UNIVERSITY OF
KWAZULU-NATAL
INYUVESI
YAKWAZULU-NATALI

Improvement of voltage and dynamic performance of transmission power networks using distributed superconducting magnetic energy storage systems (D-SMES)

Jamila Ally Kombe

204002255

A thesis submitted to
the University of KwaZulu-Natal,
College of Agriculture, Engineering and Science,
in partial fulfillment of the requirements for the degree of

Master of Science in Power and Energy Systems

Supervisor: Professor D G Dorrell
Co-Supervisor: Dr Amin Nasri

School of Engineering

University of KwaZulu-Natal

November 2019

I, Jamila Ally Kombe , declare that:

(i) The research reported in this thesis, except where otherwise indicated, is my original research.

(ii) This thesis has not been submitted for any degree or examination at any other university.

(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

(iv) This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

  a) their words have been re-written but the general information attributed to them has been referenced:

  b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced.

(v) This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation/thesis and in the References sections.

Candidate: Jamila Ally Kombe

Signature: ______________________

As the candidate's supervisor I agree to the submission of this thesis for examination.

Supervisor: Professor D G Dorrell

Signature: ______________________

ABSTRACT

Improvement of voltage and dynamic performance of transmission power networks using distributed superconducting magnetic energy storage systems (D-SMES)

Jamila Ally Kombe
School of Engineering
Master of Science in Power and Energy Systems

Over the past 30 years, a device known as a Distributed Superconducting Magnetic Energy Storage (D-SMES) has been under development and proposed to solve various grid performance challenges. A D-SMES is device with a shunt reactive power injection/voltage support with real power component. The use of a D-SMES is considered as a new option at experimental stages to solve plenty of transmission, generation, and distribution system problems, including improvement of voltage and angular stability, increasing power transfer capability, damping oscillation including smart grid. The purpose of this dissertation was to demonstrate how D-SMES can alleviate voltage instability in a network. The study gives an overview of the D-SMES applications, its characteristics and classification. Two case studies, namely; an IEEE network and a real Southern Africa network are studied with voltage instability under contingency condition. The process flow is proposed and presented using modal analysis as a tool to identify the optimal location in a network to mitigate voltage instability. The results of the two case studies demonstrated improvement in the voltage instability of the respective networks. Modal analysis proved to be an effective method to identify the optimal location of a SMES to improve voltage stability. The findings of this dissertation are in line with the literature.

Keywords: Power systems, smart grids, superconducting magnetic energy storage

PUBLICATIONS ARISING

Improvement of voltage and dynamic performance of transmission power networks using distributed superconducting magnetic energy storage systems (D-SMES)

Jamila Ally Kombe
School of Engineering
Master of Science in Power and Energy Systems

1. J.A. Kombe and T.M Bengani, "Utilization of Energy Storage System to defer Distribution And Transmission Infrastructure Investment", PowerGen, July 2018.

2. J. A. Kombe, T. M. Bengani and D. G. Dorrell, “Improved Voltage and Dynamic Performance of Transmission Power Networks Using Distributed Superconducting Magnetic Energy Storage Systems”, SAUPEC, Bloemfontein, Jan. 2019

ACKNOWLEDGMENTS

I would like to express my appreciation to the University of KWA-ZULU NATAL for granting me the opportunity to complete my studies. I thank my supervisor; Prof D.G. Dorrell for his dedication and leadership throughout the duration of the project. I would like to highly acknowledged my colleagues, Thokozani Bengani and Bruce Siavhe for their contributions on the project especially on the VSAT and PSSE program. I also would like to thank Pamela Ijumba-Kamera for always supporting me. To my boys, thank you all your support and reminding me that I can do anything.

JA Kombe

DEDICATION

I dedicate this thesis to my late father and my best friend, Dr Ally Hussein Kombe, my mom, Elieshi Ally Kombe and my sons, Wedu Imran Gwafila and Mbuso Bose Gwafila.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

Around the world, voltage or load instability is increasingly becoming a major problem in utilities . What is voltage instability? The inability of the network to maintain acceptable voltages in all the system buses after a disturbance has occurred. The disturbance could be an increase in load demand or changes in the network conditions [1]. The main cause of the instability is the lack of reactive power in the system [1][2]. It is not easy to distinguish between transient stability and voltage collapse in real-time as they manifest themselves in similar manner.

To alleviate the lack of reactive power in the system, compensating devices such as static synchronous compensator (STATCOM),static Var compensator (SVCs) have been used for many years. These devices provide the dynamic reactive power support to the network following a disturbance. The emergence of advanced reactive support devices using power electronics has presented itself to Grid planners as an alternative solution to the voltage stability problems and worst case, voltage collapse.

A device known as a Distributed Superconducting Magnetic Energy Storage (D-SMES) has been under development over the past 30 years, it proposes to solve various grid performance challenges. What is a D-SMES? This device is a shunt reactive power injection/voltage support with real power component. The use of a D-SMES is considered as a new option at experimental stages to solve plenty of transmission, generation, and distribution system problems, including improvement of voltage and angular stability, increasing power transfer capability, damping oscillation including smart grid [3][4][5][6][7][8]. This technology has been previously used since the mid-1990s in industries dealing with paper, plastics, aluminium where continuous supply of high quality power is required. At about the same time, the Wisconsin Public Service Corp (WPS) was experiencing voltage depressions in their system due to load increase [9]. D-SMES became their choice of solution after intensive system studies to determine the best solution based on their criteria, which looked at the cost as well as implementation time [3]. D-SMES applications with respect to voltage stability will be the focus of this dissertation.

1.2 Problem Statement

The definition of voltage stability is proposed by IEEE/CIGRE task force as follows: “Voltage stability refers to the ability of power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating point.” This disturbance can be in the form of:

- Steady load demand increase;

- Changes in operating conditions; and
- Disturbance (loss of generation/transformer/line).

The above results in increased reactive power demand. To resolve dynamic voltage instability, a Static Var compensator (SVC) or STATCOM would be recommended to provide the deficient dynamic reactive power. An SMES, on the other hand, is an energy storage device that has the capacity to provide both the real and reactive power to support the network. The capability to provide real power provides additional secondary benefits to the network.

Both static and dynamic approaches can be used for the analysis of voltage instability. Dynamic/Transient analysis is more accurate as it demonstrates voltage instability in time-domain, Notwithstanding, it does not provide information about the network pertaining to the sensitivity of instability. Static analysis, on the hand, where modal analysis is used will assist in providing information pertaining to the sensitivity of the network to voltage instability [10].

This dissertation will use modal analysis to identity the contributing area to the voltage stability, then place an SMES at this location to alleviate voltage instability. Dynamic simulations will be run to confirm the effectiveness of the placed D-SMES. The placement of D-SMES for voltage instability has been based on engineering judgement in the past [11] and a proposed procedure where repeated dynamic runs are required to determine the placement [12]. This procedure is regarded as laborious and time consuming. Hence this dissertation proposes the used of modal analysis. The purpose of this project is to demonstrate how D-SMES can alleviate voltage instability in a network where modal analysis will be used to single out the ideal placement of this device.

1.3 Research Objective

The objectives of this research project are:

- Find an effective solution to solve voltage instability of a reduced existing network such as that of southern Africa example used as Case Study 2 in Chapter 5, where low voltage buses are common in contingency conditions.
- This research work will look at the optimal placement of D-SMES using the steady-state method – Modal analysis.

The introduction of Superconducting Magnetic Energy Storage devices as substitute planning solution will have a positive implication to the planning fellowship. It has the potential to set aside costly infrastructure investment for Transmission and/or Distribution systems depending on the application.

1.4 Structure of Dissertation

This dissertation is structured as follows:

- Chapter 1- An introduction and overview are given. A brief description of the dissertation purpose and objectives.
- Chapter 2- The literature review describes the current state of play with SMES and the background to uses of distributed energy storage in the grid system,

- Chapter 3 - This section will entail an in-depth review of the theory behind the operation and modelling of SMES. The methodology will be proposed.
- Chapter 4 – This section presents modal analysis.
- Chapter 5 -This section will present the results and analysis of the simulations of two case studies.
- Chapter 6 - Conclusions of the findings will be drawn and recommendations put forward.

1.5 Statement on Publications

This work has led to two publications and this thesis is an expanded version of the paper:

J. A. Kombe, T. M. Bengani and D. G. Dorrell, "Improved Voltage and Dynamic Performance of Transmission Power Networks Using Distributed Superconducting Magnetic Energy Storage Systems", SAUPEC, Bloemfontein, Jan. 2019

Chapter 2

Literature Review

As mentioned in Chapter 1, due to the increase in voltage instability incidents around the world, prevention of voltage instability and voltage collapse problems have received a lot of attention in the last 15 to 25 years. This is evident in the literature. See, for example, references [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15]. Extensive research has been done in STATCOMs, but mainly comparing them with other Flexible AC Transmission Systems (FACTs) devices like Thyristor Controlled Static Series Compensator (TCSC)as shown in references [8][9][10]. Prevention of voltage collapse is presented briefly in reference [15]. Since the mid-1990s, research has been conducted in the application of D-SMES to an actual system, for example in Wisconsin and Entergy systems.[5][6][7] D-SMES has been mainly being used to prevent voltage collapse. Other benefits include to the networks:

- Increased network transfer capability;
- Damping of network oscillations;

- Increased network reliability of supply to customers; and
- Can be installed where in the place of new lines and compensating devices that are more costly and time consuming to procure and install.

To obtain maximum technical and financial benefits depending on the application, optimal placement of any FACTs device is important.

STATCOMs have received relatively more attention as they are much older technology as opposed to D-SMES in their optimal placement in a network system. As an example, STATCOM have been optimally placed based on steady-state techniques (e.g., modal analysis). However, the technique used [5] to optimally place D-SMES principle idea is to incrementally place a D-SMES unit where it is needed most until the desired network response is obtained. These devices are best connected at buses.

In this research, a static approach – modal analysis is going to be applied and confirmed with transient analysis to confirm improved voltage performance.

2.1 Review of SMES Characteristics

The way we generate, deliver and use energy has been driven by the advances in technology and changes in consumer behaviour. Energy storage is emerging as a technology that can address some of the new challenges and deriving value proposition in the new emerging markets. Three areas of application where energy storage systems provide a solution are identified. According to the Energy Storage Association (ESA) [13], they are as follows:

- Utility;
- Customers - behind the meter; and
- MicroGrids - remote power system

This research focuses on the application at utility level. The keys drivers for the application of storage at the utility level can be any or a combination of the following [13]:

- Carbon emission reduction of ;
- Aging infrastructure;
- Deferral of infrastructure;
- Increase of network reliability including network stability; and
- Impacting the following where there is a high renewable penetration:
  - True Inertia;
  - Synchronizing torque;
  - Voltage;
  - Fault levels; and
  - Fast Frequency response.

At a utility level and based on the type of energy exchange used, there are various energy storage technologies classification. Refer to Fig. 2.1. With capacities ranging from 1 kW to 1 GW and varying time responses ranging from milliseconds to hours, various storage devices exist for applications are shown in Fig. 2.2.

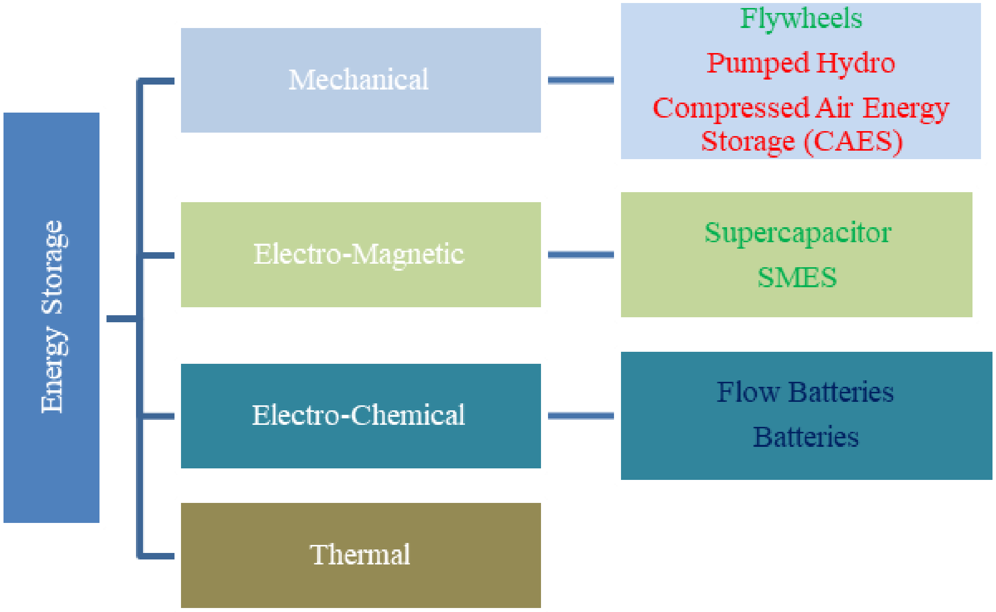

Figure 2.1 Classification of Energy Storage Technologies based on energy exchange.

SMES are characterised by having very high energy efficiency (85- 95 %), high power density and fast response times; unfortunately for very short periods and are still expensive relative to all other energy storage devices. These are illustrated in Fig. 2.3.

The application of SMES systems in power systems was first introduced in 1969 [9] for the purpose of peak shaving. The first grid connected unit to reach full commercial status was located in two 500 kV Pacific Inter-tie connecting Northwest and California. This was the first feasible application of SMES to improve transmission capacity by damping inter-area modal oscillations.

The USA and Japan have been the leaders in the installation and research of SMES. Due to SMES fast response (discharging capability) and ability to inject and absorb both real and reactive power,

Their applications are mainly focused on system stability and power quality improvements. Fig. 2.2 shows the SMES applications [8] . There are several Micro-SMES units available commer-

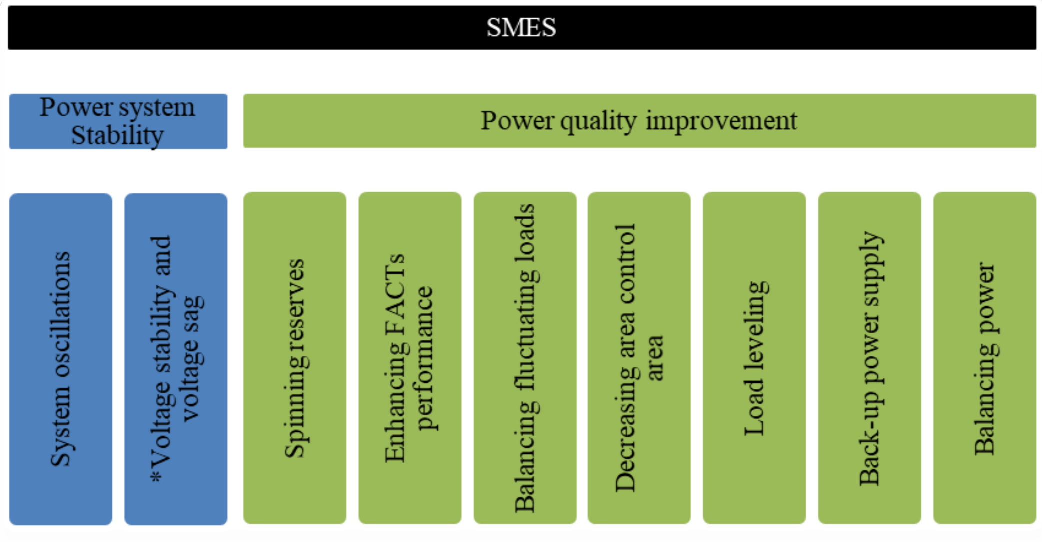

Figure 2.2 Utility applications of SMES.

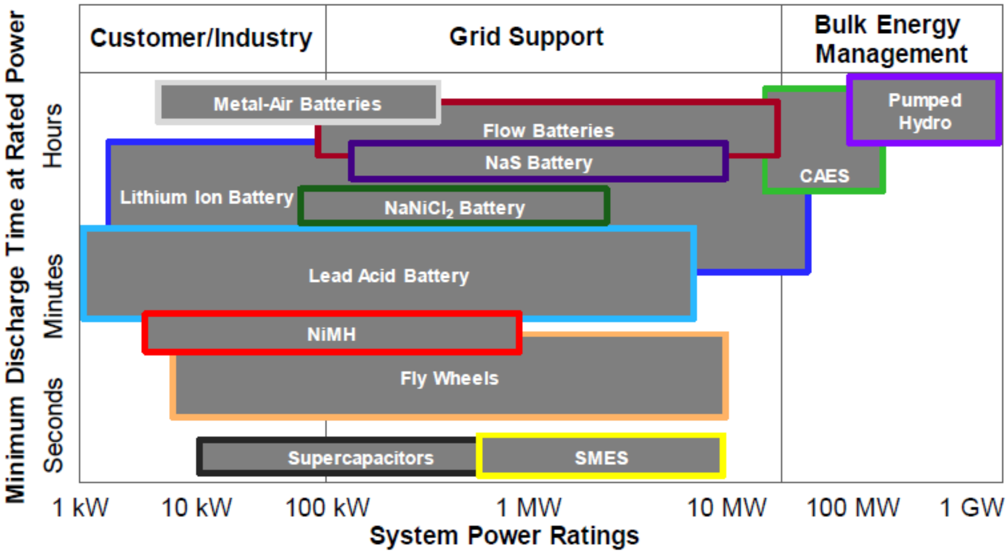

Figure 2.3 System power ratings vs Minimum discharge times for various technologies.

cially for power quality purposes, to provide quality at manufacturing plants requiring clean power such as microchip manufacturing facilities around the world [14] and smelters in South Africa to mitigate against voltage and power dips. Larger SMES have utility applications mainly used for grid stability. In Northern Wisconsin, a number of distributed units were commissioned to enhance the stability due to sudden load changes from the paper mill resulting in uncontrolled fluctuations and voltage collapse of their transmission network [9]. Fig. 2.3 demonstrates the power rangers and discharging times for the various storage technologies. It is evident that the characteristics of SMES is High power, up to 100 MW, and short discharging time over very short periods.

Investigations and installations have been happening in Japan. Based on the 10 MVA/20 MJ SMES prototype it is projected that within a few years, it may be possible to install 100 MWh SMES within the period of 2020-30 for Frequency control and power compensation and 1 GWh SMES for daily load levelling between 2030-40 [15]. SMES are typically large and are used for short durations at Transmission and sub-Transmission levels. Research is in progress of larger SMES with capacities of 20 MWh providing 400 MW for 100 seconds or 10 MW for 2 hours. This research is conducted at the Research Association of Superconducting Magnetic Energy Storage (RAsmes) in Japan [16].

2.1.1 SMES Components

The electric current in an SMES encounters no resistance and that is what makes it as the most energy efficient energy storage technology to date. It is fast charging as it is able to charge within seconds, recover and repeat the cycle again. The SMES performs a multitude of charging-discharging cycles and has no movable parts which increases its reliability. The expected lifespan is approximately 30 years [15]. A standard SMES has four major components, shown in Fig. 2.4. These

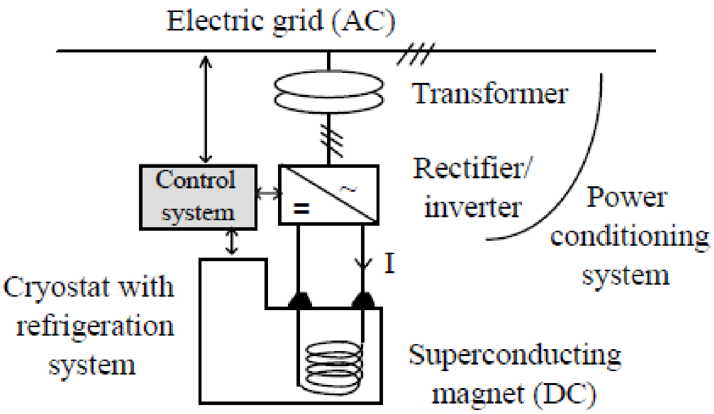

Figure 2.4 Schematic drawing of SMES connected to an electric AC grid.

are:

- **Superconducting magnet**
- **Cryogenic system:** Helium is typically used to keep the coil of niobium-titanium at -231.15°. The temperature required to keep the coil superconducting. At this temperature, the coil has literally no electrical resistance, enabling it to conduct large currents with negligible losses. SMES have demonstrated excellent energy conversion efficiencies of up to 95 % compared to the other energy storage systems like batteries 70 % to 90 % and pumped hydro 70 %;
- **Power conditioning system:** The direct current (DC) of the superconducting coil is transformed or converted to alternative current (AC) and vice versa. This is an Inverter/Rectifier model; and
- **Control systems**.

2.1.2 SMES Operation

The operating characteristics for a D-SMES unit are given in Fig. 2.5.

Controlled Voltage and Voltage Thresholds

The SMES device has the capacity to control voltage at either its terminal bus or a remote bus. Its operation depends on four voltage thresholds $V_i (i = 1,2,3,4)$ that define voltage ranges with different functions and operational conditions of the device. The voltage at a controlled bus is monitored and compared against the four values V_i to determine whether it is necessary to inject active and/or reactive power.

Active Power Operation

The SMES device starts injecting active power into the system if the controlled voltage is deemed to be low. The injection needed is provided by discharging the SMES magnet that is activated when a voltage drop occurs. The device starts injecting active power into the system when the controlled voltage crosses the voltage range. If the controlled voltage is beyond this range and $V_3 =< V_{contr} < V_2$ or $V_{contr} < V_4$, the device is able to absorb active power from the power system based on a P_{aux} signal. At the moment, the magnet is not able to absorb active power from the power system. This capability of the device is being investigated and developed, therefore only its simplified representation is provided in the present model.

Reactive Power Operation

The SMES device has the capacity to force in or consume reactive power when the controlled voltage is within any voltage band. This reactive power is provided by the Insulated Gate Bipolar Transistor (IGBT) voltage-source converter in the amount determined by an Automatic Voltage Regulator (AVR), depending on the variation between the voltage reference and controlled voltage. The device is capable of temporarily boosting the reactive power output. For boosting, the reference voltage V_{ref} is raised by a given step for a short time interval of about a second. After this interval, V_{ref} re-turns to its original value.

Overload Capability

When the voltage at the controlled bus is below a specified threshold ($V_{contr} < V_3$), a thermal overload capability of the IGBT converter is available in existing D-SMES devices. This overload capability is especially important for improving the first-swing stability and for damping power system oscillations. Since the converter has a finite thermal capability, there is a choice in sharing it among active and reactive power. Priority is given to active power, since its injecting is the primary purpose of the device.

Magnetic Energy Stored

After the superconducting coil is charged, the magnetic energy can be warehoused indefinitely as the current is not able to decay. By discharging the coil, the energy is fed back into the network. The energy is stored in the field of the magnetic coil (magnetic flux density (B)) when direct current flows through it.

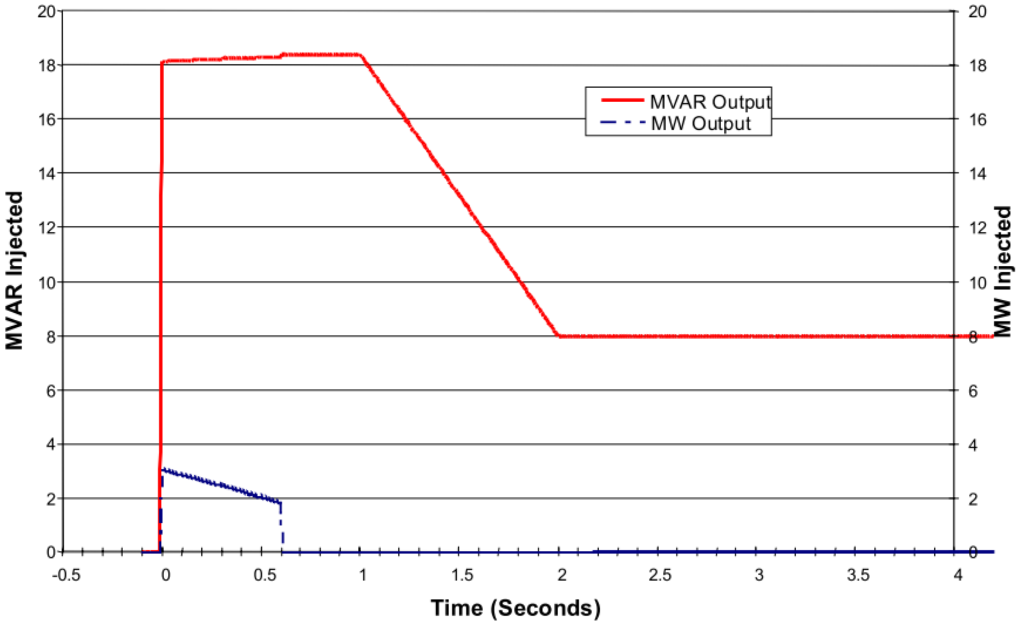

Figure 2.5 Operating Characteristics of D-SMES Unit.

The stored energy (W_{magnet}) in an inductor is

$$W_{magnet} = \frac{1}{2} L I^2 \tag{2.1}$$

where L is the self-inductance of the coil and I is the current flowing through it as shown in Fig. 2.6. Assuming that an inductor is a solenoid. When energy is stored inside an inductor, it can be thought of as being stored in the magnetic field within the loop of the wire. If an electric current, I is travelling through an inductor with inductance L, an increase in current I will increase the magnetic field. Increase in magnetic field increases magnetic flux. According to Faradays' Law, a change in the magnetic flux will induce an Elctromotive Force (EMF) inside the coil. The induced EMF will oppose the change in the magnetic flux. Because the magnetic flux is increasing, the induced EMF will create an electrical current that will oppose the motion of the initial electric current as per Lenz's Law.

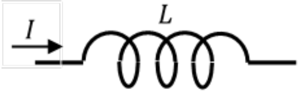

Figure 2.6 Solenoid.

The instantaneous power supplied to the inductor is via a forward-EMF which opposes the back-EMF, so that

$$P \; = I \times V \; = I \times \varepsilon \tag{2.2}$$

where P is the power supplied, V is the forward-EMF) and ε is the back-EMF which is an induced EMF. The induced ε in an inductor is obtained from

$$\varepsilon = L \times \frac{\partial I}{\partial t} \tag{2.3}$$

where $\frac{\partial I}{\partial t}$ is the rate of change of current with respect to time. Hence the power that needs to be supplied to the change in magnetic flux is

$$P \; = I \times \varepsilon = I \times L * \frac{\partial I}{\partial t} \tag{2.4}$$

The question is what is the work (energy (W)) done from current 0 to I? We can use:

$$\partial W = P \times \partial t \; = I \times L \times \frac{\partial I}{\partial t} \times \partial t = L \times I \times \partial I \tag{2.5}$$

To arrive at the total energy input into an inductor when increasing the current from 0 to I, we integrate:

$$W = \int \partial W = \int_0^I L \times I \times \partial I = \frac{L \times I^2}{2} \tag{2.6}$$

Since the work done is equal to the energy stored in the inductor:

$$W = \frac{L \times I^2}{2} = U \tag{2.7}$$

where W is the energy store and is equal to U the potential energy.

Modern power systems depend strongly on stabilizing devices to maintain a reliable network, operating within operational margin as per their respective Transmission Grid Code. These devices should provide adequate damping in the system during the transient period following a system disturbance such as a line switching, load changes and fault clearances and to avoid voltage collapse due to loss of voltage instability or synchronism. Traditionally, the synchronous power plants turbine governors are used to stabilise the network [8]. For localised voltage instability located away from generation, FACTs devices like SVC, STATCOM are able to provide this support to the network. Energy storage devices like SMES are becoming attractive solution options.

Chapter 3

Methodology

This chapter will cover the proposed research methodology. The methodology is analytical in nature.

3.1 software

The software used in the modeling of the networks for load flow and dynamics is PTI/Siemens PSS/E (Power System Software for Engineers) version 33 and 34. Modal analysis will be performed in DSA Tools VSTAB version 16.

3.2 Process

The casefile is modeled in PSSe. For the optimal placement of the D-SMES, modal analysis is the proposed technique. Network data (casefile) will be converted from .sav to .raw in PSSe. The .raw flow casefile is then imported into DSA Tools VSAT. In VSAT, modal analysis will be formed and the results documented. The results will contain eigen-values (modes) that will determine the state of the network as either being stable or unstable under contingency. For each mode, its associated participation factors will be obtained.

Eigen-values as well as participation factors will be obtained in this analysis. The Eigen-value (mode) will determine which areas are stable or unstable. Once an unstable mode has been identified, its associated participation factors can be obtained about the area. These results pinpoint exactly where SMES needs to be placed.

In PSSe, the D-SMES will be installed in the identified location in VSAT. The loadflow will be performed then dynamic analysis to confirm the effectiveness of the D-SMES in the network. Fig. 3.1 summarizes the methodology in a flowchart. The South Africa Grid Code voltage criteria will be applied in this dissertation for the transient voltage profiles i.e. must maintain a range of ± 5 % in $N-1$ contingency. It should be noted that the voltage recovery times and the fault clearing times of the transmission network is critical. The critical clearance time of a network has an impact on the size of the SMES. This is beyond this dissertation scope.

3.3 Modelling

The modeling of the two networks will be detailed from generation, transmission and the loads.

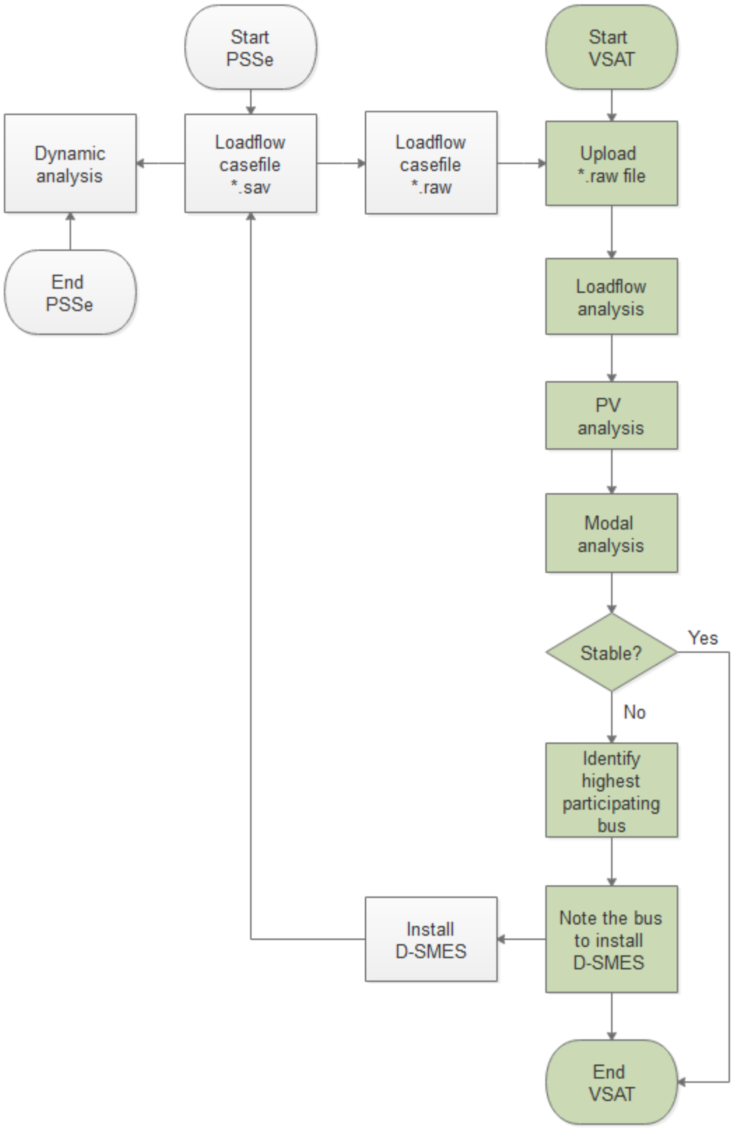

Figure 3.1 Methodology flowchart.

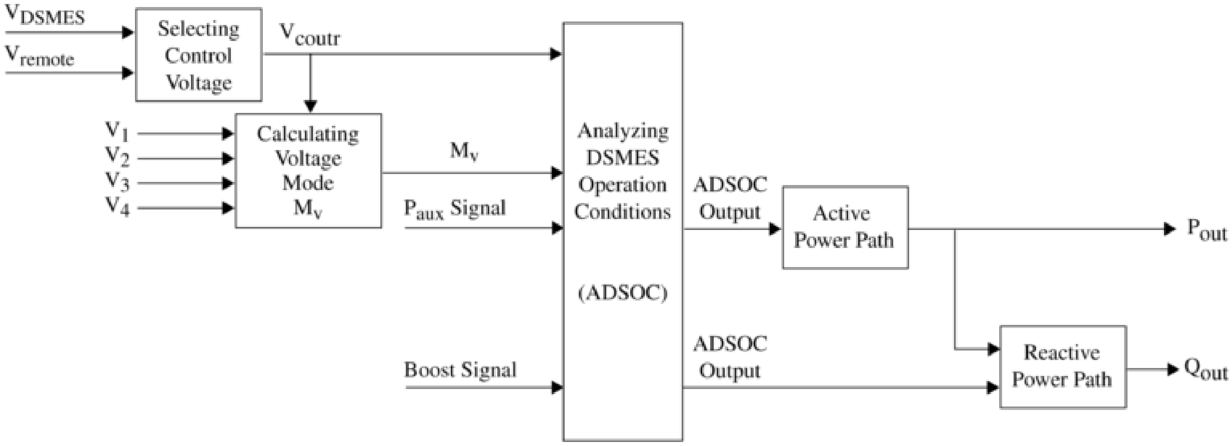

Figure 3.2 General model for SMES.

3.3.1 D-SMES

The general model for SMES used is as shown in Fig. 3.2.

3.3.2 Load

Voltage instability is also known as load instability; therefore, the load modelling is critical. According to [2], the commonly used static models for motors are totally inadequate and must not be used. Static models do not represent the high current drawn by induction motors resulting in grossly optimistic results [2]. For the purposes of this dissertation and limited scope, all load models are represented as static with constant power.

Chapter 4

Optimal Placement of SMES for Voltage Stability

It has been proven through research and studies that SMES have an important role to play in the improvement of network stability issues. The main challenges with D-SMES is location optimization, size and control devices. It is critical to identifying the location for optimal effectiveness of the device application, in this case, voltage stability of the network.

The methodology documented to resolve voltage collapse in the USA North-Western Corridor transmission network is based on a manual procedure using the lowest bus as an indicator to install the SMES. This process is repeated until the voltage collapse is resolve [12]. Another approach is the application of qualitative voltage stability index and genetic algorithm (GA) for the optimal location of SMES [17].

This dissertation introduces the application of modal analysis to identify the optimal location to install D-SMES.

4.1 Modal Analysis

Modal analysis can be used to determine which areas are most vulnerable to voltage stability problems, to select the best site for installing new dynamic reactive compensation equipment, and to determine the most effective actions such as generation redispatch and load shedding to alleviate voltage conditions [14]. Modal analysis makes use of the power system Jacobian matrix to determine the eigenvalues necessary for the evaluation of the voltage stability of the system [15]. These eigenvalues are referred to as modes.

Modal analysis for the purpose of small signal stability uses the full Jabobian Matrix on the network while for voltage stability, the reduced Jacobian of the state matrix is used [16]. It focuses on the relationship between voltage and reactive power. The eigenvalues of the Jacobian identify the different modes through which the system could become voltage unstable. The magnitude of the eigenvalues provides a relative measure of proximity to instability. The eigenvectors provide information related to the mechanism of loss of voltage stability.

The linearised steady-state system power voltage equations are given by:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{4.1}$$

where:

ΔP: Incremental change in bus real power;

ΔQ: Incremental change in bus reactive power injection;

$\Delta\theta$: Incremental change in bus voltage magnitude; and

ΔV: Incremental change in bus voltage angle.

The network voltage stability is affected by both P and Q. Although incremental changes are neglected ($\Delta P = 0$), the changes in network load or power transfer levels are taken into account by examining the incremental relationship between ΔQ and ΔV at various operating levels.

If $\Delta P = 0$:

$$\begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{4.2}$$

So that

$$\begin{aligned} 0 &= J_{P\theta}\Delta\theta + J_{PV}\Delta V \\ \Delta Q &= J_{Q\theta}\Delta\theta + J_{QV}\Delta V \end{aligned} \tag{4.3}$$

and

$$\begin{aligned} J_{P\theta}\Delta\theta &= -J_{PV}\Delta V \\ \Delta\theta &= -\left[J_{P\theta}\right]^{-1} J_{PV}\Delta V \end{aligned} \tag{4.4}$$

For ΔQ:

$$\Delta Q = \left(-J_{Q\theta}\left[J_{P\theta}\right]^{-1} J_{PV}\Delta V\right) + \left(J_{QV}\Delta V\right) \tag{4.5}$$

working through:

$$\begin{aligned} \Delta Q &= \left(\left(-J_{Q\theta}\left[J_{P\theta}\right]^{-1} J_{PV}\right) + \left(J_{QV}\right)\right)\Delta V \\ \Delta Q &= \left(J_{QV} - J_{Q\theta}\left[J_{P\theta}\right]^{-1} J_{PV}\right)\Delta V \\ \Delta Q &= J_R\Delta V \end{aligned} \tag{4.6}$$

Which finally gives

$$\Delta V = \frac{\Delta Q}{J_R} \tag{4.7}$$

where

$$J_R = \left(J_{QV} - J_{Q\theta}\left[J_{P\theta}\right]^{-1} J_{PV}\right) \tag{4.8}$$

J_R is the reduced Jacobian matrix of the network. Discarding the real power and angle part from the network steady state equation allows us to concentrate on the study of the reactive demand and supply problem [16].

It should be noted that it is allowable to perform modal analysis using the full Jacobian matrix as the SMES has both the reactive power and real power as variables.

Continuing with the reduced Jacobian, the modes of voltage instability are

$$J_R = \xi \wedge \eta \tag{4.9}$$

where:

ξ = right eigenvector matrix of J_R

η = left eigenvector matrix of J_R

$\wedge$ = diagonal eigenvector matrix of J_R

And

$$J_R{}^{-1} = \xi \wedge^{-1} \eta \tag{4.10}$$

From which

$$\Delta V = J_R{}^{-1} \Delta Q \tag{4.11}$$

Combining with (4.10) gives

$$\Delta V = \xi \wedge^{-1} \eta \Delta Q \tag{4.12}$$

Or

$$\Delta V = \int \frac{\xi_i \eta_i}{\lambda_i} \Delta Q \tag{4.13}$$

Where i^{th} is the mode of the system and λ_i is the eigenvalue. The magnitude of each eigenvalue λ_i determines the weakness of the corresponding modal voltage. The smaller the magnitude of λ_i, the weaker the corresponding modal voltage. If $|\lambda| = 0$, the i^{th} modal voltage will collapse because any changes the modal reactive power will cause infinite voltage variation.

Similar to linear dynamics systems analysis concepts, each eigenvalue λ_i and the corresponding right and left eigenvectors ξ_i and η_i define the i^{th} mode of the system. The i^{th} modal reactive power variation is,

$$\Delta Q_{mi} = K_i \xi_i \tag{4.14}$$

where

$$K_i{}^2 \sum_j \xi_{ji}{}^2 = 1 \tag{4.15}$$

where ξ_{ji} is the j^{th} element of ξ_i. The corresponding i^{th} modal voltage variation is:

$$\Delta V_{mi} = \frac{1}{\lambda_i} \Delta Q_{mi} \tag{4.16}$$

Assuming that $\Delta Q = e_k$, where e_k has all its elements are zero except for the k^{th} term which is 1. Then:

$$\Delta V = \sum_i \frac{\eta_{ik} \xi_i}{\lambda_i} \tag{4.17}$$

where η_{ik} is the k^{th} element of η_i. The $V - Q$ sensitivity at bus k is

$$\frac{\partial V_k}{\partial Q_k} = \sum_i \frac{\xi_k i \eta_{ik}}{\lambda_i} = \sum_i \frac{P_{ki}}{\lambda_i} \tag{4.18}$$

4.1.1 Participation factor (Bus, Branch and Generator)

Bus

Bus participation factors show the voltage stability of nodes in the power system. The left and right eigenvectors corresponding to the critical modes in the system/network can provide information concerning the mechanism of voltage instability [15]. The bus participation of the bus can be defined as

$$P_{ki} = \xi_k i \times \eta_{ik} \tag{4.19}$$

P_{ki} indicates the contribution of the i^{th} eigenvalue to the $V-Q$ sensitivity at bus k.

The highest values of participation factors indicate the mostly affected buses in the power system.

Branch

The participation factor of branch l_k to mode i is defined as

$$P_{gki} = \frac{\Delta Q_{lji}}{\Delta Q_{lmaxi}} \tag{4.20}$$

Generator

The participation factor of generator g_k to mode i is defined as

$$P_{gki} = \frac{\Delta Q_{gji}}{\Delta Q_{gmaxi}} \tag{4.21}$$

Chapter 5

Results and Findings

In this chapter, two case studies are presented, namely: IEEE three-machine nine-bus system and a Southern African network.

5.1 CASE STUDY 1: IEEE Three-Machine Nine-Bus System

5.1.1 Power System Modelling

Fig. 5.2 depicts the single line diagram of the IEEE three-machine nine-bus system. The network had three generators with step-up transformers to 230 kV. Generator 1 (Connected to Bus 1) is the slack bus. The network line parameters, generators and load data including the dynamic data are provided in Appendix A.

In steady-state, the network has all voltages within limits. The loss of line 7 – 8 230 kV lead

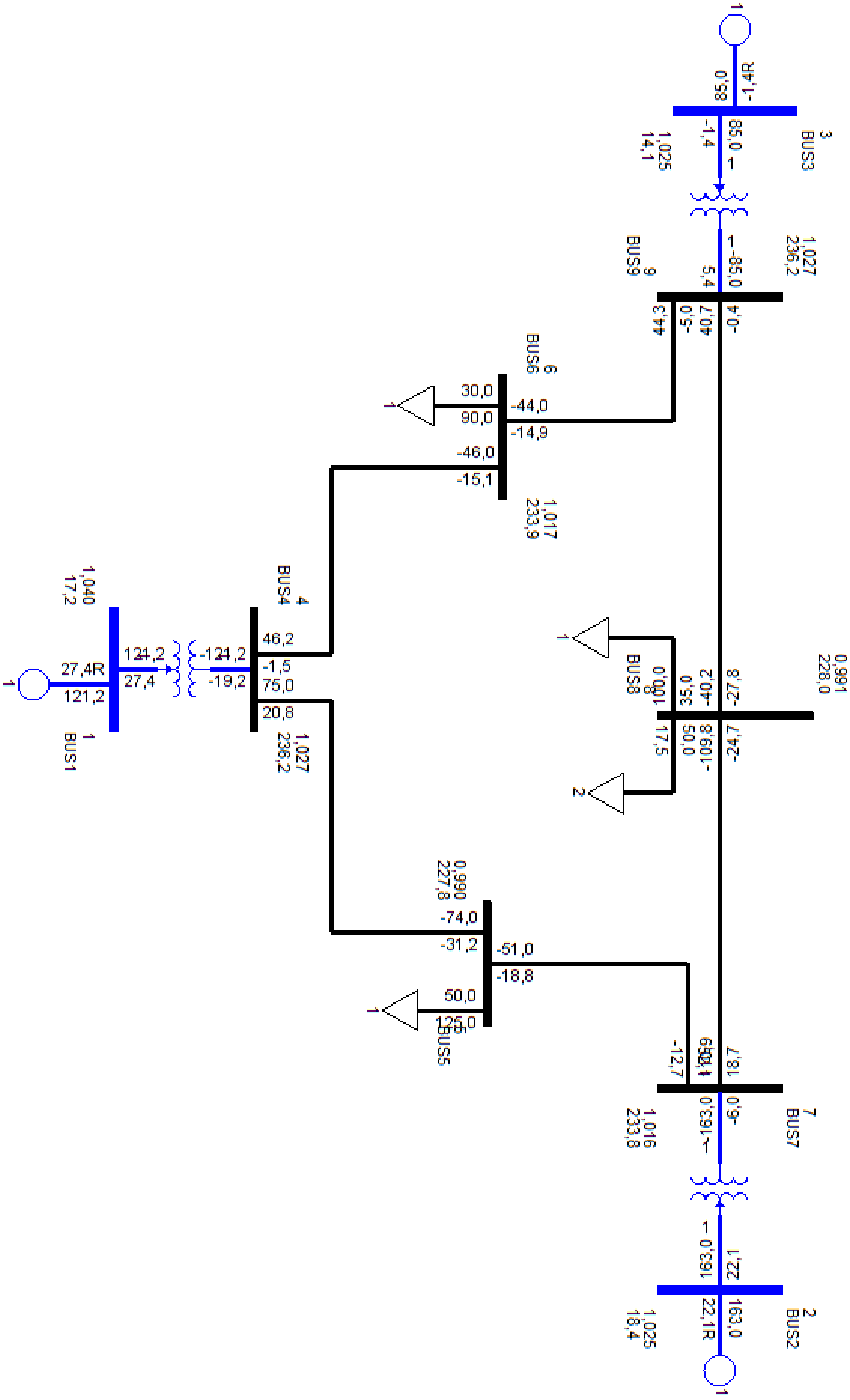

Figure 5.1 IEEE Three-Machine Nine-Bus System (System Healthy).

to the voltages below 0.95 p.u on Bus 8. Fig. **??** shows the network with the loss of line 8 – 7. Table 5.1 tabulates the summary of voltages of Bus 7, 8 and 9 under system healthy and under contingency – Loss of Line 8 - 7.

Table 5.1 Base case: System Healthy and Contingency: Loss of Line 8 - 7 voltages.

Bus #	**System Healthy Voltage (p.u.)**	**Contingency (Loss of line 8 - 7) Voltage (p.u.)**
7	1.016	1.018
8	0.991	0.759
9	1.027	0.962

The transient analysis was performed on the three-machine nine-bus system with the same contingency over 5 s. Fig. 5.3 demonstrates the time series results of the three buses monitored, namely Buses 7, 8 and 9. The results show that only Bus 8 voltage is below the acceptable voltage limits (Range: 1.05 p.u and 0.95 p.u)

To identify the optimal location for the SMES according to the proposed methodology in Chapter 3, modal analysis is performed on this network. This analysis is performed using Dynamic Security Assessment Software (DSA Tools) VSAT Ver 16.0. The modal analysis results in Table **??**, give the participating bus factors. In this case study, Bus 8 has a participation factor of 1 under the Loss of Line 8 - 7, 230 kV, and associated with the Eigenvalue 1.318895-j0.000002. The mostly affected buses in the network is indicated as having the larger bus participation factors.

Based on the modal analysis results, Bus 8 is the best candidate to install the SMES as shown in Fig. 5.4

Table5.3 shows the voltage profile of the network with an SMES on Bus 8 before and after the loss of Line 8 -7 on Bus 7, 8 as shown in Fig. 5.5. All the voltages are within limits. It is evident the voltage the SMES located at Bus 8 has a positive impact on the network.

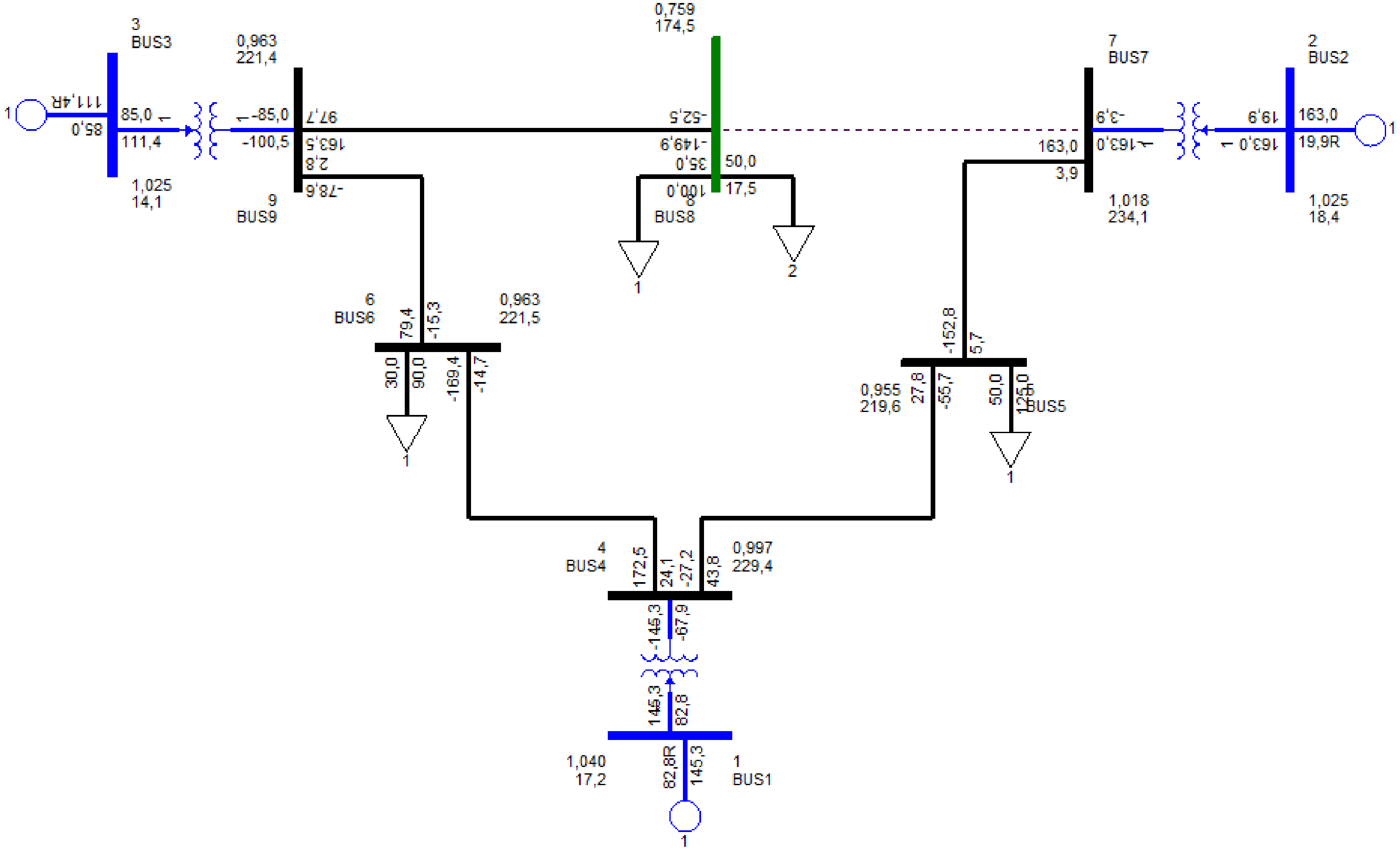

Figure 5.2 IEEE Three-Machine Nine-Bus system following the loss of Line 8 – 7 (Base case).

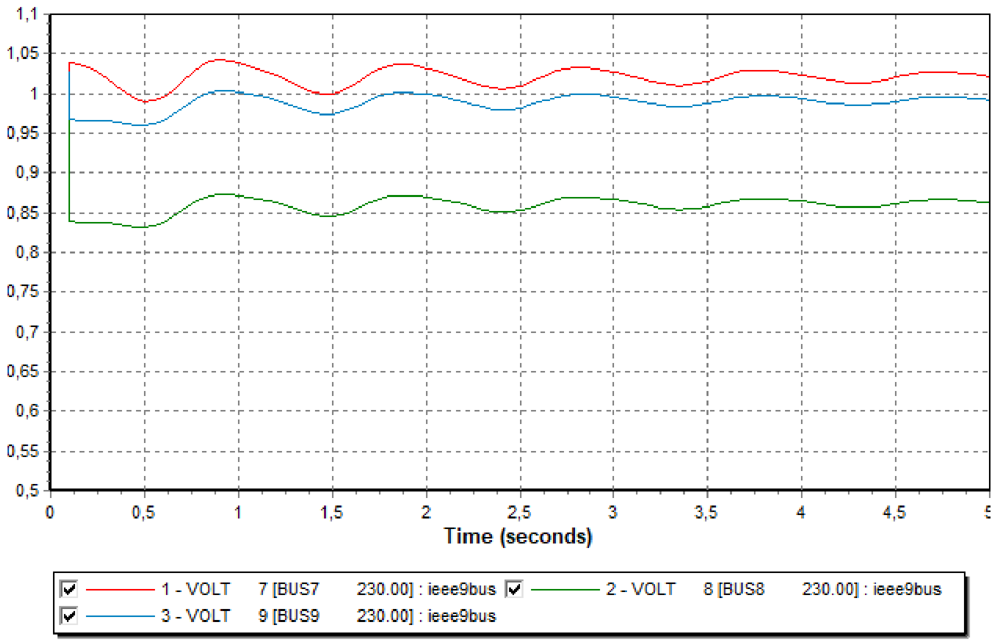

Figure 5.3 Base case: Transient results of Bus 7, 8 and 9 following the loss of Line 7 – 8
.

Table 5.2 Initial and post-disturbance voltages on load buses.

Eigenvalue	**Bus Participation**	
	Bus	**Participation Factor**
$1.318895 - j0.000002$	8	1
	9	0.04835
	6	0.02437
	4	0.00409
	5	0.00357
	7	0.0003

Table 5.3 IEEE SMES Case: System Healthy and Contingency: Loss of Line 8 - 7 voltages.

Bus #	**System Healthy Voltage (p.u.)**	**Contingency (Loss of Line 8 - 7) Voltage (p.u.)**
7	1.016	1.021
8	0.991	0.991
9	1.027	1.018

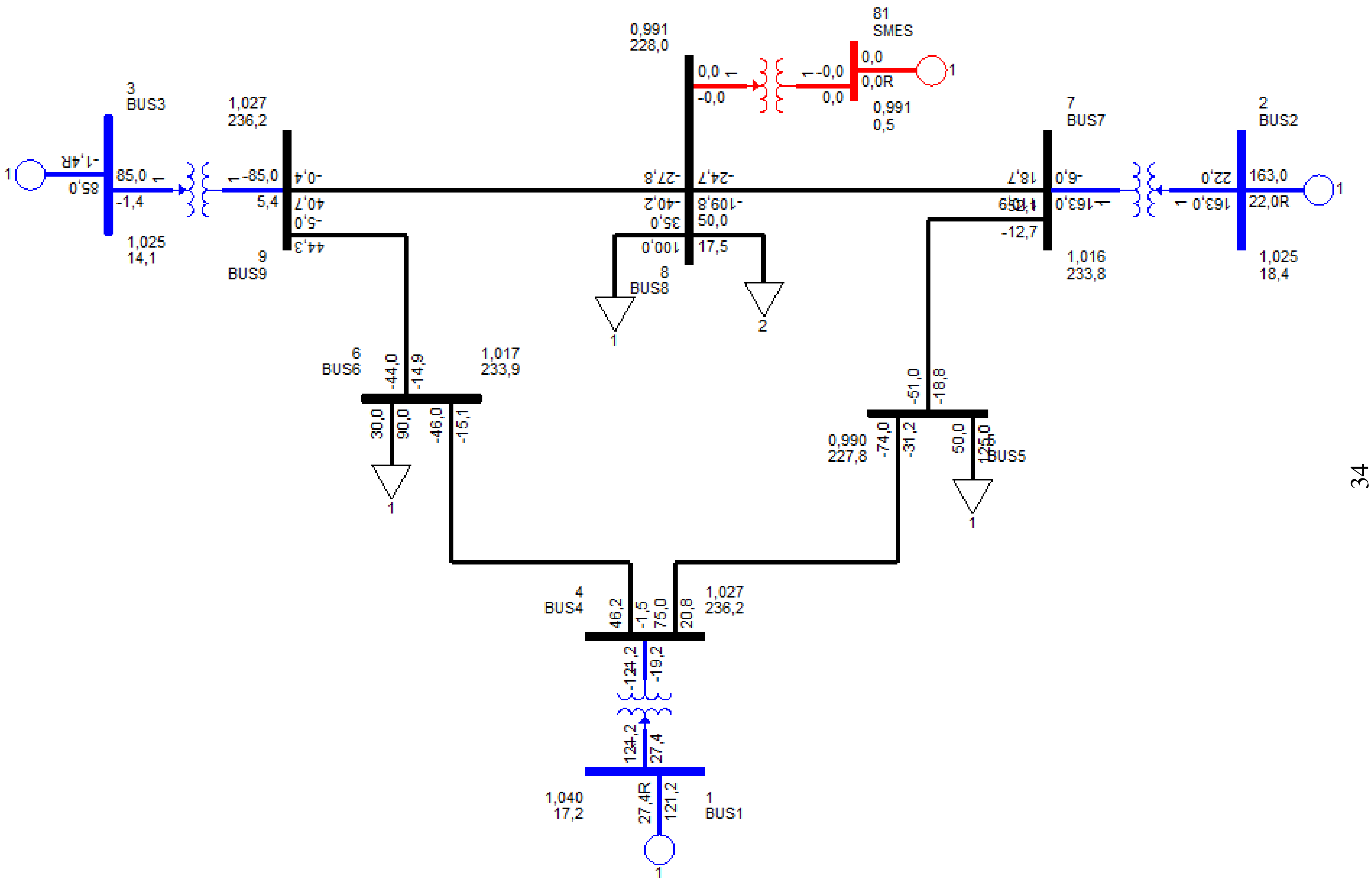

Figure 5.4 IEEE Three-Machine Nine-Bus system with an SMES at Bus 8 (SMES Case).

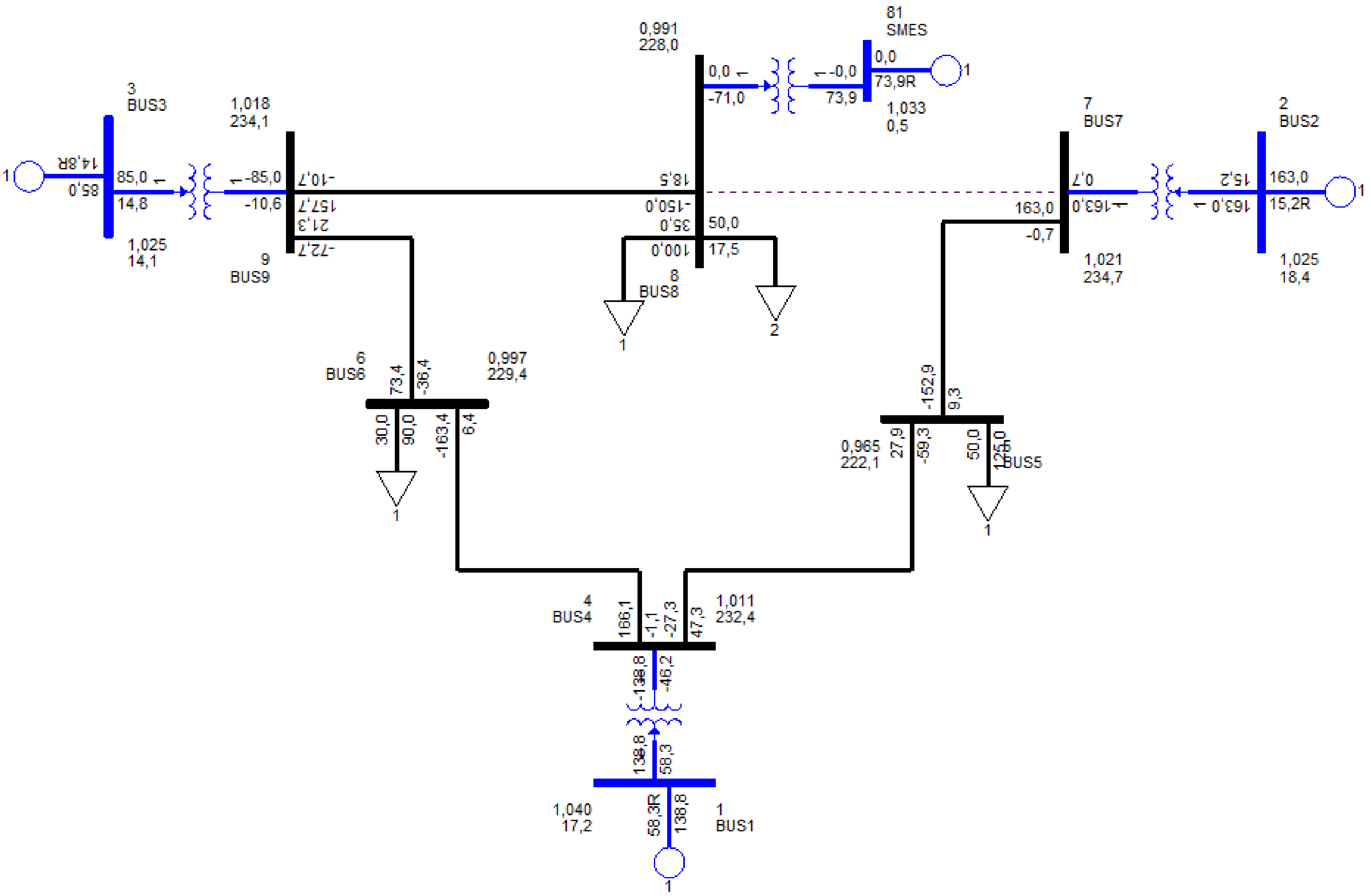

Figure 5.5 IEEE Three-Machine Nine-Bus system following the Loss of Line 8 – 7 (SMES case).

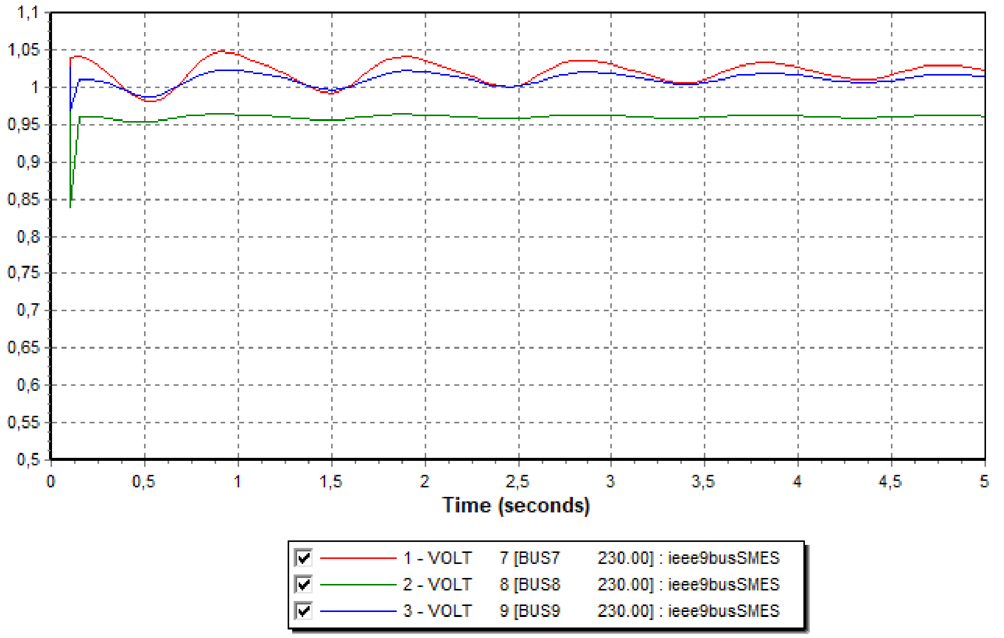

Figure 5.6 SMES case: 3M9B Voltage with SMES. Transient results of Bus 7, 8 and 9 following the loss of Line 7 – 8.

Transient analyses of the network were performed to confirm the voltage performance. Fig. 5.6 displays the results of Bus 7, 8 and 9 voltages. It is evident that all the voltages stay within the voltage limits. Fig. 5.7 shows the voltage performance improvement on Bus 8 before and after the installation of a SMES. Fig. 5.8 shows the SMES reactive power (Q) output and real power (P) output to support the network.

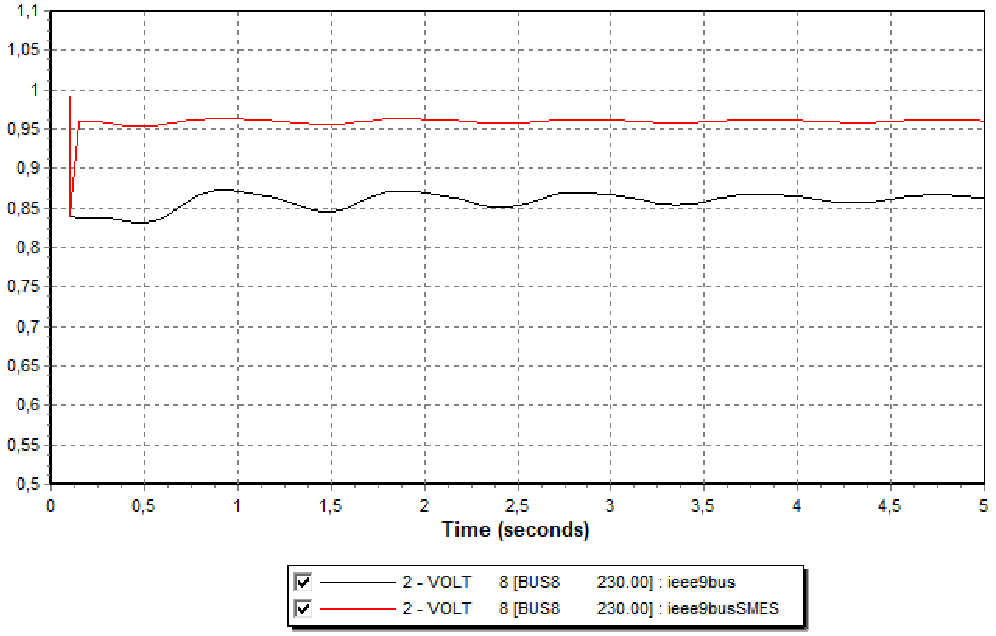

Figure 5.7 Base case and SMES case: 3M9B Voltage Bus 8. Transient results of Bus 8 for the loss of Line 7 – 8.

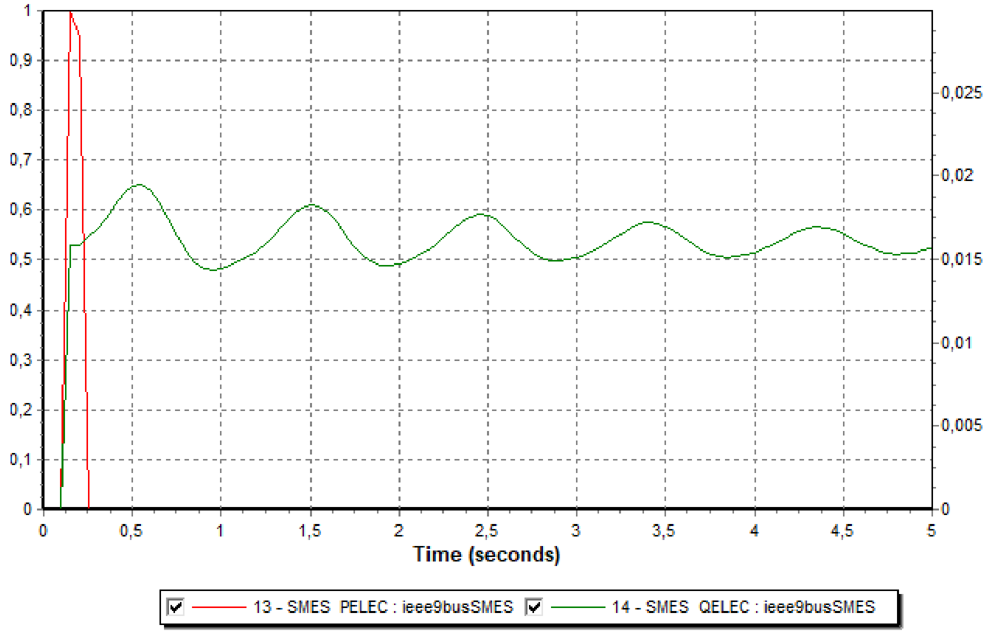

Figure 5.8 Base case: SMES *P* and *Q* output for the loss of Line 7 -8.

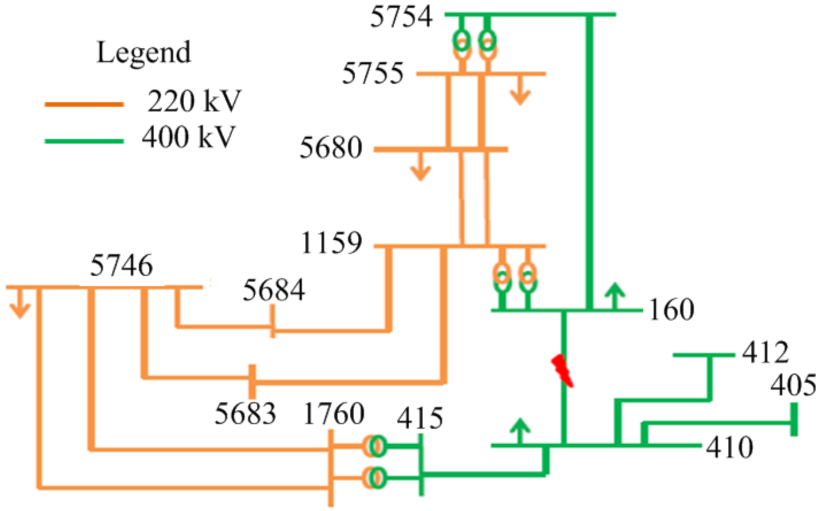

Figure 5.9 Southern Africa network.

5.2 CASE STUDY 2: Africa Network

Fig. 5.9 shows a portion of the real Southern African network. Siemens PTI PSS®E Version 34.2.0 is used for the network analysis that includes the Load flow, Contingency and Transient analysis.

The network is a mesh network of 400 kV and 220 kV. This part of the network is characterised by long transmission lines. The analysis is identical to that of Case Study 1. Load flow analysis was exected on the base case (no contingency). The worst contingency for this network is the loss of the 400 kV from Bus 410 to 160 is applied at time = 0.1 s. Fig. 5.10 indicates the voltage transient performance of Bus 5683 for the base case (Red: Africa). Modal analysis was performed and yielded the results in Table 5.4. Bus ADN is the adjacent network connected to Bus 5746.

Bus 5683 has the highest bus participation for the base case, is the candidate for the first SMES. Transient analysis was performed to determine the improvement on the network, see Fig. 5.10 again. It shows the transient voltage performance at Bus 5683 after the installation of the first SMES mitigated (Green: Africa_SMES). It is evident that the voltage instability has not been fully

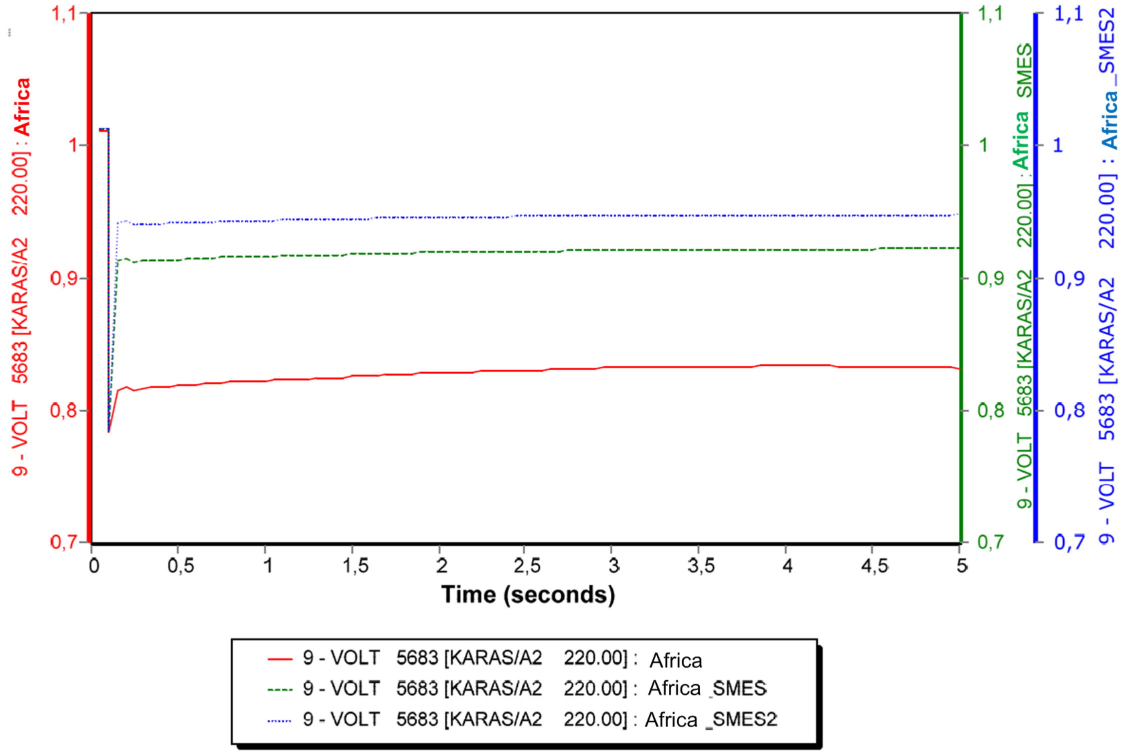

Figure 5.10 Southern Africa network: Voltage stability improvement at Bus 5683 with the placement of SMES.

mitigated.

Table 5.4 Southern Africa network: Modal analysis results on Base case: Contingency on the 410-160 400 kV line.

Eigenvalue	**Bus Participation**	
	Bus	**Participation Factor**
$4.203643 - j0.000004$	5683	1.00000
	5684	0.99708
	1307	0.25651
	5680	0.17156
	ADN	0.15160

A second iteration was required for the placement of the second SMES. The second SMES was placed/installed at Bus 5755 since it had the highest participation factor based on the modal analysis results documented in Table 5.5. Transient analysis was performed again to demonstrate the voltage improvement on the network as shown in Fig. 5.10. It shows the transient voltage performance at Bus 5683 after the installation of the second SMES (Blue: Africa_SMES2). It is evident that the voltage instability has been mitigated. Fig. 5.11 demonstrates the voltage improvement on Bus 5755 with the installation of the first (Green) and second SMES (Blue) in the network.

Table 5.5 Southern Africa network: Modal analysis results on base case with 1st SMES: Loss of the 410-160 400 kV line.

Eigenvalue	**Bus Participation**	
	Bus	**Participation Factor**
$1.811683 + j0.000000$	5755	1.00000
	5754	0.93291
	5680	0.72830
	5684	0.08474
	ADN	0.00139

The Southern Africa study case has demonstrated the transient responses of Buses 5683 and 5755 for the loss of a 400 kV line between bus 410 and bus 160 at time = 0.1 s. Three simulations simulations were performed namely 1) Base case, then 2) Base case with SMES on Bus 5683 and lastly 3) Base case with SMES on Bus 5683 and on Bus 5755. This displays improved performance of the voltage when the SMES systems are installed. Fig. 5.12 shows the reactive (Q) and real (P) outputs of the SMES located at Bus 5683 while Fig. 5.13 shows the the reactive (Q) and real (P) outputs of two SMES located at Bus 5683 and Bus 5755.

In summary, the installation of SMES in the two study cases: IEEE three-machine nine-bus system and the Southern African network has proven to improve the voltage performance under network contingencies. The results are in line with the findings of previous research found in the literature review in Section 2 and the second cast illustrates the use of SMES in the African context.

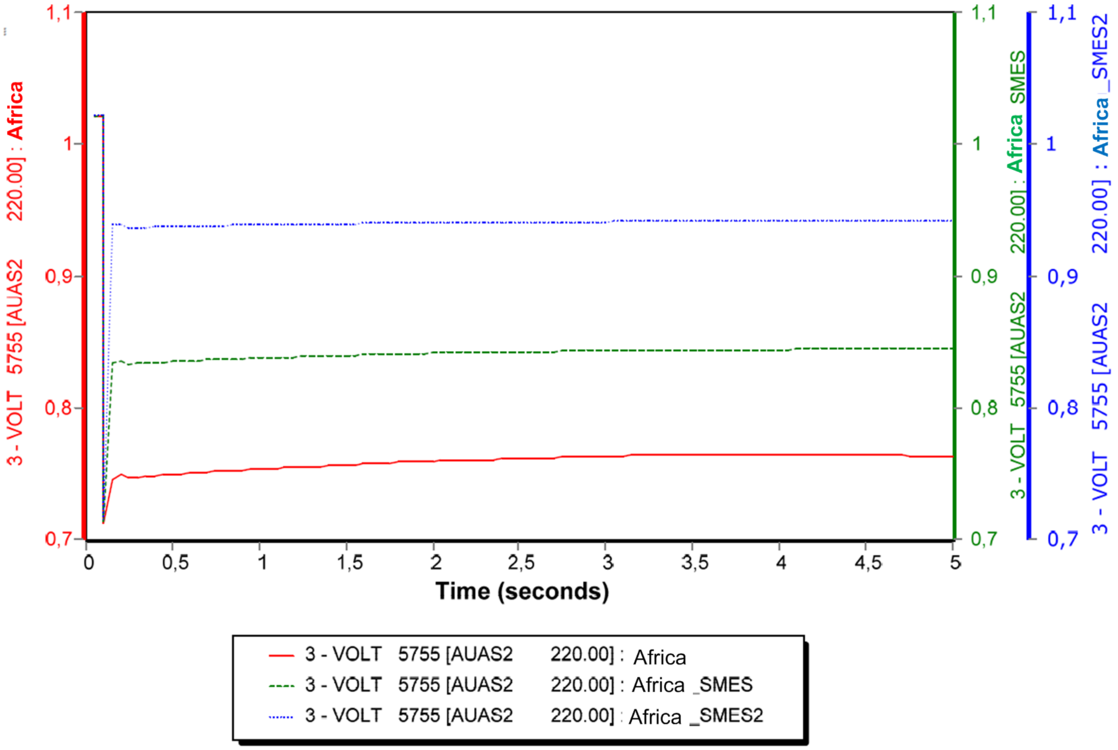

Figure 5.11 Southern Africa network: Voltage stability improvement at Bus 5755 with the placement of SMES.

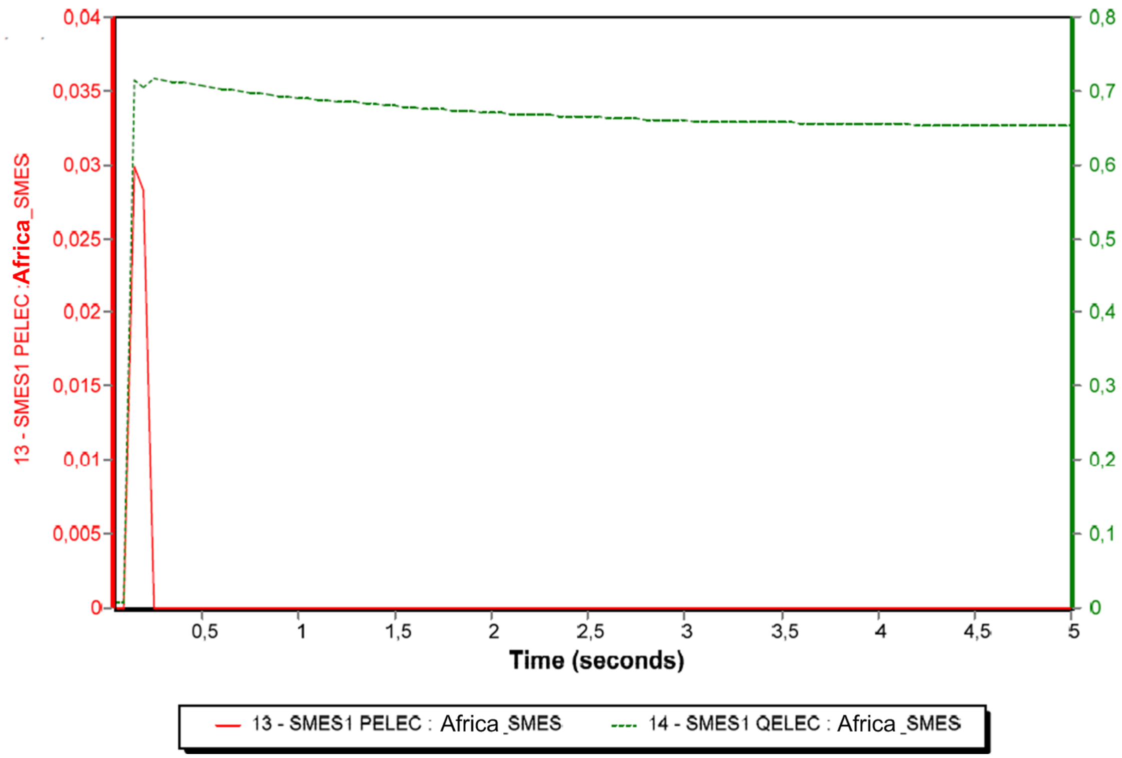

Figure 5.12 Southern Africa network: The *P* and *Q* output of the first SMES at Bus 5683.

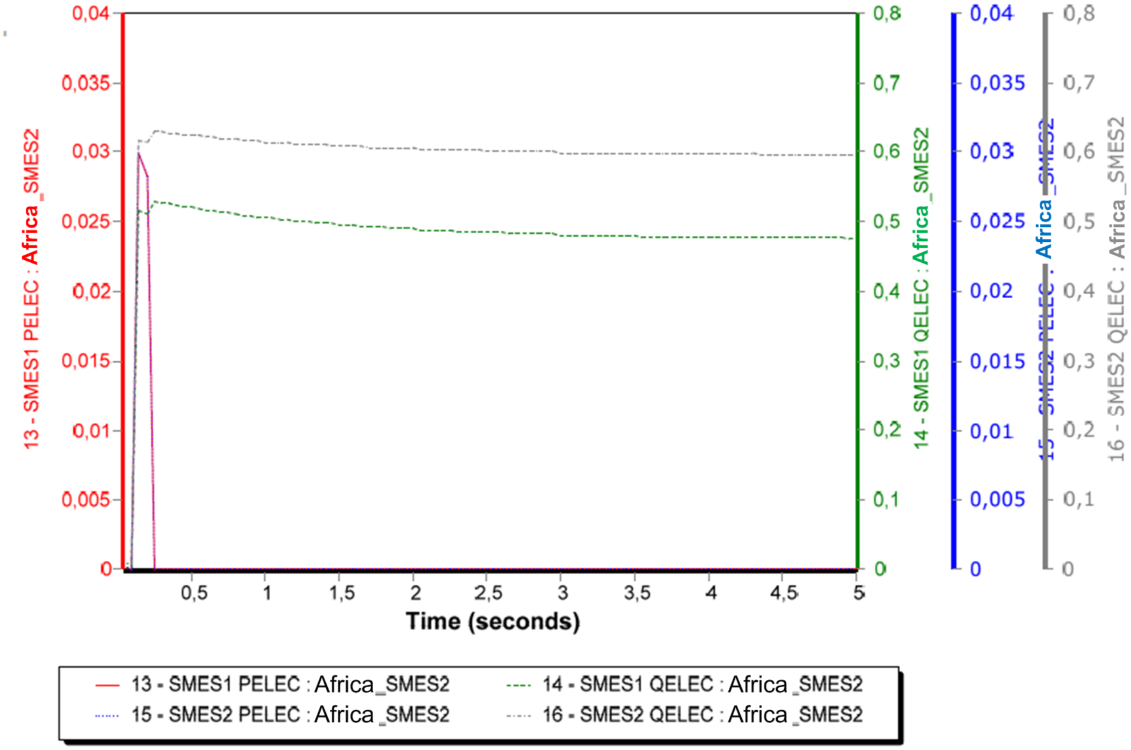

Figure 5.13 Southern Africa network: The *P* and *Q* output of the SMES at Bus 5683 and 5755.

Chapter 6

Conclusions and Recommendations

The purpose of this dissertation was to demonstrate how D-SMES can alleviate voltage instability in a network and modal analysis will be used to identify the optimal placement of this device. This study gave an overview of the D-SMES and addressed network voltage improvements on a small IEEE network as well as a real Southern Africa network. Modal analysis proved to be an effective method to identify the ideal location of a SMES to improve voltage stability.

The lessons learnt from this research are that

- The research is iterative process and that it requires the researcher to model and perform load flow, contingency analysis in PSSE, convert this data to be used in VSAT for Modal analysis. The results of the Modal analysis are used to identify the optimal location to install the SMES. Modelling the SMES in PSSE and perform Transient analysis to determine the network performance improvement.
- It is imperative to analyse the participation factors together with the network topology to

ensure $N-1$ reliability of the SMES.

- Currently, SMES are not widely used in the industry due to high capital cost, but with continuous research in technology improvements for energy storage devices, the costs will eventually go down. The findings in chapter 5 are in line with what is contained in the literature review in Chapter 2 [12]. The study did not produce any surprising findings. Nevertheless the study is necessary to show how the network performs and where best to put the SMES.

Based on this study, the following recommendations are given:

- Modal analysis can be used to determine the optimal location of any energy storage device[18].
- Potential areas for future work would be in the optimal sizing of the SMES for its various applications.
- The introduction of SMES devices as an alternative planning solution will have positive implications to the planning fraternity. It has the capacity to defer costly infrastructure investment for Transmission and/or Distribution systems depending on the application [18].

Bibliography

[1] P. Kundur, N. J. Balu, and M. G. Lauby. *Power system stability and control*. New York: McGraw-Hill, 1994.

[2] C. W. Taylor. *Power system voltage stability*. New York: McGraw-Hill, 1994.

[3] M. H. Ali, B. Wu, and R. A. Dougal. An overview of SMES applications in power and energy systems. *IEEE Transactions on Sustainable Energy*, 1:38–47, 2010.

[4] A. M. S. Yunus and M. Saini. Overview of SMES units application on smart grid systems. In *2016 International Seminar on Intelligent Technology and Its Applications*, pages 465–470. ISITIA, 2016.

[5] J. X. Jin, W. Xu, X. Y. Chen, X. Zhou, J. Y. Zhang, W. Z. Gong, et al. Developments of SMES devices and potential applications in smart grids. In *Innovative Smart Grid Technologies Conference*, pages 1–6. IEEE, 2012.

[6] V. G, V. Suresh, and S. Madichetty. Application of superconducting magnetic energy storage in electrical power and energy systems: a review. *International Journal of Energy Research*, 42:2:358–368, 2017.

[7] J. X. Jin and X. Y. Chen. Study on the SMES application solutions for smart grid. *Physics Procedia*, 36:902–907, 2012.

[8] V. Karasik, K. Dixon, C. Weber, B. Batchelder, G. Campbell, and P. Ribeiro. Smes for power utility applications: a review of technical and cost considerations. *IEEE Transactions on Applied Superconductivity*, 9:541–546, 1999.

[9] S. D. Feak. Superconducting magnetic energy storage (SMES) utility application studies. *IEEE Transactions on Power Systems*, 12:1094–1102, 1997.

[10] G. K. Morison, B. Gao, and P. Kundur. Voltage stability analysis using static and dynamic approaches. *IEEE Transactions on Power Systems*, 8:1159–1171, 1993.

[11] J. A. de Leon and D. W. Taylor. Understanding and solving short-term voltage stability problems. In *PES Power Engineering Society Summer Meeting*, pages 745–752. IEEE, 2002.

[12] M. Ross, M. Borodulin, and Y. Kazachkov. Using D-SMES devices to improve the voltage stability of a transmission system. In *PES Transmission and Distribution Conference and Exposition*, volume 2, pages 1144–1148. IEEE, 2001.

[13] E. S. A. (ESA). *35x25 A Vision for Energy Storage*. Energy Storage Association, November 2017.

[14] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Application*. EPRI, December 2003.

[15] S. Nomura, T. Shintomi, S. Akita, T. Nitta, R. Shimada, and S. Meguro. Technical and cost evaluation on SMES for electric power compensation. *IEEE Transactions on Applied Superconductivity*, 20:1373–1378, 2010.

[16] Research Association of Superconducting Magnetic Energy Storage. S. m. e. storage, 2018.

[17] X. Huang, G. Zhang, and L. Xiao. Optimal location of SMES for improving power system voltage stability. *IEEE Transactions on Applied Superconductivity*, 20:1316–1319, 2010.

[18] Kombe J. A and T. M. Bengani. Utilization of energy storage system to defer distribution and transmission infrastructure investment. PowerGen, 2019.

Appendix A

IEEE Three-Machine Nine-Bus System

A.1 Line Parameters

Line 230 kV	**Resistance (p.u.)**	**Reactance (p.u.)**	**Susceptance (p.u.)**
4 - 5	0.017000	0.092000	0.158000
4 – 6	0.010000	0.085000	0.176000
6 – 9	0.011900	0.100800	0.209000
9 - 8	0.032000	0.161000	0.306000
8 - 7	0.008500	0.072000	0.149000

A.2 Transformer Parameters

Transformer	**Reactance (p.u.)**
1 - 4	0.057600
2 - 7	0.062500
3 – 9	0.058600

A.3 Load

Bus	I_d	P **(MW)**	Q **(MVAr)**
5	1	125	50
6	1	90	30
8	1	100	35
	2	50	17.5

A.4 Machine

Parameter	**Machine 1**	**Machine 2**	**Machine 3**
H(s)	3.01	3.01	3.01
X_d (pu)	1.3125	1.3125	1.3125
X' (pu)	0.1813	0.1813	0.1813
X_q (pu)	1.2578	1.2578	1.2578
X' (pu)	0.25	0.25	0.25
T_{d0} (pu)	5.89	5.89	5.89
T_{qo} (pu)	0.6	0.6	0.6

A.5 Exciter

Parameter	**Exciter 1**	**Exciter 2**	**Exciter 3**
K_A	300	300	300
T_A (s)	0.05	0.05	0.05
K_E	0.17	0.17	0.17
T_E (s)	0.95	0.95	0.95
K_F	0.04	0.04	0.04
T_F (s)	1.0	1.0	1.0

Appendix B

D-SMES Data

B.1 Load Flow

In the load-flow, the D-SMES is represented as a generator. The system output is at 480 V, the systems should be modelled at a 480 V bus with a step-up transformer. The following parameters are used for the generator:

$P_{gen} = 0$

$Q_{max} =$ continuous rating

$Q_{min} = -($continuous rating$)$

$M_{BASE} =$ continuous rating

$Z_{SOURCE} = 0 + j99999$

B.2 Stability Model

CDSMS1	
Description	**Parameter**
VDC, Nominal coil voltage (kV)	3
INIT, Initial Coil current (kA)	1.05
IMIN, minimum coil current (kA)	0.4
TDIS, magnet full-discharge time	0.6
TON	0.1
TOFF	0.1
V1	1.03
V2	0.99
V3	0.90
V4	0.85
T1,T2,T3,T4	1
PAUX_THRESH	0.1
TOVLD	1.0
TBACK	1.0
KOL	230
KOV	110
IACMAX	3
CONV_TYPE, converter type	1
BOOST_CONTR, control flag	1
TURN_ON_VOLT	1
TURN_ON_POWER, damping control	0
TURN_ON_P, active power	1
TURN_ON_Q, reactive power	1

Appendix C

IDV and PSA Code

C.1 IDV Code

```
@! File:"C:\IEEE9Bus\SMES\ieee9busSMES.idv", generated on THU, NOV 07 2019 20:15, release 33.04.00
BAT_CASE,’C:\IEEE9Bus\SMES\ieee9busSMES.sav’
BAT_DYRE_NEW,1,1,1,1,’C:\IEEE9Bus\SMES\ieee9busSMES.dyr’,,,,;
BAT_FDNS,0,0,0,1,1,0,99,0
BAT_CONG,0
BAT_CONL,0,1,1,0,0, 100.0,0.0,0.0, 100.0
BAT_CONL,0,1,2,0,0, 100.0,0.0,0.0, 100.0
BAT_CONL,0,1,3,0,0, 100.0,0.0,0.0, 100.0
BAT_ORDR,0
BAT_FACT,;
```

```
BAT_TYSL,0
BAT_SAVE,’C:\IEEE9Bus\SMES\ieee9busSMES-Conv.sav’
BAT_DYNAMICS_SOLUTION_PARAM_2,,,,,,,,, 0.6,, 0.001,,,,,,;
BAT_SET_GENANG_2,1, 180.0,0.0
BAT_SET_RELANG,1,1,’1’
BAT_VOLTAGE_CHANNEL,1,27,18,7," "
BAT_VOLTAGE_CHANNEL,2,28,19,8," "
BAT_VOLTAGE_CHANNEL,3,29,20,9," "
BAT_MACHINE_ARRAY_CHANNEL,4,1,1,’1’,’Machine 1 Angle’
BAT_MACHINE_ARRAY_CHANNEL,5,2,1,’1’,’Machine 1 Pelec’
BAT_MACHINE_ARRAY_CHANNEL,6,3,1,’1’,’Machine 1 Qelec’
BAT_MACHINE_ARRAY_CHANNEL,7,1,2,’1’,’Machine 2 Angle’
BAT_MACHINE_ARRAY_CHANNEL,8,2,2,’1’,’Machine 2 Pelec’
BAT_MACHINE_ARRAY_CHANNEL,9,3,2,’1’,’Machine 2 Qelec’
BAT_MACHINE_ARRAY_CHANNEL,10,1,3,’1’,’Machine 3 Angle’
BAT_MACHINE_ARRAY_CHANNEL,11,2,3,’1’,’Machine 3 Pelec’
BAT_MACHINE_ARRAY_CHANNEL,12,3,3,’1’,’Machine 3 Qelec’
BAT_MACHINE_ARRAY_CHANNEL,13,2,81,’1’,’SMES Pelec’
BAT_MACHINE_ARRAY_CHANNEL,14,3,81,’1’,’SMES Qelec’
BAT_STRT,0,’C:\IEEE9Bus\SMES\ieee9busSMES.out’
BAT_SNAP,112,32,26,17,14,’C:\IEEE9Bus\SMES\ieee9busSMES.snp’
```

C.2 PSA Code

```
/Trip file for D-SMES Studies

/ CREATED BY Jamila A Kombe

/ 30 October 2019

/ D-SMES studies CaseAfrica

/—– 230kV LINE Trips ———

/ 1- Bus 7 - 8 230kV

Recover from ieee9busSMES.snp and ieee9busSMES-Conv.sav

Start output ieee9busSMES.out Snapshot ieee9busSMES.snp

Run to 0.1 second print 0 plot 50

TRIP LINE FROM BUS 7 to BUS 8 ckt 1

run to 5 seconds print 0 plot 50


    END
```

Appendix D

Published Papers

The following papers have been published through this work:

1. J.A. Kombe and T.M Bengani, "Utilization of Energy Storage System to defer Distribution And Transmission Infrastructure Investment", PowerGen, July 2018.

2. J. A. Kombe, T. M. Bengani and D. G. Dorrell, “Improved Voltage and Dynamic Performance of Transmission Power Networks Using Distributed Superconducting Magnetic Energy Storage Systems”, SAUPEC, Bloemfontein, Jan. 2019