flow solution to voltage collapse. This attempts to promote the composite power system reliability and availability in a deregulated electricity market.

(ii) Identification of the weak buses in the power transmission network through the use of heuristic method. This is further extended to the investigation of the economic impact of the menace of voltage collapse at these critical buses; in order to do this; a mathematical equation was developed to account for the cost of electric power outages (using the basic knowledge of economic dispatch). This provides an ample opportunity to assess the cost of outages and the rate of interruption of service using the solutions of the optimization approach.

(iii) A hybrid electricity market model is designed for the developing economy, such as Nigeria, in which case a very acceptable outlook is another high point of this research. This is expected to take a good advantage of the market effectively and efficiently.

6.1 WORK YET TO BE DONE

It is hereby suggested that the risk assessment studies of the system should be considered in future work as well as the evaluation of the life expectancy of these FACTS devices in comparison with the installation of new right-of-way, in order to ascertain outrightly the statement that it is more cost effective and could be further supported.

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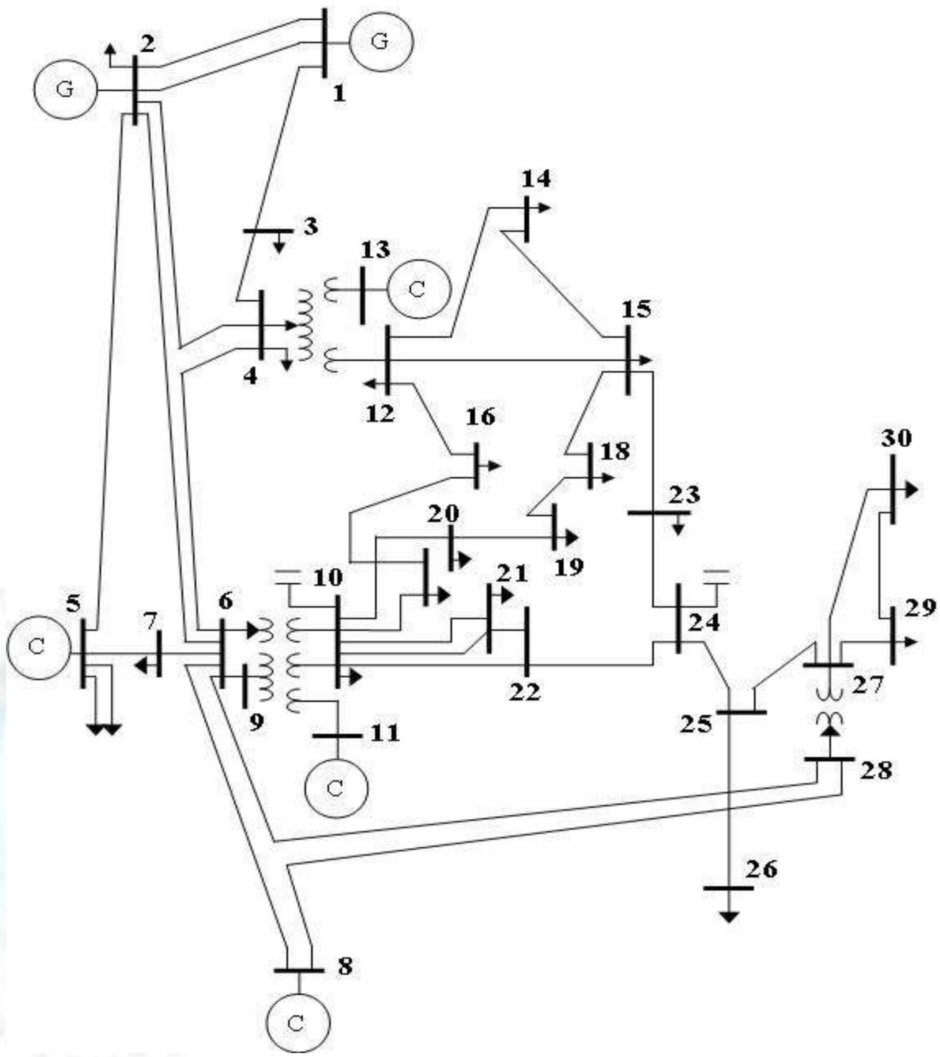
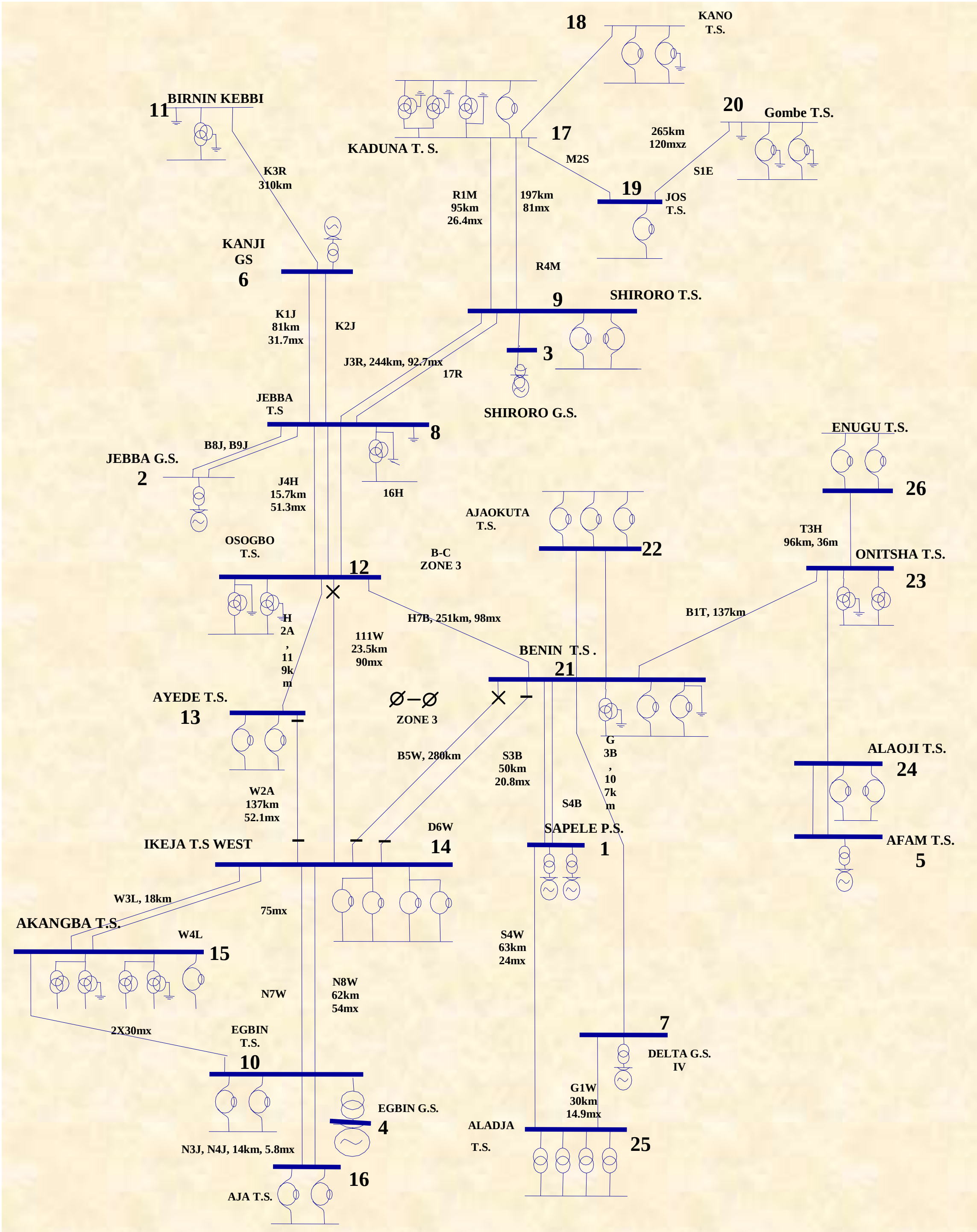
APPENDIX



Appendix 1: Single line diagram of IEEE 30 bus system



Appendix 2: Nigeria 26-Bus System for the 330kV Network

Appendix 3: MATLAB coding for calculating the optimal power flow in deregulated market

Coding for calculating the power flow convergence

```
function [converge PL Pg Pgg Pd Qg Qgg Qd Qsht deltad Vm V] ...
        =eSaadat(busdata,linedata,cost,mwlimits,varargin) %#ok<INUSL,STOUT>
% eSaadat(busdata,linedata,cost,mwlimits)
% eSaadat(busdata,linedata,cost,mwlimits,acc)
% eSaadat(busdata,linedata,cost,mwlimits,acc,basemva)
% eSaadat(busdata,linedata,cost,mwlimits,acc,basemva,mit)
%
% Encapsulates Prof. Saadat's functions

    error(nargchk(4,7,nargin));
    switch size(varargin,2)
        case 0
            accuracy=0.001;
            basemva=100;
            maxiter=15;
        case 1
            accuracy=varargin{1};
            basemva=100;
            maxiter=15;
        case 2
            accuracy=varargin{1};
            basemva=varargin{2};
            maxiter=15;
        case 3
            accuracy=varargin{1};
            basemva=varargin{2};
            maxiter=varargin{3};
    end
    lfybusx
    lfnewtonx
    blossx
end
```

Coding for calculating total generation cost

```
% This program computes the total generation cost. It requires the
% real power generation schedule and the cost matrix.
% Copyright (C) 1998 by H. Saadat
% Modified for this research work on 11:27 AM 2/12/2009

%function [totalcost]=gencost(Pgg, cost)
if exist('Pgg','var')~=1
    Pgg=input('Enter the scheduled real power gen. in row matrix ');
end
if exist('cost','var')~=1
    cost = input('Enter the cost function matrix ');
end
ngg = length(cost(:,1));
Pmt = [ones(1,ngg); Pgg; Pgg.^2];
for i = 1:ngg
```

```
    costv(i) = cost(i,:)*Pmt(:,i);
end
totalcost=sum(costv);
%fprintf('\nTotal generation cost = % 10.2f $/h \n', totalcost);




%  This program prints the power flow solution in a tabulated form
%  on the screen.
%
%  Copyright (C) 1998 by H. Saadat.

%clc
disp(tech)
fprintf('                      Maximum Power Mismatch = %g \n', maxerror)
fprintf('                             No. of Iterations = %g \n\n', iter)
head =['    Bus  Voltage  Angle    ------Load------    ---Generation---
Injected'
       '    No.  Mag.     Degree     MW       Mvar       MW       Mvar
Mvar '
       '
'];
disp(head)
for n=1:nbus
     fprintf(' %5g', n), fprintf(' %7.3f', Vm(n)),
     fprintf(' %8.3f', deltad(n)), fprintf(' %9.3f', Pd(n)),
     fprintf(' %9.3f', Qd(n)),  fprintf(' %9.3f', Pg(n)),
     fprintf(' %9.3f ', Qg(n)), fprintf(' %8.3f\n', Qsh(n))
end
    fprintf('      \n'), fprintf('    Total              ')
    fprintf(' %9.3f', Pdt), fprintf(' %9.3f', Qdt),
    fprintf(' %9.3f', Pgt), fprintf(' %9.3f', Qgt), fprintf(' %9.3f\n\n',
Qsht)



%  This program obtains the Bus Admittance Matrix for power flow solution
%  Copyright (c) 1998 by H. Saadat
%  Modified for this research work on 9:20 PM 4/9/2009

i = sqrt(-1);
j = sqrt(-1);

nl = linedata(:,1);  nr = linedata(:,2);    R = linedata(:,3);
X  = linedata(:,4);  Bc = j*linedata(:,5);  a = linedata(:,6);

nbr=length(linedata(:,1));
nbus = max(max(nl), max(nr));

Z = R + j*X; y= ones(nbr,1)./Z;%branch admittance
a(a <= 0) = 1;
Ybus=zeros(nbus,nbus);  % initialize Ybus to zero
         % formation of the off diagonal elements
for n = 1:nbr
   Ybus(nl(n),nr(n))=Ybus(nl(n),nr(n))-y(n)/a(n);
   Ybus(nr(n),nl(n))=Ybus(nl(n),nr(n));
end
             % formation of the diagonal elements
for n = 1:nbr
```

```
   Ybus(nl(n),nl(n))=Ybus(nl(n),nl(n))+y(n)/(a(n)^2) + Bc(n);
   Ybus(nr(n),nr(n))=Ybus(nr(n),nr(n))+y(n) + Bc(n);
end
```

Coding for calculating the SPEA-2 parameters

```
classdef spea2c
%   Properties:
%   Population: A structure having fields -
%       data:-  <PopulationSize x Variables> double array holding the
%               decision variable values for the individuals of the
population.
%       info:-  <PopulationSize x Objectives> double array containing the
%               objective functions' values for every individual.
%       size:-  Scalar, the size of the population.
%    Fitness:-  Fitness values of the population.
%         CV:-  Constraint violation of the population.
%   Archive:    A structure having fields -
%       data:-  <PopulationSize x Variables> double array holding the
%               decision variable values for the elites.
%       info:-  <PopulationSize x Objectives> double array containing the
%               objective functions' values for the elites.
%       size:-  Scalar, the size of the elite set.
%    Fitness:-  Fitness values of the archive set.
%         CV:-  Constraint violation of the archive set
%   Limits:     A <2 x Variables> array containing the lower(first
%               row) and upper(second row) limits for the decision variables.
%   Objectives: Scalar storing the number of objective functions
%               under optimization.
%   Variables:  The number of decision variables for each
%               individual.
%   Terminated: Logical which becomes true when the maximum number
%               of generations have been exceeded.
%
        properties (Dependent = true)
        PopulationInfo;
        CombinedInfo;
        ArchiveInfo;
        CombinedSize;
        PopulationCV;
        ArchiveCV;
    end% properties Dependent = true
    properties (Dependent = true, SetAccess = 'private')
        PopulationData;
        PopulationSize;
        PopulationFitness;
        CombinedData;
        CombinedFitness;
        ArchiveData;
        ArchiveSize;
        ArchiveFitness;
        Nondominated;
        BestCompromise;
    end% properties Dependent = true, SetAccess = 'private'
    properties (SetAccess = 'private')
        Objectives;
        Variables;
        Limits;
```

```
        CurrentGeneration;
        MaximumGeneration;
        MatingPoolSize;
        MutationProbability;
        CrossoverProbability;
        TournamentSize;
        Terminated;
        NondominatedSize;
    end% properties SetAccess = private
    properties (SetAccess = 'private', GetAccess = 'private')
        Population;
        Archive;
    end% properties SetAccess = private
    properties (SetAccess='public',GetAccess='public')
    end% properties SetAccess=private,GetAccess=private
    methods
        function obj = spea2c(varargin)
        %   S2C = SPEA2C - DEFAULT CONSTRUCTOR
        %   S2C = SPEA2C (SPEA2C) - COPY CONSTRUCTOR
        %   S2C = SPEA2C (OBJCOUNT, LIMITS)
        %   S2C = SPEA2C (OBJCOUNT, LIMITS, POPSIZE)
        %   S2C = SPEA2C (OBJCOUNT, LIMITS, POPSIZE, ARCHSIZE)
        %   S2C = SPEA2C (OBJCOUNT, LIMITS, POPSIZE, ARCHSIZE, MAXGEN)
        %   S2C = SPEA2C (OBJCOUNT, LIMITS, POPSIZE, ARCHSIZE, MAXGEN,
        %                 TOURNSIZE)
        %   S2C = SPEA2C (OBJCOUNT, LIMITS, POPSIZE, ARCHSIZE, MAXGEN,
        %                 TOURNSIZE, POOLSIZE)
        %   S2C = SPEA2C (OBJCOUNT, LIMITS, POPSIZE, ARCHSIZE, MAXGEN,
        %                 TOURNSIZE, POOLSIZE)
        %   S2C = SPEA2C (OBJCOUNT, LIMITS, POPSIZE, ARCHSIZE, MAXGEN,
        %                 TOURNSIZE, POOLSIZE, PXOVER, PMUTATE)
        %
            error(nargchk(0,9,nargin));
            switch nargin
                case 0
                    objCount=2;
                    limits=[0.95 0 180; 1.05 15 250];
                    popSize =200;
                    archSize=50;
                    maxGen  =250;
                    tournSize=2;
                    poolSize=100;
                    pXover  =0.8;
                    pMutate =0.2;
                case 1
                    s2c_obj=varargin{1};
                    if isa(s2c_obj,'spea2c')
                        obj=s2c_obj;
                    else
                        error('spea2c.m: invalid argument type');
                    end
                    return;
                case 2
                    objCount=varargin{1};
                    limits  =varargin{2};
                    popSize = 200;
                    archSize= 100;
                    maxGen  = 250;
                    tournSize=2;
                    poolSize=100;
```

```
        pXover  =0.8;
        pMutate =0.2;
    case 3
        objCount=varargin{1};
        limits  =varargin{2};
        popSize =varargin{3};
        archSize= 50;
        maxGen  = 250;
        tournSize=2;
        poolSize=round(popSize/2);
        pXover  =0.8;
        pMutate =0.2;
    case 4
        objCount=varargin{1};
        limits  =varargin{2};
        popSize =varargin{3};
        archSize=varargin{4};
        maxGen  = 250;
        tournSize=2;
        poolSize=round(popSize/2);
        pXover  =0.8;
        pMutate =0.2;
    case 5
        objCount=varargin{1};
        limits  =varargin{2};
        popSize =varargin{3};
        archSize=varargin{4};
        maxGen  =varargin{5};
        tournSize=2;
        poolSize=round(popSize/2);
        pXover  =0.8;
        pMutate =0.2;
    case 6
        objCount=varargin{1};
        limits  =varargin{2};
        popSize =varargin{3};
        archSize=varargin{4};
        maxGen  =varargin{5};
        tournSize=varargin{6};
        poolSize=round(popSize/2);
        pXover  =0.8;
        pMutate =0.2;
    case 7
        objCount=varargin{1};
        limits  =varargin{2};
        popSize =varargin{3};
        archSize=varargin{4};
        maxGen  =varargin{5};
        tournSize=varargin{6};
        poolSize=varargin{7};
        pXover  =0.8;
        pMutate =0.2;
    case 8
        objCount=varargin{1};
        limits  =varargin{2};
        popSize =varargin{3};
        archSize=varargin{4};
        maxGen  =varargin{5};
        tournSize=varargin{6};
        poolSize=varargin{7};
```

```
                pXover  =varargin{8};
                pMutate =0.2;
            case 9
                objCount=varargin{1};
                limits  =varargin{2};
                popSize =varargin{3};
                archSize=varargin{4};
                maxGen  =varargin{5};
                tournSize=varargin{6};
                poolSize=varargin{7};
                pXover  =varargin{8};
                pMutate =varargin{9};
        end
        obj.Limits=limits;
        obj.Variables=size(limits,2);
        obj.Objectives=objCount;
        obj.CurrentGeneration=1;
        obj.MaximumGeneration=maxGen;
        obj.TournamentSize=tournSize;
        obj.MatingPoolSize=poolSize;
        obj.CrossoverProbability=pXover;
        obj.MutationProbability=pMutate;
        obj.Terminated=false;

        obj.Population.Size = popSize;
        obj.Population.Data = rand(popSize,obj.Variables) .* ...
        (ones(popSize,1) * (obj.Limits(2,:) - obj.Limits(1,:)));
        obj.Population.Info = Inf * ones(popSize,obj.Objectives);
        obj.Population.Fitness = Inf * ones(popSize,1);
        obj.Population.CV = ones(popSize,1);

        obj.Archive.Size = archSize;
        obj.Archive.Data = Inf * ones(archSize,obj.Variables);%preallocate
array
        obj.Archive.Info = Inf * ones(archSize,obj.Objectives);%initialize
array
        obj.Archive.Fitness = Inf * ones(archSize,1);
        obj.Archive.CV = ones(archSize,1);

        obj.NondominatedSize = archSize;

    end % spea2c

    function c = get.PopulationInfo(obj)
        c = obj.Population.Info;
    end % get.PopulationInfo
    function c = get.PopulationData(obj)
        c = obj.Population.Data + (ones(obj.Population.Size,1) *
obj.Limits(1,:));
    end % get.PopulationData
    function c = get.PopulationSize(obj)
        c = obj.Population.Size;
    end % get.PopulationSize
    function c = get.PopulationFitness(obj)
        c = obj.Population.Fitness;
    end % get.PopulationFitness
    function c = get.PopulationCV(obj)
        c = obj.Population.CV;
    end % get.PopulationCV
```

```
        function c = get.ArchiveInfo(obj)
            c = obj.Archive.Info;
        end % get.ArchiveInfo
        function c = get.ArchiveData(obj)
            c = obj.Archive.Data + (ones(obj.Archive.Size,1) *
obj.Limits(1,:));
        end % get.ArchiveData
        function c = get.ArchiveSize(obj)
            c = obj.Archive.Size;
        end % get.ArchiveSize
        function c = get.ArchiveFitness(obj)
            c = obj.Archive.Fitness;
        end % get.ArchiveFitness
        function c = get.ArchiveCV(obj)
            c = obj.Archive.CV;
        end % get.ArchiveCV

        function c = get.CombinedInfo(obj)
            c = [obj.Archive.Info; obj.Population.Info];
        end % get.CombinedInfo
        function c = get.CombinedData(obj)
            c = [obj.Archive.Data;
obj.Population.Data]+(ones(obj.Archive.Size+...
                obj.Population.Size,1) * obj.Limits(1,:));
        end % get.CombinedData
        function c = get.CombinedSize(obj)
            c = obj.Archive.Size + obj.Population.Size;
        end % get.CombinedSize
        function c = get.CombinedFitness(obj)
            c = [obj.Archive.Fitness; obj.Population.Fitness];
        end % get.CombinedFitness

        function c = get.Nondominated(obj)
            c.Data = obj.Archive.Data(1:obj.NondominatedSize,:);
            c.Info = obj.Archive.Info(1:obj.NondominatedSize,:);
            c.Size = obj.NondominatedSize;
            c.Data = c.Data + (ones(c.Size,1)* obj.Limits(1,:));
            c.Fitness=obj.Archive.Fitness(1:obj.NondominatedSize,1);
            c.CV = obj.Archive.CV(1:obj.NondominatedSize,1);
        end % get.Nondominated
        function s2p = get.BestCompromise(obj)
            %Calculate the best compromise solution using fuzzy set theory
            nds=obj.Nondominated;
            if(nds.Size==0)% No dominating solution
                s2p.Data=obj.ArchiveData(1,:);
                s2p.Info=obj.ArchiveInfo(1,:);
                s2p.Size=1;
                s2p.Fitness=0;
                s2p.CV=obj.Archive.CV(1,1);
                return;
            end
            fmin = min(nds.Info,[],1);
            fmax = max(nds.Info,[],1);
            memFunc=zeros(size(nds.Info));%             Membership function
            normFunc=zeros(1,nds.Size);   %  Normalized membership function
            nNds=size(nds.Info,1);
            nObj=1:size(nds.Info,2);
            for iota = 1:nNds
```

```
            for jota = nObj
                if nds.Info(iota,jota) <= fmin(jota)
                    memFunc(iota,jota) = 1;
                elseif nds.Info(iota,jota) >= fmax(jota)
                    memFunc(iota,jota) = 0;
                else
                    memFunc(iota,jota)=(fmax(jota)-nds.Info(iota,jota))...
                        /(fmax(jota)-fmin(jota));
                end
            end
        end
        for iota=1:nNds
           normFunc(iota) = sum(memFunc(iota,:)) / sum(sum(memFunc));
        end
        [maxVal index] = max(normFunc,[],2);
        s2p.Data = nds.Data(index,:);
        s2p.Info = nds.Info(index,:);
        s2p.Size = 1;
        s2p.Fitness=nds.Fitness(index,1);
        s2p.CV = nds.CV(index,1);
    end%get.BestCompromise

    function obj = set.ArchiveInfo(obj,val)
        if ((size(val,1) == obj.Archive.Size) && (size(val,2) ==...
                obj.Objectives))
            obj.Archive.Info = val;
        else
            error('set.ArchiveInfo: Dimension mismatch for property');
        end
    end % set.ArchiveInfo
    function obj = set.ArchiveCV(obj,val)
        if ((size(val,1) == obj.Archive.Size) && (size(val,2) == 1))
            obj.Archive.CV = val;
        else
            error('set.ArchiveCV: Dimension mismatch for property');
        end
    end % set.ArchiveCV
    function obj = set.PopulationInfo(obj,val)
        if ((size(val,1) == obj.Population.Size) && (size(val,2) ==...
                obj.Objectives))
            obj.Population.Info = val;
        else
            error('set.PopulationInfo: Dimension mismatch for property');
        end
    end % set.PopulationInfo
    function obj = set.PopulationCV(obj,val)
        if ((size(val,1) == obj.Population.Size) && (size(val,2) == 1))
            obj.Population.CV = val;
        else
            error('set.PopulationCV: Dimension mismatch for property');
        end
    end % set.PopulationCV
    function obj = set.CombinedInfo(obj,val)
        if (size(val,1) == (obj.Archive.Size + obj.Population.Size)) &&
...
                    (size(val,2) == (obj.Objectives))
            obj.Archive.Info = val(1:obj.Archive.Size,:);
            obj.Population.Info = val(1+obj.Archive.Size:end,:);
        else
            error('set.CombinedInfo: Dimension mismatch for property');
```

```
            end
        end % set.CombinedInfo
        function disp(s2c)
            %   Objective Count
            fprintf('\t       Objectives: [%g Objectives]\n', s2c.Objectives);
            %   Variable Count
            fprintf('\t        Variables: [%g Decision
Variables]\n',s2c.Variables);
            %   LowerBound
            fprintf('\t       LowerBound: [%g', s2c.Limits(1,1));
            for iota=2:s2c.Variables
                fprintf(', %g', s2c.Limits(1,iota));
            end
            fprintf(']\n');
            %   UpperBound
            fprintf('\t       UpperBound: [%g', s2c.Limits(2,1));
            for iota=2:s2c.Variables
                fprintf(', %g', s2c.Limits(2,iota));
            end
            fprintf(']\n');
            %   CurrentGeneration
            fprintf('\tCurrentGeneration: [%g]\n', s2c.CurrentGeneration);
            %   MaximumGeneration
            fprintf('\tMaximumGeneration: [%g]\n', s2c.MaximumGeneration);
            %   ArchiveSize
            fprintf('\t      ArchiveSize: [%d]\n', s2c.Archive.Size);
            %   PopulationSize
            fprintf('\t   PopulationSize: [%d]\n', s2c.Population.Size);
            %   Terminated
            if s2c.Population.Terminated
                fprintf('\t       Terminated: [True]\n');
            else
                fprintf('\t       Terminated: [False]\n');
            end
        end% disp
        function cellR = Params(s2c)
            cellR=cell(3,1);
            %   MaximumGeneration
            cellR{1,1}=sprintf('\t      Generations: [%g]\n',
s2c.MaximumGeneration);
            %   ArchiveSize
            cellR{2,1}=sprintf('\t     Archive Size: [%d]\n',
s2c.Archive.Size);
            %   PopulationSize
            cellR{3,1}=sprintf('\t  Population Size: [%d]\n',
s2c.Population.Size);
        end% Params

        function s2c = Advance(s2c)
            %%  Begin mating selection [n-ary tournament selection with
replacement]
            matingPool.Data=Inf*ones(s2c.MatingPoolSize,s2c.Variables);
            matingPool.Info=Inf*ones(s2c.MatingPoolSize,s2c.Objectives);
            matingPool.Size=s2c.MatingPoolSize;
            matingPool.Fitness=inf*ones(s2c.MatingPoolSize,1);
            matingPool.CV=ones(s2c.MatingPoolSize,1);
            for iota=1:s2c.MatingPoolSize
                %   randomly select tournSize individuals from archive set...
                selected = spea2cseq(1,s2c.Archive.Size,s2c.TournamentSize);
                competitors.Data = s2c.Archive.Data(selected,:);
```

```
                competitors.Info = s2c.Archive.Info(selected,:);
                competitors.Size = s2c.TournamentSize;
                competitors.Fitness=s2c.Archive.Fitness(selected,1);
                competitors.CV=s2c.Archive.CV(selected,1);
                %   ...find the individual with least fitness and its index...
                [minFit winnerIdx]=min(competitors.Fitness);
                %   ...then use the index to get the winner of the
                %   tournament
                winner.Data=competitors.Data(winnerIdx,:);
                winner.Info=competitors.Info(winnerIdx,:);
                winner.Size=1;
                winner.Fitness=minFit;
                winner.CV=competitors.CV(winnerIdx,1);
                %   store the winner in the mating pool
                matingPool.Data(iota,:)=winner.Data + s2c.Limits(1,:);
                matingPool.Info(iota,:)=winner.Info;
                matingPool.Fitness(iota,1)=winner.Fitness;
                matingPool.CV(iota,1)=winner.CV;
            end
            newPop.Data=Inf*ones(s2c.Population.Size,s2c.Variables);
            newPop.Info=Inf*ones(s2c.Population.Size,s2c.Objectives);
            newPop.Size=s2c.Population.Size;
            newPop.Fitness=Inf*ones(s2c.Population.Size,1);
            newPop.CV=ones(s2c.Population.Size,1);
            %%  Applying blend crossover operator [- alpha]
            for iota=2:2:s2c.Population.Size
                % Randomly select 2 numbers between 1 and MatingPoolSize
                selectedM=spea2cseq(1,s2c.MatingPoolSize,2);
                [newPop.Data(iota-1,:) newPop.Data(iota,:)]= spea2cxva...
                    (matingPool.Data(selectedM(1,1),:),matingPool.Data...
                    (selectedM(1,2),:),s2c.CrossoverProbability);
            end
            if iota < s2c.Population.Size   %   i.e. s2c.PopSize is an odd
number
                newPop.Data(iota+1,:)=matingPool.Data(1,:);
            end
            %%  Non-uniform mutation
            newPop.Data = spea2cnum(newPop.Data, s2c.Limits, ...
                s2c.CurrentGeneration, ...
                s2c.MaximumGeneration, s2c.MutationProbability);
            %%  Update generation
            s2c.Population=newPop;
            s2c.Population.Data=s2c.Population.Data-
(ones(s2c.Population.Size,1)...
                    *s2c.Limits(1,:));

            if s2c.CurrentGeneration < s2c.MaximumGeneration
                %%  Update generation counter
                s2c.CurrentGeneration = s2c.CurrentGeneration + 1;
            else
                s2c.Terminated = true;
            end
        end% Advance
        function s2c = Update(s2c,popInfo,CV)
            s2c.PopulationInfo = popInfo;
            s2c.PopulationCV = CV;
            %%  Begin environmental selection
            if s2c.CurrentGeneration==1%   Population alone
                ttLength = s2c.Population.Size;
                multiset.Data = s2c.Population.Data + ...
```

```
                (ones(s2c.Population.Size,1)*s2c.Limits(1,:));
            multiset.Info = [s2c.Population.Info];
            multiset.Size = [s2c.Population.Size];
            multiset.Fitness = [s2c.Population.Fitness];
            multiset.CV = [s2c.Population.CV];
        else%   Vertically conbine population & archive set
            ttLength = s2c.Archive.Size + s2c.Population.Size;
            multiset.Data = [s2c.Archive.Data + ...
                                (ones(s2c.Archive.Size,1)*s2c.Limits(1,:));
...
                                 s2c.Population.Data + ...

(ones(s2c.Population.Size,1)*s2c.Limits(1,:))];
            multiset.Info = [s2c.Archive.Info; s2c.Population.Info];
            multiset.Size = [s2c.Archive.Size + s2c.Population.Size];
%#ok<NBRAK>
            multiset.Fitness = [s2c.Archive.Fitness;
s2c.Population.Fitness];
            multiset.CV = [s2c.Archive.CV; s2c.Population.CV];
        end
        Dist = zeros(ttLength); %#ok<NASGU>
        %strength as in (S)trength (P)areto (E)volutionary (A)lgorithm
        strength = zeros(1,ttLength);
        rFitness = zeros(1,ttLength);%raw fitness
        %%  Calculate strength
        % idxFeasible:  (multiset.Size x 1) logical: true if individual
        %               at index is feasible, false otherwise.
        % mIx:          objective values of the individual at index
        %               iota duplicated to fill a (multiset.Size x
        %               Objectives) double array.
        % dIx:          (multiset.Size x 1) logical: true if individual
        %               at index is dominated by the individual whose
        %               objective values are currently in mIx.
        % nIx:          (multiset.Size x 1) logical: true if individual
        %               at index dominates the individual whose
        %               objective values are currently in mIx.
        idxFeasible = multiset.CV == 0;
        for iota=1:ttLength
            if multiset.CV(iota,1) == 0 %If individual is feasible:
                %Dominates all infeasible individuals by default
                strength(1,iota) = sum(~idxFeasible);
                %Fill array with individual's info
                mIx = ones(multiset.Size,1) * multiset.Info(iota,:);
                %Test duplicated individual's info against
                %everyone at once for pareto-dominance to avoid using a
                %slow (MATLAB in-efficient compared to C++) for loop.
                dIx = all(mIx<=multiset.Info,2) & any(mIx<
multiset.Info,2);
                %Only add feasible dominated individuals as infeasible
                %ones are automatically dominated.
                strength(1,iota)= strength(1,iota) + sum(idxFeasible &
dIx);
            else
                %If an individual is infeasible, he can only dominate
                %another infeasible individual and with a higher level
                %of constraint violation (CV).
                strength(1,iota) = sum(multiset.CV > multiset.CV(iota,1));
            end
        end
        %   Calculate raw fitness
```

```
for iota=1:ttLength
    if multiset.CV(iota,1) > 0 %If individual is infeasible:
        %Dominated by all feasible individuals by default and
        %by infeasible individuals with lower costraint
        %violation (CV) but is indifferent to infeasible
        %solutions with the same level of CV.
        nIx = ~(multiset.CV >= multiset.CV(iota,1));
        rFitness(1,iota)=sum(strength(nIx));
    else
        %If an individual is feasible, he can only be dominated
        %by other feasible individuals using normal pareto-
        %dominance. Infeasible solutions need not apply.

        %Get the strengths of all feasible solutions
        fS = strength(idxFeasible);
        fInfo = multiset.Info(idxFeasible,:);
        mIx = ones(sum(idxFeasible),1) * multiset.Info(iota,:);
        nIx = all(fInfo<=mIx,2) & any(fInfo< mIx,2);
        rFitness(1,iota) = sum(fS(nIx));
    end
end%
multiset.Fitness=(rFitness)';
%%  Get nondominated set
nondomindex=multiset.Fitness<1;   %index of nondominated solutions
nondominatd.Data = multiset.Data(nondomindex,:);
nondominatd.Info = multiset.Info(nondomindex,:);
nondominatd.Size = sum(nondomindex);
nondominatd.Fitness = multiset.Fitness(nondomindex);
nondominatd.CV = multiset.CV(nondomindex);
%   if new archive set is lesser than fixed archive size, add best
%   dominated soltions to pad it up...
if nondominatd.Size<(s2c.Archive.Size)
    s2c.NondominatedSize = nondominatd.Size;
    domindex=~nondomindex;
    dominatd.Data = multiset.Data(domindex,:);
    dominatd.Info = multiset.Info(domindex,:);
    dominatd.Size = sum(domindex);
    dominatd.Fitness=multiset.Fitness(domindex);
    dominatd.CV=multiset.CV(domindex);
    %   sort dominated set in ascending order by fitness value
    for iota=1:dominatd.Size
        [dummy curBest]=min(dominatd.Fitness(iota:end));
        curBest=curBest+iota-1;
        if curBest ~= iota      %   swapping
            temp.Data = dominatd.Data(iota,:);
            temp.Info = dominatd.Info(iota,:);
            temp.Fitness=dominatd.Fitness(iota);
            temp.CV=dominatd.CV(iota);

            dominatd.Data(iota,:) = dominatd.Data(curBest,:);
            dominatd.Info(iota,:) = dominatd.Info(curBest,:);
            dominatd.Fitness(iota)= dominatd.Fitness(curBest);
            dominatd.CV(iota)= dominatd.CV(curBest);

            dominatd.Data(curBest,:) = temp.Data;
            dominatd.Info(curBest,:) = temp.Info;
            dominatd.Fitness(curBest)= temp.Fitness;
            dominatd.CV(curBest)= temp.CV;
        end                     %   end swap
```

```
                end
                needed=s2c.Archive.Size - nondominatd.Size;%   amount needed
                %   complete archive with the best needed solutions to the
                %   archive
                nondominatd.Data = [nondominatd.Data;
dominatd.Data(1:needed,:)];
                nondominatd.Info = [nondominatd.Info;
dominatd.Info(1:needed,:)];
                nondominatd.Size = nondominatd.Size + needed;
                nondominatd.Fitness = [nondominatd.Fitness;
dominatd.Fitness(1:needed,1)];
                nondominatd.CV = [nondominatd.CV; dominatd.CV(1:needed,1)];
            %   or if the new archive is greater than the fixed archive size,
            %   iteratively remove crowded solutions from the set to maintain
the
            %   diversity of the pareto optimal front (retain extreme
solutions)
            elseif nondominatd.Size > s2c.Archive.Size
                s2c.NondominatedSize = s2c.Archive.Size;
                Dist=zeros(nondominatd.Size);
                xl=min(nondominatd.Info);
                xu=max(nondominatd.Info);
                % calculate normalized euclidean distances
                for iota=1:nondominatd.Size
                    Dist(iota,:)=sum(sqrt(abs(((...
                        (ones(nondominatd.Size,1)*nondominatd.Info(iota,:)) -
...
                         nondominatd.Info)./(ones(nondominatd.Size,1) * ...
                        (xu-xl))).^2)),2)';
                end
                while nondominatd.Size > s2c.Archive.Size
                    k = round(sqrt(nondominatd.Size));
                    SortedDist=sort(Dist,2);  %sort the columns of Dist
                    kNearest=SortedDist(:,k);     %select kth nearest
neighbours
                    [minKnearest idxKnearest]=min(kNearest);
                    %Remove crowded solution from nondominated set
                    nondominatd.Data(idxKnearest,:) = [];
                    nondominatd.Info(idxKnearest,:) = [];
                    nondominatd.Size = nondominatd.Size - 1;
                    nondominatd.Fitness(idxKnearest,:) = [];
                    nondominatd.CV(idxKnearest,:) = [];
                    %Remove crowded solution distance information to avoid
                    %recalculating the distances in each repitition
                    Dist(:,idxKnearest) = [];
                    Dist(idxKnearest,:) = [];
                end
            else%   nondominated set is exactly equal to the archive size.
                s2c.NondominatedSize = s2c.Archive.Size;
            end
            %%  Update archive set in spea2c and check for size mismatches
            if s2c.Archive.Size==nondominatd.Size && size(nondominatd.Data,1)
== ...
                        s2c.Archive.Size ...
                    && size(nondominatd.Info,1) == s2c.Archive.Size
                s2c.Archive=nondominatd;
                s2c.Archive.Data=s2c.Archive.Data - (ones(s2c.Archive.Size,1)*
...
                        s2c.Limits(1,:));
            else
```

```
            error('spea2c.Update: Archive set size mismatch')
        end
        %%  Update population fitness
        if s2c.CurrentGeneration==1
            s2c.Population.Fitness=multiset.Fitness;
        else
            s2c.Population.Fitness=...
                multiset.Fitness(s2c.Archive.Size+1:s2c.Archive.Size+ ...
                    s2c.Population.Size,1);
        end
    end%Update
    function s2c = DataUpdate(s2c,Individual,DataIndex,Value)
        if Individual > (s2c.Archive.Size + s2c.Population.Size)
            error('spea2c.DataUpdate: Subscript out of range');
        else
            if DataIndex > s2c.Variables
                error('spea2c.DataUpdate: Index out of range');
            else
                Value=Value-s2c.Limits(1,DataIndex);
                if Individual > s2c.Archive.Size%Individual is in pop.
                    PopIndex = Individual-s2c.Archive.Size;
                    s2c.Population.Data(PopIndex,DataIndex)=Value;
                else%Individual is in archive
                    ArchIndex = Individual;
                    s2c.Archive.Data(ArchIndex,DataIndex)=Value;
                end
            end
        end
    end%DataUpdate
    function s2p = BestBias(s2c,objective_no)
        %Retrieves the best biased solution for a particular objective
        if(objective_no<1 || objective_no>s2c.Objectives)
            error('spea2c>BestBias: Invalid objective number');
        end
        nds=s2c.Nondominated;
        if(nds.Size==0)% No dominating solution
            s2p.Data=s2c.ArchiveData(1,:);
            s2p.Info=s2c.ArchiveInfo(1,:);
            s2p.Size=1;
            s2p.Fitness=0;
            s2p.CV=s2c.Archive.CV(1,1);
            return;
        end
        [minVal index] = min(nds.Info(:,objective_no));
        s2p.Data = nds.Data(index,:);
        s2p.Info = nds.Info(index,:);
        s2p.Size = 1;
        s2p.Fitness=nds.Fitness(index,1);
        s2p.CV = nds.CV(index,1);
    end%BestBias
    function s2p = WorstBias(s2c,objective_no)
        %Retrieves the best biased solution for a particular objective
        if(objective_no<1 || objective_no>s2c.Objectives)
            error('spea2c>BestBias: Invalid objective number');
        end
        nds=s2c.Nondominated;
        if(nds.Size==0)% No dominating solution
            s2p.Data=s2c.ArchiveData(1,:);
            s2p.Info=s2c.ArchiveInfo(1,:);
            s2p.Size=1;
```

```
                s2p.Fitness=0;
                s2p.CV=s2c.Archive.CV(1,1);
                return;
            end
            [maxVal index] = max(nds.Info(:,objective_no));
            s2p.Data = nds.Data(index,:);
            s2p.Info = nds.Info(index,:);
            s2p.Size = 1;
            s2p.Fitness=nds.Fitness(index,1);
            s2p.CV = nds.CV(index,1);
        end%WorstBias
    end% methods
end% classdef
```

```
function C = spea2cdom(A, B)
%   C = speaDominates(A, B)
%   Returns 1 (true) if A dominates B, and 0 (false) otherwise.
%
    if nargout == 0 || nargout == 1
      if nargin == 2
          if size(A) == size(B)
              c1=all(A<=B);
              c2=any(A< B);
              C =c1 && c2;
          else
              error('SPEA2Controller\speaDominates.m: Invalid input argument
dimensions!!');
          end
      else
          error('SPEA2Controller\speaDominates.m: Invalid number of input
arguments!!');
      end
    else
      error('SPEA2Controller\speaDominates.m: Invalid number of output
arguments!!');
    end
end
```

```
function z = speaDeltaB(t,gmax,y)
    %   z = speaDelta(t,gmax,y)
    %   t:      the number of the current generation
    %   gmax:   the maximum number of generations
    %   r:      random binary matrix
    %   beta:   positive constant chosen arbitarily. In this case, 5.
    %

    beta=5;
    n=size(y);
    r=rand(n(1),n(2));
    t_gmax=t/gmax;
    t_gmax=1-t_gmax;
    t_gmax=t_gmax.^beta;

    z=y.*(1-r.^t_gmax);
end
```

```
function A=spea2cnum(A, limits, t, gmax, pMu)
%SPEA2CNUM Performs nonuniform mutation on a single spea2pop object given
%the current gener
%   A = spea2cnum(A, limits, t, gmax, pMu)
%   A:       spea2pop object to mutate
%   t:       current generation
%   gmax:    total number of generations
%   pMu;     probability of mutation of an individual gene.
%

error(nargchk(5,5,nargin));

n=size(A);

idx=speaRandint(n(1),n(2),pMu);
idx=logical(idx);

expander = ones(n(1),1);
limitsEx = expander * limits(1,:);

yValsAdd = (expander * limits(2,:)) - A;
yValsSub = A - limitsEx;

mValsAdd = A + speaDeltaB(t,gmax,yValsAdd);
mValsSub = A - speaDeltaB(t,gmax,yValsSub);

tauA = floor(rand(n(1),n(2)) * 2);
tauA = logical(tauA);
tauB = ~tauA;

B = A;

B(tauA) = mValsAdd(tauA) - limitsEx(tauA);
B(tauB) = mValsSub(tauB) - limitsEx(tauB);

A(idx) = B(idx);    % Only mutate values selected by the given mutation
probability (pMu)




function spea2copf(datafile)
% spea2copf('datafile')
% where datafile is the name of the m-file containing the network data to
% be analysed
    tic
    format short g;
    clc
    %  Extract the data from the data file
    [busdata linedata gencost mwlimits basemva accuracy maxiter] = ...
        spea2cex(datafile);

    %  Create the data structures to transfer the information from the GA
    %  to the network and power flow functions
```

```
[SlkB GenB LoadB ShtB TapS sbc gbc lbc shbc tsc busc linec] = ...
    spea2ccds(busdata,linedata);

%  Limits
vmlimit = [0.95 1.05];
vmlimits = vmlimit'*ones(1,gbc-1);  %Voltage magnitude limits
rxlimits = busdata(GenB(:,4),[9 10]); %rxtv power generation limits
tslimit = [0.90 1.10];
tslimits = ones(tsc,1) * tslimit;   %Tap-setting limits

%   Optimization options; at least any two options must be true
%   options(1): optimize real power loss
%   options(2): optimize costs
%   options(3): optimize voltage profile
options=[true true true];

%   Cost optimization options; at least one option must be true
%   coptions(1): optimize real power cost
%   coptions(2): optimize rxtv power cost
%   coptions(3): optimize capacitor costs
coptions=[true true true];

% Error checking of optimization options
if(sum(options)<2),error('Selected options must be two or more'),end;
if(sum(coptions)<1),error('Selected coptions must be one or more'),end;

%%  SPEA2 Parameters  %%

%   No. of objectives
nObj = sum(options);

%   Formulate SPEA2 limits:
%   (slack bus real power generation is determined by the power flow
%   algorithm and its voltage magnitude is fixed as the reference
%   voltage)
galimits=[mwlimits(2:end,:)' vmlimits];

if tsc>0
    galimits = [galimits tslimits'];

end

%   Population size
popSize = 250; % TODO: CHANGED
%   Archive size
archSize = 20; % TODO: CHANGED
%   Maximum generation
maxGen = 200; % TODO: CHANGED
%   Tournament size
tournSize = round(popSize/10)+2; % TODO: CHANGED
%   Pool size
poolSize = round(popSize/2)+2; % TODO: CHANGED
%   Crossover probability
pCO = 0.8;
%   Mutation probability
pM = 0.5; % TODO: CHANGED
%   Create spea2c object to optimize data
spea2cobj = spea2c(nObj, galimits, popSize, archSize, maxGen, ...
```

```
                    tournSize, poolSize, pCO, pM);

   %    Variables to hold information for each solution in a generation
   powerLoss = zeros(popSize,1);%
   totalCost = zeros(popSize,1);%
   realPowerCost = zeros(popSize,1);%
   rxtvPowerCost = zeros(popSize,1);%
   capacitorCost = zeros(popSize,1);%
   voltageProfile = zeros(popSize,1);%
   busVoltages = zeros(popSize,busc);%
   busVoltageMag = zeros(popSize,busc);%
   busVoltageAng = zeros(popSize,busc);%
   constraintViolation = zeros(popSize,1);%

   realPowerGen = zeros(popSize,gbc);%
   rxtvPowerGen = zeros(popSize,gbc);%
   capacitorComp = zeros(popSize,1);%

   %    Variables to hold information about the best solution for each
   %    generation
   powerLossBS = zeros(maxGen,1);
   totalCostBS = zeros(maxGen,1);
%    realPowerCostBS = zeros(maxGen,1);
%    rxtvPowerCostBS = zeros(maxGen,1);
%    capacitorCostBS = zeros(maxGen,1);
   voltageProfileBS = zeros(maxGen,1);

   %    Variables to hold information about the best compromise solution
   %    for each generation
   powerLossBCS = zeros(maxGen,1);
   totalCostBCS = zeros(maxGen,1);
   voltageProfileBCS = zeros(maxGen,1);

   %    Variables to hold information about the worst solution for each
   %    generation
   powerLossWS = zeros(maxGen,1);
   totalCostWS = zeros(maxGen,1);
%    realPowerCostWS = zeros(maxGen,1);
%    rxtvPowerCostWS = zeros(maxGen,1);
%    capacitorCostWS = zeros(maxGen,1);
   voltageProfileWS = zeros(maxGen,1);

   %    Loop through the generations
   while ~spea2cobj.Terminated
       %%    Get decision variables from the SPEA2 Object and use it to
       %%    calculate the objective function values
       %
       data = spea2cobj.PopulationData;
       rpg = data(:,1:gbc-1);   %Real power generated
       vm = data(:,gbc:2*gbc-2);%Voltage magnitude
       if tsc>0
           offset = 2*gbc-2;
           ts = data(:,offset+1:offset+tsc);
       end

       %    Iterate through the data and calculate the objective functions
       %    for the individual soluions
       for iota=1:popSize
```

```
    %  Duplicate the busdata and linedata
    bdata = busdata;
    ldata = linedata;

    %    Fill bus and/or line data with values from the SPEA2 Object
    %    of the current individual
    bdata(GenB(2:end,4),7) = rpg(iota,:);
    bdata(GenB(2:end,4),3) = vm(iota,:);
    if tsc>0
        ldata(TapS(:,4),6) = ts(iota,:);
    end

    %    Run power flow
    [converge PL Pg Pgg Pd Qg Qgg Qd Qsht deltad Vm V] = ...
        eSaadat(bdata,ldata,gencost,mwlimits,accuracy,basemva,maxiter);

    % Store power loss
    powerLoss(iota,1) = PL;

    % Penalize non-convergent solutions
    if ~converge
        constraintViolation(iota,1) = 50;
    end

    % Store real power generated
    realPowerGen(iota,:) = Pgg;
    % Store rxtv power generated
    rxtvPowerGen(iota,:) = Qgg;
    % Store capacitor compensation
    capacitorComp(iota,1) = Qsht;
    % Store bus voltages
    busVoltages(iota,:) = V;
    % Store bus voltage magnitudes
    busVoltageMag(iota,:) = Vm;
    % Store bus voltage angles (degrees)
    busVoltageAng(iota,:) = deltad;

end
cg = spea2cobj.CurrentGeneration;

% Calculate and store costs
if options(2)
    % Calculate and store real power cost
    if coptions(1)
        realPowerCost = RPC(gencost,realPowerGen);
        totalCost = totalCost + realPowerCost;

    end
    % Calculate and store rxtv power cost
    if coptions(2)
        rxtvPowerCost = RxPC(gencost,realPowerGen,rxtvPowerGen,0.2);
        totalCost = totalCost + rxtvPowerCost;

    end
    % Calculate and store capacitor compensation
    if coptions(3)
        capacitorCost = CapC(capacitorComp,basemva);
```

```
        totalCost = totalCost + capacitorCost;

    end

end

% Calculate and store voltage profile
if options(3)
    voltageProfile = Deviation(busVoltageMag, 1.0);

end

% Checking for constraint violations
% Bus voltage magnitude violation
constraintViolation=constraintViolation+CVx(busVoltageMag,vmlimit);

% Collect objective values
if all(options)
    info = [powerLoss totalCost voltageProfile];

elseif options(1) && options(2)
    info = [powerLoss totalCost];

elseif options(3) && options(2)
    info = [totalCost voltageProfile];

else
    info = [powerLoss voltageProfile];

end

% Update the SPEA2 Object with the objective functions' values
spea2cobj = spea2cobj.Update(info,constraintViolation);

% Get the best compromise solution
BCS = spea2cobj.BestCompromise;

if all(options)
    powerLossBCS(cg,1) = BCS.Info(1,1);
    totalCostBCS(cg,1) = BCS.Info(1,2);
    voltageProfileBCS(cg,1) = BCS.Info(1,3);

    % Get the best bias solution [power loss]
    BBSpl = spea2cobj.BestBias(1);
    % Get the best bias solution [total cost]
    BBStc = spea2cobj.BestBias(2);
    % Get the best bias solution [voltage profile]
    BBSvp = spea2cobj.BestBias(3);
    % Get the worst bias solution [power loss]
    WBSpl = spea2cobj.WorstBias(1);
    % Get the worst bias solution [total cost]
    WBStc = spea2cobj.WorstBias(2);
    % Get the worst bias solution [voltage profile]
    WBSvp = spea2cobj.WorstBias(3);

    powerLossBS(cg,1) = BBSpl.Info(1,1);
    powerLossWS(cg,1) = WBSpl.Info(1,1);
```

```
        totalCostBS(cg,1) = BBStc.Info(1,2);
        totalCostWS(cg,1) = WBStc.Info(1,2);

        voltageProfileBS(cg,1) = BBSvp.Info(1,3);
        voltageProfileWS(cg,1) = WBSvp.Info(1,3);

    elseif options(1) && options(2)
        powerLossBCS(cg,1) = BCS.Info(1,1);
        totalCostBCS(cg,1) = BCS.Info(1,2);

        % Get the best bias solution [power loss]
        BBSpl = spea2cobj.BestBias(1);
        % Get the best bias solution [total cost]
        BBStc = spea2cobj.BestBias(2);
        % Get the worst bias solution [power loss]
        WBSpl = spea2cobj.WorstBias(1);
        % Get the worst bias solution [total cost]
        WBStc = spea2cobj.WorstBias(2);

        powerLossBS(cg,1) = BBSpl.Info(1,1);
        powerLossWS(cg,1) = WBSpl.Info(1,1);

        totalCostBS(cg,1) = BBStc.Info(1,2);
        totalCostWS(cg,1) = WBStc.Info(1,2);

    elseif options(3) && options(2)
        totalCostBCS(cg,1) = BCS.Info(1,1);
        voltageProfileBCS(cg,1) = BCS.Info(1,2);

        % Get the best bias solution [total cost]
        BBStc = spea2cobj.BestBias(1);
        % Get the best bias solution [voltage profile]
        BBSvp = spea2cobj.BestBias(2);
        % Get the worst bias solution [total cost]
        WBStc = spea2cobj.WorstBias(1);
        % Get the worst bias solution [voltage profile]
        WBSvp = spea2cobj.WorstBias(2);

        totalCostBS(cg,1) = BBStc.Info(1,1);
        totalCostWS(cg,1) = WBStc.Info(1,1);

        voltageProfileBS(cg,1) = BBSvp.Info(1,2);
        voltageProfileWS(cg,1) = WBSvp.Info(1,2);

    else
        powerLossBCS(cg,1) = BCS.Info(1,1);
        voltageProfileBCS(cg,1) = BCS.Info(1,2);

        % Get the best bias solution [power loss]
        BBSpl = spea2cobj.BestBias(1);
        % Get the best bias solution [voltage profile]
        BBSvp = spea2cobj.BestBias(2);
        % Get the worst bias solution [power loss]
        WBSpl = spea2cobj.WorstBias(1);
        % Get the worst bias solution [voltage profile]
        WBSvp = spea2cobj.WorstBias(2);
```

```
        powerLossBS(cg,1) = BBSpl.Info(1,1);
        powerLossWS(cg,1) = WBSpl.Info(1,1);

        voltageProfileBS(cg,1) = BBSvp.Info(1,2);
        voltageProfileWS(cg,1) = WBSvp.Info(1,2);

    end

    % Advance the SPEA2 Object to the next generation
    spea2cobj = spea2cobj.Advance;

end

% Get the best compromise solution
BCS = spea2cobj.BestCompromise;
% Get the best bias solution [power loss]
BBSpl = spea2cobj.BestBias(1);
% Get the best bias solution [total cost]
BBStc = spea2cobj.BestBias(2);
% Get the best bias solution [voltage profile]
BBSvp = spea2cobj.BestBias(3);
% Get the non-dominated solutions
NDS = spea2cobj.Nondominated;
% Get GA parameters
p = spea2cobj.Params;


% Files and directories
outDir = 'D:\oluseyi\docsx\PowerProject\Deployment test\Results\FinalRun\';

dataFile = [outDir datafile '.optimized.m'];
infoFile = [outDir datafile '.analysed.m'];
bcsFile = [outDir datafile '.BCS.m'];
convXFile = [outDir datafile '.convX.m'];

convXFileH = fopen(convXFile,'wt');
dataFileH = fopen(dataFile, 'wt');
infoFileH = fopen(infoFile, 'wt');

% Output the convergence xteristics, data and optimization info
fprintf(convXFileH,'%35s\n\n','Convergence Characteristics');

if options(1)
    fprintf(convXFileH,'\t[%25s]\n','Power Loss');
    fprintf(convXFileH,'%15s\t%15s\t%15s\n','Best','Compromise','Worst');
    fprintf(convXFileH,'%15.4f\t%15.4f\t%15.4f\n',...
        [powerLossBS powerLossBCS powerLossWS]');
    fprintf(convXFileH,'\n\n');

end

if options(2)
    fprintf(convXFileH,'\t[%25s]\n','Total Operating Cost');
    fprintf(convXFileH,'%15s\t%15s\t%15s\n','Best','Compromise','Worst');
    fprintf(convXFileH,'%15.2f\t%15.2f\t%15.2f\n', ...
        [totalCostBS totalCostBCS totalCostWS]');
```

```
        fprintf(convXFileH,'\n\n');

    end

    if options(3)
        fprintf(convXFileH,'\t[%25s]\n','Voltage Profile');
        fprintf(convXFileH,'%15s\t%15s\t%15s\n','Best','Compromise','Worst');
        fprintf(convXFileH,'%15.8f\t%15.8f\t%15.8f\n', ...
            [voltageProfileBS voltageProfileBCS voltageProfileWS]');
        fprintf(convXFileH,'\n\n');

    end

    % TODO: Make the output generic to correctly handle any config
    % Not optioned: for current run only
    fprintf(convXFileH,'%35s\n\n','Pareto Optimal Solutions');
    fprintf(convXFileH,'%50s\t%20s\t%20s\n','Power Loss','Total Operating
Cost',...
        'Voltage Profile');
    fprintf(convXFileH,'%30s%20.4f\t%20.2f\t%20.8f\n','best bias [power loss]',
...
        BBSpl.Info(1,1),BBSpl.Info(1,2),BBSpl.Info(1,3));
    fprintf(convXFileH,'%30s%20.4f\t%20.2f\t%20.8f\n','best bias [total cost]',
...
        BBStc.Info(1,1),BBStc.Info(1,2),BBStc.Info(1,3));
    fprintf(convXFileH,'%30s%20.4f\t%20.2f\t%20.8f\n','best bias [v. profile]',
...
        BBSvp.Info(1,1),BBSvp.Info(1,2),BBSvp.Info(1,3));
    fprintf(convXFileH,'%30s%20.4f\t%20.2f\t%20.8f\n','best compromise soln.',
...
        BCS.Info(1,1),BCS.Info(1,2),BCS.Info(1,3));
    fprintf(convXFileH,'\n\n');

    fprintf(convXFileH,'%35s\n\n','Non-dominated Solutions');
    fprintf(convXFileH,'%20s\t%20s\t%20s\n','Power Loss','Total Operating
Cost',...
        'Voltage Profile');
    fprintf(convXFileH,'%20.4f\t%20.2f\t%20.8f\n', ...
        NDS.Info');
    fprintf(convXFileH,'\n\n');

    fprintf(convXFileH,'%35s\n\n','Normalised Non-dominated Solutions');
    fprintf(convXFileH,'%20s\t%20s\t%20s\n','Power Loss','Total Operating
Cost',...
        'Voltage Profile');
    fprintf(convXFileH,'%20.4f\t%20.4f\t%20.4f\n', ...
        NormCols(NDS.Info)');
    fprintf(convXFileH,'\n\n');

    %fclose(convXFileH);

    % Output: Optimal Control Variables

    % Transfer CVs from GA to data matrices
    dataBCS = BCS.Data;
    rpgBCS = dataBCS(1,1:gbc-1);    %Real power generated
    vmBCS = dataBCS(1,gbc:2*gbc-2);%Voltage magnitude
    GenB(2:end,2)=rpgBCS;
```

```
    GenB(2:end,3)=vmBCS;
    if tsc>0
        offset = 2*gbc-2;
        tsBCS = dataBCS(:,offset+1:offset+tsc);
        TapS(:,3)=tsBCS;
    end

    %  Duplicate the busdata and linedata
    bdata = busdata;
    ldata = linedata;

    bdata(GenB(2:end,4),7) = rpgBCS(1,:);
    bdata(GenB(2:end,4),3) = vmBCS(1,:);
    if tsc>0
        ldata(TapS(:,4),6) = tsBCS(1,:);
    end

    % Run power flow
    [converge PL Pg Pgg Pd Qg Qgg Qd Qsht deltad Vm V] = ...
                eSaadat(bdata,ldata,gencost,mwlimits,accuracy,basemva,maxiter);

    bdata(SlkB(1,4),7) = Pgg(1,1);
    bdata(GenB(:,4),8) = Qgg;
    bdata(:,3)=Vm;
    bdata(:,4)=deltad;

    PrettySaveD(dataFileH,accuracy,basemva,maxiter,bdata,ldata, ...
                      gencost,mwlimits);


    PrettySaveR(infoFileH,busc,linec,gbc,shbc,tsc,vmlimit,tslimit,...
                      GenB,TapS,ShtB,p);

    fprintf('%10.4f\t%10.2f\t%10.4f\n',[powerLossBCS totalCostBCS ...
        voltageProfileBCS]');

    t=toc;
    fprintf('Optimization completed in %.2f secs\n',t);
    fprintf(convXFileH,'Optimization completed in %.2f secs\n',t);


    fprintf('Non-dominated Constraint Violation:\n\n');
    fprintf('\t%5d\n',NDS.CV);

    fprintf(convXFileH,'Non-dominated Constraint Violation:\n\n');
    fprintf(convXFileH,'\t%5d\n',NDS.CV);

    fclose(convXFileH);
    fclose(dataFileH);
    fclose(infoFileH);

end
```

Appendix 4: Data for Nigeria-26 Bus system

```
basemva = 100;  accuracy = 0.0001;  maxiter = 30;

 %-----------------------------------------------------------------------

 %       Bus  Bus    |V|  Ang   ---Load---     ---Gen---   Gen Mvar
Injected
%        No.  code p.u.  Deg   MW     Mvar     MW   Mvar   Min    Max    Mvar
busdata=[1    1    1.05   0    0.0    0.0     0.0   0.0    0.0    0      0
         2    2    1.0    0    0.0    0.0     6.0   0.0   -2.0   5.0     0
         3    2    1.0    0    0.0    0.0     3.5   0.0   -1.5   3.5     0
         4    2    1.0    0    0.0    0.0     5.5   0.0   -2.0   4.5     0
         5    2    1.0    0    0.0    0.0     3.0   0.0   -1.5   2.0     0
         6    2    1.0    0    0.0    0.0     4.5   0.0   -3.0   2.5     0
         7    2    1.0    0    0.0    0.0     4.5   0.0   -2.0   4.0     0
         8    0    1.0    0    0.79   0.0593  0.0   0.0    0     0       0
         9    0    1.0    0    1.096  0.822   0.0   0.0    0     0       0
         10   0    1.0    0    0.8    0.600   0.0   0.0    0     0       0
         11   0    1.0    0    0.564  0.423   0.0   0.0    0     0       0
         12   0    1.0    0    1.449  1.0868  0.0   0.0    0     0       0
         13   0    1.0    0    1.33   0.975   0.0   0.0    0     0       0
         14   0    1.0    0    3.32   2.49    0.0   0.0    0     0       0
         15   0    1.0    0    2.28   1.710   0.0   0.0    0     0       0
         16   0    1.0    0    0.95   0.712   0.0   0.0    0     0       0
         17   0    1.0    0    3.90   0.000   0.0   0.0    0     0       0
         18   0    1.0    0    1.30   0.000   0.0   0.0    0     0       0
         19   0    1.0    0    .650   0.4875  0.0   0.0    0     0       0
         20   0    1.0    0    1.328  0.996   0.0   0.0    0     0       0
         21   0    1.0    0    1.242  0.933   0.0   0.0    0     0       0
         22   0    1.0    0    0.200  0.150   0.0   0.0    0     0       0
         23   0    1.0    0    0.86   0.645   0.0   0.0    0     0       0
         24   0    1.0    0    2.648  1.980   0.0   0.0    0     0       0
         25   0    1.0    0    0.200  0.150   0.0   0.0    0     0       0
         26   0    1.0    0    0.000  0.675   0.0   0.0    0     0       0];

%         Bus    Bus     R           X           B/2     Length
%         No.    No.    p.u.        p.u.        p.u.
linedata=[1      7      0.00262     0.01998     0.2666    57
          1      21     0.00099     0.00739     0.3928    50
          1      25     0.00248     0.01861     0.2474    63
          2      8      0.00019     0.00147     0.0196    5
          3      9      0.00019     0.00147     0.0196    5
          4      10     0.00056     0.00443     0.9632    31
          5      24     0.00098     0.00738     0.0982    25
          6      8      0.00153     0.01197     0.6356    81
          6      11     0.01218     0.09162     1.2178    310
          7      25     0.00102     0.00769     0.1022    30
          8      9      0.00479     0.03606     1.9060    244
          8      12     0.00210     0.01528     1.8348    157
          9      17     0.00189     0.01419     0.7544    95
          10     14     0.00060     0.00488     0.2296    62
          10     15     0.00303     0.02276     0.3026    77
          10     16     0.00030     0.00221     0.1180    15
          12     13     0.00424     0.03232     0.4312    115
          12     14     0.00884     0.06752     0.9712    235
          12     21     0.00970     0.07380     0.9838    231
          13     14     0.00460     0.03520     0.5400    137
          14     15     0.00033     0.00251     0.1332    18
```

```
         14    21    0.00550     0.04140     2.2000    280
         17    18    0.00926     0.07052     0.9410    230
         17    19    0.00889     0.06089     0.8092    197
         19    20    0.00884     0.06752     1.1784    265
         21    22    0.00970     0.07380     1.5320    195
         21    23    0.00460     0.03520     0.5380    137
         23    24    0.00033     0.00251     0.5410    138
         23    26    0.00550     0.04140     0.3614    96];

%            C    B     A
  gencost = [240  7.0   0.007
             200  10    0.0095
             220  8.5   0.009
             200  11    0.009
             220  10.5  0.0080
             190  12    0.0075
             200  10    0.0095];

mwlimits = [1.0000    5.0000
            0.5000    6.0000
            0.5000    3.5000
            0.5000    5.5000
            0.5000    3.0000
            0.5000    4.5000
            0.5000    4.5000];


accuracy = 0.001;
basemva = 100;
maxiter = 12;

%        Bus Bus  Voltage   Angle         ---Load-----       --Generator------
------------     Injected
%        No  code Mag.      Degree         MW       Mvar         MW       Mvar
Qmin    Qmax    Mvar
busdata=[...
         1   1    1.0600    0.0000       0.00       0.00    301.71      -5.04
0.00    0.00    0.00
         2   2    1.0341   -6.5106      21.70      12.70      0.77      55.15  -
30.00   50.00    0.00
         3   0    1.0138   -8.5708       2.40       1.20      0.00       0.00
0.00    0.00    0.00
         4   0    1.0038  -10.3602       7.60       1.60      0.00       0.00
0.00    0.00    0.00
         5   2    0.9993  -15.4558      94.20      19.00      0.44      39.24  -
30.00   40.00    0.00
         6   0    0.9938  -12.1646       0.00       0.00      0.00       0.00
0.00    0.00    0.00
         7   0    0.9881  -14.0572      22.80      10.90      0.00       0.00
0.00    0.00    0.00
         8   2    0.9958  -12.9874      30.00      30.00      0.10      43.95  -
30.00   40.00    0.00
         9   0    1.0094  -15.3994       0.00       0.00      0.00       0.00
0.00    0.00    0.00
        10   0    1.0015  -17.2111       5.80       2.00      0.00       0.00
0.00    0.00   19.00
        11   2    0.9803  -15.3828       0.00       0.00      0.14     -13.70  -
20.00   20.00    0.00
```

```
        12   0    0.9916  -16.3006     11.20      7.50      0.00      0.00
0.00    0.00    0.00
        13   2    1.0159  -16.2411      0.00      0.00      0.75     17.68  -
20.00   15.00    0.00
        14   0    0.9793  -17.2833      6.20      1.60      0.00      0.00
0.00    0.00    0.00
        15   0    0.9781  -17.4412      8.20      2.50      0.00      0.00
0.00    0.00    0.00
        16   0    0.9881  -17.0104      3.50      1.80      0.00      0.00
0.00    0.00    0.00
        17   0    0.9919  -17.3851      9.00      5.80      0.00      0.00
0.00    0.00    0.00
        18   0    0.9735  -18.1342      3.20      0.90      0.00      0.00
0.00    0.00    0.00
        19   0    0.9741  -18.3307      9.50      3.40      0.00      0.00
0.00    0.00    0.00
        20   0    0.9801  -18.1155      2.20      0.70      0.00      0.00
0.00    0.00    0.00
        21   0    0.9894  -17.6907     17.50     11.20      0.00      0.00
0.00    0.00    0.00
        22   0    0.9902  -17.6747      0.00      0.00      0.00      0.00
0.00    0.00    0.00
        23   0    0.9759  -17.8870      3.20      1.60      0.00      0.00
0.00    0.00    0.00
        24   0    0.9817  -18.0898      8.70      6.70      0.00      0.00
0.00    0.00    4.30
        25   0    0.9991  -17.7348      0.00      0.00      0.00      0.00
0.00    0.00    0.00
        26   0    0.9811  -18.1702      3.50      2.30      0.00      0.00
0.00    0.00    0.00
        27   0    1.0186  -17.2288      0.00      0.00      0.00      0.00
0.00    0.00    0.00
        28   0    0.9903  -12.8852      0.00      0.00      0.00      0.00
0.00    0.00    0.00
        29   0    0.9987  -18.4701      2.40      0.90      0.00      0.00
0.00    0.00    0.00
        30   0    0.9872  -19.3614     10.60      1.90      0.00      0.00
0.00    0.00    0.00
];

%       Bus bus        R         X      1/2 B    = 1 for lines
%        nl  nr       p.u.      p.u.     p.u.    > 1 or < 1 tr. tap at bus nl
linedata=[...
          1   2    0.0192    0.0575   0.02640    1.0000
          1   3    0.0452    0.1852   0.02040    1.0000
          2   4    0.0570    0.1737   0.01840    1.0000
          3   4    0.0132    0.0379   0.00420    1.0000
          2   5    0.0472    0.1983   0.02090    1.0000
          2   6    0.0581    0.1763   0.01870    1.0000
          4   6    0.0119    0.0414   0.00450    1.0000
          5   7    0.0460    0.1160   0.01020    1.0000
          6   7    0.0267    0.0820   0.00850    1.0000
          6   8    0.0120    0.0420   0.00450    1.0000
          6   9    0.0000    0.2080   0.00000    0.9411
          6  10    0.0000    0.5560   0.00000    0.9674
          9  11    0.0000    0.2080   0.00000    1.0000
          9  10    0.0000    0.1100   0.00000    1.0000
          4  12    0.0000    0.2560   0.00000    1.0258
         12  13    0.0000    0.1400   0.00000    1.0000
         12  14    0.1231    0.2559   0.00000    1.0000
```

```
        12  15    0.0662    0.1304   0.00000    1.0000
        12  16    0.0945    0.1987   0.00000    1.0000
        14  15    0.2210    0.1997   0.00000    1.0000
        16  17    0.0824    0.1923   0.00000    1.0000
        15  18    0.1073    0.2185   0.00000    1.0000
        18  19    0.0639    0.1292   0.00000    1.0000
        19  20    0.0340    0.0680   0.00000    1.0000
        10  20    0.0936    0.2090   0.00000    1.0000
        10  17    0.0324    0.0845   0.00000    1.0000
        10  21    0.0348    0.0749   0.00000    1.0000
        10  22    0.0727    0.1499   0.00000    1.0000
        21  22    0.0116    0.0236   0.00000    1.0000
        15  23    0.1000    0.2020   0.00000    1.0000
        22  24    0.1150    0.1790   0.00000    1.0000
        23  24    0.1320    0.2700   0.00000    1.0000
        24  25    0.1885    0.3292   0.00000    1.0000
        25  26    0.2544    0.3800   0.00000    1.0000
        25  27    0.1093    0.2087   0.00000    1.0000
        28  27    0.0000    0.3960   0.00000    0.9370
        27  29    0.2198    0.4153   0.00000    1.0000
        27  30    0.3202    0.6027   0.00000    1.0000
        29  30    0.2399    0.4533   0.00000    1.0000
         8  28    0.0636    0.2000   0.02140    1.0000
         6  28    0.0169    0.0599   0.06500    1.0000
];

gencost=[...
         0.0     20.00  0.038432
         0.0     20.00  0.250000
         0.0     40.00  0.010000
         0.0     40.00  0.010000
         0.0     40.00  0.010000
         0.0     40.00  0.010000
];

mwlimits=[...
          0.00      360
          0.00      140
          0.00      100
          0.00      100
          0.00      100
          0.00      100
];
```

```
basemva = 100;  accuracy = 0.0001;  maxiter = 30;
%       Nigeria 26-BUS SYSTEM (Power Holding Company of Nigeria [PHCN])
%       Bus Bus   |V|  Ang    --Load----    ---Gen---   Gen Mvar Shunt
%       No. code p.u.  Deg     MW    Mvar     MW   Mvar   Min Max   Mvar
busdata=[1   1   1.05   0     0.0    0.00    0.0    0.0      0    0    0
         2   2   1.0    0     0.0    0.00   90.0    0.0   -200  200    0
         3   2   1.0    0     0.0    0.00  150.0    0.0   -120  264    0
         4   2   1.0    0     0.0    0.00  220.0    0.0   -260  412    0
         5   2   1.0    0     0.0    0.00   72.0    0.0   -141  159    0
         6   2   1.0    0     0.0    0.00  230.0    0.0   -300  200    0
         7   2   1.0    0     0.0    0.00   70.0    0.0   -249  342    0
         8   0   1.0    0    79.0    5.93    0.0    0.0      0    0    0
         9   0   1.0    0   109.6   82.20    0.0    0.0      0    0    0
         10  0   1.0    0    80.0   60.00    0.0    0.0      0    0    0
         11  0   1.0    0    56.4   42.30    0.0    0.0      0    0    0
         12  0   1.0    0   144.9  108.68    0.0    0.0      0    0    0
         13  0   1.0    0   133.0   97.50    0.0    0.0      0    0    0
         14  0   1.0    0   332.0  249.00    0.0    0.0      0    0    0
         15  0   1.0    0   228.0  171.00    0.0    0.0      0    0    0
         16  0   1.0    0   095.0  071.20    0.0    0.0      0    0    0
         17  0   1.0    0   390.0    0.00    0.0    0.0      0    0    0
         18  0   1.0    0   130.0    0.00    0.0    0.0      0    0    0
         19  0   1.0    0    65.0   48.75    0.0    0.0      0    0    0
         20  0   1.0    0   132.8   99.60    0.0    0.0      0    0    0
         21  0   1.0    0   124.2   93.30    0.0    0.0      0    0    0
         22  0   1.0    0    20.0   15.00    0.0    0.0      0    0    0
         23  0   1.0    0    86.0   64.50    0.0    0.0      0    0    0
         24  0   1.0    0   264.8  198.00    0.0    0.0      0    0    0
         25  0   1.0    0    20.0   15.00    0.0    0.0      0    0    0
         26  0   1.0    0     0.0   67.50    0.0    0.0      0    0    0];

%         Bus    Bus     R           X           B/2    Length
%         No.    No.    p.u.        p.u.        p.u.
linedata=[1      7     0.00262     0.01998     0.2666    1
          1      21    0.00099     0.00739     0.3928    1
          1      25    0.00248     0.01861     0.2474    1
          2      8     0.00019     0.00147     0.0196    1
          3      9     0.00019     0.00147     0.0196    1
          4      10    0.00056     0.00443     0.9632    1
          5      24    0.00098     0.00738     0.0982    1
          6      8     0.00153     0.01197     0.6356    1
          6      11    0.01218     0.09162     1.2178    1
          7      25    0.00102     0.00769     0.1022    1
          8      9     0.00479     0.03606     1.9060    1
          8      12    0.00210     0.01528     1.8348    1
          9      17    0.00189     0.01419     0.7544    1
          10     14    0.00060     0.00488     0.2296    1
          10     15    0.00303     0.02276     0.3026    1
          10     16    0.00030     0.00221     0.1180    1
          12     13    0.00424     0.03232     0.4312    1
          12     14    0.00884     0.06752     0.9712    1
          12     21    0.00970     0.07380     0.9838    1
          13     14    0.00460     0.03520     0.5400    1
          14     15    0.00033     0.00251     0.1332    1
          14     21    0.00550     0.04140     2.2000    1
          17     18    0.00926     0.07052     0.9410    1
          17     19    0.00889     0.06089     0.8092    1
          19     20    0.00884     0.06752     1.1784    1
```

```
        21    22    0.00970     0.07380     1.5320    1
        21    23    0.00460     0.03520     0.5380    1
        23    24    0.00033     0.00251     0.5410    1
        23    26    0.00550     0.04140     0.3614    1];

%            C    B     A
  gencost = [240  7.0   0.007
             200  10    0.0095
             220  8.5   0.009
             200  11    0.009
             220  10.5  0.0080
             190  12    0.0075
             200  10    0.0095];
%           lower upper
 mwlimits = [100  500
             50   200
             80   300
             50   280
             50   120
             80   300
             50   200];
```