IMPROVING THE VOLTAGE STABILITY OF ELECTRICAL POWER SYSTEMS USING SHUNT FACTS DEVICES

By

Ahmed Mostafa Mohammed Mohammed

A thesis submitted to the Faculty of Engineering at Cairo University In Partial Fulfillment of the Requirements for the Degree of MASTER OF SCIENCE In Electrical Power and Machines Engineering
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Under supervision of

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FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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LIST OF SYMBOLS AND ABBREVIATIONS

• Symbols

\( x \) : State vector of the system.

\( V \) : Bus voltage vector.

\( I \) : Current injection vector.

\( Y_N \) : Network admittance matrix.

\( J_{PF} \) : The Jacobian of the power flow equations.

\( y \) : The vector of power flow variables.

\( \frac{\partial f_{PF}}{\partial P} \) : The partial derivative of the power flow equations with respect to the changing parameter \( P \).

\( k \) : Constant

\( I_{SVC} \) : The total current of the SVC.

\( V_{REF} \) : The reference voltage.

\( X_{SL} \) : Small slope of the V-I characteristics of SVC of typical values of 2 to 5%, with respect to the SVC base.

\( V_d \) and \( V_q \) : d- and q-axis components of the generator terminal voltage.

\( I_d \) and \( I_q \) : d- and q-axis components of the generator current \( I_g \).

\( E'_d \) and \( E'_q \) : d- and q-axis components of internal voltage of the generator.

\( \theta_n \) : Angle between the terminal voltage and the reference of the generator.

\( \theta_i \) : Angle between the reference and the generator current.

\( \delta \) : Angle between the reference and q-axis of the generator.

\( R \) : Stator resistance of the generator.

\( x'_d \) and \( x'_q \) : d- and q-axis transient reactances of the generator.

\( \omega \) : Rotor speed of generator

\( T_m \) : Mechanical torque.

\( D \) : Damping coefficient.

\( \tau_j \) : Constant representing the generator inertia.
E_{FD} : Excitation voltage
E_I : q-axis component of induced voltage E.
T'_d0 and T'_{q0} : Transient time constants of open circuits in d- and q-axis.
V_{OEL} : Output voltage from the Over Excitation Limiter.
I_{FD} : Excitation current
I_{FLM2} : Continuous operation limit of the excitation current.
K_2 and K_3 : Gains
T_{OEL} : Time constant.
R_S and R_r : Stator and rotor resistances of the induction motor.
X_S and X_r : Stator and rotor leakage reactances.
X_{mag} : Magnetization reactance.
\sigma : Motor slip
V_n : Motor bus voltage
I_s and I_r : Stator and rotor currents.
P_{sh} : Motor shaft power or the mechanical power given to the motor load.
P_{gap} : Motor air-gap power or the power that is transferred through the air-gap from stator to rotor.
\omega_m : Per unit value of the motor rotor speed.
T_{m0} : Value of the load torque at the speed \omega_m0.
A, B, and C : Appropriate coefficients of quadratic, linear and constant term of the motor mechanical torque.
d and a_m : Constants to define initial value of the motor load torque.
H : Motor inertia constant
\alpha : The firing angle of the thyristor
\gamma : The conduction angle of the thyristor
X_{TCR} : The effective reactance of the TCR
B_{SVC} : The equivalent susceptance of FC-TCR
X_C : The fundamental frequency reactance of the fixed capacitor
• Abbreviations

AVR : Automatic Voltage Regulator
FACTS : Flexible Alternating Current Transmission Systems
FC : Fixed Capacitor
HVDC : High Voltage Direct Current
LTC : Load Tap Changer
OEL : Over Excitation Limiter
OPF : Optimal Power Flow
PAR : Phase Angle Regulator
PSAT : Power System Analysis Toolbox
RTS-96 : Reliability Test System – 1996 version
SMIB : Single Machine Infinite Bus
SSR : Sub-Synchronous Resonance
STATCOM : STATic COMpensator
SVC : Static VAr Compensator
TCR : Thyristor Controlled Reactor
TCSC : Thyristor Controlled Series Capacitor
TSC : Thyristor Switched Capacitor
ULTC : Under Load Tap Changer
UPFC : Unified Power Flow Controller
ABSTRACT

Voltage stability refers to “the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition”. In general, the inability of the system to supply the required demand leads to voltage instability (voltage collapse). The nature of voltage instability phenomenon can be either fast (short-term) or slow (long-term). Short-term voltage stability problems are usually associated with the rapid response of voltage controllers for example generators’ AVR (Automatic Voltage Regulator) and power electronic converters, such as those encountered in HVDC (High Voltage DC) links.

In this thesis, the voltage stability problem is approached from its dynamic (short-term) aspect with the stalling of the induction motors is the main scenario leading to the voltage collapse. A 20-bus system was chosen with some features for the phenomenon revealing such as very long lines and some single circuit transmission lines which act as throttling points for the reactive power transmission. In order to clearly reveal the voltage stability problem during the study, the load was increased using a constant power factor scheme and the generation was also increased in such a way that the reactive power sources were piled away from the load centers resulting in a bad distribution of the reactive power sources all over the network.

For different induction motor penetration levels, namely 30%, 40%, 50%, and 60% of the total load, and different fault locations and system contingencies, a FACTS device, Static VAr Compensator (SVC), was then optimally allocated and sized to prevent the voltage collapse from happening. This allocation and sizing were done by using a build up search program based on the heuristic optimization technique. Also, the built-in Genetic Algorithm toolbox in Matlab was used to verify the results obtained by the search program.
CHAPTER 1
INTRODUCTION AND REVIEW OF LITERATURE

1.1 Thesis motivation and objectives

This topic was chosen since the voltage instability problem with the dynamics of the induction motors as its main driving force is becoming an emerging problem. This is because of the excessive usage of the air conditions as in the south of California, the Gulf countries, and other hot parts of the world especially during the summer season. In some of these places, air condition (induction motor) loads may amount up to about 60% of the total system load creating a reactive power crisis leading to complete voltage collapse, if disturbances aren’t well foreseen and the remedy tools are prepared for such cases.

The objectives of the thesis are to study the effect of the different induction motor penetration levels on the short-term voltage stability of multi-machine system and how, if encountered, the voltage instability with the voltage collapse as its final dramatic end could be prevented by using shunt FACTS device, namely SVC. The SVC has been chosen because it is a well-known compensation device, and it is inexpensive since its technology isn’t new. Thus, it is used by many systems as the main source of reactive power required for the dynamic support of the system to ride-through any disturbance it is subjected to.

1.2 Overview of the voltage stability problem

The voltage stability problem with voltage collapse as its final consequence is an emerging phenomenon in planning and operation of modern power systems. The increase in utilization of existing power systems may get the system operating point closer to voltage stability boundaries making it
subject to the risk of voltage collapse. This possibility in association with several incidents throughout the world have given major impetus for analyzing the problem with increased interest in modeling of generation, transmission and distribution/load equipment of electric power systems. Fast advances in computer analysis of power systems have enabled appearance of extensive knowledge related to general power system control and stability. Many general guides [1-2] and books [3-4] cover modeling issues in depth. Some of them directly concern the voltage stability problem [5-7]. Useful definitions of terms related to stability are provided within several publications [8].

A large number of researchers and engineers have been attracted by the voltage stability problem. Their attention has resulted with a number of papers being published in journals and conference proceedings. Extensive bibliography [9] treats the most referenced ones among them. Voltage stability phenomena have been comprehensively treated from the early beginnings with the dynamic simulation of power system as one of the most important tools of its assessment [10-15]. It enables different studies of coordinated control to be carried out. Load behavior is recognized as one of the main driving forces of the voltage collapse. Bibliography [16] covers main references, which are related either to modeling techniques [17-18] or to field measurements and identification. The dynamic load represents a composite load as it is seen from a high-voltage network bus. Usually, response of this composite load is dominated by a behavior of an LTC (Load Tap Changing) transformer [19-20], an induction motor load [21-25], and thermostatically controlled load [5-6]. The other important driving force is related to a limited reactive power production of synchronous generators.

1.3 Overview of the FACTS devices

Since the rapid development of power electronics has made it possible to design power electronic equipment of high rating for high voltage systems, the voltage stability problem resulting from transmission system may be, at
least partly, improved by use of the equipment well-known as FACTS-controllers. A number of papers treat development status of this technology from the early years up to date [26-34]. The de-regulation (restructuring) of power networks will probably imply new loading conditions and new power flow situations. Analysis of a power system with embedded FACTS controllers calls for development of adequate models [35-38]. Models largely depend on the type of analysis, which is generally either component or system orientated. In the component orientated analysis, individual physical elements of a FACTS-controller are concerned. On the other side, the system orientated analysis needs answers on achievements that could be possibly gained by using a FACTS-controller.

1.4 Some voltage Stability incidents

Historically power system stability has been considered to be based on synchronous operation of the system. However, many power system blackouts all over the world have been reported where the reason for the blackout has been voltage instability. The following list includes some of them:

- **France 1978 [6]**: The load increment was 1600 MW higher than the one at previous day between 7am and 8am. Voltages on the eastern 400 kV transmission network were between 342 and 374 kV at 8.20 am. Low voltage reduced some thermal production and caused an overload relay tripping (an alarm that the line would trip with 20 minutes time delay) on major 400 kV line at 8.26am. During restoration process another collapse occurred. Load interruption was 29 GW and 100 GWh. The restoration was finished at 12.30am.

- **Belgium 1982 [6]**: A total collapse occurred in about four minutes due to the disconnection of a 700 MW unit during commissioning test.
- **Florida USA 1985 [6]**: A brush fire caused the tripping of three 500 kV lines and resulted in voltage collapse in a few seconds.

- **Western France 1987 [6]**: Voltages decayed due to the tripping of four thermal units which resulted in the tripping of nine other thermal units and defect of eight unit over-excitation protection, thus voltages stabilized at a very low level (0.5-0.8 pu). After about six minutes of voltage collapse load shedding recovered the voltage.

- **WSCC USA July 2 1996 [6]**: A short circuit on a 345 kV line started a chain of events leading to a break-up of the western North American power system. The final reason for the break-up was rapid overload/voltage collapse/angular instability.

- **Southern California USA August 5, 1997 [25]**: Southern California Edison Company was operating at a new summer peak. A small plane contacted shield wires of two 500-kV lines. Subsequently, one of the lines was reclosed into a three-phase fault, with two-cycle fault clearing. The fault caused voltage dips to 0.6 per unit at distribution buses, with stalling of residential air conditioners. Fifty-nine distribution circuits tripped, and approximately 3525 MW of load was lost. Voltages took 20–25 seconds to recover. The fast, low voltage tripping of industrial and commercial load was essential to the recovery. Tripping of distribution circuits by ground over-current relays took 2.5–3 seconds, which would be too slow to prevent complete area collapse for a slightly more severe condition such as higher residential air conditioning load (weekend load).

- **Northeastern USA August 14 2003[39]**: A plant operator pushed one generator near Cleveland too hard, exceeding its limits and resulting in automatic shutdown at 1:31 that afternoon. At 2:02, one line failed because although it was carrying less than half the power it was designed for, it sagged into a tree that had not been trimmed recently, causing a
short that took the line out of service. With both the generator and the line out of commission, other lines were overstressed and failed between 3:05 and 3:39 p.m. that led to more failures and the blackout at 4:08 p.m.

1.5 Thesis layout

Chapter one; “Introduction and review of literature” begins with the thesis objective and motivation then gives a general overview of the voltage stability problem and a literature review of the main publications considering the voltage stability problem. Also, a brief overview and literature review about the FACTS devices is given. Finally some of the major incidents that caused by voltage instabilities across the world are illustrated.

Chapter two; “Basic definitions and concepts” is divided into two main parts. In the first part, some terms concerning the voltage stability are defined and the aspects of the voltage stability are classified. After that the scenarios of classic voltage collapse incidents are presented to describe the problem. Finally, the different analysis methods of the voltage stability problem are discussed. In the second part, a brief introduction is made about the FACTS devices in general. Then, the construction and principle of operation of the SVC is described.

Chapter three; “System dynamic modeling” describes the dynamic models of the different components in the power system, contributing to the short-term voltage stability scenario. These dynamic models include the models for the synchronous generators with their control systems, AVR and OEL (Over Excitation Limiter), and the induction motors which are the driving force in this case. Finally, the dynamic model of the FACTS device, SVC, used as a remedy tool to prevent the voltage instability is presented.
Chapter four; “Proposed approach and test system” begins with the description of the proposed approach of the analysis of the short-term voltage stability and the procedures made for this analysis. Then, the test system used for the study and the procedures made to prepare this system to clearly reveal the problem are described. Finally, the different cases that encountered severe voltage decrease following a disturbance are illustrated.

Chapter five “Optimal allocation and sizing of SVC” shows the simulation results of the optimal allocation and sizing of the FACTS device, SVC, used to improve the short-term voltage stability of the modified test system for the different cases. First, the optimization programs used are being explained. Then, the optimization results for the optimal allocation and sizing of the SVC are illustrated.

Chapter six “Conclusions and future work” gives conclusions about the thesis and suggestion for future work.
2.1 Introduction

Voltage stability is a problem in power systems which are heavily loaded, faulted or have a shortage in reactive power. The nature of voltage stability can be analyzed by examining the generation, transmission and consumption of reactive power. The problem of voltage stability concerns the whole power system, although it usually has a large involvement in one critical area of the power system.

This chapter is divided into two main parts. The first part describes the voltage stability phenomenon and the second part gives a description for a remedy method which is the shunt FACTS devices. In the first part, some terms concerning the voltage stability are defined and the aspects of the voltage stability are classified. After that the scenarios of classic voltage collapse are presented to describe the problem. Then the different analysis methods of the voltage stability problem are described. Finally, the proposed method of the analysis will be stated. In the second part, a brief introduction will be made about the FACTS devices in general. Then, the construction and principle of operation of the SVC will be described.

2.2 The voltage stability phenomenon

2.2.1 Definition of voltage stability

Power system stability is defined as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [8]. Traditionally, the stability problem has been the rotor angle stability, i.e.
maintaining synchronous operation. Instability may also occur without loss of synchronism, in which case the concern is the control and stability of the voltage. Kundur P. defines the voltage stability as follows [5]:

“The voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system at normal operating conditions and after being subjected to a disturbance.”

A power system is voltage stable if voltages after a disturbance are close to voltages at normal operating condition. A power system becomes unstable when voltages uncontrollably decrease due to outage of equipment (generator, line, transformer, etc.), increment of load, decrement of generation and/or weakening of voltage control. According to [7]

“Voltage instability stems from the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system.”

Voltage control and stability are local problems. However, the consequences of voltage instability may have a widespread impact. Voltage collapse is the catastrophic result of a sequence of events leading to a low-voltage profile suddenly in a major part of the power system.

Voltage stability can also be called “load stability”. The main factor causing voltage instability is the inability of the power system to meet the demands for reactive power in the heavily stressed systems to keep desired voltages. Other factors contributing to voltage stability are the generator reactive power limits, the load characteristics, the characteristics of the reactive power compensation devices and the action of the voltage control devices. The reactive characteristics of AC transmission lines, transformers and loads restrict the maximum of power system transfers. The power system lacks the capability to transfer power over long distances or through high reactance due to the requirement of a large amount of reactive power at some critical value of power or distance. Transfer of reactive power is difficult due to extremely high
reactive power losses; that is why the reactive power required for voltage control is produced and consumed at the control area.

### 2.2.2 Difference between voltage and rotor angle stabilities [6]

Voltage stability and rotor angle stability are more or less interlinked. Short-term (transient) voltage stability is often interlinked with transient rotor angle stability, and slower forms of voltage stability are interlinked with small-disturbance rotor angle stability. Often, the mechanisms are difficult to separate. There are many cases, however, where one form of instability is predominant. Figure 2.1 shows the extreme cases. These extreme situations are:

a) A remote synchronous generator connected by transmission lines to a large system. This is a pure rotor angle stability case. (Single machine to infinite bus (SMIB) problem).

b) A large system connected by transmission lines to an asynchronous load. This is a pure voltage stability case.

![Figure 2.1: The two extreme cases of the stability problem](image)

Rotor angle stability, as well as voltage stability, is affected by reactive power control. In particular, small-disturbance “steady-state” instability involving aperiodically increasing angles was a major problem before
continuously–acting automatic voltage regulators became available. However, voltage stability is concerned with load areas and load characteristics. In a large interconnected system, voltage collapse of a load area is possible without the loss of synchronism of any generator. However, short-term voltage stability is usually associated with transient rotor angle stability. Longer-term voltage stability is less interlinked with rotor angle stability. It could be said that if the voltage collapses at a point in a transmission system remote from the load, this can be attributed to rotor angle stability. However, if the voltage collapses in a load area, it is mainly a voltage instability problem.

### 2.2.3 Classification of power system voltage stability

The voltage problem is a load-driven problem as described above. It may be divided into short-term (transient) and longer-term voltage stability according to the time scale of load component dynamics. Figure 2.2 shows the contribution of the different components of the power system in the voltage stability phenomenon [6].

![Figure 2.2: Voltage stability phenomenon and time responses](image)
Short-term voltage stability is characterized by the power systems components such as induction motors, excitation of synchronous generators, and electronically controlled devices such as HVDC and SVC [7]. The time scale of short-term voltage stability is the same as the time scale of rotor angle stability. The modeling and the analysis of these problems are similar. The distinction between rotor angle and short-term voltage instability is sometimes difficult, because most practical voltage collapses include some element of both voltage and angle instability [6].

When short-term dynamics have died out some time after the disturbance, the system enters a slower time frame. The dynamics of the long-term voltage stability last for several minutes. The analysis of long-term voltage stability requires detailed modeling of long-term dynamics. The long-term voltage stability is characterized by scenarios such as load recovery by the action of on-load tap changer or through load self-restoration, delayed corrective control actions such as shunt compensation switching or load shedding. The long-term dynamics such as response of power plant controls, boiler dynamics and automatic generation control also affect long-term voltage stability [8]. The modeling of long-term voltage stability requires consideration of transformer on-load tap changers, characteristics of static loads, manual control actions of operators, and automatic generation control.

For purposes of analysis, it is sometimes useful to classify voltage stability into small and large disturbances. Small disturbance voltage stability considers the power system’s ability to control voltages after small disturbances, e.g. changes in load [5]. The analysis of small disturbance voltage stability is done in steady state. In that case, the power system can be linearised around an operating point and the analysis is typically based on Eigen value and Eigen vector techniques. Large disturbance voltage stability analyses the response of the power system to large disturbances e.g. faults, switching or loss of load, or loss of generation [5]. Large disturbance voltage stability can be studied by using non-linear time domain simulations in the short-term time frame and load-flow analysis in the long-term time frame. The voltage stability
is, however, a single problem on which a combination of both linear and non-linear tools can be used.

2.2.4 Scenarios of power system voltage instability

2.2.4.1 Short-term voltage instability [40], [41]

The time frame of this type of voltage instability is about ten seconds. When subject to a step drop in voltage, the motor active power $P$ first decreases as the square of the voltage $V$ (constant impedance behavior), then recovers close to its pre-disturbance value in the time frame of a second. The internal variable of this process is the rotor slip. In fact, a motor with constant mechanical torque and negligible stator losses restores to constant active power. Taking into account these losses and more realistic torque behaviors, there is a small steady-state dependence of $P$ with respect to $V$. The steady state dependence of the reactive power $Q$ is a little more complex. First $Q$ decreases somewhat quadratically with $V$, reaches a minimum, and then increases up to the point where the motor stalls due to low voltage. In large three-phase industrial motors, the stalling voltage can be as low as 0.7 pu while in smaller appliances (or heavily loaded motors) it is higher. Load restoration by induction motors may play a significant role in systems having a summer peak load, with a large amount of air conditioning.

In the time frame of the short term dynamics, it may be difficult to distinguish between angle and voltage instabilities. There are however some cases of “pure” voltage instability. Consider for instance a system where the load consists of a large induction motor. A typical voltage collapse scenario may be one of the following or a combination of both.

- Following a line outage, the maximum load power that could be supplied from the generation system decreases. If it becomes smaller than the power the motor tends to restore, the latter stalls and the load voltage collapses, and the system looses its short-term equilibrium.
• A short-circuit near the motor causes the latter to decelerate. If the fault is not cleared fast enough, the motor is unable to reaccelerate and again, the load voltage collapses. In this case, the long-lasting fault makes the system escape from the region of attraction of its post disturbance equilibrium.

2.2.4.2 Middle term voltage instability [6]

The time frame of this scenario is several minutes, typically two to three minutes. This scenario involves high loads, high power imports from remote generation, and a sudden large disturbance. The system is transiently stable because of the voltage sensitivity of loads. The disturbance (loss of large generators in a load area or loss of major transmission lines) causes high reactive power losses and voltage sags in load areas. Tap changers on bulk power delivery LTC transformers and distribution voltage regulators sense the low voltages and act to restore distribution voltages, thereby restoring load power levels.

The load restoration causes further sags of transmission voltages. Nearby generators are overexcited and overloaded, but over excitation limiters return field currents to rated values as the time-overload capability expires. Generators farther away must then provide the reactive power which is inefficient and ineffective. The generation and transmission system can no longer support the loads and the reactive losses, and rapid voltage decay ensues and partial or complete voltage collapse follows. The final stages may involve induction motor stalling and protective relay operations.

2.2.4.3 Long-term voltage instability [6]

The instability evolves over a longer time period and is driven by a very large load buildup (morning or afternoon peak loads), or a large rapid power transfer increase. The load buildup, measured in megawatts/minute, may be quite rapid. Operator actions, such as timely application of reactive power
equipment or load shedding, may be necessary to prevent instability. Factors such as the time-overload limit of transmission lines (tens of minutes) and loss of load diversity due to low voltage (due to constant energy, thermostatically controlled loads) may be important. The final stages of instability involve actions of faster equipment.

2.2.5 Analysis of power system voltage stability problem

The voltage stability phenomenon is a dynamic phenomenon by its nature thus the main analysis method of this phenomenon is the time domain simulations. These simulations are very helpful in the analysis of the short-term (transient) voltage stability cases where the components dynamics is the driving force of the instability with the voltage collapse as its final result. However, in case of middle and long-term voltage instabilities, these dynamics are fast and die out long before the collapse starts. In this case, the voltage instability problem could be considered as quasi-static or static problem. This allows the investigation of the voltage stability problem by using several approaches based on the steady state analysis. These methods of analysis, if used properly, can provide much insight into the voltage stability problem. In the following section some of the methods used in the analysis of the voltage stability are illustrated.

2.2.5.1 Dynamic Analysis [5]

Since the dynamic simulation is the main tool of analysis in cases of short-term voltage instabilities, thus extensive modeling of the different components of the power system must be done in order to capture the events and their chronology leading to instability. The following are the descriptions of models of power system components that have a significant impact on voltage stability:
a. Loads

Load characteristics could be critical in voltage stability analysis. Unlike in conventional transient stability and power-flow analyses, extended subtransmission system representation in a voltage-weak area may be necessary. This should include transformer Under Load Tap Changer (ULTC) action, reactive power compensation, and voltage regulators in the subtransmission system.

b. Generators and their excitation controls

Synchronous generators are the primary devices for voltage and reactive power control in power systems. In voltage stability studies active and reactive power capability of generators is needed to consider accurately achieving the best results. The active power limits are due to the design of the turbine and the boiler. Active power limits are strict. Reactive power limits are more complicated, which have a circular shape and are voltage dependent. Normally reactive power limits are described as constant limits in the load-flow programs. The voltage dependence of generator reactive power limits is, however, an important aspect in voltage stability studies and should be taken into account in these studies. The limitation of reactive power has three different causes: stator current, over-excitation and under-excitation limits. Figure 2.3 shows a part of a typical capability curve of a synchronous generator.

c. The VAr compensation systems

The VAr compensation systems are divided into two main categories, the mechanically switched capacitor banks and the static VAr compensation systems.

- The mechanically switched capacitor banks

They are the most inexpensive means of providing reactive power and voltage support. However, they have a number of inherent limitations from the voltage stability point of view. The most important one is that the reactive
power generated is proportional to the square of the voltage; during system conditions of low voltage the VAr support drops, thus compounding the problem.

Figure 2.3: The capability curve of a typical synchronous generator
\( (X_s=0.45 \text{ pu}, I_{\text{max}}=1.05, E_{\text{max}}=1.35\text{pu}) \)

- **The Static VAr Systems (SVS)**

  When an SVS is operating within the normal voltage control range, it maintains the bus voltage with slight droop characteristics. However, when it is operating at the reactive power limits, it becomes a simple capacitor or reactor which could have a very significant effect on the voltage stability. These characteristics should be represented appropriately in voltage stability studies.

  
  \[ d. \text{ Protection and controls} \]

  These include generating units and transmission network controls and protection. Examples are the generator excitation protection, armature and
transmission lines over-current protection, phase-shifting regulators, and under-voltage load shedding.

The general structure of the system model for voltage stability, comprising a set of first-order differential equations, may be expressed in the following general form (a complete description of these equations will be given in details in the following chapter):

\[ \dot{x} = f(x, V) \]  

(2.1)

And a set of algebraic equations

\[ I(x, V) = Y_N V \]  

(2.2)

\[ g(x, V) = 0 \]  

(2.3)

With a set of known initial condition \((x_0, V_0)\), found from the algebraic equations of the different system components models (equation 2.3) is to be solved.

Where

- \(x\) : state vector of the system
- \(V\) : bus voltage vector
- \(I\) : current injection vector
- \(Y_N\) : network admittance matrix

Since there may be a line outage and due to the representation of the controls and protection systems and the transformer tap-changer controls, the elements of \(Y_N\) change as a function of time as there could be lines outages. Also, the current injection vector \(I\) is a function of the system states \(x\) and bus voltage vector \(V\), representing the boundary conditions at the terminals of the various devices. Due to the time-dependant nature of devices such as field current limiters, the relationship between \(I\) and \(x\) can be a function of time.

Equations 2.1 and 2.2 can be solved in the time-domain by using any of the well-known numerical integration methods as Forward-Euler, Trapezoidal
or Runge-Kutta methods and the power-flow analysis methods. The study period is typically in the order of several minutes. Implicit integration methods are ideally suited for such applications. Facilities to automatically change the integration time step, as the solution progresses and fast transients decay, greatly enhance the computational efficiency of such techniques.

### 2.2.5.2 Static Analysis

In these cases, the slow nature of the network and load response associated with the phenomenon makes it possible to analyze the problem in the steady-state framework (e.g., power flow) to determine if the system can reach a stable operating point following a particular contingency. This operating point could be a final state or a midpoint following a step of a discrete control action (e.g., transformer tap change). The proximity of a given system to voltage instability and the control actions that may be taken to avoid voltage collapse are typically assessed by various indices and sensitivities. The most widely used are [15]

- Loadability margins, i.e., the “distance” in MW or MVA to a point of voltage collapse, and sensitivities of these margins with respect to a variety of parameters, such as active/reactive power load variations or reactive power levels at different sources.
- Singular values of the system Jacobian or other matrices obtained from these Jacobians, and their sensitivities with respect to various system parameters.
- Bus voltage profiles and their sensitivity to variations in active and reactive power of the load and generators, or other reactive power sources.
- Availability of reactive power supplied by generators, synchronous condensers, and static VAr compensators and its sensitivity to variations in load bus active and/or reactive power.
These indices and sensitivities, as well as their associated control actions, can be determined using a variety of the computational methods described below.

a. Power Flow Analysis

Partial P-V and Q-V curves can be readily calculated using power flow programs. In this case, the demand of load center buses is increased in steps at a constant power factor while the generators’ terminal voltages are held at their nominal value, as long as their reactive power outputs are within limits; if a generator’s reactive power limit is reached, the corresponding generator bus is treated as another load bus. The P-V relation can then be plotted by recording the MW demand level against a “central” load bus voltage at the load center. It should be noted that power flow solution algorithms diverge very close to or past the maximum loading point, and do not produce the unstable portion of the P-V relation.

The Q-V relation, however, can be produced in full by assuming a fictitious synchronous condenser at a central load bus in the load center. The Q-V relation is then plotted for this particular bus as a representative of the load center by varying the voltage of the bus (now converted to a voltage control bus by the addition of the synchronous condenser) and recording its value against the reactive power injection of the synchronous condenser. If the limits on the reactive power capability of the synchronous condenser are made very high, the power flow solution algorithm will always converge at either side of the Q-V relation.

b. Continuation Methods

A popular and robust technique to obtain full P-V and/or Q-V curves is the continuation method [15]. This methodology basically consists of two power flow-based steps: the predictor and the corrector, as illustrated in Fig.2.4. In the predictor step, an estimate of the power flow solution for a load P increase (point 2 in Fig. 2.4) is determined based on the starting solution (point 1) and an estimate of the changes in the power flow variables (e.g., bus
voltages and angles). This estimate may be computed using a linearization of the power flow equations, i.e., determining the “tangent vector” to the manifold of power flow solutions. Thus, in the example depicted in fig. 2.4:

![Figure 2.4: Continuation power flow](image)

\[ \Delta y = y_2 - y_1 \]

\[ = k J_{PF1}^{-1} \frac{\partial f_{PF}}{\partial P} \bigg|_1 \Delta P \]  \hspace{1cm} (2.4)

Where:

- \( J_{PF1} \): The Jacobian of the power flow equations, evaluated at the operating point 1.
- \( y \): The vector of power flow variables.
- \( \frac{\partial f_{PF}}{\partial P} \bigg|_1 \): The partial derivative of the power flow equations with respect to the changing parameter P evaluated at the operating point 1.
- \( k \): Constant used to control the length of the step (typically \( k=1 \)), which is usually reduced by halves to guarantee a solution of the corrector step near the maximum loading point.

The predictor step basically determines the sensitivities of the power flow variables \( x \) with respect to changes in the loading level \( P \). The corrector step can be as simple as solving the power flow equations for \( P=P_2 \) to obtain the
operating point 2 in Fig. 2.4, using the estimated values of x yielded by the predictor as initial guesses.

c. Optimization or Direct Methods

The maximum loading point can be directly computed using optimization-based methodologies which yield the maximum loading margin to a voltage collapse point and a variety of sensitivities of the power flow variables with respect to any system parameter, including the loading levels. These methods basically consist on solving the OPF (Optimal Power Flow) problem:

\[
\text{Max. } P \\
\text{s.t. } P_f(y, P) = 0 \rightarrow \text{Power flow equations} \\
\quad y_{\min} \leq y \leq y_{\max} \rightarrow \text{Limits}
\]

Where

P: the system loading level.

The power flow equations and variables x should include the reactive power flow equations of the generators so that the generator’s reactive power limits can be considered in the computation. The Lagrange multipliers associated with the constraints are basically sensitivities that can be used for further analyses or control purposes. Well-known optimization techniques, such as interior point methods, can be used to obtain loadability margins and sensitivities by solving this particular OPF problem for real-sized systems.

Approaching voltage stability analysis from the optimization point of view has the advantage that certain variables, such as generator bus voltages or active power outputs, can be treated as optimization parameters. This allows treating the problem not only as a voltage stability margin computation, but also as a means to obtain an optimal dispatch to maximize the voltage stability margins.
2.3 Flexible AC Transmission Systems (FACTS)

2.3.1 Introduction

The concept of using solid state power electronic converters for power flow control at transmission level has been known as FACTS. The idea has had some success in certain areas such as reactive power dispatch and control. However, the full use of FACTS for power flow control has had limited applications in part due to reliability concerns and in part due to availability of components. Perhaps the most salient consideration is the cost of these devices. A potential motivation for accelerated use of FACTS is the deregulation/competitive environment in contemporary utility business. The potential ability of controlling the flow of electric power, and the ability to effectively join electric power networks that are not strongly interconnected, suggest that the FACTS may find new applications [42].

2.3.2 Types of FACTS

The types of FACTS currently available can be categorized into devices that control certain electrical parameters. For example, the UPFC (Unified Power Flow Controller) can be used to control active and reactive line flows. The PAR (Phase Angle Regulator) can be used to control active power flow. Another type of FACTS, the STATCOM (STATic COMpensator) is a shunt-connected reactive power compensation device that is capable of generating or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. In general, the several types of existing and proposed FACTS devices can be categorized into three types termed A, B, and C for convenience. Table 2.1 lists the types of FACTS devices with the controlled parameters and examples of actual devices that most closely match the models.
Table 2.1: Types of FACTS devices models

<table>
<thead>
<tr>
<th>Type</th>
<th>Controlled Parameter</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>Shunt Q</td>
<td>SVC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STATCOM</td>
</tr>
<tr>
<td>Type B</td>
<td>Series P</td>
<td>TCSC (Thyristor Controlled Series Capacitor), PAR</td>
</tr>
<tr>
<td>Type C</td>
<td>Series P and Q</td>
<td>UPFC</td>
</tr>
</tbody>
</table>

2.3.3 Optimal allocation and sizing of FACTS devices

Having made the decision to install a FACTS device in the system, there are main issues that must be addressed: what type of device should be used, how much capacity should it have, and where in the system should it be placed. Assuming that the cost of a particular device is a function of its capacity, it would not be desirable to install a device that is overall larger for its intended purpose. For example, if the capacity of a series connected FACTS device is larger than the rating of the transmission line in which it will be installed would not be economic since the line limit would prohibit the device from being used to its full potential. Likewise, if the device is too small and it can not handle as much power flow as the transmission line, the utility has effectively reduced the rating of the associated transmission line, keeping in mind the potential for later line upgrade.

Like the discussion of where to place the FACTS device, the choice of which type of devices will have the highest impact in the desired effect. For instance, a type A device should be considered when reactive power control or voltage support is necessary. Type B devices may not perform well in lines with high reactive power flow. Also, the relative cost of the devices will have a considerable effect on which device is chosen. It is likely that the cost of a device is inversely proportional to the maturity of the technology. This would indicate that the SVC, type A devices, is among the cheapest and the UPFC, type C devices, would be one of the more expensive.
The decision of where to place a FACTS device is largely dependant on the desired effect and characteristics of the specific system. One possible method for determining the optimal location of the device is to simulate the operation of the device in all the possible locations of installation. However, this could be very time consuming specially for large systems. Thus, there are some guidelines to identify places in the system that are potential candidates for the FACTS controllers. Some of these guidelines are:

- **Prevention of loop flows**
  The placement of FACTS controllers in the power system, to prevent loop flow, depends primarily on the location of the loop flows. The device should be placed in one of the transmission lines on which the loop flow occurs, with either being forced to zero or sent to the opposite direction of the loop flow. If a parallel path exists, such as another line between the same buses, the effectiveness of the device for this purpose will be greatly reduced. This is because some of the power that is being directed through the FACTS device will be shunted back to the sending bus by the parallel path. Either type B or C devices are suitable for this purpose.

- **Electronic fence**
  The concept of an electronic fence is an attempt by a utility to protect its property rights by preventing other utilities from using its transmission system. In this case, there are limited number of access points, these being the tie lines connecting the utility to its neighbors, in order to completely control the amount of power passing through the utility, it would need to control the flow on all but one of the tie lines, which would be prohibitively expensive. However, some success can be achieved by fewer devices if they are strategically located, especially if the number of interconnections is low. The key locations for these devices are those tie-lines that are most heavily loaded. A weak tie-line connection is not likely to be heavily used. Therefore, a FACTS device in that line will not have a great effect. If two or more parallel
paths exist, a single device will have little effect, since the flow will travel over uncontrolled tie lines

- **Enhanced economic operation**

  There are two distinct means of placing a FACTS device in a transmission system for the purpose of increasing the system’s ability to transmit power, thereby allowing for use of more economic generation units. The first way is to place the device in an underutilized line. This allows more power to be pushed through the line. The second way is to place the device in the most heavily loaded line to limit the flow in this line. This allows more power to be sent through the remaining portion of the system while protecting the line with the device from being overloaded. In general, either type B or C devices may be used for this purpose.

- **Obtaining a specific operating condition**

  FACTS may be placed in order to obtain a desired operating condition, such as correcting an under-voltage or forcing a certain amount of current flow through a line. The proper type and location of the device will be determined by specific condition. Type A is suitable to overcome under voltage problems at certain bus, obviously this bus will be the first candidate to be the location of the device. If the utility wants to be able to control the flow in specific line Type B or C may be used in this line

  The intended objective of the FACTS will have a large impact on the optimal location of the device. A location that is best for certain objective may be non-optimal for another. Additionally, since the characteristics of each utility’s system are unique, the optimal location may vary between utilities.
2.3.4 FACTS applications for improving system stability

FACTS can be used for several power system performance enhancements, for example TCSC can be used to improve the system transient rotor angle stability, damping of the power oscillations, and alleviation of SSR (Sub-Synchronous Resonance). However, SVC can be used to increase the system steady-state power transfer capacity, enhancement of the system transient rotor angle stability, and prevention of voltage instability. The effectiveness of the FACTS devices depends largely on their placement with the careful selection of control signals for achieving different functions.

2.3.5 Static VAr Compensator (SVC)

2.3.5.1 Introduction [43]

The SVC is now a mature technology that is widely used for transmission applications for several purposes. The primary purpose is usually rapid control of voltage at weak points in the network. Worldwide, there is a steady increase in the number of installations. The IEEE-definition of an SVC is as follows:

“Static VAr Compensator (SVC): A shunt-connected static VAr generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).”

By placing the shunt in the middle of a line and therefore dividing the line into two segments, the voltage at this point can be controlled such that it has the same value as the end line voltages. This has the advantage that the maximal power transmission is increased. If the shunt compensator is located at the end of a line in parallel to a load it is possible to regulate the voltage at this end and therefore to prevent voltage instability caused by load variations or generation or line outages.
2.3.5.2 Components of SVC

SVC is an umbrella term for several devices. The SVC devices discussed in the following sections are the TCR (Thyristor Controlled reactor), FC (Fixed Capacitor) and TSC (Thyristor Switched Capacitor). The components of an SVC may include: transformer between the high voltage network bus and medium voltage bus where the power electronic equipment is connected, a fixed (usually air-core) reactor of inductance $L$ and a bidirectional thyristor. The thyristors are fired symmetrically in an angle $\alpha$ in control range of 90° to nearly 180°, with respect to the capacitor voltage. The TSC is often used in order to decrease the standby losses. Figure 2.5 shows a common structure of SVC.

![Common structure of SVC](image)

2.3.5.3 SVC steady-state model [36] [42]

The main component of the SVC is the TCR, thus the main objective in this section is to determine the steady state model of the TCR. The TCR current is essentially reactive, lagging the voltage by nearly 90°. The active component of the current is very small; therefore, one of the modeling assumptions is that the resistance of the inductor may be neglected. Another assumption is that the voltage applied to the TCR is sinusoidal, which for the SVC, a shunt device, is reasonable as the supply voltage is the bus voltage.
The firing angle $\alpha$ is defined as the angle between the positive-going zero-crossing of the voltage across the inductor and the positive-going zero-crossing of the current through it. The thyristors are fired symmetrically; therefore, the maximum possible firing angle is $180^\circ$. Full conduction is obtained with a firing angle of $90^\circ$ while partial conduction is achieved for a firing angle between $90^\circ$ and $180^\circ$. Firing angles less than $90^\circ$ are not allowed, as they result in unsymmetrical currents with large dc component. The fundamental component of the current is reduced as the firing angle increases. This is equivalent to an increase in the inductance of the reactor, reducing its current as well as its reactive power.

In Figure 2.6, the voltage across the TCR inductor and the current through it are shown at full conduction angle. The current lags the voltage by $90^\circ$ with the current having a pure sinusoidal wave form and the equivalent reactance of the TCR is equal to the inductor fundamental frequency reactance $X_L$. Figure 2.7 shows the current through and the voltage applied to the inductor of the TCR for a firing angle $\alpha = 120^\circ$. In this case, the current through the inductor is not sinusoidal anymore and its fundamental component is less than the current at $90^\circ$ firing angle. This is equivalent to increasing the reactance of the TCR. At $180^\circ$ firing angle, the equivalent reactance of the TCR becomes practically infinity.

The conduction angle $\gamma$ is defined as the angle for which the thyristor is conducting. The conduction angle $\gamma$ and the firing angle $\alpha$ are related by the following equation:

$$\gamma = 2 \left( \pi - \alpha \right) \quad (2.5)$$

The steady state voltage waveform applied to the inductor for a period is described in Equation 2.6

$$v_L(t) = \begin{cases} V_M \sin \omega t & \text{for } 0 \leq \omega t \leq \pi - \alpha, \ \alpha \leq \omega t \leq 2\pi - \alpha, \ \pi + \alpha \leq \omega t \leq 2\pi \\ 0 & \text{for } \pi - \alpha \leq \omega t \leq \alpha, \ 2\pi - \alpha \leq \omega t \leq \pi + \alpha \end{cases} \quad (2.6)$$
Figure 2.6: TCR current and voltage waveforms for $\alpha = 90^\circ$

Figure 2.7: TCR current and voltage waveforms for $\alpha = 120^\circ$
The voltage across an inductor and the current through it are related by

\[ v_L = L \frac{di_L}{dt} \]  \hspace{1cm} (2.7)

If the time origin is chosen to coincide with the positive-going zero-crossing of the voltage, the current waveform can be found by integrating Equation 2.6 and this integration is described by the equations in Table 2.2

<table>
<thead>
<tr>
<th>( \omega t )</th>
<th>( i_L(\alpha, \omega t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega t \in [0, \pi - \alpha] )</td>
<td>( I_M(-\cos \alpha - \cos \omega t) )</td>
</tr>
<tr>
<td>( \omega t \in [\pi - \alpha, \alpha] )</td>
<td>0</td>
</tr>
<tr>
<td>( \omega t \in [\alpha, 2\pi - \alpha] )</td>
<td>( I_M(\cos \alpha - \cos \omega t) )</td>
</tr>
<tr>
<td>( \omega t \in [2\pi - \alpha, \pi + \alpha] )</td>
<td>0</td>
</tr>
<tr>
<td>( \omega t \in [\pi + \alpha, 2\pi] )</td>
<td>( I_M(-\cos \alpha - \cos \omega t) )</td>
</tr>
</tbody>
</table>

Where:

\[ I_M = \frac{V_M}{X_L} \], is the maximum value of the inductor current.

A periodic function \( f(\theta) \) with period \( T \) can be expressed as a trigonometric Fourier series of the form:

\[ f(\theta) = \frac{A_0}{2} + \sum_{n=1}^{\infty} \left( A_n \cos n\theta + B_n \sin n\theta \right) \]  \hspace{1cm} (2.8)

Where

\[ A_0 = \frac{1}{\pi} \int_0^{2\pi} f(\theta) d\theta \]
\[ A_n = \frac{1}{\pi} \int_0^{2\pi} f(\theta) \cos n\theta \quad d\theta \]  \hspace{1cm} (2.9)
\[ B_n = \frac{1}{\pi} \int_0^{2\pi} f(\theta) \sin n\theta \quad d\theta \]
The TCR instantaneous current is symmetric and even waveform: therefore, the corresponding Fourier series has $A_0 = 0$ and $B_n = 0$ for all values of $n$. In order to get the fundamental frequency component of the current, only $A_1$ will be calculated. By substituting with the values of the inductor current form Table 2.2 in Equation 2.9 and evaluating the integration, the final expression for $A_1$ is

$$A_1 = -\frac{I_M}{\pi} [2(\pi - \alpha) + \sin 2\alpha]$$

(2.10)

The fundamental frequency current lags the voltage by 90°; hence it can be written as, after substituting with the expression of $I_M$

$$i_L(\omega t) = -\frac{V_M}{X_{TCR}} \cos \omega t$$

(2.11)

From the Fourier series, and from Equation 2.11, the effective reactance of the TCR, $X_{TCR}$, is given as

$$X_{TCR} = X_L \frac{\pi}{2(\pi - \alpha) + \sin 2\alpha}$$

(2.12)

In a three phase system, three single phase thyristor controlled reactors are used in delta connection. Under balanced conditions, the triplen harmonic currents circulate in the delta connected TCRs and do not enter the power system. A step down transformer is required in HV or EHV applications as the TCR voltage is limited for technical and economic reasons to 50 kV or below. For an SVC, with a structure of FC-TCR, the equivalent susceptance is given by:

$$B_{SVC} = \frac{2(\pi - \alpha) + \sin 2\alpha}{\pi \left( X_L / X_C \right)}$$

(2.13)

Where $X_C$ is the fundamental frequency reactance of the fixed capacitor

Figure 2.8 and Figure 2.9 show the SVC (FC - TCR) equivalent reactance and susceptance respectively with the variation of the firing angle.
The typical steady-state control law of SVC is given by Equation 2.14. Figure 2.10 represents a typical V-I characteristics of an SVC.

\[
V = V_{REF} + X_{SL} I_{SVC} \tag{2.14}
\]
Where

\( V \): The voltage of the bus at which the SVC is connected.

\( I_{SVC} \): The total current of the SVC.

\( V_{REF} \): The reference voltage of the SVC bus.

\( X_{SL} \): A small slope of typical values of 2 to 5%, with respect to the SVC base. It is required to avoid hitting the limits for small variations of the bus voltage.

For the steady-state model to be complete, all SVC limits must be adequately represented. The proper handling of the firing angle limit is shown in Figure 2.11, where \( V_{REF} \) is kept fixed until \( \alpha \) reaches a limit, at which point \( V_{REF} \) is allowed to change while \( \alpha \) is kept at its limit value. The voltage control is regained when \( V_{REF} \) returns to its original value.
3.1 Introduction

This chapter describes in details the dynamic models of the different components in the power system contributing in the short-term voltage stability scenario. These dynamic models include the models for the synchronous generators with their control systems, AVR and OEL and the induction motors which are the driving force in this case. Finally, the dynamic model of the FACTS device, SVC, used a remediation tool to prevent the voltage instability.

3.2 Synchronous generator

Dynamics of synchronous generator is represented by appropriate transient model [1, 4, and 5]. In order to take into account the saliency of the rotor and the effect of the field flux linkage changes, the d-q axes are used and $E'$ must be corrected by $(x'_q - x'_d)I_q$ resulting in $E'$. The phasor diagram in this case is shown in Figure 3.1 (the superscript $^\text{gen}$ is omitted from the text for simplification).

![Figure 3.1: The phasor diagram of the synchronous generator](image)
After decomposition of the voltage, $E'$ into $d$ and $q$-axis components, the differential equations are written for its variables $E'_d$ and $E'_q$, belonging to the two-axis transient model of the synchronous generator. The algebraic equations describing the generator voltage relations are the stator voltage equations which are given as flows:

\[
V_n = V_d + jV_q \quad (3.1)
\]

\[
I_g = I_d + jI_q \quad (3.2)
\]

\[
E' = E'_d + jE'_q \quad (3.3)
\]

\[
V_d - V_n \sin (\theta_n - \delta) = 0 \quad (3.4)
\]

\[
V_q - V_n \cos (\theta_n - \delta) = 0 \quad (3.5)
\]

\[
I_d - I_g \sin (\theta_i - \delta) = 0 \quad (3.6)
\]

\[
I_q - I_g \cos(\theta_i - \delta) = 0 \quad (3.7)
\]

\[
E'_q - V_q - RI_q - x'_d I_d = 0 \quad (3.8)
\]

\[
E'_d - V_d - RI_d - x'_d I_q - (x'_q - x'_d) I_q = 0 \quad (3.9)
\]

While the differential equations describing dynamics of synchronous generator are given as

\[
\frac{d\delta}{dt} = \omega - 1 \quad (3.10)
\]

\[
\frac{d\omega}{dt} = \frac{T_m}{\tau_j} - \frac{E'_d I_d + E'_q I_q - (x'_q - x'_d) I_d I_q}{\tau_j} - \frac{D(\omega - 1)}{\tau_j} \quad (3.11)
\]

\[
\frac{dE'_q}{dt} = \frac{E_{FD} - E_I}{T'_{do}} = \frac{E_{FD} - E'_q + (x'_d - x'_q) I_q}{T'_{do}} \quad (3.12)
\]

\[
\frac{dE'_d}{dt} = - \frac{E'_d + (x'_q - x'_d) I_q}{T'_{dq}} \quad (3.13)
\]
Where:

\( V_d \) and \( V_q \) : d and q-axis components of the generator terminal voltage
\( I_d \) and \( I_q \) : d and q-axis components of the generator current \( I_g \)
\( E'_d \) and \( E'_q \) : d and q-axis components of internal voltage of the generator
\( \theta_n \) : Angle between the terminal voltage and the reference of the generator.
\( \theta_i \) : Angle between the reference and the generator current
\( \delta \) : Angle between the reference and q-axis of the generator
\( R \) : Stator resistance of the generator
\( x'_d \) and \( x'_q \) : d and q-axis transient reactances of the generator
\( \omega \) : Rotor speed
\( T_m \) : Mechanical torque
\( D \) : Damping coefficient
\( \tau_j \) : Constant proportional to the generator inertia
\( E_{FD} \) : Excitation voltage
\( E_i \) : q-axis component of induced voltage \( E \)
\( T'_{do} \) and \( T'_{qo} \) : Transient time constants of open circuits in d and q-axis

It must be stated that in order to control the excitation voltage and the mechanical torque, models for the exciter and turbine-speed governor must be included. However, the dynamics of the turbine-speed governor are too slow when compared to the time frame of the short-term voltage stability study. Therefore, the model of the turbine-speed governor won’t be included.

### 3.3 Excitation control system

The model shown in Figure 3.2, designated as Type AC5A, is a simplified model for brushless excitation systems [2, 4, and 5]. The regulator is supplied from a source, such as a permanent magnet generator, which is not affected by system disturbances. Because the model has been widely implemented by the industry, it is sometimes used to represent other types of
systems when either detailed data for them are not available or simplified models are required.

![Figure 3.2: Block diagram of Type AC5A excitation system](image)

The principal input to this model is the output, $V_C$, from the terminal voltage transducer. At the summing junction, terminal voltage transducer output, $V_C$, is subtracted from the set point reference, $V_{REF}$. The stabilizing feedback, $V_F$, is subtracted and the power system stabilizing signal, $V_S$, is added to produce an error voltage. In the steady state, these last two signals are zero, leaving only the terminal voltage error signal. The resulting signal is amplified in the regulator. The major time constant, $T_A$, and gain, $K_A$, associated with the voltage regulator are shown incorporating non-windup limits typical of saturation or amplifier power supply limitations. These voltage regulators utilize power sources that are essentially unaffected by brief transients on the synchronous machine or auxiliary buses. The voltage regulator output, $V_R$, is used to control the exciter, which may be an ac alternator and either stationary or rotating rectifiers to produce the dc field requirements.
3.4 Over excitation limiter

In voltage stability analysis of the systems where the problem except from transmission part arises also from the generator regulation circuits, it is necessary to include the OEL model [5, 45] in the model. Figure 3.3 shows the block diagram of the OEL dynamic model.

![Block diagram of the over excitation limiter](image)

Figure 3.3: Block diagram of the over excitation limiter

The OEL differential equation is given as

\[
\frac{dV_{OEL}}{dt} = \frac{(I_{FD} - I_{FLM2})K_2K_3}{T_{OEL}}
\]  

(3.14)

Where

- \( V_{OEL} \) : Output voltage from the OEL
- \( I_{FD} \) : Excitation current
- \( I_{FLM2} \) : Continuous operation limit of the excitation current
- \( K_2 \) and \( K_3 \) : Gains
- \( T_{OEL} \) : Time constant.

The algebraic equation belonging to the OEL is given as

\[
E'_q - (x_d - x'_d) I_d - I_{FD} = 0
\]  

(3.15)

Where \( x_d \) denotes d-axis synchronous reactance.
By approximate reasoning, the maximum allowable excitation current in continuous operation, $I_{FLM2}$, could be defined according to the operating diagrams of generator with a round rotor as shown in Figure 3.4, and a rotor with salient poles as shown in Figure 3.5.

![Figure 3.4: Operating diagram of a generator with round rotor](image)

The q-axis component, $E_I$, of the induced voltage $E$ is set to be equal to the maximum value $I_{FLM2}$ due to initial steady state conditions of the model.

For the generator with a round rotor, the $E_I$ is defined as

$$E_I = \frac{x_d}{V_n} \sqrt{P_n^2 + \left( Q_n + \frac{V_n^2}{x_d} \right)^2} \quad (3.16)$$

Where

$P_n$ and $Q_n$ denote nominal active and reactive power.

For the generator with salient poles, the $E_I$ is

$$E_I = \frac{x_d}{V_n} \left[ \frac{P_n}{\sin \delta_n} - V_n^2 \left( \frac{x_d - x_q}{x_d x_q} \right) \cos \delta_n \right] \quad (3.17)$$
The angle $\delta_n$ in Equation 3.17 is computed as

$$\delta_n = \tan^{-1}\left( \frac{P_n}{Q_n + \frac{V_n^2}{x_q}} \right)$$  \hspace{1cm} (3.18)

### 3.5 Induction Motor

The induction motor is the main driving force in the short-term voltage stability problem. Therefore, detailed models will be presented either for the steady state representation for the power flow procedure or the dynamic model for the voltage stability problem [5, 20–25, and 40].

#### 3.5.1 Power flow model

As a starting point in derivation of the power flow model, standard impedance scheme of induction motor is used and it is shown in Figure 3.6.
Figure 3.6: Standard impedance of induction motor

Where

- $R_S$ and $R_r$: Stator and rotor resistances
- $X_S$ and $X_r$: Stator and rotor leakage reactances
- $X_{mag}$: Magnetization reactance
- $\sigma$: Motor slip
- $V_n$: Motor bus voltage
- $I_s$ and $I_r$: Stator and rotor currents

In order to compute initial steady state operating point of the system with induction motors included, first it is necessary to define initial equivalent impedance $R_m(\sigma) + jX_m(\sigma)$. It is valid only for steady state (Figure 3.7), and helps motor power consumption being computed.

Figure 3.7: Initial steady state equivalent impedance

The equivalent impedance depends on induction motor slip, and it could be computed according to following expression
\[
R_m(\sigma) + jX_m(\sigma) = (R_s + jX_s) + \frac{jX_{mag}}{\frac{R_r}{\sigma} + j(X_{mag} + X_r)}
\] (3.19)

After some elaboration, it results with the expressions

\[
R_m(\sigma) = R_s + \frac{1}{\sigma} \times \frac{X_{mag}^2 R_r}{\left(\frac{R_r}{\sigma}\right)^2 + \left(X_{mag} + X_r\right)^2}
\] (3.20)

\[
X_m(\sigma) = X_s + \frac{X_{mag}^2 R_r}{\sigma^2} + \frac{X_{mag} X_r \left(X_{mag} + X_r\right)}{\left(\frac{R_r}{\sigma}\right)^2 + \left(X_{mag} + X_r\right)^2}
\] (3.21)

The current \(I_s\), which flows through the impedance \(R_m(\sigma) + jX_m(\sigma)\), is defined as

\[
\bar{I}_s = \frac{\bar{V}_n}{R_m(\sigma) + jX_m(\sigma)}
\] (3.22)

Consequently, the apparent electric power is defined as

\[
\bar{S} = \bar{V}_n \bar{I}_s^* = \frac{V_n^2}{R_m(\sigma) - jX_m(\sigma)}
\] (3.23)

Further elaboration gives active and reactive power as

\[
P_e = \frac{R_m(\sigma)}{R_m(\sigma)^2 + X_m(\sigma)^2} V_n^2
\] (3.24)

\[
Q_e = \frac{X_m(\sigma)}{R_m(\sigma)^2 + X_m(\sigma)^2} V_n^2
\] (3.25)
In order to compute a complete set of motor variables valid for initial steady state operating point, the series equivalent scheme is used which is shown in Figure 3.8.

![Series equivalent scheme of induction motor](image)

Figure 3.8: Series equivalent scheme of induction motor

The equivalent series resistance, $R_e$, and reactance, $X_e$, are derived from

$$R_e + jX_e = \frac{jX_{\text{mag}} (R_s + jX_s)}{R_s + j(X_s + X_{\text{mag}})} \quad (3.26)$$

and given as

$$R_e = \frac{R_s X_{\text{mag}}^2}{R_s^2 + (X_s + X_{\text{mag}})^2} \quad (3.27)$$

$$X_e = \frac{R_s^2 X_{\text{mag}} + X_s^2 X_{\text{mag}} + X_{\text{mag}}^2 X_s}{R_s^2 + (X_s + X_{\text{mag}})^2} \quad (3.28)$$

If the equivalent voltage $V_e$ is defined as

$$V_e = V_n \frac{jX_{\text{mag}}}{R_s + j(X_s + X_{\text{mag}})} \quad (3.29)$$

The rotor current $I_r$ results as

$$I_r = \frac{V_e}{\left(\frac{R_s + R_r}{\sigma}\right) + j(X_e + X_r)} \quad (3.30)$$
Hereby, the electromagnetic torque, $T_e$, developed by the motor is defined as

$$
T_e = \frac{P_{sh}}{\omega_m} = \frac{P_{gap}}{\omega_s} = \frac{R_r}{\sigma \omega_s} I_r^2
= \frac{R_r}{\sigma \omega_s} \left( \frac{R_e + \frac{R_r}{\sigma}}{V_e} \right)^2 + (X_e + X_r)^2
$$

(3.31)

Where

- $P_{sh}$: Motor shaft power or the mechanical power given to the motor load.
- $P_{gap}$: Motor air-gap power or the power that is transferred through the air-gap from stator to rotor.
- $\omega_m$: Per unit value of the rotor speed that is equal to $(1- \sigma) \omega_S$.

Mechanical load torque of the motor, $T_m$, is defined according to

$$
T_m = T_{m0} \left[ A \left( \frac{\omega_m}{\omega_{m0}} \right)^2 + B \left( \frac{\omega_m}{\omega_{m0}} \right) + C + d \left( \frac{\omega_m}{\omega_{m0}} \right)^{a_m} \right]
$$

(3.32)

Where

- $T_{m0}$: Value of the load torque at the speed $\omega_{m0}$.
- $A$, $B$, and $C$: Appropriate coefficients of quadratic, linear and constant term.
- $d$ and $a_m$: Define initial value of the torque.

The exact solution for the initial steady state operating point of the system with induction motors included is obtained iteratively as shown in Figure 3.9. In the sequence, the motor initialization is followed by the load flow procedure, which calls for the motor adjustment. Upon satisfying iterative difference in motor electric powers, the base case is completed as the motors are concerned.
Figure 3.9: Iterative procedure for determination of the exact initial steady state operating point

First, the set of parameters ($R_e$, $X_e$, and $V_e$) is computed. Then, the second one ($T_m$, $T_e$, and $\sigma$) is determined. Using the value of the motor slip $\sigma$, the motor speed $\omega_m$ is calculated. If the difference of the value of the motor speed $\omega_m$ from two consecutive iterations is larger than the value of pre-established threshold (e.g. $1.e^{-6}$), the procedure is taken backward to the evaluation of the second set of the parameters. Iterative procedure is stopped when the value of $\omega_m$ from two consecutive iterations becomes small enough. Afterwards, the third set of parameters ($R_m$ ($\sigma$), $X_m$ ($\sigma$), $P_e$, and $Q_e$) is computed. The active, $P_e$, and reactive, $Q_e$, power of the motor are necessary inputs for the initial load flow procedure. The powers are considered as the bus load injections. They are added to the load powers of the other loads at the same bus. The whole procedure is stopped when the changes $\Delta P_e$ and $\Delta Q_e$ between two consecutive iterations satisfy pre-established thresholds $\varepsilon_P$ and $\varepsilon_{Q_e}$. 

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3.5.2 Dynamic model

The induction motor is represented by using its transient model. Appropriate algebraic and differential equations are included in the system model. The equivalent circuit of the induction motor that is used for the transient study is shown in Figure 3.10 and the phasor diagram of the induction motor is shown in Figure 3.11.

\[ E_{\text{mot}}' = \frac{1}{R_s + jX'} \]  

Where

\[ X' = X_s + \frac{X_m X_r}{X_m + X_r} \]  

\[ (3.33) \]
The complete transient third order model of the induction motor consists of five algebraic equations and three differential equations as follows:

\[ V_d - V_n \sin \theta_n = 0 \quad (3.34) \]
\[ V_q - V_n \cos \theta_n = 0 \quad (3.35) \]
\[ R_s E'_q + X'E'_d + (R_s^2 + X'^2)I_q - X'V_d - R_s V_q = 0 \quad (3.36) \]
\[ -X'E'_q + R_s E'_d + (R_s^2 + X'^2)I_d - R_s V_d + X'V_q = 0 \quad (3.37) \]
\[ T_e = \frac{E'_d I_d + E'_q I_q}{\omega_s} \quad (3.38) \]
\[ \frac{d\omega_m}{dt} = \frac{T_e - T_m}{2H} \quad (3.39) \]
\[ \frac{dE'_d}{dt} = -(\omega_s - \omega_m)E'_q - \frac{E'_d}{T'_o} + \frac{(X - X')}{T'_o} I_q \quad (3.40) \]
\[ \frac{dE'_q}{dt} = (\omega_s - \omega_m)E'_d - \frac{E'_q}{T'_o} - \frac{(X - X')}{T'_o} I_d \quad (3.41) \]

Where

\[ X = X_s + X_m \quad (3.42) \]
\[ T'_o = \frac{X_r + X_m}{\omega_s R_r} \quad (3.43) \]

H: Motor inertia constant

### 3.6 SVC (Static VAr Compensator)

The steady state model of the SVC has been discussed in the previous chapter. It must be noted that the equations developed in the steady state model will be used as the algebraic equations of the dynamic models. In this section the dynamic models of the SVC will be presented. There are two models for the SVC which could be used as mentioned in [46]. These models are:
3.6.1 Model 1

In this model, a simple time constant regulator is assumed as shown in Figure 3.12. The governing equations in this case are:

\[
\frac{db_{svc}}{dt} = \frac{K_r(V_{ref} - V) - b_{svc}}{T_r} \tag{3.44}
\]

\[
Q = -b_{svc} V^2 \tag{3.45}
\]

![Figure 3.12: The block diagram of the SVC model 1](image)

3.6.2 Model 2

In this model, the dynamics of the firing angle (\(\alpha\)) is considered. The block diagram of this model is shown in Figure 3.13 and the model equations are as follows

\[
\frac{dV_m}{dt} = \frac{K_m V - V_m}{T_m} \tag{3.46}
\]

\[
\frac{d\alpha}{dt} = -K_p\alpha + \frac{K T_1}{T_m} (V_m - K_m V) + K (V_{ref} - V_m) \tag{3.47}
\]

\[
Q = -b_{svc} V^2 \tag{3.48}
\]
Figure 3.13: The block diagram of SVC model 2

Where:

$\alpha_0$ is a bias for the controller which could be determined by solving the non-linear equation

$$2\alpha_0 - \sin(2\alpha_0) - \pi \left(2 - \frac{X_L}{X_C}\right) = 0 \quad (3.49)$$
CHAPTER 4
PROPOSED APPROACH AND TEST SYSTEM

4.1 Introduction

This chapter begins with the description of the proposed approach of the analysis of the short-term voltage stability and the procedures made in order to carry out this analysis. Then, the test system used for the study and the procedures made to prepare the test system to clearly reveal the problem are described. This includes the system load increase and the introduction of the induction motor loads with different penetration levels. Finally, the different cases that encountered severe voltage decrease, following a disturbance, are illustrated.

4.2 The proposed approach of analysis

The motivation of this study is the increasing importance of the analysis of the voltage instability cases resulting from the dynamics of the induction motors. This is the case in the hot parts of the world, where there is excessive usage of the air conditions in the summer season. This is the case in the Gulf countries where the outside temperature may reach 50°C. Thus, these air condition (induction motor) loads may reach up to 60% of the total load of the system. For such cases, if a disturbance happens, with the reactive power resources available in the system aren’t capable to support the reactive power requirements in the due time; a complete voltage collapse may be encountered. Thus, the main objectives of this work are to study the effect of the induction motor penetration level increase on the short-term voltage stability of the electric power systems and how to improve the voltage instability by using SVC, shunt FACTS device.
Since the main concern of the thesis was the short-term voltage stability, so the dynamic analysis method would be used for this purpose. This method of analysis was explained in details in the second chapter of the thesis. In order to be able to use this method of analysis, extensive modeling of the different components of the power system has been done. This was presented in chapter three where the dynamic models of the synchronous generators and their control systems, the over excitation limiters, the induction motors, and the FACTS device, SVC were derived in details.

After the dynamic models have been prepared for the analysis, the main challenge was the selection of the test system that would be used for the study. This test system had to be characterized with some features that would help in revealing the voltage instability problem. These features were the poor distribution of the reactive power sources all over the network and their inadequacy and the presence of long transmission lines and single-circuit ones that would act as throttling points facing the reactive power transmission from its sources to the load centers. Though, these features were found in the chosen test system, it was required to slightly modify the operating conditions, system loading, to clearly reveal the voltage instability. This was done by increasing the system load using a constant power factor scheme. This was done in steps of 10% of the total system. This load increase was confronted by generation increase. However, this generation increase adopted a scheme which would help reveal the voltage instability problem. This generation increase scheme depended mainly on accumulating the reactive power sources away from the load centers resulting in a worse distribution of the reactive power sources all over the network. This load increase continued till the power flow couldn’t converge to a feasible solution under the same scheme of the generation increase. The final output of this stage is a test system heavily stressed from the reactive power point of view and on the edge of collapse if subjected to any disturbance.
After the system was modified to reveal the voltage stability problem, the induction motor load was presented. This was done for different penetration levels, namely 30%, 40%, 50%, and 60% in order to study the effect of increasing the penetration level of the induction motor loads. Finally, for each of these study cases, the system was subjected to different disturbances. These disturbances were in the form of three phase faults at different buses of the system. These faults last for three cycles (0.06 seconds) followed by a transmission line outage acting as the fault clearing procedure, thus determining the cases that encountered voltage instability and would require placement of SVC to avoid this instability. This SVC placement, namely the size and location, was done optimally using the Heuristic and Genetic optimization techniques. The results of this optimal allocation and sizing of the SVC for the cases that suffered from severe voltage decrease are illustrated in the next chapter.

4.3 Test System Description

The selected system is a simple 6-machine, 400 kV-20 bus test system. A single line diagram of this system is shown in Figure 4.1. This system is the one often used in CIGRÉ reports [44]. The system is comprised of two main areas (left and right hand ones). Six generators are located in the system being divided equally in the two areas. The loads are located in both areas which are of two types, the static type and the dynamic one. The system is characterized by two main features that help in revealing the short-term voltage stability problem. These features are the presence of long transmission lines as lines 12-17 and the presence of single-circuit transmission lines as lines 20, 21 and 26 and it must be noted that the latter transmission lines are used to supply heavily loaded portions of the system which could act as throttling points in the system.
Also, initially the generation is piled up away from the load centers and this is clear in the two areas where the generation is concentrated at one end, for example gen. 1 and gen. 2, while the main load center is concentrated at the other end as the loads at buses 10 and 11. Figure 4.1 shows the basic data of the system which are the lengths and parameters (R, X_L, and C per unit length) of the transmission lines, the loads at each bus given in MW and the power factor adopted for each area, and the power flow data of the generating units. The remaining data of the system is given in Appendix (A). In the next sections, the power flow results of the base case of the system loading and the subsequent cases as the load is increased will be presented, also the scheme of the generation increase will be thoroughly illustrated. However, at first the program used for the power flow and dynamic analyses, used in the next chapter, will be briefly introduced. This program is PSAT (Power System Analysis Toolbox).
4.4 Introduction to Power System Analysis Toolbox (PSAT) [47]

PSAT is a Matlab toolbox for electric power system analysis and control. The command line version of PSAT is also GNU Octave compatible. PSAT includes power flow, continuation power flow, optimal power flow, small signal stability analysis, and time domain simulation. All operations can be assessed by means of graphical user interfaces (GUIs) and a Simulink-based library provides user friendly tool for network design. PSAT core is the power flow routine, which also takes care of state variable initialization. Once the power flow has been solved, further static and/or dynamic analysis can be performed. These routines are:

1. Continuation power flow
2. Optimal power flow
3. Small signal stability analysis
4. Time domain simulations
5. PMU (Phasor Measurement Unit) placement

In order to perform accurate power system analysis, PSAT supports a variety of static and dynamic component models, as follows:

- **Power Flow Data**: Bus bars, transmission lines and transformers, slack buses, PV generators, constant power loads, and shunt admittances.
- **CPF and OPF Data**: Power supply bids and limits, generator power reserves, generator ramping data, and power demand bids and limits.
- **Switching Operations**: Transmission line faults and transmission line breakers.
- **Measurements**: Bus frequency and phasor measurement units (PMU).
- **Loads**: Voltage dependent loads, frequency dependent loads, ZIP (impedance, constant current and constant power) loads, exponential recovery loads, thermostatically controlled loads, and mixed loads.
- **Machines**: Synchronous machines (dynamic order from 2 to 8) and induction motors (dynamic order from 1 to 5).
• **Controls**: Turbine Governors, Automatic Voltage Regulators, Power System Stabilizer, Over-excitation limiters, Secondary Voltage Regulation (Central Area Controllers and Cluster Controllers), and a Supplementary Stabilizing Control Loop for SVCs.

• **Regulating Transformers**: Load tap changer with voltage or reactive power regulators and phase shifting transformers.

• **FACTS**: Static VAr Compensators, Thyristor Controlled Series Capacitors, Static Synchronous Source Series Compensators, Unified Power Flow Controllers, and High Voltage DC transmission systems.

• **Wind Turbines**: Wind models, Constant speed wind turbine with squirrel cage induction motor, variable speed wind turbine with doubly fed induction generator, and variable speed wind turbine with direct drive synchronous generator.

• **Other Models**: Synchronous machine dynamic shaft, sub-synchronous resonance model, and Solid Oxide Fuel Cell.

Besides mathematical routines and models, PSAT includes a variety of utilities, as follows:

1. Single-line network diagram editor (Simulink library)
2. GUIs for settings system and routine parameters
3. User defined model construction and installation
4. GUI for plotting results
5. Filters for converting data to and from other formats
6. Command logs

Finally, PSAT includes bridges to GAMS and UWPFLOW programs, which highly extend PSAT ability of performing optimization and continuation power flow analysis.
4.5 Generation data completion

Before proceeding to the part in which the system loading level and the corresponding generation are increased, the generation data must be first completed. This is because the generation data given in the CIGRÉ report is limited to the loading level of the base case and can’t be used for the load increase. Also, the reactive power limits of the generating units were not given. Therefore, the generation data of another system will be used in order to complete the missing data and to make the generation of the system extendable. This will be done under the constraint that the new generation data gives the same power flow results as those obtained from using the generation data for the CIGRÉ report. The additional data of the generation was used from a well-known IEEE system, Reliability Test System-1996 revision (RTS-96) [48]. Table 4.1 shows the generation data from the RTS-96.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Type</th>
<th>Size (MW)</th>
<th>Max. reactive power (MVAr)</th>
<th>Min. reactive power (MVAr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U12</td>
<td>Oil/Steam</td>
<td>12</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>U20</td>
<td>Oil/CT</td>
<td>20</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>U50</td>
<td>Hydro</td>
<td>50</td>
<td>16</td>
<td>-10</td>
</tr>
<tr>
<td>U76</td>
<td>Coal/Steam</td>
<td>76</td>
<td>30</td>
<td>-25</td>
</tr>
<tr>
<td>U100</td>
<td>Oil/Steam</td>
<td>100</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>U155</td>
<td>Coal/Steam</td>
<td>155</td>
<td>80</td>
<td>-50</td>
</tr>
<tr>
<td>U197</td>
<td>Oil/Steam</td>
<td>197</td>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>U350</td>
<td>Coal/Steam</td>
<td>350</td>
<td>150</td>
<td>-25</td>
</tr>
<tr>
<td>U400</td>
<td>Nuclear</td>
<td>400</td>
<td>200</td>
<td>-50</td>
</tr>
</tbody>
</table>

Using the above data, the generation capacities of the test system could be assumed as shown in Table 4.2. It is clear that the most of the reactive power sources are piled at the generating units connected to buses 1 and 4 which are far from the load centers.
Table 4.2: The decomposition of the generation data of the test system

<table>
<thead>
<tr>
<th>Bus</th>
<th>capacity of the generating plant (MW)</th>
<th>Generating units according to RTS-96 data</th>
<th>$Q_{\text{max}}$ (MVAR)</th>
<th>$Q_{\text{min}}$ (MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1890</td>
<td>$4\times U400 + 2\times U100 + U50 + 2\times U20$</td>
<td>956</td>
<td>-210</td>
</tr>
<tr>
<td>2</td>
<td>1085</td>
<td>$U400 + U197 + 4\times U100 + U76 + U12$</td>
<td>556</td>
<td>-75</td>
</tr>
<tr>
<td>3</td>
<td>1085</td>
<td>$U400 + U197 + 4\times U100 + U76 + U12$</td>
<td>556</td>
<td>-75</td>
</tr>
<tr>
<td>4</td>
<td>1890</td>
<td>$4\times U400 + 2\times U100 + U50 + 2\times U20$</td>
<td>956</td>
<td>-210</td>
</tr>
<tr>
<td>5</td>
<td>1085</td>
<td>$U400 + U197 + 4\times U100 + U76 + U12$</td>
<td>556</td>
<td>-75</td>
</tr>
<tr>
<td>6</td>
<td>1085</td>
<td>$U400 + U197 + 4\times U100 + U76 + U12$</td>
<td>556</td>
<td>-75</td>
</tr>
</tbody>
</table>

Table 4.3 shows the power flow results of the base case of the system loading. It is clear that the reactive power generation at buses 3 and 6 is very close to the reactive power limit while the reactive power generation at the remaining buses is far away from the limit. This indicates that the buses near these two generating plants will be subjected to the most dramatic decrease of the voltage when subjected to any disturbance.

Table 4.3: The power flow results of the base case of the system loading

<table>
<thead>
<tr>
<th>Bus</th>
<th>$V$ [pu]</th>
<th>Phase [rad]</th>
<th>$P_{\text{gen}}$ [pu]</th>
<th>$Q_{\text{gen}}$ [pu]</th>
<th>$P_{\text{load}}$ [pu]</th>
<th>$Q_{\text{load}}$ [pu]</th>
<th>$Q_{\text{max}}$ [pu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.025</td>
<td>0</td>
<td>15.925</td>
<td>1.500</td>
<td>0</td>
<td>0</td>
<td>9.56</td>
</tr>
<tr>
<td>2</td>
<td>1.025</td>
<td>-0.132</td>
<td>10.8</td>
<td>0.988</td>
<td>0</td>
<td>0</td>
<td>5.56</td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>-0.356</td>
<td>9.5</td>
<td>5.357</td>
<td>0</td>
<td>0</td>
<td>5.56</td>
</tr>
<tr>
<td>4</td>
<td>1.02</td>
<td>-0.231</td>
<td>18.5</td>
<td>0.469</td>
<td>0</td>
<td>0</td>
<td>9.56</td>
</tr>
<tr>
<td>5</td>
<td>1.02</td>
<td>-0.442</td>
<td>10.8</td>
<td>0.204</td>
<td>0</td>
<td>0</td>
<td>5.56</td>
</tr>
<tr>
<td>6</td>
<td>1.02</td>
<td>-0.777</td>
<td>9.5</td>
<td>5.467</td>
<td>0</td>
<td>0</td>
<td>5.56</td>
</tr>
<tr>
<td>7</td>
<td>1.039</td>
<td>-0.070</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>1.013</td>
<td>-0.216</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1.186</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>1.003</td>
<td>-0.334</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0.790</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 4.3 (cont'): The power flow results of the base case of the system loading

<table>
<thead>
<tr>
<th>Bus</th>
<th>V [pu]</th>
<th>Phase [rad]</th>
<th>$P_{gen}$ [pu]</th>
<th>$Q_{gen}$ [pu]</th>
<th>$P_{load}$ [pu]</th>
<th>$Q_{load}$ [pu]</th>
<th>$Q_{max}$ [pu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.999</td>
<td>-0.432</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>7.905</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>1.003</td>
<td>-0.457</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>3.952</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>1.016</td>
<td>-0.345</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0.790</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>1.039</td>
<td>-0.216</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>1.021</td>
<td>-0.315</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>1.022</td>
<td>-0.528</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>0.989</td>
<td>-0.454</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0.986</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>0.997</td>
<td>-0.657</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0.657</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>0.969</td>
<td>-0.678</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0.657</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>0.981</td>
<td>-0.802</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>1.458</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>0.992</td>
<td>-0.855</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>2.144</td>
<td>-</td>
</tr>
</tbody>
</table>

4.6 Load increase procedure

As stated in the previous section, there is a reactive power problem in the horizon for the buses around the generating plants 3 and 6 for the base case loading level. In order to help reveal the short-term voltage stability problem, the load will be increased using a constant power factor scheme. This will be done as a percentage of the loads at each bus, thus preserving the same distribution of the loads all over the system. In the same sense, the generation has to be increased. The adopted scheme to increase the generation was as follows:

- First, the needed increase in the generation of the active power will be determined. This additional needed capacity is determined as the increased amount of the load active power increased by 20%. This 20% is for the regulating margins.
Then, using the generation data given in Table 4.1, the number and capacity of the units to be added will be determined and distributed all over the network in a fashion such that the system becomes weaker from the reactive power sources point of view.

In the following sections, the results of the load increase will be illustrated.

### 4.6.1 The 10% load increase

In this case, the load is increased by 10% of the base case. As stated above, the increase in the load was done using a constant power factor scheme. From the base case loading, the total load of the system is 7400 MW and 2052.65 MVAr, thus the total load for the new case became 8140 MW and 2258 MVAr. Therefore, the additional needed capacity of the generation was about 900 MW; 740 MVAr, the load increase, multiplied by 1.2 for the regulating margins. By using the data given in Table 4.1, two units of U400 and one unit of U100 were added to the system to confront the load increase. The placement of these units was the turning point that helped reveal the short-term voltage stability problem during the time domain simulation study. Therefore, the reactive power sources were piled at buses 1 and 2 by assigning the two large units, U400, at these buses. The remaining unit, U100, was assigned at bus 6. This resulted in adding 200 MVAr at buses 1 and 2 while adding 60 MVAr at bus 6 Table 4.4 shows the power flow results for the 10% load increase.

From the results shown in Table 4.4, it is clear that the addition of the two U400 units to buses 1 and 2 meant that the reactive power generation capacity is piled up at these two buses while the actual reactive power generated at these two buses are away from their limits. However, the generated reactive power at bus 6 is nearly at its limit for the same bus voltage while the voltage at bus 3 could not be maintained at the same value for the
base case which resulted in general decrease in the buses voltages all over the network.

Table 4.4: The power flow results of the 10% load increase of the base case

<table>
<thead>
<tr>
<th>Bus</th>
<th>V [pu]</th>
<th>Phase [rad]</th>
<th>P_{gen} [pu]</th>
<th>Q_{gen} [pu]</th>
<th>P_{load} [pu]</th>
<th>Q_{load} [pu]</th>
<th>Q_{max} [pu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>1.025</td>
<td>0</td>
<td>18.731</td>
<td>4.303</td>
<td>0</td>
<td>0</td>
<td>11.56</td>
</tr>
<tr>
<td>Bus 2</td>
<td>1.025</td>
<td>-0.108</td>
<td>14.8</td>
<td>4.264</td>
<td>0</td>
<td>0</td>
<td>7.56</td>
</tr>
<tr>
<td>Bus 3</td>
<td>0.975</td>
<td>-0.457</td>
<td>9.5</td>
<td>5.449</td>
<td>0</td>
<td>0</td>
<td>5.56</td>
</tr>
<tr>
<td>Bus 4</td>
<td>1.025</td>
<td>-0.388</td>
<td>18.5</td>
<td>2.729</td>
<td>0</td>
<td>0</td>
<td>9.56</td>
</tr>
<tr>
<td>Bus 5</td>
<td>1.025</td>
<td>-0.601</td>
<td>10.8</td>
<td>2.425</td>
<td>0</td>
<td>0</td>
<td>5.56</td>
</tr>
<tr>
<td>Bus 6</td>
<td>1.01</td>
<td>-0.969</td>
<td>10.5</td>
<td>6.083</td>
<td>0</td>
<td>0</td>
<td>6.16</td>
</tr>
<tr>
<td>Bus 7</td>
<td>1.045</td>
<td>-0.081</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Bus 8</td>
<td>0.997</td>
<td>-0.257</td>
<td>0</td>
<td>0</td>
<td>3.3</td>
<td>1.304</td>
<td>-</td>
</tr>
<tr>
<td>Bus 9</td>
<td>0.977</td>
<td>-0.408</td>
<td>0</td>
<td>0</td>
<td>2.2</td>
<td>0.869</td>
<td>-</td>
</tr>
<tr>
<td>Bus 10</td>
<td>0.972</td>
<td>-0.538</td>
<td>0</td>
<td>0</td>
<td>22</td>
<td>8.695</td>
<td>-</td>
</tr>
<tr>
<td>Bus 11</td>
<td>0.978</td>
<td>-0.546</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>4.347</td>
<td>-</td>
</tr>
<tr>
<td>Bus 12</td>
<td>1.000</td>
<td>-0.389</td>
<td>0</td>
<td>0</td>
<td>22</td>
<td>8.695</td>
<td>-</td>
</tr>
<tr>
<td>Bus 13</td>
<td>1.044</td>
<td>-0.218</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Bus 14</td>
<td>1.037</td>
<td>-0.470</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Bus 15</td>
<td>1.025</td>
<td>-0.685</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Bus 16</td>
<td>0.992</td>
<td>-0.617</td>
<td>0</td>
<td>0</td>
<td>3.3</td>
<td>1.085</td>
<td>-</td>
</tr>
<tr>
<td>Bus 17</td>
<td>0.989</td>
<td>-0.829</td>
<td>0</td>
<td>0</td>
<td>2.2</td>
<td>0.723</td>
<td>-</td>
</tr>
<tr>
<td>Bus 18</td>
<td>0.959</td>
<td>-0.861</td>
<td>0</td>
<td>0</td>
<td>2.2</td>
<td>0.723</td>
<td>-</td>
</tr>
<tr>
<td>Bus 19</td>
<td>0.966</td>
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<td>0</td>
<td>0</td>
<td>11</td>
<td>1.664</td>
<td>-</td>
</tr>
<tr>
<td>Bus 20</td>
<td>0.977</td>
<td>-1.056</td>
<td>0</td>
<td>0</td>
<td>22</td>
<td>2.503</td>
<td>-</td>
</tr>
</tbody>
</table>
4.6.2 The 20% load increase

Although the 10% load increase resulted in increasing the reactive power problem, it was decided to test the system limits by increasing the system loading by another 10% to reach a 20% load increase from the base case loading level. As what was done in the previous case, the increase in the load was done using a constant power factor scheme. Thus the total load for the new case became 8880 MW and 2463 MVAr. Therefore, the additional needed capacity of the generation was about 900 MW, the same added capacity in the previous case. By using the data given in Table 4.1, two units of U400 and one unit of U100 were added to the system to confront this load increase. However, if the same assignment of the units was done as in the 10% load increase case, no feasible solution for the power flow study could have been achieved. So, the additional units were distributed to the remaining generator buses. However to achieve the main goal, which is piling up the reactive power sources away from the load centers to help reveal the short-term voltage stability problem in the next stage of the study, the two large units, U400, were assigned to buses 4 and 5 and the remaining unit was assigned to bus 3. This resulted in adding 200 MVAr at buses 4 and 5 while adding 60 MVAr at bus 6. This distribution returned the system to the original symmetrical distribution of the reactive power sources between the two areas of the system once more Table 4.5 shows the power flow results for the 20% load increase.

From the results shown in Table 4.5, it is clear that the new load increase made the situation worse since the most of the reactive power sources are away from the load centers which resulted in decreasing the bus voltages all over the network and two of the generating stations are working at their reactive power limits. This voltage decrease made any increase in the loading of the system impossible without breaching the ±5% voltage condition and preserving the same generating units’ distribution scheme. This is because if the load was increased and another generating units’ distribution scheme was adopted, the system would have been relieved from the reactive power stresses
imposed on it which help reveal the voltage stability problem. Thus, the load increase was seized at 20% increase from the base case loading level.

<table>
<thead>
<tr>
<th>Bus</th>
<th>V [pu]</th>
<th>Phase [rad]</th>
<th>(P_{\text{gen}}) [pu]</th>
<th>(Q_{\text{gen}}) [pu]</th>
<th>(P_{\text{load}}) [pu]</th>
<th>(Q_{\text{load}}) [pu]</th>
<th>(Q_{\text{max}}) [pu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>1.025</td>
<td>0.000</td>
<td>17.269</td>
<td>3.402</td>
<td>0</td>
<td>0</td>
<td>11.56</td>
</tr>
<tr>
<td>Bus 2</td>
<td>1.025</td>
<td>-0.065</td>
<td>14.8</td>
<td>3.737</td>
<td>0</td>
<td>0</td>
<td>7.56</td>
</tr>
<tr>
<td>Bus 3</td>
<td>0.985</td>
<td>-0.395</td>
<td>10.5</td>
<td>6.110</td>
<td>0</td>
<td>0</td>
<td>6.16</td>
</tr>
<tr>
<td>Bus 4</td>
<td>1.05</td>
<td>-0.231</td>
<td>22.5</td>
<td>5.502</td>
<td>0</td>
<td>0</td>
<td>11.56</td>
</tr>
<tr>
<td>Bus 5</td>
<td>1.05</td>
<td>-0.448</td>
<td>14.8</td>
<td>6.508</td>
<td>0</td>
<td>0</td>
<td>7.56</td>
</tr>
<tr>
<td>Bus 6</td>
<td>0.975</td>
<td>-0.904</td>
<td>10.5</td>
<td>6.103</td>
<td>0</td>
<td>0</td>
<td>6.16</td>
</tr>
<tr>
<td>Bus 7</td>
<td>1.048</td>
<td>-0.074</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Bus 8</td>
<td>1.006</td>
<td>-0.238</td>
<td>0</td>
<td>0</td>
<td>3.6</td>
<td>1.423</td>
<td>-</td>
</tr>
<tr>
<td>Bus 9</td>
<td>0.988</td>
<td>-0.372</td>
<td>0</td>
<td>0</td>
<td>2.4</td>
<td>0.949</td>
<td>-</td>
</tr>
<tr>
<td>Bus 10</td>
<td>0.981</td>
<td>-0.482</td>
<td>0</td>
<td>0</td>
<td>24</td>
<td>9.485</td>
<td>-</td>
</tr>
<tr>
<td>Bus 11</td>
<td>0.988</td>
<td>-0.488</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>4.743</td>
<td>-</td>
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<tr>
<td>Bus 12</td>
<td>1.008</td>
<td>-0.340</td>
<td>0</td>
<td>0</td>
<td>2.4</td>
<td>0.949</td>
<td>-</td>
</tr>
<tr>
<td>Bus 13</td>
<td>1.048</td>
<td>-0.176</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Bus 14</td>
<td>1.049</td>
<td>-0.326</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Bus 15</td>
<td>1.048</td>
<td>-0.556</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Bus 16</td>
<td>0.985</td>
<td>-0.487</td>
<td>0</td>
<td>0</td>
<td>3.6</td>
<td>1.183</td>
<td>-</td>
</tr>
<tr>
<td>Bus 17</td>
<td>0.989</td>
<td>-0.716</td>
<td>0</td>
<td>0</td>
<td>2.4</td>
<td>0.789</td>
<td>-</td>
</tr>
<tr>
<td>Bus 18</td>
<td>0.927</td>
<td>-0.767</td>
<td>0</td>
<td>0</td>
<td>2.4</td>
<td>0.789</td>
<td>-</td>
</tr>
<tr>
<td>Bus 19</td>
<td>0.946</td>
<td>-0.909</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>1.905</td>
<td>-</td>
</tr>
<tr>
<td>Bus 20</td>
<td>0.940</td>
<td>-0.998</td>
<td>0</td>
<td>0</td>
<td>24</td>
<td>3.113</td>
<td>-</td>
</tr>
</tbody>
</table>
4.7 Cases of voltage instability

In this section, the time domain simulation results of the different fault locations with the contingencies, for the different induction motor penetration levels, are shown and thus the cases that need the placement of SVC are deduced. These time domain simulations are made under some assumptions. These assumptions are:

1. The generator step-up transformer buses are excluded from the probable fault locations. This is because these fault locations would result in rotor-angle instability which is not the phenomenon under study.
2. The fault duration is chosen to be 0.06 seconds (three cycles) which is a typical fault-clearing duration of the circuit breakers used at this transmission level.
3. The fault clearing is done by opening a transmission line connected to the faulted bus. This transmission line remains opened till the end of the time domain simulation period.

Due to the large amount of the figures resulting from these time domain simulations and in order to preserve the continuity of the text, all the figures that will be mentioned in the course of the following sections, are gathered in Appendix (B).

4.7.1 Results for 30% induction motor penetration level

For the 30% induction motor penetration level, the faults were applied on each bus, except the excluded ones as stated above, with all the possible contingencies; only four cases resulted in voltage instability. These cases are:

1. Fault at bus 16 and line 20 outage

This case is a result of one of the main features chosen to be found in the test system which is the presence of single-circuit transmission lines. The disconnection of this line following a fault at the same bus which is bus 16 resulted in nearly the stalling of 60% of the induction motors found in the
second area. Figure B.1 and Figure B.2 show the slips of the stalling induction motors and the voltages of the buses in the second area respectively. It is clear that following the fault-clearing and the line outage, the voltages of buses 18, 19, and 20 couldn’t recover reaching values around 0.70 pu. This is because the loads in this area depended mainly on the generators found in the first area and gen 6 couldn’t support the area by itself since it was working at it reactive power limit. Thus, when the only link was cut, the reactive power was transmitted through other paths which increased the voltage drop and wasn’t adequate enough to support the bus voltages of the second area. This resulted in the increase of the reactive power demand of the induction motors connected at these buses, consequently. These motors stalled after 4 seconds of the fault occurrence. As for the first area, the bus voltages weren’t affected this is because the induction motor penetration level wasn’t high enough such that the dynamics of the induction motors in the second area would propagate to affect the first area.

2. Fault at bus 18 and line 20 outage

This case resulted in nearly the same performance encountered in the previous case. This is because the same conditions of the previous case weren’t changed except for the fault location. However, this change didn’t affect the results much since the fault was at the end of the transmission line instead of being at its beginning. Figure B.3 and Figure B.4 show the slips of the stalling induction motors and the voltages of the buses in the second area respectively.

3. Fault at bus 18 and line 21 outage

This case is different from the previous two cases where severe voltage decrease was encountered for only two buses, namely bus 19 and bus 20 while the remaining buses of the system were able to maintain acceptable voltage levels. However, the main cause of the voltage instability in this case was just the same as in the previous two cases. This is the disconnection of a single-circuit transmission line used for the voltage support of these two buses. Figure
B.5 shows the slips of the induction motors connected to these two buses and Figure B.6 shows their voltages. It is clear from these two figures that the bus voltages recovered to acceptable limits, around 0.9 pu but this recovery couldn’t be maintained due to the lack of dynamic reactive power support from the system even though there is a fixed capacitor connected to bus 19. Thus, the bus voltages again decreased. The voltage collapse in this case was some what delayed but couldn’t be prevented. As for the remaining buses of the area, bus 18 maintained its pre-fault bus voltage level. This is because it was isolated from the origin of the voltage collapse by disconnecting line 21. As for bus 17, it reached around its pre-fault voltage value but encountered some oscillations that dyed out after some time.

4. Fault at bus 19 and line 26 outage

In this case, the voltage instability was in the form of oscillations with increased amplitude. Figure B.7 shows the slips of the induction motors connected at buses 18 and 20. It is clear that the voltage collapse happened after about one minute from the fault occurrence. This means that the system was very near to the stability region but needed some reactive power support however this support wasn’t found thus the voltage collapsed. Figure B.8 shows the voltage of bus 20.

From the above cases, it is clear that all the cases resulting from this induction motor penetration level are located in the second (right-side) area. This is due to many reasons:

1. The presence of single-circuit transmission lines in the second area which act as a throttling point for the reactive power transmitted from the first area. This was the main cause for the first three cases.
2. In all the cases, buses 19 and 20 were the origin of the voltage instability. This is because the largest induction motor loads are connected to these two buses making them the most probable buses to collapse if the system is subjected to a disturbance.
3. The better distribution of the reactive power sources for the first area than for the second one. This is because the reactive power could be transmitted from two directions; from gen. 1 and gen. 2 or from gen. 4 and 5. While for the second area, the reactive power transmission is only from one direction; gen. 4 and gen. 5. This made the voltage support in the second area more difficult especially if an important links as lines 20 and 21 are cut.

4. The induction motor penetration level isn’t high enough in this case such that the dynamics of the induction motors in the second area would affect the first area.

Thus, only the buses in the second area were the ones that suffered from severe decrease in the voltage while the buses in the first area maintained almost their pre-fault voltage levels.

4.7.2 Results for 40% induction motor penetration level

As in the previous induction motor penetration level, the same disturbances were applied. These disturbances resulted in five cases that suffered from the voltage instability. These cases are the same as those encountered for the 30% induction motor penetration level. However, some cases started to show up at the boundaries of the two areas. The cases that encountered for the 40% induction motor penetration level are:

1. Fault at bus 11 and line 7 outage

This is the first case that started to show up at the boundaries of the first area. Figure B.9 shows the slip of the induction motor connected at bus 19 and Figure B.10 and Figure B.11 show the voltages of buses 9 and 20 respectively. In this case, the voltages didn’t collapse however they encountered a sustained oscillatory response with the voltages of all the buses of the network oscillating between ±0.05 pu from their pre-fault values. This oscillatory response was due
to the disconnection of line 7. This is because when this line was disconnected the system interconnection became weaker since the upper part (buses 8, 9, and 10) and lower part (buses 11 and 12) of the first area were disconnected. This resulted in decreasing the buses voltages thus, increasing the reactive power demand of the induction motors connected at these buses. However, the area’s main connections were still intact thus; this higher reactive power demand was supported by the nearby generators (gen 4 and gen 5) thus increasing the voltage. But the transmission of the reactive power was over longer transmission paths which resulted in the decrease of the voltage and so on. Thus, the sustained oscillatory response was obtained. This could be over come by the presence of a reactive power source near the load centers, for example at bus 10 or 11, which would act as a fixing point for the buses voltages.

2. Fault at bus 16 and line 20 outage

This fault location-line outage combination resulted in a voltage collapse in the second area just as the 30% induction motor penetration level. Figure B.12 shows the slips of the stalling induction motors. They were the same induction motors that stalled in the previous penetration. However, the time to stalling decreased from nearly 5 seconds for the 30% penetration level to 4 seconds for the 40% penetration level. Also, as shown in Figure B.13, the voltages of the buses of the second area completely collapsed to low levels around 0.6 pu which is lower than the levels encountered in the 30% penetration level. However, buses 16 and 17 some how could ride-through the disturbance and maintained voltages around 0.85 pu. This is because they are well connected by medium-length double-circuit-transmission lines to the first area. These connections were the main reason these buses could maintain much higher voltages than the remaining buses of the second area. Another thing is that the voltage collapse in this case was much faster than that in the 30% penetration level. This is because in this case the dynamics of the induction motors were more severe since the penetration level increased. Although the penetration level increased, it wasn’t high enough such that the dynamics of the
induction motors in the second area could affect the voltages of the first area lead to its collapse.

3. Fault at bus 18 and line 20 outage

Just as what happened in the 30% penetration level, the results obtained for this fault location –line outage combination were the same as those obtained for the previous case. This is because the fault location change didn’t change the characteristics of the disturbance much since the only change was that the fault was at the end of the line instead of being at its beginning. Figure B.14 and Figure B.15 show the slips of the stalling induction motors and the voltages of the buses they are connected to.

4. Fault at bus 18 and line 21 outage

This case resulted in nearly the same response of the same fault location-line outage combination for the 30% penetration level with the voltage collapse encountered at two buses of the second area, namely buses 19 and 20. However, it was much faster. As shown in Figure B.16 the induction motors stalled after about 5 seconds from the fault clearing while in the 30% penetration level, the motors stalled after about 10 seconds which is double the time for the 40% penetration level. Also, as shown in Figure B.17, the voltages couldn’t recover to an acceptable level even for one time which didn’t happen in the 30% penetration level where the voltages recovered to an acceptable level but couldn’t sustain this recovery. As for the remaining buses of the area, bus 18 maintained its pre-fault bus voltage level. This is because it was isolated from the origin of the voltage collapse by disconnecting line 21. As for bus 17, the voltage reached a value of 0.85 pu but encountered some oscillations that dyed out after a time period which is longer than that in the 30% penetration level.
5. **Fault at bus 19 and line 26 outage**

As in the first case of this induction motor penetration level, this fault location and line outage resulted in an oscillatory response. However, the oscillations in this case were more severe to the extend that the voltage at some buses were in the range of 0.15 pu. Figure B.18 and Figure B.19 show the voltages of buses 16 and 18 respectively.

From the above results, the induction motor penetration level increase had a great effect on the system response to the different disturbance. This was clear in many forms as:

1. The appearance of new cases that didn’t suffer from the voltage instability in the 30% penetration level.
2. The recovery level of the voltages immediately after the fault clearance decreased very much that it couldn’t reach an acceptable level even for one time. While in the 30% penetration level, the voltages recovered to acceptable levels but couldn’t maintain these levels.
3. The time to stall of the induction motors decreased nearly to half its value for the same fault location-line outage combination in the 30% penetration level which indicate faster voltage collapse, thus fast acting SVC’s would be required if this collapse is to be prevented.
4. The oscillations of the voltage at some buses became more severe where it reached for some buses to the range of 0.15 pu.

4.7.3 **Results for 50% induction motor penetration level**

For the 50% induction motor penetration level, nearly all fault locations in the two areas resulted in severe decrease in the bus voltages. This is because the induction motor penetration level became high enough that the system became weaker to the extend that the dynamics of the induction motors in either area would affect the voltages of the other area. Also, most of the cases that resulted from this penetration level were characterized by oscillations with
increasing amplitude before the occurrence of the complete voltage collapse while the other cases were characterized by having sustained oscillations. The cases that resulted in severe voltage decrease were:

1. **Fault at bus 8 and line 1 outage**

   This case didn’t appear in the previous penetration levels. This is because the induction motor penetration level became high enough that the disturbance in the first area resulted in nearly the collapse of all the buses of the two areas. As shown in Figure B.20, two induction motors in the second area and a single one in the first area stalled. This is because these induction motors are the largest all over the network and it is clear that the stalling took about a minute to occur. This means that the system was trying to recover but couldn’t support the voltage. This is clear in Figure B.21 and Figure B.22 which show the voltages of some buses in the first and second areas respectively. It is clear that the voltages oscillated in an attempt to recover but each time the reached levels couldn’t be maintained and collapsed once again till the voltage couldn’t be recovered and reached a very low level.

2. **Fault at bus 8 and line 3 outage**

   This fault location-line outage combination resulted nearly in the same response as in the previous case. However, the final buses voltages decrease was delayed by about 10 seconds as shown in Figure B.23 and Figure B.24. This is because the availability of both circuits of the line between bus 7 and bus 8 increased the ability to recover from the disturbance because the reactive power capability of gen. 1. However, this wasn’t enough to prevent the voltage from collapse.

3. **Fault at bus 9 and line 3 outage**

   This fault location accompanied by line 3 outage gave the same response as for fault at bus 8 and the same line outage. Thus, for simplicity these two cases will be treated as the same case.
4. **Fault at bus 9 and line 5 outage**

This case resulted in an oscillatory response with the amplitude of the oscillations increasing. These oscillations were severe such that it reached a range of 0.15 pu at some buses. As shown in Figure B.25 and Figure B.26 the voltages of the buses started to collapse near the end of the simulation period where the oscillations reached 0.3 pu. This prolonged oscillation before the collapse response was obtained because the dynamics of induction motors in the first area in addition to the dynamics of the induction motors in the second area weren’t severe to make the voltage collapse immediately after the fault. Also, the reactive power capability of the system weren’t sufficient enough to maintain acceptable voltage levels. Thus, the voltages of the buses oscillated with the oscillations increasing till the voltage started to collapse.

5. **Fault at bus 11**

This fault location with all the possible contingencies that could accompany it resulted in an oscillatory response at all the buses of the system. The voltages of the buses oscillated in the range of ±0.1 pu from the pre-fault value of the bus voltage. These cases were considered to be requiring placement of SVC to improve these responses. Figure B.27 shows the voltage of bus 20 for line 8 outage as an example for the response obtained for this fault location. As stated in the previous case, the voltages started to collapse at the end of the simulation period.

6. **Fault at bus 12**

The fault at bus 12 gave the same results as those obtained from the fault at bus 9 with its both lines outages. The fault at bus 12 and line 8 outage resulted in an oscillatory response just as the response obtained from the case of the fault at bus 9 and line 5. As for the case of fault at bus 12 and line 10 outage; the voltages oscillated for a period of time and then collapsed with two induction motors in the second area and a single induction motor in the first area. Figure B.28 shows the slips of the stalling induction motors for the
combination of fault at bus 12 and line 10 outage and Figure B.29 shows the voltages of some buses in the second area.

7. **Fault at bus 16 and line 20 outage**

This case was repeated for the 30% and 40% induction motor penetration levels. The voltages of the buses in the second area suffered from severe voltage decrease. Immediately after the fault clearing and couldn’t recover which resulted in stalling of three induction motors in the second area after about 3 seconds of the fault clearing. Figure B.30 shows the slips of the stalling induction motors and Figure B.31 shows the voltages of the buses in the second area. By comparing the results obtained from the three penetration levels, 30%, 40%, and 50%, it is clear as the penetration level increases, the recovery level of the bus voltages decreases and the time to stalling of the induction motors also decreases which results in quicker voltage collapse. This would require faster dynamics of the SVC to be used for the prevention of the voltage collapse.

8. **Fault at bus 18 and line 20 outage**

Just as what happened in the 30% and 40% penetration level, the results obtained for this fault location–line outage combination were the same as those obtained for the fault at bus 16 and line 20 outage case. This is because the fault location change didn’t change the characteristics of the disturbance much since the only change was that the fault was at the end of the line instead of being at its beginning. Figure B.32 and Figure B.33 show the slips of the stalling induction motors and the voltages of the buses they are connected to.

9. **Fault at bus 18 and line 21 outage**

This case resulted in nearly the same response of the same fault location-line outage combination for the previous penetration levels with the voltage collapse encountered at two buses of the second area, namely buses 19 and 20. However, it was much faster than the other two cases. As shown in
Figure B.34 the induction motors stalled after about 3 seconds from the fault clearing while in the previous penetration levels, the motors stalled after about 10 seconds for the 30% penetration level and 5 seconds for the 40% penetration level. Also, as shown in Figure B.35, the voltages couldn’t recover to an acceptable level which is the same as the case for the 40% penetration level which didn’t happen in the 30% penetration level where the voltages recovered to an acceptable level but couldn’t sustain this recovery.

From the above results, the induction motor penetration level increase had a great effect on the system response to the different disturbance. This was clear in many forms as:

1. Most of the fault locations resulted in voltage instability problems. This is because the induction motor penetration level became high enough that the dynamics of either area affected the other one.
2. The cases in the first area were mainly characterized by severe oscillations ranging from 0.1 pu to 0.3 pu. Some cases suffered from prolonged oscillations. This is because the dynamics of the induction motors weren’t severe enough to cause the voltage collapse and the reactive power sources weren’t adequate enough to support the voltage.
3. The recovery level of the voltages immediately after the fault clearance decreased very much more than the case for the 40% penetration level.
4. The time to stall of the induction motors decreased very much for the same fault location-line outage combination in the 30% and 40% penetration levels which indicate faster voltage collapse, thus fast acting SVC’s would be required if this collapse is to be prevented.
4.7.4 Results for 60% induction motor penetration level

For this induction motor penetration level, all the fault locations resulted in dramatic decrease in the bus voltages. The main characteristics of these cases is that the voltage collapse of most cases, either in the first area or in the second, was very fast at most after 5 seconds from the fault clearance. Very few cases suffered from oscillatory response before the voltage collapsed. The cases that resulted in voltage instability are:

1. Fault at bus 8 with all line outage combinations
2. Fault at bus 9 with all line outage combinations
3. Fault at bus 11 with all line outage combinations
4. Fault at bus 12 with all line outage combinations
5. Fault at bus 16 and line 20 outage
6. Fault at bus 17 and line 22 outage
7. Fault at bus 18 with all line outage combinations
8. Fault at bus 19 with line 26 outage

For the purpose of briefing, since most of the cases resulted in nearly the same response with slight changes; only the first case will be thoroughly illustrated. This is because all the other combination of the fault locations and lines outage resulted in a voltage collapse either in a single area, as the response obtained in the case fault at bus 8 and line 1 outage, or a voltage collapse in both areas as the response obtained in the case of fault at bus 8 and line 3 outage. As for the first case (fault at bus 8 and line 1 outage), Figure B.36 shows the slips of the stalling induction motors. It is clear that the motors took about 10 seconds to stall while in the 50% penetration level the time to stalling was about one minute after some oscillations. Figure B.37 shows the bus voltages of the second area which encountered the voltage instability. It is clear that the voltage recovered to an acceptable level but this recovery couldn’t be maintained and the voltage decreased once more.
As for the second case (fault at bus 8 and line 3 outage); a complete voltage collapse was encountered in both areas and most of the induction motors in the system stalled. Figure B.38 and Figure B.39 show the slips of the stalling induction motors in the first and second areas respectively. It is clear, as in the first case, the time to stalling of the induction motors decreased very much. Figure B.40 and Figure B.41 show the bus voltages of the buses of the first and second areas respectively. Also, as in the first case, the voltages recovered to acceptable levels but these levels couldn’t be maintained.

4.8 Conclusions

From the analysis made through the chapter, the some conclusions could be made out. These conclusions are:

1. The presence of single-circuit transmission lines in the second area which act as throttling points for the reactive power transmitted from the first area. This was the main cause of the voltage instability of many cases regardless of the induction motor penetration level.

2. The reactive power sources for the first area are distributed in a better way than for the second. This is because the reactive power, for the first area, could be transmitted from two directions; from gen. 1 and gen. 2 or from gen.4 and 5. While for the second area, the reactive power transmission is only from one direction; gen.4 and gen.5. This made the voltage support in the second area more difficult especially if important links as lines 20 and 21 are cut.

3. In most cases, buses 19 and 20 were the origin of the voltage instability. This is because the largest induction motor loads are connected to these two buses making them the most probable buses to collapse if the system is subjected to a disturbance.

4. The 30% and 40% induction motor penetration levels weren’t high enough such that the dynamics of the induction motors in the second area couldn’t affect the voltages in the first area. While as the
penetration level increased to 50% the cases of the voltage instability started to show up in the form of oscillations with increasing amplitudes. However, as the penetration level reached 60%, any disturbance either in the first area or in the second one resulted in voltage collapse in both areas.

5. For the 50% induction motor penetration level, the cases in the first area were mainly characterized by severe oscillations ranging from 0.1 pu to 0.3 pu. Some cases suffered from prolonged oscillations. This is because the dynamics of the induction motors weren’t severe enough to cause the voltage collapse and the reactive power sources weren’t adequate enough to support the voltage.

6. As the induction motor penetration level increase, the recovery level of the voltages immediately after the fault clearance decreased very much that it couldn’t reach an acceptable level even for one time for the 40%, 50%, and 60% penetration levels. While in the 30% penetration level, the voltages recovered to acceptable levels but couldn’t maintain these levels.

7. The time to stall of the induction motors decreased very much for the same fault location-line outage combination as the induction motor penetration level increases. This indicates faster voltage collapse, thus fast acting SVC’s would be required if this collapse is to be prevented.

After all the cases that encountered voltage instability or voltage collapse have been determined for the different induction motor penetration levels, an optimization problem will be formulated to optimally allocate and size the SVC that would be used to improve the voltage stability problem.
CHAPTER 5
OPTIMAL ALLOCATION AND SIZING OF SVC

5.1 Introduction

In the previous chapter, the test system was modified in such a way that helped reveal the phenomenon under study. This was done by increasing the system loading level and replacing portions of the static loads with induction motor loads which is the main driving force in the short-term voltage stability problem. Then, the cases that would require placement of an SVC to improve the voltage stability of the system have been illustrated. This chapter shows the simulation results of the optimal allocation and sizing of the SVC, used to improve the short-term voltage stability of the modified test system for the different cases. First, the optimization programs used are explained. Then, the optimization results for the optimal allocation and sizing of the SVC are illustrated.

5.2 Optimization problem formulation

In this section, the formulation of the optimization problem to optimally allocate and size will be explained. This will be done for the Genetic Algorithm toolbox which is built-in Matlab and for the search program built to do the same function.

5.2.1 Search program

The main idea on which the search program depends is very simple. It depends on the concept of trial and error. The search program is divided into two stages:

1. The determination of the maximum voltage improvement.
2. The optimal allocation and sizing of the SVC.
As for the first stage, for every fault location-line outage combination, an SVC with a relatively large size, $B_{svc} = 20$ pu, is placed at a certain bus. Then the average value of each bus voltage is calculated and the minimum value of the calculated average bus voltage is selected. These procedures are repeated for all the buses of the network. Then, the maximum value of these stored average bus voltage values is selected to be the threshold the SVC must achieve with the minimum size. This threshold must be greater than 0.85 pu to insure proper operation of the network in this emergency mode of operation. If this condition isn’t achieved, the case is considered unsolvable and the second stage is bypassed. Figure 5.1 shows a block diagram for the first stage of the search program and the code of this stage is in Appendix (C).
As for the second stage, using the determined threshold of the improved bus voltage and the location that would achieve this threshold, the search program starts to decrease the size of the SVC using the bi-section method. This process continues till the threshold couldn’t be maintained. This means that the achieved size couldn’t be decreased no more at the same location. Therefore, the achieved size is reduced by a small amount, 0.1 pu, and used at another location. If the new size at the new location resulted in minimum average bus voltage greater than the pre-determined threshold, the bi-section method is used again to determine the minimum size at the new location. If not, the location is changed till all the locations are studied. Figure 5.2 shows a block diagram for the second stage of the search program and the code of this stage is in Appendix (C)

5.2.2 Genetic Algorithm

The genetic optimization technique was used in order to optimally allocate and size the SVC for the different cases previously illustrated. The variables of this optimization problem were the size of the SVC and its location. This technique was implemented using the built-in Genetic Algorithm Toolbox of the Matlab. During this implementation all the parameters that govern the performance of the algorithm were set to their default values and the constraints were

\[ 0 \leq B_{svc} \leq 20 \]
\[ 7 \leq \text{location} \leq 20 \]  \hspace{1cm} (5.1)

As for the maximum voltage improvement that was implemented in the search program, it was required to do the same in the genetic algorithm. This was done by making the fitness function discrete. This was done by using an IF function. Thus, if the minimum average bus voltage is less than an acceptable
value, the fitness function is given a very high value so that the values of the variables are given a very low priority in the next generation.

Figure 5.2: The block diagram of the second stage of the search program
While if the minimum average bus voltage is in the acceptable range, the fitness function is calculated using another formula which would give a low value depending on the values of the variables. The code of the function used with the built-in toolbox in the Matlab is given in Appendix (C).

5.3 Optimization results

Using the above optimization programs, the optimum locations and sizes of the SVC were found for the cases derived in the previous chapter. These results will be illustrated in the following sub-sections. As what was done in the previous chapter for preserving the continuity of the text, all the figures that will be mentioned in the course of the following sub-sections, are gathered in Appendix (D).

5.3.1 Results for the 30% induction motor penetration level

Table 5.1 shows the optimum locations and sizes of the SVCs for the cases encountered for the 30% induction motor penetration level. These results are obtained from the search program and the Genetic Algorithm toolbox. The figures from Figure D.1 to Figure D.8 show the bus voltages of some buses for the different voltage instability cases encountered.

<table>
<thead>
<tr>
<th>Faulted Bus</th>
<th>Disconnected Line</th>
<th>Search Program Location</th>
<th>G.A. Toolbox Location</th>
<th>Case</th>
<th>Search Program Size (b_{SVC} in pu)</th>
<th>G.A. Toolbox Size (b_{SVC} in pu)</th>
</tr>
</thead>
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<tr>
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<td>18</td>
<td>18</td>
<td>3.125</td>
<td>2.86527</td>
</tr>
</tbody>
</table>
From the above results and the figures mentioned, the following conclusions could be made out:

1. The first two cases required very high compensation level, nearly around 75% of the total system reactive power load. This is because these cases were caused due to the disconnection of a single-circuit transmission line which resulted in removing of the support generator 6 could have provided.

2. The optimal location of the SVC, for the first three cases, could have been predicted from the analysis made in the previous chapter. Thus is because the results obtained showed that buses 18, 19, and 20 were the buses that suffered from the severe decrease in the voltage. Thus, the optimum location for the SVC would be a bus that was the main cause of this voltage decrease. This bus is bus 19 since the largest induction motor load is connected to it. Thus, if this bus was prevented from collapse, the remaining buses could ride-through the disturbance.

3. From the figures mentioned above, it is clear that in some cases, such as the first two cases, the voltages encountered some oscillations before settling at acceptable levels. While in the other two cases, the voltages settled at the acceptable levels smoothly. This is because of the dynamics of the added SVC where in the cases were the transient response suffered from some oscillations, the chosen parameters of the added SVC weren’t well tuned. While in the other cases, these parameters were well tuned. Here, it must be stated that the parameters of the SVC weren’t changed but they are kept constant for all the cases. However, by incidence, these parameters resulted in a smooth transient response in some cases while in the other cases, this wasn’t achieved. This is because the transient response of the voltages wasn’t considered in this optimization problem but the main concern was the prevention of the voltage collapse.
5.3.2 Results for the 40% induction motor penetration level

Table 5.2 shows the optimum locations and sizes of the SVCs for the cases that encountered voltage instability for the 40% induction motor penetration level. These results are obtained from the search program and the Genetic Algorithm toolbox. The figures from Figure D.9 to Figure D.18 show the bus voltages of some buses for the different voltage instability cases encountered.

<table>
<thead>
<tr>
<th>Faulted Bus</th>
<th>Disconnected Line</th>
<th>Case</th>
<th>Search Program Location</th>
<th>Size ((b_{\text{SVC}} \text{ in pu}))</th>
<th>G.A. Toolbox Location</th>
<th>Size ((b_{\text{SVC}} \text{ in pu}))</th>
</tr>
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<tbody>
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</tbody>
</table>

From the above results and the figures mentioned, the following conclusions could be made out:

1. As in the 30% induction motor penetration level, the cases in which a single-circuit transmission line is disconnected required a very high compensation level, around 85% of the total system reactive power load which may be considered as an impractical application. Also, the compensation level for these cases is higher for the 40% induction motor penetration level than that for the 30% induction motor penetration level. Therefore, following a simple logic, the voltage collapse due to the same reason for higher induction motor penetration levels wouldn’t be improved.
2. Comparing the optimal size of the SVC for the first case of this penetration level with the other cases, it is clear that the optimal size of the SVC required for this case is approximately 15% of the smallest size of the other cases. This is because the voltage in this case (fault at bus 11 and line 7 outage) didn’t collapse, it oscillated. Thus, the SVC required for such case was just to help damp these oscillations not to support the voltage.

3. When the optimization results of this induction motor penetration level were compared with the optimization results of the 30% induction motor penetration level, it was clear that the penetration level didn’t affect the optimum location. This is because this location is the location where the voltage instability originated because at bus 19 the largest induction motor load is connected as it was explained in the previous sub-section.

4. From the figures mentioned above, the transient response of the voltages in some cases became worse than that obtained for the same cases in the 30% induction motor penetration level. This is because the dynamics of the system became faster due to the increase in the induction motor loads. Thus, the dynamics of the SVC became faster so as to cop with the system dynamics to prevent the voltage from collapse. This resulted in the increased oscillations of the voltages before settling to the acceptable levels.

5.3.3 Results for the 50% induction motor penetration level

Table 5.3 shows the optimum locations and sizes of the SVCs for the cases that encountered voltage instability for the 50% induction motor penetration level. These results are obtained from the search program and the Genetic Algorithm toolbox. The figures from Figure D.19 to Figure D.38 show the bus voltages of some buses for the different voltage instability cases encountered.
Table 5.3: Optimization results for the cases of 50% induction motor penetration level

<table>
<thead>
<tr>
<th>Faulted Bus</th>
<th>Disconnected Line</th>
<th>Search Program Location</th>
<th>Size (b_{SVC} in pu)</th>
<th>G.A. Toolbox Location</th>
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</table>

From the above results and the figures mentioned, the following conclusions could be made out:

1. As predicted in the previous sub-section, no feasible solution could be found for the two cases that were accompanied by single-circuit transmission line disconnection. This is because the induction motor penetration level was high enough such that the system couldn’t ride through the disturbance. Thus, in order to prevent the voltage collapse in these cases, another circuit must be added to these transmission lines.

2. The optimum size of the SVC required to improve the voltage stability was relatively small, at most 1pu except for the last case. This is because the voltage response was oscillatory and encountered severe decrease after some time. Thus, an SVC with relatively small size was required to prevent that oscillatory response from the beginning.
5.3.4 Results for the 60% induction motor penetration level

Table 5.4 shows the optimum locations and sizes of the SVCs for the cases that encountered voltage instability for the 60% induction motor penetration level. These results are obtained from the search program and the Genetic Algorithm toolbox. The figures from Figure D.39 to Figure D.62 show the bus voltages of some buses for the different voltage instability cases encountered.

Table 5.4: Optimization results for the cases of 60% induction motor penetration level

<table>
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<tr>
<th>Case Faulted Bus</th>
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</tr>
</tbody>
</table>
From the above results and the figures mentioned, the following conclusions could be made out:

1. The compensation level increased for the same cases for the 50% penetration level and a new case appeared in the second area which is for a fault at bus 17. This case required a relatively high level of compensation. This is because the dynamics of the induction motors became more severe.

2. The optimum location of the SVC for the cases of this penetration level followed the pattern of the bus at which the largest induction motor is connected. This wasn’t the case for the 50% penetration level. This because at the 50% penetration level, the voltage was oscillatory and the collapse was delayed for long times, at some cases till the end of the simulation results. Thus any location in the area would act as a fixing point for the voltage and these oscillations would be damped. But for the 60% penetration level, the voltages weren’t oscillatory but encountered collapse after a short period of time. Thus, in this case the optimum location won’t be at any bus but it would be at the bus at which the dynamics of induction motor connected to it are dominating the performance of the system. These locations are usually at the buses where the largest induction motors are connected.

3. Also, as the induction motor penetration level increased the compensation level required in order to prevent the voltage collapse increases but mainly at the same locations.
5.4 Conclusions

From the analysis made through the chapter, the following conclusions could be made out. These conclusions are:

1. In the 30% induction motor penetration level, the cases in which a single-circuit transmission line was disconnected required a very high compensation level, around 75% of the total system reactive power load which increased to 85% for 40% penetration level. These cases couldn’t be compensated for higher penetration levels.

2. The optimal location of the SVC could be predicted from the analysis made in the previous chapter. This is because the results obtained showed that the buses at which the largest induction motors are connected are the buses that suffered from the severe decrease in the voltage. Thus, the optimum location for the SVC would be a bus that was the main cause of this voltage decrease. This bus is the bus at which a large induction motor is connected. Thus, if this bus was prevented from collapse, the remaining buses could ride-through the disturbance.

3. The optimum size of the SVC required to improve the voltage stability for the cases that suffered from oscillatory voltage response was relatively small, at most 1pu. This is because the voltages encountered severe decrease after some time. Thus, an SVC with relatively small size would be required to prevent that oscillatory response from the beginning and help damp these oscillations.

4. In some cases, the voltages encountered some oscillations before settling at acceptable levels after the SVC was added. While in other cases, the voltages settled at the acceptable levels smoothly. This is due to the dynamics of the added SVC where in the cases were the transient response suffered from some oscillations, the chosen parameters of the added SVC weren’t well tuned. While in the other cases, these parameters were well tuned. These parameters weren’t tuned on purpose
but, by incidence, these parameters resulted in a smooth transient response in some cases while in the other cases, this wasn’t achieved. This is because the transient response of the voltages wasn’t considered in this optimization problem but the main concern was the prevention of the voltage collapse.

5. As the induction motor penetration level increases, the transient response of the voltages in some cases becomes worse. This is because the dynamics of the system become faster. Thus, the dynamics of the SVC become faster so as to cope with the system dynamics to prevent the voltage from collapse. This resulted in the increased oscillations of the voltages before settling to the acceptable levels.
CHAPTER 6
CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The conclusions of the thesis could be summarized in the following points:

1. The main driving force to the short-term voltage stability was the dynamics of the induction motors. However, the reactive power capability of the generators, especially those near the load centers, and their distribution all over the system had an important role in the scenarios seen through the research.

2. The presence of single-circuit transmission lines in the second area which act as throttling points for the reactive power transmitted from the first area. This was the main cause of the voltage instability of many cases regardless of the induction motor penetration level.

3. The reactive power sources for the first area are distributed in a better way than for the second. This is because the reactive power, for the first area, could be transmitted form two directions; from gen. 1 and gen. 2 or from gen.4 and 5. While for the second area, the reactive power transmission is only from one direction; gen.4 and gen.5. This made the voltage support in the second area more difficult especially if important links as lines 20 and 21 are cut.

4. In most cases, buses 19 and 20 were the origin of the voltage instability. This is because the largest induction motor loads are connected to these two buses making them the most probable buses to collapse if the system is subjected to a disturbance.
5. The 30% and 40% induction motor penetration levels weren’t high enough such that the dynamics of the induction motors in the second area couldn’t affect the voltages in the first area. While as the penetration level increased to 50% the cases of the voltage instability started to show up in the form of oscillations with increasing amplitudes. However, as the penetration level reached 60%, any disturbance either in the first area or in the second one resulted in voltage collapse in both areas.

6. For the 50% induction motor penetration level, the cases in the first area were mainly characterized by severe oscillations ranging from 0.1 pu to 0.3 pu. Some cases suffered from prolonged oscillations. This is because the dynamics of the induction motors weren’t severe enough to cause the voltage collapse and the reactive power sources weren’t adequate enough to support the voltage.

7. As the induction motor penetration level increase, the recovery level of the voltages immediately after the fault clearance decreased very much that it couldn’t reach an acceptable level even for one time for the 40%, 50%, and 60% penetration levels. While in the 30% penetration level, the voltages recovered to acceptable levels but couldn’t maintain these levels.

8. The time to stall of the induction motors decreased very much for the same fault location-line outage combination as the induction motor penetration level increases. This indicates faster voltage collapse, thus fast acting SVC’s would be required if this collapse is to be prevented.

9. In the 30% induction motor penetration level, the cases in which a single-circuit transmission line was disconnected required a very high compensation level, around 75% of the total system reactive power load which increased to 85% for 40% penetration level. These cases couldn’t be compensated for higher penetration levels.
10. The optimal location of the SVC could be predicted from the analysis made in the previous chapter. This is because the results obtained showed that the buses at which the largest induction motors are connected are the buses that suffered from the severe decrease in the voltage. Thus, the optimum location for the SVC would be a bus that was the main cause of this voltage decrease. This bus is the bus at which a large induction motor is connected. Thus, if this bus was prevented from collapse, the remaining buses could ride-through the disturbance.

11. The optimum size of the SVC required to improve the voltage stability for the cases that suffered from oscillatory voltage response was relatively small, at most 1pu. This is because the voltages encountered severe decrease after some time. Thus, an SVC with relatively small size would be required to prevent that oscillatory response from the beginning and help damp these oscillations.

12. In some cases, the voltages encountered some oscillations before settling at acceptable levels after the SVC was added. While in other cases, the voltages settled at the acceptable levels smoothly. This is due to the dynamics of the added SVC where in the cases were the transient response suffered from some oscillations, the chosen parameters of the added SVC weren’t well tuned. While in the other cases, these parameters were well tuned. These parameters weren’t tuned on purpose but, by incidence, these parameters resulted in a smooth transient response in some cases while in the other cases, this wasn’t achieved. This is because the transient response of the voltages wasn’t considered in this optimization problem but the main concern was the prevention of the voltage collapse.

13. As the induction motor penetration level increases, the transient response of the voltages in some cases becomes worse. This is because the dynamics of the system become faster. Thus, the dynamics of the SVC become faster so
as to cope with the system dynamics to prevent the voltage from collapse. This resulted in the increased oscillations of the voltages before settling to the acceptable levels.

### 6.2 Future work

The recommended future work may be:

1. Finding one or more location and size for the SVC that would improve the short-term voltage stability problem for all or nearly all the probable fault locations.

2. Increasing the limits of the optimization problem to include the probability of using more than single SVC for the same fault location-contingency which would result in more optimized solution.

3. Introducing the effect of the transient bus voltage response in the optimization problem such that it could be improved as well as preventing the voltage instability. This could be done by making the SVC dynamic model parameters as variables in the optimization problem.

4. Studying the effect of implementing the load shedding schemes in addition to the presence of the SVC and the optimal coordination between both of them.

5. Studying the effect of the introduced FACTS devices for the short-term voltage stability improvement for systems containing HVDC links which are now common in many systems.

6. Studying the effect of presence of other FACTS devices in the system, not tuned for the voltage stability enhancement, on the optimal allocation and sizing of the FACTS device for the short-term voltage stability improvement.
REFERENCES


APPENDIX (A)
THE DATA OF THE TEST SYSTEM

Table A1.1: Generator data

<table>
<thead>
<tr>
<th>generator</th>
<th>GEN1</th>
<th>GEN2</th>
<th>GEN3</th>
<th>GEN4</th>
<th>GEN5</th>
<th>GEN6</th>
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</thead>
<tbody>
<tr>
<td>( x_l ) (pu)</td>
<td>0.228</td>
<td>0.135</td>
<td>0.135</td>
<td>0.228</td>
<td>0.135</td>
<td>0.135</td>
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<tr>
<td>( R ) (pu)</td>
<td>0.0021</td>
<td>0.0010</td>
<td>0.0010</td>
<td>0.0021</td>
<td>0.0010</td>
<td>0.0010</td>
</tr>
<tr>
<td>( x_d ) (pu)</td>
<td>1.693</td>
<td>1.79</td>
<td>1.79</td>
<td>1.693</td>
<td>1.79</td>
<td>1.79</td>
</tr>
<tr>
<td>( x'_d ) (pu)</td>
<td>0.346</td>
<td>0.22</td>
<td>0.22</td>
<td>0.346</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>( T'_{do} ) (pu)</td>
<td>6.58</td>
<td>4.3</td>
<td>4.3</td>
<td>6.58</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>( x_q ) (pu)</td>
<td>1.636</td>
<td>1.715</td>
<td>1.715</td>
<td>1.636</td>
<td>1.715</td>
<td>1.715</td>
</tr>
<tr>
<td>( x'_q ) (pu)</td>
<td>0.346</td>
<td>0.4</td>
<td>0.4</td>
<td>0.346</td>
<td>0.4</td>
<td>0.4</td>
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<tr>
<td>( T'_{q0} ) (pu)</td>
<td>1.5</td>
<td>0.9</td>
<td>0.9</td>
<td>1.5</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>( H ) (s)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( D ) (gain)</td>
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<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
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Table A1.2: Excitation system data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>( V_{Rmax} ) (pu)</td>
<td>3</td>
</tr>
<tr>
<td>( V_{Rmin} ) (pu)</td>
<td>-2</td>
</tr>
<tr>
<td>( K_A ) (gain)</td>
<td>187</td>
</tr>
<tr>
<td>( T_A ) (s)</td>
<td>0.89</td>
</tr>
<tr>
<td>( K_F ) (gain)</td>
<td>0.058</td>
</tr>
<tr>
<td>( T_{F1} ) (s)</td>
<td>0.62</td>
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<td>( T_{F2} ) (s)</td>
<td>0</td>
</tr>
<tr>
<td>( T_{F3} ) (s)</td>
<td>0</td>
</tr>
<tr>
<td>( K_E ) (gain)</td>
<td>1</td>
</tr>
<tr>
<td>( T_E ) (s)</td>
<td>1.15</td>
</tr>
<tr>
<td>( A_E )</td>
<td>0.014</td>
</tr>
<tr>
<td>( B_E )</td>
<td>1.55</td>
</tr>
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</table>
### Table A1.3: Over Excitation Limiter data

<table>
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<th>Variable</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$T_{OEL}$ (s)</td>
<td>10</td>
</tr>
<tr>
<td>$K_2$ (gain)</td>
<td>1</td>
</tr>
<tr>
<td>$K_3$ (gain)</td>
<td>0.5</td>
</tr>
<tr>
<td>$I_{FLM2}$ (pu)</td>
<td>2.4</td>
</tr>
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</table>

### Table A1.4: Induction motor data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$ (s)</td>
<td>0.833</td>
</tr>
<tr>
<td>$X_s$ (pu)</td>
<td>0.087</td>
</tr>
<tr>
<td>$X_r$ (pu)</td>
<td>0.162</td>
</tr>
<tr>
<td>$R_s$ (pu)</td>
<td>0.029</td>
</tr>
<tr>
<td>$R_i$ (pu)</td>
<td>0.034</td>
</tr>
<tr>
<td>$A$</td>
<td>0.8</td>
</tr>
<tr>
<td>$B$</td>
<td>0</td>
</tr>
<tr>
<td>$C$</td>
<td>0.2</td>
</tr>
<tr>
<td>$X_{mag}$ (pu)</td>
<td>3.08</td>
</tr>
</tbody>
</table>

### Table A1.5: Induction motor data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_t$ (gain)</td>
<td>100</td>
</tr>
<tr>
<td>$T_t$ (s)</td>
<td>3</td>
</tr>
</tbody>
</table>
APPENDIX (B)

FIGURES OF THE VOLTAGE INSTABILITY CASES

Figure B.1: Slip of induction motor for fault at bus 16 and line 20 outage for 30% induction motor penetration level

Figure B.2: The voltages of some buses for fault at bus 16 and line 20 outage for 30% induction motor penetration level
Figure B.3: Slip of induction motor for fault at bus 18 and line 20 outage for 30% induction motor penetration level

Figure B.4: The voltages of some buses for fault at bus 18 and line 20 outage for 30% induction motor penetration level
Figure B.5: Slip of induction motor for fault at bus 18 and line 21 outage for 30% induction motor penetration level

Figure B.6: The voltages of some buses for fault at bus 18 and line 21 outage for 30% induction motor penetration level
Figure B.7: Slip of induction motor for fault at bus 19 and line 26 outage for 30% induction motor penetration level

Figure B.8: The voltage of bus 20 for fault at bus 19 and line 26 outage for 30% induction motor penetration level
Figure B.9: Slip of induction motor at bus 19 for fault at bus 11 and line 7 outage for 40% induction motor penetration level

Figure B.10: The voltage of bus 9 for fault at bus 11 and line 7 outage for 40% induction motor penetration level
Figure B.11: The voltage of bus 20 for fault at bus 11 and line 7 outage for 40% induction motor penetration level

Figure B.12: Slip of induction motor for fault at bus 16 and line 20 outage for 40% induction motor penetration level
Figure B.13: The voltages of some buses for fault at bus 16 and line 20 outage for 40% induction motor penetration level

Figure B.14: Slip of induction motor for fault at bus 18 and line 20 outage for 40% induction motor penetration level
Figure B.15: The voltages of some buses for fault at bus 18 and line 20 outage for 40% induction motor penetration level

Figure B.16: Slip of induction motors for fault at bus 18 and line 21 outage for 40% induction motor penetration level
Figure B.17: The voltages of some buses for fault at bus 18 and line 21 outage for 40% induction motor penetration level

Figure B.18: The voltage of bus 16 for fault at bus 19 and line 26 outage for 40% induction motor penetration level
Figure B.19: The voltage of bus 18 for fault at bus 19 and line 26 outage for 40% induction motor penetration level

Figure B.20: Slip of induction motors for fault at bus 8 and line 1 outage for 50% induction motor penetration level
Figure B.21: The voltage of buses 9, 10, and 11 for fault at bus 8 and line 1 outage for 50% induction motor penetration level

Figure B.22: The voltage of buses 18, 19, and 20 for fault at bus 8 and line 1 outage for 50% induction motor penetration level
Figure B.23: The voltage of buses 9, 10, and 11 for fault at bus 8 and line 3 outage for 50% induction motor penetration level

Figure B.24: The voltage of buses 18, 19, and 20 for fault at bus 8 and line 1 outage for 50% induction motor penetration level
Figure B.25: The voltage of bus 11 for fault at bus 9 and line 5 outage for 50% induction motor penetration level

Figure B.26: The voltage of bus 20 for fault at bus 9 and line 5 outage for 50% induction motor penetration level
Figure B.27: The voltage of bus 20 for fault at bus 11 and line 8 outage for 50% induction motor penetration level

Figure B.28: Slip of induction motors for fault at bus 12 and line 10 outage for 50% induction motor penetration level
Figure B.29: The voltage of buses 18, 19, and 20 for fault at bus 12 and line 10 outage for 50% induction motor penetration level

Figure B.30: Slip of induction motor for fault at bus 16 and line 20 outage for 50% induction motor penetration level
Figure B.31: The voltages of some buses for fault at bus 16 and line 20 outage for 50% induction motor penetration level

Figure B.32: Slip of induction motor for fault at bus 18 and line 20 outage for 50% induction motor penetration level
Figure B.33: The voltages of some buses for fault at bus 18 and line 20 outage for 50% induction motor penetration level

Figure B.34: Slip of induction motors for fault at bus 18 and line 21 outage for 50% induction motor penetration level
Figure B.35: The voltages of some buses for fault at bus 18 and line 21 outage for 50% induction motor penetration level

Figure B.36: Slip of induction motors for fault at bus 8 and line 1 outage for 60% induction motor penetration level
Figure B.37: The voltages of some buses for fault at bus 8 and line 1 outage for 60% induction motor penetration level

Figure B.38: Slip of induction motors in the first area for fault at bus 8 and line 3 outage for 60% induction motor penetration level
Figure B.39: Slip of induction motors in the first area for fault at bus 8 and line 3 outage for 60% induction motor penetration level

Figure B.40: The voltage of buses of the first area for fault at bus 8 and line 3 outage for 60% induction motor penetration level
Figure B.41: The voltage of buses of the second area for fault at bus 8 and line 3 outage for 60% induction motor penetration level
APPENDIX (C)

THE OPTIMIZATION PROGRAMS

C.1 Code of the search program

clc
initpsat
Settings.tf=100;
Settings.fx=1;
Settings.tstep=0.05;
Settings.checkdelta=1;
Settings.deltadelta=180;
Settings.pq2z=1;
clpsat.readfile=0;
clpsat.mesg=0;
for n=1:4
  switch n
  case 1
    disp('The 60% file')
    runpsat('yrab_60_mdl.m','data')
    cases=[19 19 19;19 17 19;18 14 20;17 17 19;17 15 12;12 25 12;11 07 11;11 25 11;11 24 11;09 22 09;09 20 08;08 20 08;08 01 08];
  case 2
    disp('The 50% file')
    runpsat('yrab_50_mdl.m','data')
    cases=[19 19 19;18 14 20;18 13 16;12 02 12;12 25 12;11 07 11;11 25 11;11 24 11;09 22 09;09 20 08;08 20 08;08 01 08];
  case 3
    disp('The 40% file')
    runpsat('yrab_40_mdl.m','data')
    cases=[19 19 19;18 14 20;18 13 16;16 13 16;11 24 11];
  case 4
    disp('The 30% file')
    runpsat('yrab_30_mdl.m','data')
    cases=[19 19 19;18 14 20;18 13 16;16 13 16];
  end
runpsat('pf')
Vo=DAE.y(1+Bus.n:2*Bus.n);
fault=Fault.store;
breaker=Breaker.store;
svc=[19 100 400 50 1 0.5 100 0.946166 1 -1.5 0.001 0 1 0.01 0.1 0.2 0;]
19 100 400 50 1 0.5 100 0.953579 1 -1.5 0.001 0 1 0.01 0.1 0.2 0;
19 100 400 50 1 0.5 100 0.952689 1 -1.5 0.001 0 1 0.01 0.1 0.2 0;
19 100 400 50 1 0.5 100 0.948422 1 -1.5 0.001 0 1 0.01 0.1 0.2 0;

`pv=PV.store;`
`cn=size(cases,1);`
`sol=zeros(cn,3);`
`for i=1:cn`
  `disp('Case')`
  `disp(i)`
  `idx=find(Fault.store(:,1)==cases(i,1));`
  `Fault.store(idx,[5 6])=[1 1.06];`
  `Breaker.store(1,[1 2 7])=[cases(i,[2 3]) 1.06];`
  `runpsat('pf')`
  `runpsat('td')`
  `t=Varout.t;`
  `Vbus=Varout.vars(:,DAE.n+Bus.n+1:DAE.n+2*Bus.n);`
  `Vavg1=sum(Vbus)/length(t)';`
  `for j=1:14`
    `Vavg(j,[1 2])=[Vavg1(j+6) j+6];`
  `end`
  `Vavg=sortrows(Vavg);`
  `j=1;`
  `while j<=length(Vavg)`
    `Svc.store(1,[1 8 9 17])=[Vavg(j,2) Vo(Vavg(j,2)) 0 1];`
    `x=PV.store;`
    `PV.store(find(x(:,3)==400),[1 5])=[Vavg(j,2) Vo(Vavg(j,2));`
    `bc=20;`
    `while bc<=20`
      `Svc.store(1,[9 10])=[bc -bc];`
      `disp('trying bus')`
      `disp(Vavg(j,2))`
      `disp('at bc = ')`
      `disp(bc)`
      `runpsat('pf')`
      `runpsat('td')`
      `t=Varout.t;`
      `Vbus=Varout.vars(:,DAE.n+Bus.n+1:DAE.n+2*Bus.n);`
      `Vavg1=sum(Vbus)/length(t)';`
      `disp(min(Vavg1))`
      `if min(Vavg1)>0.854`
        `break`
      `end`
      `bc=bc+1;`
    `end`
    `if bc<=20`
      `break`
end
j=j+1;
end
if j<=length(Vavg)
   sol(i,[1 2 3])=[Vavg(j,2) bc min(Vavg1)];
disp('Initial sol. for case')
disp(i)
disp('is')
disp(sol(i,:))
else
   sol(i,[1 2 3])=[0 0 0];
disp('No initial solution found for case')
disp(i)
disp('______________________________')
end
if sol(i,1)~=0
   disp('Starting the search loop')
   idx=find(Vavg(:,2)==sol(i,1));
b_i=1;
   for j=idx:size(Vavg,1)
      bcs=sol(i,2);
      bcu=0;
      e=bcs;
      Vavg_min=sol(i,3);
      while (e>=0.5&b_i)
         bc=(bcs+bcu)/2;
         Svc.store(1,[1 8 9 10 17])=[Vavg(j,2) Vo(Vavg(j,2)) bc -bc 1];
         x=PV.store;
         PV.store(find(x(:,3)==400),[1 5])=[Vavg(j,2) Vo(Vavg(j,2))];
         runpsat('pf')
         runpsat('td')
         t=Varout.t;
         Vbus=Varout.vars(:,DAE.n+Bus.n+1:DAE.n+2*Bus.n);
         Vavg1=sum(Vbus)/length(t)';
         if min(Vavg1)<Vavg_min
            e=bc-bcu;
            bcu=bc;
         else
            e=bcu-bc;
            bcs=bc;
            Vavg_min=min(Vavg1);
            end
            sol(i,[1 2 3])=[Vavg(j,2) bcs Vavg_min];
         end
         if b_i==0
            bc=sol(i,2)-0.5;
Svc.store(1,[1 8 9 10 17])=[Vavg(j,2) Vo(Vavg(j,2)) bc -bc 1];
x=PV.store;
PV.store(find(x(:,3)==400),[1 5])=[Vavg(j,2) Vo(Vavg(j,2))];
runpsat('pf')
runpsat('td')
t=Varout.t;
Vbus=Varout.vars(:,DAE.n+Bus.n+1:DAE.n+2*Bus.n);
Vavg1=sum(Vbus)/length(t)'
if min(Vavg1)>=sol(i,3)
    sol(i,[1 2 3])=[Vavg(j,2) bc Vavg_min];
bcs=sol(i,2);
bcu=0;
e=bcs;
Vavg_min=sol(i,3);
while (e>=0.5)
    bc=(bcs+bcu)/2;
    Svc.store(1,[1 8 9 10 17])=[Vavg(j,2) Vo(Vavg(j,2)) bc -bc 1];
x=PV.store;
PV.store(find(x(:,3)==400),[1 5])=[Vavg(j,2) Vo(Vavg(j,2))];
runpsat('pf')
runpsat('td')
t=Varout.t;
Vbus=Varout.vars(:,DAE.n+Bus.n+1:DAE.n+2*Bus.n);
Vavg1=sum(Vbus)/length(t)'
if min(Vavg1)<Vavg_min
    e=bc-bcu;
    bcu=bc;
else
    e=bcs-bc;
    bcs=bc;
    Vavg_min=min(Vavg1);
end
sol(i,[1 2 3])=[Vavg(j,2) bcs Vavg_min];
end
end
bi=0;
end
disp('Optimal size and location found')
disp('_____________________________________')
end
Fault.store=fault;
Breaker.store=breaker;
Svc.store=svc(n,:);
PV.store=pv;
end
switch n
    case 1
        Sol_60=sol;
    case 2
        Sol_50=sol;
    case 3
        Sol_40=sol;
    case 4
        Sol_30=sol;
end
end
disp('the final sol. is')
disp(sol)
disp('All cases have been done')
closepsat
C.2 Code of the program for the genetic algorithm

function fitness=yrab_ga(x)
    svcb=round(x(2))
    bc=x(1)
    initpsat
    Settings.tf=100;
    Settings.fxt=0;
    Settings.checkdelta=1;
    Setting.deltadelta=180;
    Settings.pq2z=1;
    clpsat.readfile=0;
    clpsat.msg=0;
    cases=[08 01 08]; % this is changed according to the case under study
    runpsat('yrab_50_mdl.m','data') %this is changed according to the level
    runpsat('pf')
    Vo=DAE.y(1+Bus.n:2*Bus.n);
    idx=find(Fault.store(:,1)==cases(1,1));
    Fault.store(idx,[5 6])=[1 1.06];
    Breaker.store(1,[1 2 7])=[cases(1,[2 3]) 1.06];
    Svc.store(1,[1 8 9 10 17])=[svcb Vo(svcb) bc -bc 1];
    pv=PV.store;
    PV.store(find(pv(:,3)==400),[1 5])=[svcb Vo(svcb)];
    runpsat('pf')
    runpsat('td')
    t=Varout.t;
    Vbus=Varout.vars(:,DAE.n+Bus.n+1:DAE.n+2*Bus.n);
    Vavg1=sum(Vbus)/length(t);
    if min(Vavg1)<0.92
        fitness=1000/min(Vavg1)-5*bc
    else
        fitness=bc-5*min(Vavg1)
    end
    closepsat
end
APPENDIX (D)

FIGURES OF THE OPTIMAL ALLOCATION AND SIZING OF SVC

Figure D.1: The voltage of bus 20 for fault at bus 16 and line 20 outage for 30% induction motor penetration level after the addition of SVC

Figure D.2: The voltage of bus 19 for fault at bus 16 and line 20 outage for 30% induction motor penetration level after the addition of SVC
Figure D.3: The voltage of bus 18 for fault at bus 18 and line 20 outage for 30% induction motor penetration level after the addition of SVC

Figure D.4: The voltage of bus 19 for fault at bus 18 and line 20 outage for 30% induction motor penetration level after the addition of SVC
Figure D.5: The voltage of bus 20 for fault at bus 18 and line 21 outage for 30\% induction motor penetration level after the addition of SVC

Figure D.6: The voltage of bus 19 for fault at bus 18 and line 21 outage for 30\% induction motor penetration level after the addition of SVC
Figure D.7: The voltage of bus 20 for fault at bus 19 and line 26 outage for 30% induction motor penetration level after the addition of SVC

Figure D.8: The voltage of bus 18 for fault at bus 19 and line 26 outage for 30% induction motor penetration level after the addition of SVC
Figure D.9: The voltage of buses 6 and 9 for fault at bus 11 and line 7 outage for 40% induction motor penetration level after the addition of SVC

Figure D.10: The voltage of buses 19 and 20 for fault at bus 11 and line 7 outage for 40% induction motor penetration level after the addition of SVC
Figure D.11: The voltage of bus 19 for fault at bus 16 and line 20 outage for 40% induction motor penetration level after the addition of SVC

Figure D.12: The voltage of bus 20 for fault at bus 16 and line 20 outage for 40% induction motor penetration level after the addition of SVC
Figure D.13: The voltage of bus 18 for fault at bus 18 and line 20 outage for 40% induction motor penetration level after the addition of SVC

Figure D.14: The voltage of bus 19 for fault at bus 18 and line 20 outage for 40% induction motor penetration level after the addition of SVC
Figure D.15: The voltage of bus 19 for fault at bus 18 and line 21 outage for 40% induction motor penetration level after the addition of SVC

Figure D.16: The voltage of bus 20 for fault at bus 18 and line 21 outage for 40% induction motor penetration level after the addition of SVC
Figure D.17: The voltage of bus 6 for fault at bus 19 and line 26 outage for 40% induction motor penetration level after the addition of SVC

Figure D.18: The voltage of bus 20 for fault at bus 19 and line 26 outage for 40% induction motor penetration level after the addition of SVC
Figure D.19: The voltage of buses 10 and 11 for fault at bus 8 and line 1 outage for 50% induction motor penetration level after the addition of SVC

Figure D.20: The voltage of buses 18 and 19 for fault at bus 8 and line 1 outage for 50% induction motor penetration level after the addition of SVC
Figure D.21: The voltage of buses 10 and 11 for fault at bus 8 and line 3 outage for 50% induction motor penetration level after the addition of SVC

Figure D.22: The voltage of buses 19 and 20 for fault at bus 8 and line 3 outage for 50% induction motor penetration level after the addition of SVC
Figure D.23: The voltage of buses 10 and 11 for fault at bus 9 and line 3 outage for 50% induction motor penetration level after the addition of SVC

Figure D.24: The voltage of buses 19 and 20 for fault at bus 9 and line 3 outage for 50% induction motor penetration level after the addition of SVC
Figure D.25: The voltage of buses 10 and 11 for fault at bus 9 and line 5 outage for 50% induction motor penetration level after the addition of SVC.

Figure D.26: The voltage of buses 18 and 19 for fault at bus 9 and line 5 outage for 50% induction motor penetration level after the addition of SVC.
Figure D.27: The voltage of buses 9 and 10 for fault at bus 11 and line 7 outage for 50% induction motor penetration level after the addition of SVC.

Figure D.28: The voltage of buses 19 and 20 for fault at bus 11 and line 7 outage for 50% induction motor penetration level after the addition of SVC.
Figure D.29: The voltage of buses 9 and 10 for fault at bus 11 and line 8 outage for 50% induction motor penetration level after the addition of SVC

Figure D.30: The voltage of buses 19 and 20 for fault at bus 11 and line 8 outage for 50% induction motor penetration level after the addition of SVC
Figure D.31: The voltage of buses 9 and 10 for fault at bus 11 and line 15 outage for 50% induction motor penetration level after the addition of SVC

Figure D.32: The voltage of buses 17 and 19 for fault at bus 11 and line 15 outage for 50% induction motor penetration level after the addition of SVC
Figure D.33: The voltage of buses 9 and 10 for fault at bus 12 and line 8 outage for 50% induction motor penetration level after the addition of SVC

Figure D.34: The voltage of buses 18 and 19 for fault at bus 12 and line 8 outage for 50% induction motor penetration level after the addition of SVC
Figure D.35: The voltage of bus 9 for fault at bus 12 and line 10 outage for 50% induction motor penetration level after the addition of SVC

Figure D.36: The voltage of bus 20 for fault at bus 12 and line 10 outage for 50% induction motor penetration level after the addition of SVC
Figure D.37: The voltage of bus 11 for fault at bus 18 and line 21 outage for 50% induction motor penetration level after the addition of SVC

Figure D.38: The voltage of bus 20 for fault at bus 18 and line 21 outage for 50% induction motor penetration level after the addition of SVC
Figure D.39: The voltage of buses 8 and 9 for fault at bus 8 and line 1 outage for 60% induction motor penetration level after the addition of SVC

Figure D.40: The voltage of buses 18 and 19 for fault at bus 8 and line 1 outage for 60% induction motor penetration level after the addition of SVC
Figure D.41: The voltage of buses 10 and 11 for fault at bus 8 and line 3 outage for 60% induction motor penetration level after the addition of SVC

Figure D.42: The voltage of buses 19 and 20 for fault at bus 8 and line 3 outage for 60% induction motor penetration level after the addition of SVC
Figure D.43: The voltage of buses 10 and 11 for fault at bus 9 and line 3 outage for 60% induction motor penetration level after the addition of SVC

Figure D.44: The voltage of buses 19 and 20 for fault at bus 9 and line 3 outage for 60% induction motor penetration level after the addition of SVC
Figure D.45: The voltage of buses 10 and 11 for fault at bus 9 and line 5 outage for 60% induction motor penetration level after the addition of SVC

Figure D.46: The voltage of buses 18 and 19 for fault at bus 9 and line 5 outage for 60% induction motor penetration level after the addition of SVC
Figure D.47: The voltage of buses 10 and 11 for fault at bus 11 and line 7 outage for 60% induction motor penetration level after the addition of SVC.

Figure D.48: The voltage of buses 19 and 20 for fault at bus 11 and line 7 outage for 60% induction motor penetration level after the addition of SVC.
Figure D.49: The voltage of buses 9 and 10 for fault at bus 11 and line 8 outage for 60% induction motor penetration level after the addition of SVC.

Figure D.50: The voltage of buses 18 and 19 for fault at bus 11 and line 8 outage for 60% induction motor penetration level after the addition of SVC.
Figure D.51: The voltage of buses 9 and 10 for fault at bus 11 and line 15 outage for 60% induction motor penetration level after the addition of SVC

Figure D.52: The voltage of buses 17 and 19 for fault at bus 11 and line 15 outage for 60% induction motor penetration level after the addition of SVC
Figure D.53: The voltage of buses 9 and 10 for fault at bus 12 and line 8 outage for 60% induction motor penetration level after the addition of SVC

Figure D.54: The voltage of buses 18 and 19 for fault at bus 12 and line 8 outage for 60% induction motor penetration level after the addition of SVC
Figure D.55: The voltage of buses 9 and 10 for fault at bus 12 and line 10 outage for 60% induction motor penetration level after the addition of SVC.

Figure D.56: The voltage of buses 18 and 19 for fault at bus 12 and line 10 outage for 60% induction motor penetration level after the addition of SVC.
Figure D.57: The voltage of buses 9 and 10 for fault at bus 17 and line 22 outage for 60% induction motor penetration level after the addition of SVC.

Figure D.58: The voltage of buses 17 and 18 for fault at bus 17 and line 22 outage for 60% induction motor penetration level after the addition of SVC.
Figure D.59: The voltage of bus 19 for fault at bus 18 and line 21 outage for 60% induction motor penetration level after the addition of SVC

Figure D.60: The voltage of bus 20 for fault at bus 18 and line 21 outage for 60% induction motor penetration level after the addition of SVC
Figure D.61: The voltage of bus 18 for fault at bus 19 and line 26 outage for 60% induction motor penetration level after the addition of SVC

Figure D.62: The voltage of bus 20 for fault at bus 19 and line 26 outage for 60% induction motor penetration level after the addition of SVC
ملخص الرسالة

إن إستقرار الجهد هو قدرة النظام الكهربائي على استعادة إستقرار الجهد عند جميع القضايا بعد تعرض النظام الكهربائي لإضطراب ما، وتتسبب عدم قدرة النظام على توفير التغذية اللازمة للأحمال في عدم إستقرار الجهد أو إنهياره، ويمكن لظاهرة عدم إستقرار الجهد أن تكون سريعة (قصيرة المدى) أو بطيئة (طويلة المدى)، وغالبًا ما يصاحب عدم إستقرار الجهد قصير المدى الاستجابه السريعة لمنظمات الجهد، كمنظم الجهد الأوتوماتيكي للمولدات ومحولات القوى الإلكتروني كالمستخدمة في دوائر ربط التيار المستمر.

في هذا البحث، يتم التعرض لمشكلة إستقرار الجهد من خلال المنظور الديناميكي قصير المدى المصاحب لتوقف محركات الحث كسبب رئيسي لإنهيار الجهد، ولتمثيل هذه الظاهرة، فقد تم اختيار نظام مكون من 20 قاية متضمناً خطوط نقل طويلة وبعض دوائر النقل مفردة الدائرة والتي تعمل كنقطة إختياق للقدرة غير الفعلية المفقودة، ولمزيد من إظهار مشكلة إستقرار الجهد في الدراسة، فقد تم رفع قيمة الحمل - مع ثبات عامل القدرة - وبالتالي رفع قيمة التوليد بحيث تكون مصادر القدرة غير الفعلية بعيدة عن مراكز الأحمال، مما أدى إلى سوء توزيع القدرة غير الفعلية على جميع أنحاء الشبكة.

وتلى ذلك تحديد أماكن تركيب وسعتات أجهزة التقل المرنة وبالتحديد أجهزة تعويض القدرة غير الفعلية الإستاتيكي واتجاه تجنب إنهيار الجهد، وقد تم ذلك لنسب مختلفة من مساهمة محركات الحث في الحمل الإجمالي (30% و40% و50% و10%)، وفي أماكن قصر وأوضاع تشغيل إضطرارية متعددة، ولقد تم تحديد هذه السعات والأماكن باستخدام برنامج بحث يتمتع على تقنية Heuristic Optimization المنااحة في برنامج MatLab وهى Genetic Algorithm toolbox البرنامج.

الرسالة مرتية كالآتي:

الباب الأول يعرض سبب اختيار هذا الموضوع كنقطة بحث والأهداف المرجوة من هذه الرسالة، ثم يعرض نظرة عامة حول مشكلة إستقرار الجهد ونظام النقل المرن المثلى المستخدمة لتحسين مشكلة إستقرار الجهد، ثم تم إستعراض أهم المقالات العلمية المتعلقة بمشكلة إستقرار الجهد.
الجهد وتسمِّم النقل المرة، وأخيراً تم عرض بعض حالات عدم استقرار الجهد ثم مخطط لهيكل الرسالة.

الباب الثاني مقسم إلى جزئين رئيسيين، بالنسبة للجزء الأول تم استعراض بعض التعريفات الأساسية الخاصة بمشكلة استقرار الجهد والسيناريوهات الكلاسيكية الخاصة بمشكلة إنهيار الجهد وطرق التحليل المختلفة سواء الإستاتيكية أو الديناميكية، وأما بالنسبة للجزء الثاني فقد تم التعرض خلاله إلى مقدمة عامة عن نظم النقل المرة بشكل عام وشكل خاص تركيب وفكرة عمل أجهزة تعويض القدرة غير الفعالة الإستاتيكية.

الباب الثالث يعرض النماذج الديناميكية للمكونات المختلفة المشارك في عدم استقرار الجهد قصير الأجل، وتشتمل هذه النماذج الديناميكية على نماذج المولدات وأجهزة التحكم الخاصة بها ومنظمات الجهد الأوتوماتيكية ومانعات زيادة الإستنارة ومحركات الحث التي تعتبر الدافع الرئيسي لمشكلة استقرار الجهد قصيرة المدى وأخيراً أجهزة النقل المرة المستخدمة كوسيلة علاجية لمشكلة استقرار الجهد.

الباب الرابع يصف النظام الكهربائي المستخدم لتوضيح مشكلة استقرار الجهد والخطوات التي تم إخاذها لتوضيح المشكلة بشكل أوضح وقد تم عمل ذلك عن طريق زيادة الأحمال باستخدام معاملقية ثابتة مع زيادة التوليد وتوزيعه على الشبكة بحيث تكون مصادر القدرة غير الفعالة بعيدة عن مراكز الأحمال ثم تم إدخال أحمال محركات الحث بنسب مختلفة، 30% و 40% و 50% و 60% وأخيراً تم تحديد الحالات التي أنتجت تدهور شديد في الجهود والتي تحتاج إلى وضع أجهزة تعويض القدرة غير الفعالة الإستاتيكية.

الباب الخامس يتناول كيفية تحديد الأماكن والسلاسل المثلى الخاصة بأجهزة تعويض القدرة غير الفعالة الإستاتيكية المستخدمة لتحسن مشكلة استقرار الجهد قصيرة المدى للحالات المختلفة التي تم استعراضها في الباب السابق.

الباب السادس يتناول النتائج المستخلصة من البحث والأعمال المستقبلية.
تحسين إستقرار الجهد بنظم القوى الكهربية باستخدام أنظمة النقل المرنة

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كجزء من متطلبات الحصول على درجة الماجستير
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