2019-10

Voltage Stability Analysis of Ethio-Sudan Power System Interconnection, Its Potential Impacts and Improvement Methods

Yigzaw, Yalemsew

http://hdl.handle.net/123456789/10974

Downloaded from DSpace Repository, DSpace Institution's institutional repository
VOLTAGE STABILITY ANALYSIS OF ETHIO-SUDAN POWER SYSTEM INTERCONNECTION, ITS POTENTIAL IMPACTS AND IMPROVEMENT METHODS

BY:

YALEMSEW YIGZAW

ADVISOR: DR.-ING BELACHEW BANTYIRGA

Bahir Dar, Ethiopia

October 17, 2019
VOLTAGE STABILITY ANALYSIS OF ETHIO-SUDAN POWER SYSTEM INTERCONNECTION, ITS POTENTIAL IMPACTS AND IMPROVEMENT METHODS

Yalemsew Yigzaw Agaje

A thesis submitted to the school of Research and Graduate Studies of Bahir Dar Institute of Technology, Bahir Dar University in partial fulfillment of the requirements for the degree of Master’s in Power Systems Engineering in the Faculty of Electrical and Computer Engineering

Advisor Name: Dr.-Ing Belachew Bantyirga

Bahir Dar, Ethiopia
October 17, 2019
DECLARATION

I, the undersigned, declare that the thesis comprises my own work. In compliance with internationally accepted practices, I have acknowledged and referred all materials used in this work. I understand that non-adherence to the principles of academic honesty and integrity, misrepresentation/ fabrication of any idea/data/fact/source will constitute sufficient ground for disciplinary action by the University and can also evoke penal action from the sources which have not been properly cited or acknowledged.

Name of the student Yalemsew Yigzaw Agaje Signature ____________
Date of submission: ________________
Place: Bahir Dar

This thesis has been submitted for examination with my approval as a university advisor.

Advisor Name: Dr.-Ing Belachew Bantyirga
Advisor’s Signature: ___________________ Date: __/___/2019
The following graduate faculty members certify that this student has successfully presented the necessary written final thesis and oral presentation for partial fulfillment of the thesis requirements for the Degree of Master of Science in Power Systems Engineering.

Approved By:
Advisor:
Dr.-Ing Belachew Bantyirga
Name
Signature
Date

External Examiner:
Dr. 
Name
Signature
Date

Internal Examiner:
Mr. Ahunm Abebe
Name
Signature
Date

Chair Holder:
Mr. Tewodros Gera
Name
Signature
Date

Faculty Dean:
Mr. Solomon Lule
Name
Signature
Date
To my beloved wife Zeneb Awoke (MSc.)
ACKNOWLEDGEMENTS

First of all, I shall praise and thank the almighty Lord for helping us through this difficult but very inspiring work and for providing us with the ideas and patience necessary for the successful completion of this thesis.

Then, I would like to express my deepest gratitude and appreciation to my supervisor and mentor, Dr.-Ing Belachew Bantyirga, for their guidance and encouragement through this journey starting from selection of thesis title up to end of thesis presentation. His patience and support has enabled us to achieve our highest potential in both academic and professional work. This has been an opportunity of a lifetime for which I am truly thankful.

Finally, I would like to thank EEP officials for their valuable help in data collection and for giving PSS/E software where we have used throughout the end of thesis and all my friends in Bahir Dar University and around the world, who helped me through the course of my studies, discussed ideas about my thesis, and made my life enjoyable.

Thank you all!!!

Yalemsew Yigzaw
ABSTRACT

The Ethiopian Electric Power (EEP) is undertaking a huge electric power generation, transmission and distribution expansion and it also started exporting electric power to neighboring East African Power Pool (EAPP) member countries since 2011 G.C. With the increase in power demand, operation and planning of large interconnected power system are becoming more and more complex, so power system would become less stable. Voltage instability is one of the phenomena which have resulted in a major blackout in Ethiopian power system grid. To maintain stability of such systems, it is desirable to plan suitable measures to improve power system stability and increase voltage stability margins. FACTS devices and HVDC transmissions have emerged as solutions to help power systems to increase the stability margins. Integration of Voltage Source Converter based HVDC and STATCOM can regulate the voltage-magnitude control as well as adaptive to active and reactive power control simultaneously because of their flexibility and fast control characteristics. This thesis investigated the voltage stability improvements that can be attained through integrating VSC-HVDC and STATCOM transmission system. North West Region (NWR) interconnected to Sudan through tie-line as well as VSC-HVDC and STATCOM device transmission model with a complete control system have been modelled and simulated on Power System Simulator for Engineers (PSS/E) software version 34.2. Then the performance of both improvement methods are evaluated and found to function satisfactorily at supporting bidirectional power flow from Ethiopia to Sudan or vice versa and at maintaining stability during disturbances. The fault on Sudan affected the system stability of Ethiopia when they are interconnected through AC transmission line but it can’t affect when it is connected by VSC-HVDC. As a general conclusion it was shown that integrating STATCOM and VSC-HVDC transmissions with an appropriate control strategy was an effective means to improve the system stability of interconnected areas where VSC-HVDC performed as firewall for fault on opposite area bus not to affect other area.

Key words: STATCOM, voltage stability improvement, VSC-HVDC
# Table of Contents

DECLARATION .................................................................................................................. II

ACKNOWLEDGEMENTS ................................................................................................. VI

ABSTRACT ....................................................................................................................... VII

LIST OF FIGURES ........................................................................................................... XII

LIST OF TABLES ............................................................................................................. XVI

LIST OF ABBREVIATIONS ............................................................................................... XVII

LIST OF SYMBOLS .......................................................................................................... XIX

CHAPTER ONE ................................................................................................................. 1

1. INTRODUCTION ........................................................................................................... 1

1.1. BACKGROUND ......................................................................................................... 1

1.2. STATEMENT OF THE PROBLEM ......................................................................... 4

1.3. OBJECTIVES OF THE STUDY ............................................................................. 5

1.3.1 General objective ................................................................................................. 5

1.3.2 Specific objectives ............................................................................................... 5

1.4. SCOPE OF THE STUDY ......................................................................................... 5

1.5. SIGNIFICANCE OF THE STUDY .......................................................................... 6

1.6. THESIS OUTLINE ................................................................................................. 6

CHAPTER TWO ............................................................................................................... 8

2. LITERATURE REVIEW ............................................................................................... 8

CHAPTER THREE ........................................................................................................... 11

3. METHODOLOGY ......................................................................................................... 11

3.1. INTRODUCTION ..................................................................................................... 11

3.2. DATA COLLECTION ............................................................................................... 12

3.3. DATA ANALYSIS ................................................................................................... 12

3.4. NETWORK MODEL ................................................................................................. 12

3.4.1. Bus Model ........................................................................................................... 13

3.4.2. Generator Model ............................................................................................... 13

3.4.3. Transformer Model ............................................................................................ 14

3.4.4. Line and Load Model ......................................................................................... 15
3.4.5. External Grid Model ................................................................. 15
3.5. NET INTERCHANGE CONTROL ...................................................... 16

CHAPTER FOUR ................................................................................. 17
4. THEORETICAL BACKGROUND AND SYSTEM MODELLING ............. 17
4.1. POWER SYSTEM STABILITY ANALYSIS ......................................... 17
  4.1.1. Rotor Angle Stability ............................................................. 18
  4.1.2. Frequency Stability ............................................................... 18
  4.1.3. Voltage Stability ................................................................. 18
4.2. POWER SYSTEM STABILITY IMPROVEMENT METHODS .......... 19
4.3. OVERVIEW OF FACTS DEVICES .................................................. 20
  4.3.1. Overview of STATCOM ......................................................... 22
4.4. OVERVIEW OF HVDC TRANSMISSION SYSTEM ....................... 23
  4.4.1. Common System Topologies .................................................. 26
  4.4.2. Main Components of a VSC-HVDC Transmission System ....... 27
  4.4.3. Pulse Width Modulation (PWM) ............................................ 35
  4.4.4. VSC Capability Curve .......................................................... 36
4.5. VSC-HVDC MATHEMATICAL MODELING .................................... 38
4.6. VSC CONVERTER CONTROL ......................................................... 42
4.7. VECTOR CURRENT CONTROL ....................................................... 43
  4.7.1. Inner Current controller ......................................................... 43
  4.7.2. Phase-Locked Loop (PLL) ...................................................... 46
4.8. OUTER CONTROLLERS ................................................................. 47
  4.8.1. Direct Voltage Controller ...................................................... 47
  4.8.2. AC voltage controller ........................................................... 48
  4.8.3. Active Power Controller ....................................................... 49
  4.8.4. Reactive Power Controller .................................................... 50
4.9. TUNING CONTROLLERS ............................................................... 50
  4.9.1. Current Controller Tuning ..................................................... 51
  4.9.2. Direct Voltage Controller Tuning .......................................... 53
4.10. STATCOM MATHEMATICAL MODELLING .................................... 55
CONTROLLING STRUCTURE OF STATCOM IN PSS/E ........................................ 57

4.11.1. STATCOM Control Functions ................................................................. 58

4.11.2. STATCOM Protective Functions ............................................................. 61

4.12. APPLICATION OF VOLTAGE STABILITY INDICES FOR PLACEMENT OF STATCOM 62

4.12.1. Line voltage stability indices ................................................................. 62

CHAPTER FIVE ........................................................................................................... 67

5. SIMULATION RESULTS AND DISCUSSION ..................................................... 67

5.1. INTRODUCTION ............................................................................................... 67

5.2. POTENTIAL IMPACTS OF INTERCONNECTION ............................................. 68

5.2.1. 3-Phase to Ground Fault on Rabak (area 2) ........................................ 68

5.2.2. 3-Phase to Ground Fault on Mekelle 230kV bus (Area 1) ....................... 70

5.2.3. Outage of Belles Generating Unit ............................................................... 72

5.3. SYSTEM STABILITY IMPROVEMENT BY USING STATCOM ....................... 75

5.3.1. Fault on Area 1 ......................................................................................... 76

5.3.2. Fault on Area 2 ......................................................................................... 80

5.4. SYSTEM STABILITY IMPROVEMENT BY USING VSC-HVDC ...................... 82

5.4.1. Fault on Area 1 ......................................................................................... 83

5.4.2. Fault on Area 2 ......................................................................................... 86

5.5. COMPARISON OF STABILITY IMPROVEMENT METHODS ....................... 88

5.6. SYSTEM STABILITY IMPROVEMENT BY INTEGRATING BOTH STRATEGIES .... 92

5.6.1. With VSC-HVDC interconnection and STATCOM on area 1 ............... 93

5.6.2. With VSC-HVDC interconnection and STATCOM on area 2 ............... 96

5.7. ECONOMICAL COST ANALYSIS ................................................................. 100

CHAPTER SIX ............................................................................................................ 106

6. CONCLUSION AND RECOMMENDATIONS ..................................................... 106

6.1. CONCLUSION ................................................................................................. 106

6.2. RECOMMENDATIONS .................................................................................... 107

6.3. SUGGESTIONS FOR FUTURE WORK ............................................................ 107

REFERENCES ........................................................................................................... 109

APPENDIX A ............................................................................................................. 115
List of Figures

Figure 1.1 Installed capacity of area 1 and area 2 ................................................................. 1
Figure 1.2 Sub-regional interconnected and planned interconnections of Ethiopia ................. 2
Figure 3.1 Methodology flow chart .......................................................................................... 11
Figure 3.2 Identical generators at bus ...................................................................................... 14
Figure 3.3 PSS®E transmission branch equivalent Pi model ....................................................... 15
Figure 4.1 Classification of power system stability .................................................................... 17
Figure 4.2 Power system stability improvement strategies .......................................................... 20
Figure 4.3 Types of FACTS devices based on power electronics devices ................................. 22
Figure 4.4 Common system topologies (a) symmetric monopole (b) asymmetric monopole (c) series bridge (d) bipolar (e) multi-terminal ........................................................................... 27
Figure 4.5 Components of VSC HVDC .................................................................................... 27
Figure 4.6 Three-phase six-bridge VSC converter .................................................................... 28
Figure 4.7 Plot of the converter losses at 150kV, modules M4, M5 and M6 ............................. 30
Figure 4.8 VSCDCT PSS/E model ............................................................................................. 31
Figure 4.9 AC-side filters. (a) 2\textsuperscript{nd} order filter, (b) 3\textsuperscript{rd} order filter and (c) Notch filter .... 33
Figure 4.10 Pi-model of a single pole for a dc-transmission link ................................................ 34
Figure 4.11 Classification of modulating signals ....................................................................... 35
Figure 4.12 Capability curve of a VSC-HVDC station ................................................................. 37
Figure 4.13 Single-line representation of VSC .......................................................................... 38
Figure 4.14 Stationary reference frames: $abc$ and $\alpha$-$\beta$ ...................................................... 39
Figure 4.15 The inner current control loop set up ...................................................................... 43
Figure 4.16 Decoupled current and voltage feed-forward compensation ................................ 45
Figure 4.17 The inner current control loop with the compensation terms ............................... 46
Figure 4.18 Reduced form of the inner current control loop ...................................................... 46
Figure 4.19 Block diagram of PLL ............................................................................................ 47
Figure 4.20 Block diagram of dc voltage controller ................................................................. 48
Figure 4.21 AC voltage control by reactive power compensation .......................................... 49
Figure 4.22 PI controller for active power control ................................................................. 50
Figure 4.23 PI controller for reactive power control .......................................................... 50
Figure 4.24 Step response of the inner current control loop .............................................. 52
Figure 4.25 Step response of DC voltage controller .......................................................... 54
Figure 4.26 STATCOM circuit and connection to the network ......................................... 55
Figure 4.27 V-I characteristics of the STATCOM ............................................................... 56
Figure 4.28 Voltage regulator in STATCOM ................................................................. 58
Figure 4.29 STATCOM Slow MVAR function ................................................................. 59
Figure 4.30 STATCOM POD function .............................................................................. 60
Figure 4.31 STATCOM gain Supervisor and Optimizer ...................................................... 61
Figure 4.32 Block diagram of the SVSMO3 STATCOM model ........................................ 62
Figure 4.33 Two bus single line diagram ........................................................................... 62
Figure 4.34 Area 1 PCC for STATCOM placement .......................................................... 65
Figure 4.35 Area 2 PCC for STATCOM placement .......................................................... 66
Figure 5.1 Single line diagram of area 1 and area 2 under study on PSS/E ...................... 67
Figure 5.2 Bus voltage dynamics for a fault at Rabak 220kV bus (a) Area 1 (b) Area 2 .... 69
Figure 5.3 Generator rotor angle oscillations (a) Area 1 (b) Area 2 ................................. 69
Figure 5.4 Bus frequency deviation (a) Area 1 and (b) Area 2 ........................................ 70
Figure 5.5 Bus voltage dynamics for a fault at Mekelle 230kV bus (a) Area 1 (b) Area 2 .... 70
Figure 5.6 Generator rotor angle oscillations (a) Area 1 (b) Area 2 ................................. 71
Figure 5.7 Bus frequency deviation (a) Area 1 and (b) Area 2 ........................................ 71
Figure 5.8 Bus voltage dynamics for a fault at Mekelle 230kV bus (a) Area 1 (b) Area 2 with interconnection ............................................................... 72
Figure 5.9 Bus voltage dynamics for a fault at Mekelle bus 230kV without interconnection ............................................................... 73
Figure 5.10 Area 1 bus voltage dynamics for a fault at Mekelle 230kV bus with and without interconnection (a) Bahir Dar II bus (b) Mekelle bus ................. 74
Figure 5.11 Rotor angle when 3-phase to ground fault on Mekelle bus (a) Area 1 (b) Area 2 ........................................................................ ............................................................... 74
Figure 5.12 Bus frequency deviation on 3-phase to ground fault at Mekelle bus (a) area 1 (b) area 2 ............................................................................................................................... 75
Figure 5.13 Bus voltages (a) Bahir Dar II 230kV bus (b) Rabak 220kV bus .................. 76
Figure 5.14 Rotor angle (a) Tekeze PP (b) Fincha PP (c) Tis-Abay2 PP (d) Beles PP ... 78
Figure 5.15 Rotor angle (a) Sennar PP (b) Roseires PP ............................................... 78
Figure 5.16 Bus frequency deviation (a) PCC1 (b) PCC2 ............................................. 78
Figure 5.17 Bus voltage dynamics with and without STATCOM for a fault at Mekelle 230kV BB .................................................................................................................... 79
Figure 5.18 Bus voltages with fault on Rabak bus (a) Rabak 220kV BB (b) Bahir Dar II 230kV BB .............................................................................................................................. 80
Figure 5.19 Bus voltages with fault on Gadaref bus (a) Gadaref 220kV BB (b) Gondar 230kV BB ............................................................................................................................. 81
Figure 5.20 Bus voltages with fault on Rosier bus (a) Rosier 220kV BB (b) Debre-Markos 230kV BB .............................................................................................................................. 82
Figure 5.21 The screen show of system with VSC-HVDC on PSS/E .................................. 82
Figure 5.22 Improved voltage output of Metema bus bar ............................................... 83
Figure 5.23 Gadaref bus voltage dynamics ..................................................................... 84
Figure 5.24 Bus voltage dynamics with and without VSC-HVDC for a fault at Metema bus bar ............................................................................................................................ 85
Figure 5.25 Bus voltage dynamics when fault on (a) Fincha bus bar (b) Debre Markos 230 kV bus .......................................................................................................................... 85
Figure 5.26 Bus voltage dynamics of Gadaref 220 kV bus ............................................. 86
Figure 5.27 Bahir Dar II bus voltage dynamic when fault on Gadaref .............................. 87
Figure 5.28 Bus voltage dynamics of (a) Mekelle 230kV bus (b) Tis-Abay II 132kV bus for fault on Gadaref .......................................................................................................................... 87
Figure 5.29 Bus voltage dynamics of (a) Rabak bus (b) Metema 230kV bus for fault on Rabak bus .......................................................................................................................... 88
Figure 5.30 Voltage profile improvement at Gondar 230 kV bus .................................. 90
Figure 5.31 Rabak 220kV bus voltage when fault on Gondar bus ................................. 91
Figure 5.32 Bus voltage dynamics for fault on Gondar (a) Bahir-Dar II 230kV bus (b) Sudan-Gadaref 220kV bus................................................................. 91
Figure 5.33 Bus voltage dynamics for fault on Sudan-Gadaref (a) Sudan-Gadaref 220kV bus (b) Tis-Abay II 132 kV bus ................................................................. 92
Figure 5.34 Bahir Dar II 230kV bus voltage dynamics ........................................... 93
Figure 5.35 Sudan-Rabak bus voltage dynamics for fault on Bahir Dar II 230kV bus.... 94
Figure 5.36 Sudan-Gadaref 220kV bus voltage dynamics ........................................ 95
Figure 5.37 Mota 230kV bus voltage for fault on Sudan-Gadaref 220kV bus .......... 95
Figure 5.38 Tis-Abay II 132kV bus voltage dynamics ............................................. 96
Figure 5.39 Sudan-Gadaref 220kV bus voltage dynamics for fault on Tis-Abay II 132kV bus ........................................................................................................ 97
Figure 5.40 Sudan-Gadaref 220kV bus voltage dynamics ......................................... 98
Figure 5.41 Metema 230kV bus voltage dynamics for fault on Sudan-Gadaref 220kV bus ........................................................................................................ 98
Figure 5.42 Belles generator output for fault on Bahir Dar II 230kV bus (a) active power (b) reactive power .................................................................................. 99
Figure 5.43 Rotor angle for fault on Bahir Dar II bus (a) Beles generating unit (b) Rosier power plant .................................................................................................... 99
Figure 5.44 Comparison of costs for AC and DC transmission conductor .............. 100
Figure D.1 Tis-Abay II generator electrical power for fault on Rabak bus ................. 128
Figure D.2 Tekeze generator rotor angle for fault on Rabak bus .............................. 128
Figure D.3 Location of proposed transmission line routes between Ethiopia and Sudan on planning phase .......................................................................................... 129
List of Tables

Table 4.1 Types of FACTS devices based on their interconnection ........................................ 21
Table 4.2 Services performed by STATCOM ................................................................. 23
Table 4.3 Summary of fully controlled high power semiconductors .................................. 24
Table 4.4 Summary on comparison of classic and VSC-HVDC systems .............................. 25
Table 4.5 Different HVDC light base modules ..................................................................... 28
Table 4.6 Data for +150 kV symmetric base modules, typical values ................................. 29
Table 4.7 Transfer capability for different conductor lengths ................................................ 29
Table 4.8 Voltage stability indices for area 1 on simultaneous Load change (load increase by 50%) .................................................................................................................. 64
Table 4.9 Voltage stability indices for area 2 on simultaneous Load change (load increase by 50%) .................................................................................................................. 65
Table 5.1 Comparison of steady-state bus voltage profiles .................................................. 89
Table 5.2 The overall cost of VSC-HVDC (M$) ................................................................. 101
Table 5.3 Cost of different FACTS devices ....................................................................... 101
Table 5.4 Power loss without and with STATCOM .......................................................... 101
Table 5.5 NPV analysis of installation of STATCOM at both areas .................................... 103
Table A.1 Bus data of northern and NWR (Ethiopian side) .................................................. 115
Table A.2 Bus data from SETCO (Sudan side) .................................................................... 115
Table A.3 NWR and SETCO transmission line data ......................................................... 115
Table A.4 Sudan transmission Lines (OHL) ....................................................................... 116
Table A.5 Generation Data ............................................................................................... 116
Table A.6 Two winding transformer data .......................................................................... 116
Table A.7 Three winding transformer data ........................................................................ 117
Table A.8 Generator dynamic parameters for both areas .................................................... 117
Table A.9 Line stability indices for both areas under normal conditions ............................. 117
Table A.10 Case study load data ....................................................................................... 118
### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABB</td>
<td>Asia Brown Bovary</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AVR</td>
<td>Automatic Voltage Regulators</td>
</tr>
<tr>
<td>BB</td>
<td>Bus Bar</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
</tr>
<tr>
<td>CCC</td>
<td>Capacitor Commutated Converters</td>
</tr>
<tr>
<td>CIGRE</td>
<td>Conseil International des Grands Réseaux Electriques</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DFC</td>
<td>Dynamic Flow Controller</td>
</tr>
<tr>
<td>EAPP</td>
<td>East African Power Pool</td>
</tr>
<tr>
<td>EEP</td>
<td>Ethiopian Electric Power</td>
</tr>
<tr>
<td>EEU</td>
<td>Ethiopian Electric Utility</td>
</tr>
<tr>
<td>ENB</td>
<td>Eastern Nile Basin</td>
</tr>
<tr>
<td>ENSAP</td>
<td>Eastern Nile Subsidiary Action Program</td>
</tr>
<tr>
<td>ENTRO</td>
<td>Eastern Nile Technical Regional Office</td>
</tr>
<tr>
<td>FACTS</td>
<td>Flexible AC Transmission System</td>
</tr>
<tr>
<td>FVSI</td>
<td>Fast Voltage Stability Index</td>
</tr>
<tr>
<td>GCT</td>
<td>Gate Commutated Turn-Off thyristor</td>
</tr>
<tr>
<td>GENCLS</td>
<td>Classical machine model</td>
</tr>
<tr>
<td>GTO</td>
<td>Gate Turn Off thyristor</td>
</tr>
<tr>
<td>HEPP</td>
<td>Hydro-Electric Power Plants</td>
</tr>
<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
</tr>
<tr>
<td>HYGOV</td>
<td>HYdroelectric plant GOVernor</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IEGT</td>
<td>Injection Enhanced Gate Transistor</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>IGCT</td>
<td>Integrated Gate Commutated Thyristor</td>
</tr>
<tr>
<td>IPFC</td>
<td>Inter-line Power Flow Controller</td>
</tr>
<tr>
<td>LQP</td>
<td>Line Stability Factor</td>
</tr>
<tr>
<td>ms</td>
<td>milliseconds</td>
</tr>
<tr>
<td>MSS</td>
<td>Mechanically Switched Shunts</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>NCC</td>
<td>Natural Commutated Converters</td>
</tr>
<tr>
<td>NEC</td>
<td>National Electricity Corporation</td>
</tr>
<tr>
<td>NVSI</td>
<td>New Voltage Stability Index</td>
</tr>
<tr>
<td>NWR</td>
<td>North Western Region</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional and Integral controller</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
</tr>
<tr>
<td>POD</td>
<td>Power Oscillation Damping</td>
</tr>
<tr>
<td>PSS/E</td>
<td>Power System Simulator for Engineers</td>
</tr>
<tr>
<td>PSSs</td>
<td>Power System Stabilizers</td>
</tr>
<tr>
<td>PTI</td>
<td>Power Technologies International</td>
</tr>
<tr>
<td>PP</td>
<td>Power Plant</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>sec</td>
<td>Seconds</td>
</tr>
<tr>
<td>SETCO</td>
<td>Sudanese Electricity Transmission Co Ltd</td>
</tr>
<tr>
<td>SPWM</td>
<td>Sinusoidal Pulse Width Modulation</td>
</tr>
<tr>
<td>SSSC</td>
<td>Static Synchronous Series Compensator</td>
</tr>
<tr>
<td>STATCOM</td>
<td>STATic COMpensator</td>
</tr>
<tr>
<td>SVC</td>
<td>Static Var Compensator</td>
</tr>
<tr>
<td>SVSMO3</td>
<td>Static Var System (SVS) model for STATCOM</td>
</tr>
<tr>
<td>TCSC</td>
<td>Thyristor Controlled Series Compensator</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>THI</td>
<td>Third Harmonic Injection</td>
</tr>
<tr>
<td>UPFC</td>
<td>Unified Power Flow Controller</td>
</tr>
<tr>
<td>UV or OV</td>
<td>Under Voltage or Over Voltage</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage-Source Converter</td>
</tr>
<tr>
<td>VSCDCT</td>
<td>DC transmission line dynamics model</td>
</tr>
<tr>
<td>VSI</td>
<td>Voltage Stability Indices</td>
</tr>
<tr>
<td>WECC</td>
<td>Western Electricity Coordinating Council</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

\( i_{abc} \)  AC current in abc reference frame
\( i_d \)  Active current
\( p \)  Active power
\( X_{\alpha\beta} \)  Alpha-beta frame of reference
\( m \)  Amplitude
\( \delta \)  Angle difference
\( a_{PLL} \)  Bandwidth of the PLL
\( c \)  Capacitance
\( \tau \)  Capacitor time constant
\( k \)  Constant number
\( V_{c,abc} \)  Converter AC side output voltage in abc reference frame
\( I_r \)  Current through reactor
\( \zeta \)  Damping constant
\( U_{dc} \)  DC Voltage
\( d \)  Direct Axis
\( V_{g,abc} \)  Grid Ac voltage in abc reference frame
\( \theta \)  Grid voltage angle
\( h \)  Harmonic order
\( H \)  Henry
\( L \)  Inductance
\( K_i \)  Integral gain.
\( T_i \)  Integral time constant
\( \omega_n \)  Natural oscillation
\( \phi \)  Phase angle
\( K_p \)  Proportional gain
\( q \)  Quadrature Axis
\( Q_f \)  Quality factor
\( X_r \)  Reactance of reactor
\( i_q \)  Reactive current
\( Q \)  Reactive power
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>Resistance</td>
</tr>
<tr>
<td>$d$</td>
<td>Symmetrical distance</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Time delay</td>
</tr>
<tr>
<td>$T_{eq}$</td>
<td>Time delay due to the current control loop</td>
</tr>
<tr>
<td>$V$</td>
<td>Voltage</td>
</tr>
<tr>
<td>$V_{err}$</td>
<td>Voltage error</td>
</tr>
</tbody>
</table>
CHAPTER ONE
1. INTRODUCTION

1.1. Background

A power system network is customarily divided into multiple areas with tie-lines connecting an area with its neighboring area because a utility in one area is sometimes unable to meet its own load demand due to an abrupt increase in electricity use or an outage of a generating station. The utility will resort to importing power from neighboring utilities or power producers in order to satisfy the load demand required to stay within normal operating conditions like Sudan where it imports bulk power from Ethiopia. Undoubtedly, the generation at the selling (supplying) side might have to be increased to meet the buyer’s demand as well as its own demand. Real power is then transferred from the seller to buyer across tie-lines, while transferring a minor fault on a heavily loaded line may result in cascading problem which can eventually lead to systems collapse if proper preventive measures are not taken. From these problems the voltage instability is the major one. The following Figure 1.1 shows the installed capacity of both areas (Ethiopia and Sudan) where Sudan have lower hydroelectric power plants (HEPP) than Ethiopia.

![Figure 1.1 Installed capacity of area 1 and area 2 [1, 2]](image)

The EEP grid consists a total capacity of 4244.01 MW [1, 3], of which 89.9 % is generated from hydropower plants as indicated on Figure 1.1 above. There are particular projects under construction such as Grand Renaissance Dam with capacity of 6450MW,
CHAPTER 1: INTRODUCTION

and Genale Dawa 2 & 3 348MW. Sudan have some of the lowest level of electricity generation per capita in the world with installed capacity of 3177.8 MW operational and 2257MW (under construction and planned) [4, 5]. Ethio-Sudan power transmission interconnection is one component of the fast-track projects that was first recognized for implementation under the Eastern Nile Subsidiary Action Program (ENSAP). The project was implemented under the supports of the Eastern Nile Technical Regional Office (ENTRO) and the power authorities in both Ethiopia and Sudan, namely, the Ethiopian Electric Power (EEP) in Ethiopia and the National Electricity Corporation (NEC) in Sudan which is under the Ministry of Electricity and Dams. The project involved the construction of a high voltage transmission line from Ethiopia to Sudan [6]. The immediate objective was to facilitate cross-border trade between the two countries and thus optimize utilization of existing and planned generation capacity. The long-term objective is to promote regional power trade through coordinated planning and development of power generation and transmission interconnections in the context of multipurpose water resources development in the Eastern Nile Basin (ENB). Ethiopian is not limited in exporting electric power only to Sudan, EEP also started export of electricity to other neighboring and planned to export it beyond EAPP member countries as shown on Figure 1.2 below.

Figure 1.2 Sub-regional interconnected and planned interconnections of Ethiopia [4]
CHAPTER 1: INTRODUCTION

The 230/220 kV cross-border transmission line stretches for 296 km from Ethiopia to Sudan border and 157.5 km from Sudan border to Gadderif with total length of 453.5 km. The transmission has four sections: the 137.2km-long Bahir Dar-Gondar section, the 122km-long Gondar-Shehedie section and the 37km-long Shehedie-Metema on Ethiopian side and Metema to Gadarif 157.5 km on Sudan side stretch with capacity of 400 MW of electricity via the Gedaref-Galabat transmission line, which will in the long-term enable Khartoum to replace its thermal power generating units with Ethiopia’s renewable and clean hydro-power generated energy [7].

The final section of the Ethiopia-Sudan power transfer connect with a transmission line in the eastern Sudanese city of Gadderif, which have joined the power grids of the two countries. The Ethiopia-Sudan transmission line will eventually link Ethiopia’s hydro-electric power source to the rest of East Africa via projects between Ethiopia-Kenya, Tanzania-Zambia-Kenya-Uganda and Ethiopia-Sudan-Egypt.

Voltage stability studies are now receiving special attention in developed power networks due to their increasingly heavy loading [8]. Improvement of voltage stability is very much essential in order to ensure desired power transfer at rated voltage. Voltage stability concerned is with the ability of power system to maintain the acceptable voltages at all system buses under normal conditions as well as when the system is being subjected to a disturbance. The analysis of voltage stability and improvement methods is an important part of study.

HVDC power transmission systems and technologies associated with the flexible ac transmission system (FACTS) continue to advance as they make their way to commercial applications. Both HVDC and FACTS systems underwent research and development for many years, and they were based initially on thyristor technology and more recently on fully controlled semiconductors and voltage-source converter (VSC) topologies [9].

This thesis deals on the analysis of voltage stability on Ethio-Sudan transmission system to study its impacts and improve the performance of a system by integrating VSC-HVDC and FACTS devices models specifically STATic COMpensator (STATCOM).
1.2. Statement of the Problem

Even though EEP is exporting electric power to abroad especially to Sudan many voltage fluctuations and blackout events have been registered in the Ethiopian electric power system, in the past years. According to the blackout reports collected from National Grid Control Center, the primary reason for blackout was reported as voltage stability problem [1]. Shunt reactors are installed at various points in the system [10] which cannot maintain system stability in well manner. This situation shows that the reactive power provision and control within the system is poor even though, Sudan is strongly attached to Ethiopia to purchase a firm energy of 100 MW and/above by using AC transmission lines in order to bring an access of electrification to its population and for industrialization of the country itself. But because of voltage instability and other factors the country does not reach expected power [11] that initiates to study its voltage stability improvement methods.

The voltages on the East African Power Pool (EAPP)\(^1\) interconnected transmission system shall normally be maintained within the operating voltage range of 0.80 to 1.20 per unit after any multiple contingency or severe system stress [7], but in Ethio-Sudan transmission system voltage is not in range sometimes below range (0.95 pu) for the case of Bahir Dar to Gadarif transmission system [1]. Therefore, it is necessary to consider design solutions that maintain the future system stability thereby increasing the existing system voltage stability.

On this respect, this thesis investigates the integration of VSC-HVDC and STATCOM transmission system so as to improve the existing as well as the upcoming EEP and EAPP system stability.

\(^1\) **Power Pool**: An association of two or more interconnected electric systems having an agreement to coordinate operations and planning for improved reliability and efficiencies.
CHAPTER 1: INTRODUCTION

1.3. Objectives of the study

1.3.1 General objective

The main objective of this thesis is to study the impact of Ethio-Sudan transmission system on voltage stability of EEP high voltage grid (230kV and above) and to put forward the stability improvement methods.

1.3.2 Specific objectives

As specific objective it is targeted at

- Modelling north western part of EEP high voltage grid system.
- Modelling Ethio-Sudan transmission system.
- Calculating the weak and weakest bus for placing FACTS devices.
- Developing the control system for VSC-HVDC and STATCOM devices transmission system.
- Studying the impact of Ethio-Sudan transmission system on voltage stability of EEP high voltage grid.
- Carrying out time domain simulations with and without VSC-HVDC and/or STATCOM transmission schemes and show system stability performance improvement under disturbance scenarios.

1.4. Scope of the study

Though the country has been engaged in expansion to many regions and in exporting electricity to the neighboring countries like Djibouti, Kenya, and Sudan. This paper have focused only on the north western region of EEP high voltage grid (230 kV and above) and export of electric energy to Sudan (220 kV).

The power system has a lot of problems like instability in frequency and angle. This thesis deals only on voltage stability analysis and improvement methods, namely VSC-HVDC and STATCOM. Here again VSC-HVDC is tested on Ethio-Sudan transmission system and STATCOM have been installed on selected buses to see voltage stability profile.
In this thesis work there is no any practical implementation of system models where analysis and simulation of the system as well as improvement methods will be discussed.

1.5. Significance of the study

This work provides important insight into potential improvements of voltage stability and can be used as an input for other existing transmissions and for those which are under construction. It is also expected to have the following merits;

- It distinguishes problems of voltage instability and solutions to be taken.
- It identifies the weakest bus of the region.
- It analyzes tie line voltage stability and its potential impacts.
- It gives the advantages and disadvantages of tie lines on Ethiopian grid.
- It informs the exporting and importing countries to use the developed transmission system model to improve system stability.
- It gives an idea to select in using either VSC-HVDC or STATCOM transmission system or integration of both for their projects.
- It helps for further studies while implementing the tie lines.

1.6. Thesis Outline

The thesis is structured as follows;

Chapter 1: Is an introductory part giving a highlight on background of the study. The basic problem is labeled here. Also the objectives of the thesis work are described. Finally the scope as well as significance of the study are discussed.

Chapter 2: Reviews literatures of previous works which are related to dynamic performance improvement of a power system using various techniques.

Chapter 3: Deals with methodologies that are followed through this thesis.

Chapter 4: Deals on theoretical background about power system stability and VSC-HVDC, FACTS devices was discussed and a classification of different FACT devices for power system has been presented, converter reactive power capability is formulated Here again the system is mathematically modelled, controllers are also established and weak buses are identified for STATCOM placement.
CHAPTER 1: INTRODUCTION

Chapter 5: In this chapter impact of interconnection on one to other is argued, time domain results with and without STATCOM and VSC-HVDC was discussed by initiating disturbance on different buses at both areas.

Chapter 6: This chapter encompasses conclusion and recommendations and future mechanisms to be focused.
CHAPTER TWO

2. LITERATURE REVIEW

Many researchers have done studies on VSC-HVDC transmission system and selection and placement of FACTS devices for voltage stability improvement and some of the literatures are reviewed here.

In December 2010, M. V. Reddy et al [12], argued on comprehensive analysis of both steady state and dynamic voltage instability phenomenon under contingency conditions. The paper proposed contingency severity index as better voltage stability index for finding severe contingencies. Dynamic voltage profile is improved by locating static var compensator (SVC) as per the severity index as indicated in this paper. Finally the paper concluded that only steady state analysis cannot guarantee the short-term stability because sometimes system may seem stable in long-term but it may not stable in short-term.

In January 2011, Raja Lakshmi et al. in 2011 [13] explained that the proper placement of a FACTS device can increase the transmission capability of transmission lines. The authors have implemented a technique for proper location of FACTS device which is based on the performance index and reduction of total reactive power losses.

On 13 December 2012, Dr. RL Sellick and M Åkerberg [14], compared the site aspects of a Voltage Sourced Converter (VSC-HVDC) project and a Line-Commutated Converter (LCC-HVDC) project of similar rating. They have showed that apart from the cable length issue VSC-HVDC also allows controllability, black-start and active / reactive power support.

In February 2013, Asha Vijayan and S.Padma [15], investigated suitable measures to improve power system voltage stability by using FACTS devices such as static synchronous compensator (STATCOM) and thyristor controlled series compensator (TCSC). This devices are placed at the weakest bus to enhance voltage stability margin which can be obtained from voltage collapse proximity index prediction index (VCPI) is calculated at every bus as suggested by this paper article. Finally the paper concludes that after placement of FACTS devices using voltage collapse proximity index (VCPI) on the weakest bus the voltage profile has been improved to a given nominal value.
In April 2013, H. B. Nagesh and P. S. Puttaswamy, \cite{16} presented L-index of load buses for selecting location of static VAR compensator based on static voltage stability. It compares SVC and STATCOM where both SVC and STATCOM are capable of increasing static voltage stability margin as well as power transfer capability. The paper also recommended that when the load margin (LM) is considered then SVC is the better choice, whereas when the voltage profile is considered then better choice is STATCOM.

In February 2014, N. Venugopal Reddy \cite{9}, presented recent advances of the VSC-based HVDC technology. It also discussed on development of high-voltage high-power semiconductors have successfully assisted utilities to exploit the benefits of the four quadrant static converter interlinking two ac systems through HVDC with a number of key benefits, namely independent control of active and reactive power through the PWM control of the converter, fast dynamic response.

In 2015, G. Stamatiou \cite{17}, performed stability and control studies in the area of VSC-HVDC. A range of interlinked controllers that perform the operation of a typical VSC station were presented, within the general context of vector control. Added details were provided on the derivation and tuning of the current controller and the direct-voltage controller. Finally, the operational strategy of a two-terminal VSC-HVDC system was presented and demonstrated through a simple simulation result.

In 2016, S. R. Inkollu and V. R. Kota \cite{18} presented a technique for optimizing the FACTS devices, so as to maintain the voltage stability in the power transmission systems. Here, the particle swarm optimization algorithm (PSO) and the adaptive gravitational search algorithm (GSA) technique are proposed for improving the voltage stability of the power transmission systems. In the proposed approach, the PSO algorithm is used for optimizing the gravitational constant and to improve the searching performance of the GSA. Using the proposed technique, the optimal settings of the FACTS devices are determined. But the technique is time consuming.

On 21 March 2017, P. Choudekar, S. K. Sinha and A. Siddiqui \cite{19}, studied Voltage instability as it is a major problem in power system it seldom results in voltage collapse and blackout. The paper also proposed optimal location of static var compensator (SVC) which is used to improve voltage stability by that is found by continuation power flow and by finding fast voltage stability index.
CHAPTER 2: LITERATURE REVIEW

In 2017, A. Singhal and V. Ajjarapu [20], have argued on Long-term voltage stability assessment of independent transmission and distribution systems have been studied since long to estimate load margins. This work investigates the voltage stability assessment of integrated transmission-distribution using PV curve superimposition approach and reveals the possibility that the overall system loadability may be limited by the distribution system rather than the transmission system.

On March 2019, D.V Tien et al [21], presented load flow analysis and the mathematical steady-state modeling of STATCOM to study its effect on the power system network. They have simulated IEEE 5-bus, IEEE 14-bus and IEEE 30-bus systems to show that the STATCOM is able to inject or absorb reactive power to regulate the voltage magnitude of the buses where it is connected.

Hence, it can be said that using VSC-HVDC transmission system and proper placement to FACTS device can reduce the instability and hence reduce surplus power loss cost. But all of upper literatures deal on showing the advantages of using HVDC as well as FACTS devices independently with respect to voltage instability, in this thesis integration of both control models have been investigated. The improvement method models have not proposed or applied until now on Ethiopian grid to the best of our knowledge even there are no (may be limited) literatures on Ethio-Sudan transmission system analysis that have documented officially. To fill this gaps and to limit the stated problem (voltage instability) analysis of Ethio-Sudan transmission system and modelling the proposed improvement methods is necessary to Ethiopia as well as Sudan and even to EAPP power system interconnection.

To conclude, in this chapter we have described known facts about power system stability, stability improvement strategies (generation level and transmission level) and we have specified the improvement method that is used in this thesis and finally related literatures have been reviewed. On the next chapter the methodology while doing the thesis is considered.
3.1. Introduction

In this chapter all the methods, steps to be followed and materials to be used are described briefly. In this thesis, power flow analysis, power system stability analysis, dynamic modelling of generators and controller design and simulation for both STATCOM and VSC-HVDC is done for the network at different system operating conditions by using PSS/E version 34.2 software. The final goal behind this study is analyzing the effect of Ethio-Sudan interconnection on EEP grid and to show the effectiveness of integrating STATCOM and VSC-HVDC while exporting and importing electricity for power flow control and bus voltage profile improvement. The tasks/steps followed to conduct this work start from reviewing related literatures up to simulating the network with optimal setting and placement of STATCOM as well as significant controller design for the VSC-HVDC.

In general, the methodologies followed are summarized by the following flow chart on Figure 3.1 below.
3.2. Data Collection

In EEP (Ethiopia) and SETCO (Sudan) transmission system, the Interconnected System (ICS) links the major generation to load centers via transmission lines at 500 kV, 400 kV, 230 kV, 220 kV, 132 kV, 110 kV, 66 kV and 45 kV. The data used in this analysis is obtained from EEP and EEU as well as Sudanese Electricity Transmission Co Ltd (SETCO) in reference to previous latest research works.

For this work, generator data, transmission line data and bus data as well as transformer and other system data are collected from EEU as well as SETCO and previous literatures as given in Appendix A (from Table A.1 to Table A.8).

Tables from Table A.1 to Table A.4 describes all line and bus data’s that are collected from EEP and SETCO where data’s are converted in to per unit (pu) values in terms of their own base values which is suitable for simulating in PSS/E simulator.

Tables from Table A.5 to Table A.8 describes the generators and transformers (two/three winding) that are found in selected case study. The generator type and dynamic modelling values of it and governor as well as exciter have been listed on Appendix A Table A.8.

3.3. Data Analysis

The data collected from primary and secondary sources are manipulated and converted to PSS/E compatible forms. Where we use this software in next simulation studies.

3.4. Network Model

The software used in this study for modelling and analysis is the professional software package, Power System Simulator for Engineering (PSS/E) developed by Siemens PTI (Power Technologies International) version 34.2 as listed above. PSS/E is composed of an all-inclusive set of programs for studies of power system transmission network and generation performance in both steady-state and dynamic conditions. PSS/E can be used for handling a wide range of investigations including:

a. Data handling, updating, and manipulation

b. Power flow and related network functions
c. Optimal power flow

d. Open network Access and Price calculation

e. Balanced and unbalanced faults analysis

f. Network equivalent construction

g. Dynamic simulation

This software was chosen because it allows the performance of power flow analysis, dynamic simulations and stability studies, among other features. Besides that, all the models needed for this study were available in its library and this is a software used in EEP, from Ethiopia and from the rest of the world in more than 141 countries [22], to perform power system simulations.

3.4.1. Bus Model

In this case study there are total of 30 buses including external buses, of which 9 buses are from area 2. But why we include this other area buses is to study the tie line in detail because any tie line is constructed to import and/or export the real power to each other. The buses in the power system of this case study have been numbered to fit in the numbering standard of EEP numbering system while modelling on PSS/E. The number starts at 101001 where the first digit of the number represents the nominal bus voltage value. For example, if the number’s first digit is 1 its voltage value is 132 kV, if it is 2 the voltage level is 230 kV or 220 kV, if the first digit is 4 the bus voltage is 400 kV, if it is 5 the bus voltage is 500 kV, although the numbering can be started by first digit of 6 or 7 where they represent 66 kV and 45 kV sub transmission buses respectively. When the first digit is 8 the voltage level is less than or equal to 33 kV distribution bus and finally if it started by 9 the bus is identified as generating unit bus. The External buses are taken as swing bus for Ethiopian side (area 1) and for Sudan side (area 2) for modelling and simulation analysis.

3.4.2. Generator Model

The total production from the generators in the case study model is 1284.12MW where 298.8 MW is generated from Area 2 (Sudan side) from two generating units (Roseirs and Sennar). The generator model in PSS/E has to control either voltage or reactive power and a machine in a swing bus has to control the voltage in its own bus. Multiple,
identical generators may be represented by the standard model, as shown in Figure 3.2, by specifying the generator MVA base to be the total MVA rating of all connected generators and specifying $Z_t$ as the impedance of a single step-up transformer on its own single generator rating.

![Diagram of identical generators at bus](image)

As shown above in this thesis each identical generators of the same station are represented by one generator with its total generating capacity. The PSS®E library includes a family of generator models such as GENSAL, GENSAE, GENROU, GENROE, GENDCO, GENTRA, GENCLS for dynamic modelling.

Details of generator, exciter and governor PSSE models assigned to each generator in the network is listed on Appendix A where the types of generator, exciter and governor as well as generator dynamic parameters for model type, control parameters for generators with given exciter type, and control parameters for generators with specified governor type have shown. For all generating units the generator type is GENSAL (Salient Pole Generator Model (Quadratic Saturation on d-Axis)), the exciters of all generators is exciter type EXST1 except Fincha generators with exciter type SCRX. All generators are modelled with governor type HYGOV.

3.4.3. **Transformer Model**

There are a total of 10 transformers in the selected case study model. Nine transformers are two-winding transformers and one transformer is a three-winding transformer. Where transformers have a voltage control function of which four transformers have been modelled with 5 steps, three transformers with 17 steps, and three with 21 number of steps.
3.4.4. Line and Load Model

PSS/E represents a branch with a $\pi$-equivalent transmission system where we have 22 of AC lines in our model. The transmission line in PSS/E is modelled by general equivalent branch shown on Figure 3.3 below.

![Figure 3.3 PSS®E transmission branch equivalent Pi model](image)

The load is modelled as constant MVA load where it can be also modelled either as constant current load or constant admittance load. In dynamic simulations constant MVA load at each bus is transferred to each of the other two load characteristics because treating loads as purely constant MVA at the reference load value is not acceptable in switching studies and dynamic simulations because time delays in distribution voltage regulating devices prevent them from adjusting customer voltages in the period of interest.

3.4.5. External Grid Model

An external grid in power systems is defined as a constant frequency and constant voltage (both magnitude and angle) source. In PSS/E, the classical generator model is used to represent the external grid. The GENCLS model is intended to be used primarily as an effective short circuit current source in setting up approximate equivalents of segments of large interconnected power systems that are far removed from the area of specific interest.

For the classical generator to be a constant voltage and constant frequency source, the inertia constant of the machine is set to zero ($H=0$). In this model, the $d$-axis transient reactance is equal to the synchronous reactance ($X_d = X_d'$). In transient calculations,
this reactance represents the short circuit reactance at the external grid. Short circuit power of area 1 external grid is taken as 2000 MVA and 1509MVA in case of area 2.

3.5. Net Interchange Control

The net interchange of both areas of the power system is controlled during power flow solutions to lie within a specified band (100 MW from area 1 to area 2) for steady state operation. Control is achieved by adjusting the output of a single area-swing generator within each area. While a net interchange control band may be specified for the area, or areas, containing a Type 3 (system swing) bus, no control can be exerted over the net interchange of zones, which are intended to facilitate the monitoring of the net interchange and losses that occur in subsections of the power system as a result of the imposition of a given load and generation distribution.
CHAPTER FOUR
4. THEORETICAL BACKGROUND AND SYSTEM MODELLING

4.1. Power System Stability Analysis

Power system stability is broadly defined as the property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [23].

According to the International Electrical and Electronics Engineering/International Council on Large Electric Systems (IEEE/ CIGRE) joint task force classification, power system stability is classified to the following categories [24]:

![Diagram of power system stability categories]

Figure 4.1 Classification of power system stability

Power system analyses are very crucial tools to identify system stability problems and demonstrate the effectiveness of stability improvement solutions. Power system dynamics analysis involves the study of the behavior of a power system under conditions before and after sudden changes in load or generation, during faults and outages. Hence, power system dynamics analysis is an important part of power system operation and planning [8]. Power system stability types are described below.
4.1.1. Rotor Angle Stability

Rotor angle stability refers to the ability of synchronous machines to maintain synchronism when subjected to a system disturbance. It depends on the ability of the machine to maintain equilibrium between the electromagnetic torque and mechanical torque. The instability may occur as a result of increasing angular swings of some generators leading to their loss of synchronism with other generators.

The rotor angle of a generator depends on the balance between the electromagnetic torque due to the generator electrical power output and mechanical torque due to the input mechanical power through a prime mover. Remaining in synchronism means that all the generators electromagnetic torque is exactly equal to the mechanical torque in the opposite direction. If in a generator the balance between electromagnetic and mechanical torque is disturbed, due to disturbances in the system, then this will lead to oscillations in the rotor angle [23].

4.1.2. Frequency Stability

It refers to the ability of a power system to maintain steady frequency following a severe disturbance between generation and load. It depends on the ability to restore equilibrium between system generation and load, with minimum loss of load. Frequency instability may lead to sustained frequency swings leading to tripping of generating units or loads [20]. During frequency excursions, the characteristic times of the processes and devices that are activated will range from fraction of seconds like under frequency control to several minutes, corresponding to the response of devices such as prime mover and hence frequency stability may be short-term phenomenon or long-term phenomenon [23].

4.1.3. Voltage Stability

It is the ability of the system to maintain steady state voltages at all the system buses when subjected to a disturbance. If the disturbance is large then it is called as large-disturbance voltage stability and if the disturbance is small it is called as small disturbance voltage stability. The main difference between voltage stability and angle stability is that voltage stability depends on the balance of reactive power demand and
generation in the system where as the angle stability mainly depends on the balance between real power generation and load demand.

Voltage conditions in high voltage grid are directly related to the reactive power balance at the system nodes. Unlike active power reactive power cannot be transmitted over long distances, since the transmission of reactive power generates an additional demand for reactive power in the system components, thereby causing voltage drops. In order to obtain an acceptable voltage level, reactive power generation and consumption have to be situated as close to each other as possible to avoid excessive reactive power transmission.

The voltages on the EAPP interconnected transmission systems shall normally be maintained within the limits as set out below [7]:

- Operating voltage range of 0.95 to 1.05 per unit in steady state normal conditions for nominal voltages used in the EAPP interconnected transmission system namely 500kV, 400 kV, 230kV, 220kV, 132kV, 110kV and 66kV.
- Operating voltage range of 0.90 to 1.10 per unit after any single contingency, and
- Operating voltage range of 0.85 to 1.20 per unit after any multiple contingency or severe system stress.

Though, stability is classified into rotor angle, voltage and frequency stability they need not be independent isolated events. A voltage collapse at a bus can lead to large excursions in rotor angle and frequency. Similarly, large frequency deviations can lead to large changes in voltage magnitude. So keeping voltage in the standard value means helping the rotor angle and frequency in their optimum value also.

4.2. Power System Stability Improvement Methods

The stability of power systems depends on the active and reactive power balance between generation and load within the system. Losing this balance leads to loss of system integrity leading to system collapse which has damaging impact on daily economic activities. In order to avoid such devastating impacts there should be effective mechanism for maintaining this balance. These days’ different solution mechanisms are continued to be employed by power utilities worldwide for insuring this balance and bring about improved system stability [8].
Strategies for power system stability improvement are implemented at two levels as shown in the Figure 4.2 below. The first is at generating units through the action of power system stabilizers (PSSs), automatic voltage regulators (AVRs) and other supplementary controllers. The power utilities worldwide are currently implementing PSSs and AVRs as excitation controllers to enhance power system stability. However, due to limited capacity and large system voltage variations introduced during disturbances upon utilizing them, they are getting insufficient to create system wide influences [14, 25]. The other solution group is through the application of FACTS devices and HVDC controls at the transmission level.

![Power system stability improvement strategies diagram](image)

In EEP and SETCO power system interconnection generator level improvement methods such as AVRs and PSSs, and capacitor banks and switched as well as fixed shunts are commonly applied. But only this methods are not sufficient for the stable operation of the system where the faults and disturbances occur on transmission lines. So it is crucial to deal on transmission level improvement methods like VSC-HVDC and FACTS devices transmission system as in this thesis.

### 4.3. Overview of FACTS Devices

The concept of FACTS refers to a family of power electronics-based devices able to enhance AC system controllability and stability and to increase power transfer capability. FACTS devices have several advantages such as transmission capacity
enhancement, power flow control, transient stability improvement, power oscillation damping, voltage stability and control.

Traditional solutions to upgrading the electrical transmission system infrastructure have been primarily in the form of new transmission lines, substations, and associated equipment [26]. However, as experiences have proven over the past decade or more, the process to permit, site, and construct new transmission lines has become extremely difficult, expensive, time-consuming, and controversial especially for developing countries as Ethiopia and Sudan. FACTS technologies provide advanced solutions as cost-effective alternatives to new transmission line construction.

There are three main types of FACTS devices based on their connection to the system as shown on Table 4.1 below.

<table>
<thead>
<tr>
<th>Types of FACTS</th>
<th>Groups</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series</td>
<td>TSSC, TCSC, SSSC</td>
<td>Improve the voltage stability limit, increase the transient stability margin, power oscillation damping and sub-synchronous oscillation damping</td>
</tr>
<tr>
<td>Shunt</td>
<td>SVC, STATCOM</td>
<td>Improve the voltage profile of a specific bus, improve the transient stability and power oscillation damping</td>
</tr>
<tr>
<td>Series-Shunt</td>
<td>UPFC/IPFC, DFC</td>
<td>Provides multifunctional flexibility required to solve many of the problems</td>
</tr>
</tbody>
</table>

Based on power electronic devices employed, FACTS devices are classified in to two groups [27] as shown on Figure 4.3 below. The SVC and STATCOM have a strong influence on voltage quality improvement and show good performance with respect to overall system stability [28]. The unified power flow controllers (UPFC) have shown efficient performance in terms of load flow support, stability and voltage quality [29], but UPFC is not very economical and requires more complicated control techniques for exploiting its complete capabilities.
The main objective in this thesis is to look for solutions to provide voltage stability to the system in order to operate in accordance with the grid codes. The STATCOM is the best option available for providing efficient voltage stability in the power system. That is why it is selected for this analysis.

### 4.3.1. Overview of STATCOM

Static synchronous compensator, popularly known as STATCOM is a shunt connected reactive power compensation device used on alternating current electricity transmission network. It is capable of generating and/or absorbing reactive power and its output can be varied to control certain power parameters. It is a power electronic based voltage source converter (VSC) that can act as either a source or a sink of reactive power in an AC power system. A STATCOM is used to regulate the voltage of the bus that it is connected to, therefore only reactive power is exchanged between the AC system and the device [21, 28]. The voltage-sourced converter (VSC) is the basic electronic part of a STATCOM, which converts the dc voltage into a three-phase set of output voltages with desired amplitude, frequency, and phase. STATCOM can provide smooth, continuous voltage regulation, prevent voltage collapse and improve transmission stability. We can conclude the main services as Table 4.2 below.
Table 4.2 Services performed by STATCOM [28]

<table>
<thead>
<tr>
<th>STATCOM service</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Excellent</td>
</tr>
<tr>
<td>Reactive power compensation</td>
<td>✓</td>
</tr>
<tr>
<td>Active power compensation</td>
<td></td>
</tr>
<tr>
<td>Voltage regulation</td>
<td>✓</td>
</tr>
<tr>
<td>Voltage stability improvement</td>
<td>✓</td>
</tr>
<tr>
<td>Steady-state improvement</td>
<td></td>
</tr>
<tr>
<td>Transient stability improvement</td>
<td>✓</td>
</tr>
<tr>
<td>Dynamic stability improvement</td>
<td></td>
</tr>
<tr>
<td>Power flow control</td>
<td></td>
</tr>
<tr>
<td>Power oscillation damping</td>
<td>✓</td>
</tr>
<tr>
<td>Low frequency oscillation damping</td>
<td></td>
</tr>
<tr>
<td>Rotor angle stability</td>
<td></td>
</tr>
<tr>
<td>Power quality improvements</td>
<td></td>
</tr>
<tr>
<td>Transmission line capacity enhancement</td>
<td></td>
</tr>
<tr>
<td>Asynchronous tie</td>
<td>✓</td>
</tr>
</tbody>
</table>

4.4. Overview of HVDC Transmission System

First commercial electricity generated (by Thomas Alva Edison) was direct current (DC) electrical power. The first electricity transmission systems were also direct current systems. However, DC power at low voltage could not be transmitted over long distances, thus giving rise to high voltage alternating current (AC) electrical systems [9]. Nevertheless, with the development of high voltage valves, it was possible to once again transmit DC power at high voltages and over long distances.

The fundamental process that occurs in an HVDC system is the conversion of electrical current from AC to DC (rectifier) at the transmitting end, and from DC to AC (inverter) at the receiving end. To perform this task the converters use either transistors or thyristors as listed in Table 4.3 below.
Table 4.3 Summary of fully controlled high power semiconductors [30]

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Type</th>
<th>Full Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT</td>
<td>Transistor</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>IEGT</td>
<td>Transistor</td>
<td>Injection Enhanced Gate Transistor</td>
</tr>
<tr>
<td>GTO</td>
<td>Thyristor</td>
<td>Gate Turn Off thyristor</td>
</tr>
<tr>
<td>IGCT</td>
<td>Thyristor</td>
<td>Integrated Gate Commutated Thyristor</td>
</tr>
<tr>
<td>GCT</td>
<td>Thyristor</td>
<td>Gate Commutated Turn-Off thyristor</td>
</tr>
</tbody>
</table>

There are three ways of achieving conversion:

Natural Commutated Converters: The component that enables this conversion process is the thyristor, which is a controllable semiconductor that can carry very high currents (4000 A) and is able to block very high voltages (up to 10 kV). By means of connecting the thyristors in series it is possible to build up a thyristor valve, which is able to operate at very high voltages (several hundred of kV). The thyristor valve is operated at net frequency (50 Hz or 60 Hz) and by means of a control angle it is possible to change the DC voltage level of the bridge. This ability is the way by which the transmitted power is controlled rapidly and efficiently.

Capacitor Commutated Converters (CCC): An improvement in the thyristor-based commutation, the CCC concept is characterized by the use of commutation capacitors inserted in series between the converter transformers and the thyristor valves. The commutation capacitors improve the commutation failure performance of the converters when connected to weak networks.

Forced Commutated Converters: The valves of these converters are built up with semiconductors with the ability not only to turn-on but also to turn-off. They are known as VSC (Voltage Source Converters). Two types of semiconductors are normally used in the voltage source converters: the GTO or the IGBT. Both of them have been in frequent use in industrial applications since early eighties. The VSC commutates with high frequency (not with the net frequency). The operation of the converter is achieved by Pulse Width Modulation (PWM). With PWM it is possible to create any phase angle and/or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. Thus, PWM offers the possibility to control both active
and reactive power independently. This makes the PWM Voltage Source Converter a close to ideal component in the transmission network. From a transmission network viewpoint, it acts as a motor or generator without mass that can control active and reactive power almost instantaneously.

Conventional HVDC transmission employs line-commutated, current-source converters with thyristor valves. These converters require a relatively strong synchronous voltage source in order to commutate. The conversion process demands reactive power from filters, shunt banks, or series capacitors, which are an integral part of the converter station. Any surplus or deficit in reactive power must be accommodated by the ac system. This difference in reactive power needs to be kept within a given band to keep the ac voltage within the desired tolerance. The weaker the system or the further away from generation, the tighter the reactive power exchange must be to stay within the desired voltage tolerance as in [31]. But VSC-based systems are force-commutated with insulated-gate bipolar transistor (IGBT) valves and reactive power compensation with VSC technology has certain attributes which can be beneficial to overall system performance. VSC converter technology can rapidly control both active and reactive power independently of one another as summarized on Table 4.4 below. Reactive power can also be controlled at each terminal independent of the dc transmission voltage level. Forced commutation with VSC even permits black start, that is, the converter can be used to synthesize a balanced set of 3-phase voltages like a virtual synchronous generator. The dynamic support of the ac voltage at each converter terminal improves the voltage stability and increases the transfer capability of the sending and receiving end AC systems.

<table>
<thead>
<tr>
<th>Function</th>
<th>Classic HVDC</th>
<th>VSC- HVDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter valves</td>
<td>Thyristor</td>
<td>Transistor (IGBT)</td>
</tr>
<tr>
<td>Connection valve - AC grid</td>
<td>Converter transformer</td>
<td>Series reactor (+ transformer)</td>
</tr>
<tr>
<td>Filtering and reactive compensation</td>
<td>50% in filters and shunt capacitors</td>
<td>Only small filter</td>
</tr>
<tr>
<td>DC current smoothing</td>
<td>Smoothing reactor + DC filter</td>
<td>DC capacitor</td>
</tr>
<tr>
<td>Telecom between converter station Controls</td>
<td>Needed</td>
<td>Not needed</td>
</tr>
</tbody>
</table>
In terms of construction, it can take from three years for thyristor-based large HVDC systems, two years for CCC based HVDC to just one year for VSC based HVDC systems to go from contract date to commissioning [9]. Because of its many advantages mentioned above VSC based HVDC is proposed as voltage stability improvement for this thesis.

This VSC converter has been developed recently by ABB known as HVDC Light, by Siemens known as HVDC PLUS, and known as MaxSine for the Alstom technology. Commercial systems are available with the power between 100 MW and 11008 MW and with voltages up to ±300 kV. The voltages available in commercial systems are ±80 kV, ±150 kV and ±300 kV [32].

### 4.4.1. Common System Topologies

The dc-transmission link may consist of overhead or cable type of conductors, based on the operational characteristics of the transmission system. The types and schematic diagram of the some common system topologies are listed below.

**Symmetric Monopole:** A single converter with mid-point ground between positive and negative voltage polarities.

**Asymmetric Monopole:** A single converter with grounded neutral. This could be with either ground or metallic return.

**Bipolar:** A converter comprised of two monopoles. This could be with either ground or metallic neutral.

**Series Bridge Scheme:** A converter comprised of monopoles in series. This could be with either ground or metallic return.

**Multi-Terminal:** Multiple converters (more than two) connected to a DC network. This topologies are shown in chart form on Figure 4.4 below.
CHAPTER 4: THEORETICAL BACKGROUND

Figure 4.4 Common system topologies (a) symmetric monopole (b) asymmetric monopole (c) series bridge (d) bipolar (e) multi-terminal

The transmission line of the Ethio-Sudan interconnection is overhead, and symmetric monopolar system configuration is selected because of its’ simplicity for modelling and analysis where its’ cost is also moderate with respect to bipolar and other topologies.

4.4.2. Main Components of a VSC-HVDC Transmission System

The main components of the VSC-HVDC transmission system is described in Figure 4.5. The main part of the station, comprising of the switching valves, is surrounded by a number of key components that are necessary for the proper operation of the converter. These are the DC-side capacitor, AC-side filters, the phase reactor, the coupling transformer and the dc-transmission lines as shown on Figure 4.5 below.

I. Converters

Converters are the most important parts of VSC-HVDC system. They play the role of converting AC power to DC power (rectifier) or DC power to AC power (inverter). The converter valves are built with IGBT power semiconductors. They are provided with R-C snubbers and series R-L elements to reduce dv/dt and di/dt stresses that occur during ON/OF transitions. In VSC HVDC transmission one of the converter acts as a rectifier
and the other acts as an inverter. The two converters can be connected either via a DC cable, or an overhead line or in back-to-back connection depending on the application. The IGBT valves are arranged in different ways resulting converter topologies. There are different converter topologies as discussed on section 4.4.1 above. These topologies are broadly classified as two level topology and a multi-level topology [33]. Common aims of these topologies are:

(i) To minimize the switching losses of the semiconductors inside the VSC.

(ii) To produce a high-quality sinusoidal voltage waveform with minimum or no filtering requirements.

The two level converter topology is the simplest circuit configuration that can be used to construct 3-phase VSC. It consists of six valves and generates only two DC voltage values \( \pm U_{dc} \) which is shown on Figure 4.6 below.

![Figure 4.6 Three-phase six-bridge VSC converter [33]](image)

In this thesis we have used \textit{hvdc light} which is ABB’s VSC based transmission system which is programmed and modelled on PSS/E software for steady state and transient simulations. The “Standard PSS/E model” contains two converters and one DC cable in the power-flow setup of the HVDC Light link. The inverter controls the active power drawn from the grid and the AC voltage. The converter in controls the AC voltage in node and the DC voltage on the DC cable. The following tables (Table 4.5 to Table 4.7) shows the HVDC light modules with their current carrying capacity and power transfer capability which are found from ABB company website.

<table>
<thead>
<tr>
<th>HVDC light symmetric modules</th>
<th>AC currents</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+80kV)</td>
<td>M1</td>
</tr>
<tr>
<td>(+150kV)</td>
<td>M4</td>
</tr>
<tr>
<td>(+320kV)</td>
<td>M7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DC voltages</th>
<th>M2</th>
<th>M3</th>
<th>M5</th>
<th>M6</th>
<th>M8</th>
<th>M9</th>
</tr>
</thead>
<tbody>
<tr>
<td>+80kV</td>
<td>M1</td>
<td>M2</td>
<td>M3</td>
<td>M3x</td>
<td>M4</td>
<td>M5</td>
</tr>
<tr>
<td>+150kV</td>
<td>M4</td>
<td>M5</td>
<td>M6</td>
<td>M6x</td>
<td>M7</td>
<td>M8</td>
</tr>
<tr>
<td>+320kV</td>
<td>M7</td>
<td>M8</td>
<td>M9</td>
<td>M9x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
After consulting these tables the converter “M5” was chosen because this converter has the base power and the DC current values that could handle the values chosen to this connection (Ethiopia to Sudan interconnection) which have 400 MW carrying capacity.

Converter losses were also calculated from the data given by ABB as Table 4.5 to Table 4.7 above. The losses of each VSC converter were calculated by using Equation (4.1).

\[
P_{loss_{VSC}} = \frac{P_{sending} - P_{backtoback}}{2} \tag{4.1}
\]

Where:

- \(P_{loss_{VSC}}\) – power losses of a single VSC converter (MW)
- \(P_{sending}\) – sending power (MW)
- \(P_{backtoback}\) – receiving power in back to back system (MW)

By calculating these losses for the three 150kV VSC modules of the Table 4.7, it was possible to draw a graphic of the converter losses and find an equation to describe the influence of the DC current on the converter losses as shown on Figure 4.7 below.
CHAPTER 4: THEORETICAL BACKGROUND

Figure 4.7 Plot of the converter losses at 150kV, modules M4, M5 and M6

PSS/E user’s manual [35] states that the converter losses are represented by the linear equation:

$$KW_{\text{conv,loss}} (kW) = A_{\text{loss}} (kW) + I_{\text{dc}} (A) \times B_{\text{loss}} (kW / A)$$  \hspace{1cm} (4.2)

Where:
- $KW_{\text{conv,loss}} (kW)$ – Represents the Power Losses of a single VSC Converter in kW
- $I_{\text{dc}} (A)$ – Represents the DC Line Current in A
- $A_{\text{loss}}$ & $B_{\text{loss}}$ – Represent Coefficients of Converter Losses in kW and kW/A, respectively

Now if we compare Equation (4.2) to the equation on Figure 4.7 we could get that $A_{\text{loss}} = 20kW$ and $B_{\text{loss}} = 5.7kW / A$ which are required on steady state model of the PSS/E.

The transient model used in the dynamic mode of PSS/E is “VSCDCT”. The dc transmission line dynamics model (VSCDCT) in PSS®E is composed by the integration of three modules, two voltage source converter modules (VSCDYN) for the VSCs at each DC line terminals and one DC transmission line module (DCLINE) for the DC link. VSCDCT. The Figure 4.8 shows schematically the modules for the VSCDCT PSS®E dynamic model.
Figure 4.8 VSCDCT PSS/E model

Fundamental frequency component voltage output of the converter can be related to the DC operating voltage by the following equation [33].

\[
U_{L-L} = \frac{\sqrt{3}M U_{dc}}{2\sqrt{2}} \approx 0.612M * U_{dc}
\] (4.3)

Where:

- \(U_{L-L}\) - line to line voltage
- \(U_{dc}\) - DC voltage
- \(M\) - modulation index

The choice of the modulation index is a tradeoff between output power and dynamic response. The higher the modulation index, the higher the output power rating, i.e. \(S \propto M * U_{dc} * I_{rms}\). Higher \(M\) is also preferred from the standpoint of harmonics, i.e. high \(M\) for \(M < 1\) results in low total harmonic distortion (THD) [36]. In most commercial applications \(M = 0.9\) [37] is taken as a design parameter. According to Equation (4.3) for \(U_{L-L} = 150 \text{kV}\) and \(M = 0.9\), \(U_{dc} = 272.3 \text{kV}\).

II. AC-side transformer

A VSC station is usually connected to an AC grid via a converter transformer. Its main function is to facilitate the connection of the converter to an AC system whose voltage has a different rated value. Or simply it transforms the voltage level of the AC bus bar to the required entry voltage level of the converter. Furthermore, the transformer blocks the propagation of third-order harmonics and multiples to the main ac system.
The transformers were not included in PSS/E VSC package model and had to be modelled according to [35] that explicitly written that “Any transformer associated with the VSC DC line should be modelled by an explicit transformer record in the PSS/E power flow data”. According to [33] the leakage reactance of the transformer is usually in the range 0.1-0.2 pu

III. Phase reactor

The phase reactor is one of the key components of a VSC station. Its main function is to facilitate the active and reactive power transfer between the station and the rest of the ac system. With the one side of the reactor connected to the ac system, the VSC is able to apply a fully controlled voltage to the other side of the reactor. The magnitude and phase difference of the latter, compared to the ac-system voltage will induce a controlled amount of active and reactive power transfer over the reactor.

It reduces the rate of rise of DC current following disturbances on either side of the converter. This in turn reduces the number of commutation failures following ac voltage reductions and limits the current peak seen by the rectifying station during DC line short circuits. It is also applicable to provide high impedance to the flow of the harmonic currents, reduce their magnitude and thus making the DC current more smooth.

According to [17, 38, 39], the typical short-circuit impedance of this type of phase reactor is 0.15 pu. The phase reactor is modeled as an inductor in series with a small resistance, which takes into account the reactor losses. In this study based on PSS/E user manual [22] the inductor dimensioning is done in order to guarantee the current ripple less than 10%. Accordingly the total inductance (L) of 13.5 mH and resistance (R) of 0.712 Ω is taken.

IV. AC-side filters

The harmonic filters, on the AC side of a HVDC converter station, are used to absorb harmonic currents generated by the HVDC converter and to supply reactive power. The voltage output of the HVDC converters is not purely sinusoidal but contains a certain amount of harmonics, due to the commutation valve switching process. This causes the current in the phase reactor to also contain harmonics at the same frequencies, apart from the desired sinusoidal component at the grid frequency. These currents are
not desired to flow in the rest of the ac grid as they could cause additional losses in other components and distorted voltage waveforms.

![AC-side filters](image)

**Figure 4.9 AC-side filters. (a) 2nd order filter, (b) 3rd order filter and (c) Notch filter**

AC filters corresponding to a VSC can be modeled as fixed or switched capacitive shunt at the ac bus to which the VSC is connected on PSS/E modelling [35].

Quality factor $Q_f$ of typical values between 0.5% and 5%, AC-filter rating, $Q_{filter}$ and harmonic order $h$ are used as a design parameters. The resistance $R_{filter}$, capacitance $C_{filter}$, and inductances $L_{filter}$ are calculated based on the following equations [40],

$$
C_{filter} = \frac{(h^2-1)Q_{filter}}{h^2\omega_e v_{LL}^2},
$$

$$
L_{filter} = \frac{1}{C_{filter}h^2\omega_e^2},
$$

$$
R_{filter} = Q_f\sqrt{\frac{L_{filter}}{C_{filter}}}.
$$

(4.4)

Here $\omega_e$ is electrical frequency. In this thesis typical values of $Q_{filter}$=15 % of converter rating [40], $Q_f$ = 3% , and h=35 [41] are used as design inputs. Accordingly $C_{filter}$ = 8.5 μF, $L_{filter}$ = 0.98 mH and $R_{filter}$ = 0.32 Ω.

V. DC-side capacitor

The main function of the DC-side capacitor is to reduce the voltage ripple on the DC-side and provide a sufficiently stable direct-voltage from which alternating voltage will be generated on the AC-side of the converter. Furthermore, the capacitor acts as a sink for undesired high frequency current components that are generated by the switching action of the converter and are injected to the DC-side. These currents are prevented from propagating to the rest of the DC transmission link, being filtered by the inductance and resistance of the DC lines. Additionally, the DC -side capacitor acts as a temporary
energy storage where the converters can momentarily store or absorb energy, keeping the power balance during transients.

The capacitor sizing is usually performed considering the amount of power to be stored. Consequently, the capacitor is characterized by the \textit{capacitor time constant}, defined as

$$\tau = \frac{C_{dc} V_{dc,N}}{2 \pi P_N} \quad (4.5)$$

Where $C_{dc}$ is the capacitance, $V_{dc,N}$ is the rated pole-to-pole dc voltage and $P_N$ is the rated active power of the VSC. The time constant is equal to the time needed to charge the capacitor of capacitance $C_{dc}$ from zero to $V_{dc,N}$, by providing it with a constant amount of power $P_N$.

In order to obtain a small ripple in the DC voltage, large DC capacitors are required. According to \cite{39} \(\tau\) should be selected between 4 ms to 10 ms to obtain small ripple and fast response of the DC voltage upon changes in the power exchanged at the DC side of the converter. In this thesis time constant of 4 ms is used to achieve a small ripple in the DC voltage where the capacitance of the DC capacitor is 43.2 μF from Equation (4.5).

\section{VI. DC-lines}

The transmission of power between VSC-HVDC stations is performed using dc-lines. Each dc pole can be modeled as a Π-model, with resistance $R_{pole}$, and two identical capacitors with capacitance $C_{pole}/2$ each. This is depicted in Figure 4.10 below. Transmission lines are normally described in terms of resistance/km/pole, $r$, inductance/km/pole, $l$, and capacitance/km/pole, $c$. With the length of the dc-transmission system being provided in km units, the conductor elements are defined as

- $R_{pole} = r \cdot$ (transmission line length), $L_{pole} = l \cdot$ (transmission line length)
- $C_{pole} = c \cdot$ (transmission line length)

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{pi_model.png}
\caption{Figure 4.10 Pi-model of a single pole for a dc-transmission link}
\end{figure}
But according to \cite{35,40} dc link is modeled as series resistance and shunt capacitance where the shunt capacitance is lumped to the capacitance of the dc capacitors. Thus, only the series resistance will appear in the dc link model. In this thesis, the resistance of $0.0178 \, \Omega/km$ \cite{17} per pole is chosen for the series resistance of the dc link. The overhead transmission line length of our site (Metema to Gadarif) is 160 km, where the resistance of the line becomes,

$$R_{\text{pole}} = r \times L = 0.0178 \times 160 \, \Omega$$

$$R_{\text{pole}} = 2.848 \, \Omega,$$

\subsection*{4.4.3. Pulse Width Modulation (PWM)}

Pulse Width Modulation (PWM) is a modulation technique that generates variable-width pulses to represent the amplitude of an analog input signal. The main aims of modulation are: wide linear modulation range; low switching loss; low total harmonic distortion (THD); easy implementation and low computation time.

The modulating signal can be used as a criterion for the classification of PWM techniques, as shown in Figure 4.11, where the first two methods (sinusoidal pulse-width modulation (SPWM) and third harmonic injection (THI)) have been implemented with HVDC converters. Sinusoidal PWM refers to the generation of PWM AC voltage with a sine wave as the modulating signal. The ON and OFF instants of a PWM signal, in this case, can be determined by comparing a reference sine wave (the modulating wave) with a high-frequency wave (the carrier wave).

![Figure 4.11 Classification of modulating signals](image)

The most frequently used modulation method is the SPWM, where the modulating signal is a pure sinusoidal waveform \cite{33,41}.
4.4.4. VSC Capability Curve

Active and reactive power can be individually selected, but must remain within certain limits. Failure to model operating limits can lead to unrealistic behavior of the model. With the connection point having a voltage phasors $\bar{V}_g = V_g \angle 0$, the VSC can produce an output voltage $\bar{V}_c = V_c \angle \delta$ with a desired magnitude and an angle difference $\delta$, compared to $\bar{V}_g$, by considering phase reactor and the valves of the station as lossless for simplicity purposes. For such a system, the steady-state per-unit complex power absorbed by the VSC at the connection point of the phase reactor to the rest of the ac system is equal to,

$$S_g = \bar{V}_g [l_r] = V_g \left[ \frac{V_g - V_c \angle \delta}{j X_r} \right] = \frac{V_g V_c}{X_r} \sin \delta + j \frac{V_g^2}{X_r} - j \frac{V_g V_c}{X_r} \cos \delta$$

(4.7)

Where $I_r$ and $X_r$ are the current through reactor and reactance of reactor respectively. The active and reactive power are

$$P_g = \frac{V_g V_c}{X_r} \sin \delta$$

(4.8)

$$Q_g = \frac{V_g^2}{X_r} - \frac{V_g V_c}{X_r} \cos \delta$$

(4.9)

Considering that phase shift angle $\delta$ is usually very small, the Taylor approximation of $\sin \delta$ and $\cos \delta$ gives $\delta$ and 1, respectively. So the above Equations (4.8) and (4.9) are rearranged as,

$$P_g = \frac{V_g V_c}{X_r} \delta$$

(4.10)

$$Q_g = \frac{V_g (V_g - V_c)}{X_r}$$

(4.11)

Taking into account that $V_g$ is expected to be relatively stiff and the variation range of $V_c$ is normally small (0.9-1.1 p.u.), it can be seen that $\delta$ is the dominant term in Equation (4.10) in defining the allowable $P_g$. Likewise, the term $\delta$ is absent in Equation (4.11), indicating that the magnitude difference $V_g - V_c$ is dominant in defining the amount of $Q_g$. The operation range of a VSC HVDC system is limited by three factors: current through the converter, DC voltage, and rating of the conductor.
CHAPTER 4: THEORETICAL BACKGROUND

The current through the converter needs to be limited in order to protect the switching elements. The maximum apparent power $|S_{\text{max}}|$ that the VSC can output at its ac-side is

$$|S_{\text{max}}| = |P_c + jQ_c|_{\text{max}} = \sqrt{(P_c^2 + Q_c^2)_{\text{max}}} = V_e I_{c,\text{max}}$$ (4.12)

Here; $I_{c,\text{max}}$ is the maximum current through IGBT. Equation (4.12) indicates the circle of maximum MVA, with radius $V_e I_{c,\text{max}}$. Therefore, for a given $I_{c,\text{max}}$ and varying $V_e$, the maximum allowed MVA limit of the VSC changes, as three circles are shown on Figure 4.12 for $V_e$ equal to 0.9, 1.0 and 1.1 pu.

The second limit is the maximum steady-state direct-voltage level $V_{dc,\text{max}}$. The reactive power is mainly dependent on the voltage difference between the alternating voltage that the VSC can generate from the direct voltage on its dc side (with the amplitude of the fundamental being directly related to $V_{dc}$), and the grid ac voltage. If the grid ac voltage is high, the difference between $V_{dc,\text{max}}$ and ac voltage will be low. The reactive power capability is then moderate but increases with decreasing ac voltage. The third limit is the maximum direct current through the conductor. This affects only the active power and is drawn by a straight line in Figure 4.12 below.

Figure 4.12 Capability curve of a VSC-HVDC station

If $V_g$ is in phase-lag, the active power flows from AC to DC side (rectifier), if $V_g$ is in phase-lead, the active power flows from DC to AC side (inverter), if $V_e > V_g$, the converter consumes reactive power and if $V_g > V_e$, the converter generates reactive power.
4.5. VSC-HVDC Mathematical Modeling

In order to use VSC-HVDC in simulations, equations are needed to represent its behavior. This section will give a brief overview of how the VSC-HVDC system is designed and modelled for use in simulations.

The voltage source converter can be represented by a controlled voltage source for the AC side and a current source for the DC side as in Figure 4.13. Therefore, we can represent the converter and grid interaction by the following equivalent circuit.

![Figure 4.13 Single-line representation of VSC](image)

On the Figure 4.13 above $L$ and $R$ represent the total inductance and resistance coming from transformer and phase reactor of grid side. Point $g$ is the PCC of the VSC and the ac grid system. This is the reference point for measuring ac quantities. Where $V_{g,abc}$ and $V_{c,abc}$ refer to ac voltage at point’s $g$ and $c$ respectively. Point $c$ is a fictitious measurement point for converter output voltage.

Now if we apply Kirchhoff’s Voltage Law (KVL) across point’s $g$ and $c$, we get

$$V_{g,abc} - V_{c,abc} = R i_{abc} + L \frac{di_{abc}}{dt}$$  \hspace{1cm} (4.13)

Where:

- $V_{g,abc}$ – Grid AC voltage in abc reference frame
- $V_{c,abc}$ – Converter AC side output voltage in abc reference frame
- $i_{abc}$ – AC current through the reactor in abc reference frame
- $R$ – Reactor resistance
- $L$ – Reactor inductance
The phase transformation from stationary \(abc\) to stationary \(X_{\alpha\beta}\) frame of reference is by Clark transformation as Equation (4.13), where \(abc\) and \(\alpha - \beta\) reference frames are shown on Figure 4.14 below.

\[
X_{\alpha\beta} = X_a + jX_\beta = k \left[ X_a + X_\delta e^{\frac{2\pi}{3}} + X_\epsilon e^{\frac{4\pi}{3}} \right]
\]  

(4.14)

In matrix form Clark transformation is given by

\[
\begin{bmatrix}
X_a \\
X_\beta
\end{bmatrix} = k
\begin{bmatrix}
1 & \cos \frac{2\pi}{3} & \cos \frac{4\pi}{3} \\
0 & \sin \frac{2\pi}{3} & \sin \frac{4\pi}{3}
\end{bmatrix}
\begin{bmatrix}
X_a \\
X_b \\
X_c
\end{bmatrix}
\]  

(4.15)

Where \(k\) is a constant number. If \(k\) is taken as \(\sqrt{2}/3\), the power calculated in the \(dq\) reference frame will have the same magnitude as the power calculated from \(abc\) reference frame and the transformation is said to be power invariant. On the other hand if \(k = 2/3\) is chosen, the amplitude of the phase voltages in both \(dq\) and \(abc\) reference frames will be the same and the transformation is said to be voltage invariant [17]. In this thesis work, voltage invariant have been used. By applying Clarke’s transformation the Equation (4.13) can be expressed in the fixed \(\alpha\beta\)-coordinate system as

\[
V_{\alpha\beta} - V_{\epsilon\delta} = R_{\alpha\beta} i_{\alpha\beta} + L \frac{di_{\alpha\beta}}{dt}
\]  

(4.16)

A further step is to apply the Park transformation. The considered voltage and current vectors can then be expressed as

\[
\begin{align*}
V_{\alpha\beta} &= V_{\alpha\delta} e^{j\omega t} \\
V_{\epsilon\delta} &= V_{\epsilon\delta} e^{j\omega t} \\
i_{\alpha\beta} &= i_{\epsilon\delta} e^{j\omega t}
\end{align*}
\]  

(4.17)

Then substituting Equation (4.17) to (4.16) above gives,
\[ V_{g,dq}e^{j\omega t} - V_{c,dq}e^{j\omega t} = Ri_{dq}e^{j\omega t} + L \frac{d(i_{dq} e^{j\omega t})}{dt} \]
\[ = Ri_{dq}e^{j\omega t} + j\omega L i_{dq}e^{j\omega t} + e^{j\omega t} L \frac{di_{dq}}{dt} \] (4.18)

By dividing both sides by \( e^{j\omega t} \) of Equation (4.18) we can get,
\[ V_{g,dq} - V_{c,dq} = Ri_{dq} + j\omega L i_{dq} + L \frac{di_{dq}}{dt} \] (4.19)

Rearranging Equation (4.19) to get
\[ L \frac{di_{dq}}{dt} = V_{g,dq} - V_{c,dq} - Ri_{dq} - j\omega L i_{dq} \] (4.20)

Which can be expanded to its real and imaginary part as
\[ L \frac{di_d}{dt} = V_{g,d} - V_{c,d} - Ri_d + j\omega L i_q \]
\[ L \frac{di_q}{dt} = V_{g,q} - V_{c,q} - Ri_q - j\omega L i_d \] (4.21)

These are two cross-coupled first-order subsystems, with the cross-coupling being initiated by the terms \( j\omega L i_q \) and \( j\omega L i_d \) as shown on Equation (4.21).

The apparent power exchange, \( S \), observed from reference point \( g \) in \( d - q \) reference frame is given by
\[ S = \frac{3}{2} \{ V_{g,dq} \ast i_{dq} \}^* \]
\[ = \frac{3}{2} \{ (V_{g,d} + jV_{g,q})(i_d - ji_q) \} \]
\[ = \frac{3}{2} \{ (V_{g,d}i_d + V_{g,q}i_q) + j(V_{g,q}i_d - V_{g,d}i_q) \} \] (4.22)

From the equation (4.22) above,
\[ P_g = \frac{3}{2} (V_{g,q}i_d + V_{g,d}i_q) \]
\[ Q_g = \frac{3}{2} (V_{g,q}i_d - V_{g,d}i_q) \] (4.23)

For a steady-state operation, active power exchange, \( P_g \) at the ac side (at PCC) will be equal to the power exchange at the dc-bus, \( P_c \) (neglecting the semiconductor and filter losses). This is mathematically given as follows:
According to Equation (4.24) the dc current at steady-state becomes

\[
P_g = \frac{3}{2}(V_{g,d}i_d + V_{g,q}i_q) = U_{dc}I_{DC}
\]

(4.25)

The d-q reference frame is selected in such a way that the d-axis is aligned to the voltage phasor of phase-A of point g. This means that the PLL should be phase locked to phase-A voltage phasor of the reference point, g. This results in, Equation (4.26).

\[
\begin{aligned}
V_{g,q} &= 0 \\
V_{g,d} &= V_g
\end{aligned}
\]

(4.26)

Hence active power \( P_g \) and reactive power \( Q_g \) of the VSC at PCC (point g) becomes:

\[
\begin{aligned}
P_g &= \frac{3}{2}V_{g,d}i_d \\
Q_g &= -\frac{3}{2}V_{g,q}i_q
\end{aligned}
\]

(4.27)

Equation (4.27) indicates that active power is dependent on the d-axis current while reactive power is dependent on q-axis current. Hence, active and reactive powers are decoupled and independent control is possible by independently controlling \( i_d \) and \( i_q \).

The power equation for the DC side becomes

\[
P_{DC} = V_iI_{dc}
\]

(4.28)

On the other hand when we are, applying Kirchhoff’s current low at the node on the DC side in Figure 4.13 which is expressed by:

\[
C_{dc} \frac{dU_{dc}}{dt} = I_{dc} - i_L
\]

(4.29)

Where:

\[
\begin{aligned}
i_{dc} &- \text{Converter output DC current} \\
i_L &- \text{DC current through DC link} \\
C_{dc} &- \text{DC capacitor capacitance}
\end{aligned}
\]
Now we have finished the mathematical modelling of VSC-HVDC, where it is the starting point for designing the controller models.

4.6. VSC Converter Control

According to [41] a controller for the VSC converter should meet the following goals:

- **Regulation of system variables of importance**: Typically some of the following variables are regulated at reference values:
  - **DC voltage**: to ensure minimum losses and to prevent insulation damage.
  - **Power transfer**: according to scheduling demands.
  - Reactive power exchange.
  - **AC voltage level**: this control may be of importance with very weak (high impedance) AC grids.
- Protect converter from damage caused by currents or voltages exceeding rated values.
- **Ensure system stability and good speed of responses**. This requirement implies bounded responses and good transient performance of system variables under all foreseen operating conditions and all disturbances.

In order to achieve the objective of power flow control different types of control strategies have been proposed. The direct power control and the vector current control [38] strategies are the two most known. The first one, here referred as $m - \phi$, involves direct control of the amplitude ($m$) and phase angle ($\phi$) of the VSC output voltage with respect to the ac voltage at PCC. The second one, usually referred as $dq$ control, depends upon synchronously rotating reference frame for observing all the ac voltage and current quantities involved in the VSC control.

The $dq$ control approach is based upon representing the three-phase ac quantities by an equivalent set of two-phase quantities resulting in identical resultant space vector as the original three-phase space-time phasor representation [38]. The $dq$ control approach originated from electric machine and drives application areas and became the most dominant control approach in many applications involving VSCs.

Vector current control is the latest and well known control strategy as discussed in various literatures [17, 33, 38, 41, 42]. The control method for VSC HVDC in this work uses this type of strategy to control system parameters.
4.7. Vector current control

This control scheme is named vector current control because the control strategy is implemented on the vectors of currents as represented in a $dq$ rotating reference frame. By utilizing synchronously rotating $dq$ reference frame independent active and reactive power control is possible. Initially, system currents and voltages are described as vectors in a stationary $\alpha\beta$ reference frame, then they are transformed to the rotating $dq$ coordinate system. Decoupled control is used, which means that voltages and currents are decomposed in $d$ and $q$ components, controlled independently. Usually, the currents and the AC three phase voltages are transformed from the $abc$ system to the rotating $dq$ coordinate system, which will then be synchronized with the AC network through the phase lock loop (PLL). The converter voltage references will be determined by the control system in the $dq$ framework and then they will be transformed back to the $abc$ quantities before they are provided to the converter’s PWM control.

4.7.1. Inner Current controller

The inner current control loop can be implemented in the $dq$ -frame, based on the basic relationship of the system model. The control loop consists of controllers, decoupling factors and feed-forward terms as will be described further. The current control block is represented by the following general block diagram.

![Figure 4.15 The inner current control loop set up](Image)

Inside the controller block, there are two regulators, respectively for $d$ and $q$ axis current control. In order to have a detailed overview of the control system, each block of the control system is discussed below.

I. PI regulator:

PI stands for proportional and integral controller. Due to DC vectors produced by $dq$ transformation a PI controller is sufficient to reduce the steady state error signal to zero. The PI regulator is represented as
\[
K_p \left( 1 + \frac{1}{sT_i} \right)
\]
(4.30)

Where \( K_p \) stands for proportional gain and \( K_i \) stands for integral gain.

Now the output of regulator from Figure 4.15 is

\[
U_{dc dq}^{ref} (s) = K_p \left( 1 + \frac{1}{sT_i} \right) (i_{dq}^{ref} - i_{dq})
\]
(4.31)

II. PWM converter

It produces the output voltage that is converter side voltage \( U_{dq} \), where it is approximated by first order equation and now we can represent it as in Equation (4.32) below,

\[
U_{dc dq} = \left( \frac{1}{1 + sT_a} \right) U_{dc dq}^{ref}
\]
(4.32)

III. System transfer equation

The system can be represented by transfer equation from Figure 4.13 and Equations (4.13) through (4.21). Where the system behavior is governed by Equation (4.21) which is rewritten as

\[
\begin{align*}
L \frac{di_d}{dt} + Ri_d - \omega Li_q &= V_{g,d} - V_{c,d} \\
L \frac{di_q}{dt} + Ri_q + \omega Li_d &= V_{g,q} - V_{c,q}
\end{align*}
\]
(4.33)

Equation (4.33) above shows that the model of the VSC in the \( d-q \) reference frame is a multiple-input multiple output, strongly coupled nonlinear system where it contains a cross coupling terms \( \omega Li_q \) and \( \omega Li_d \). From the control point of view this term is considered as a disturbance for each axis. In order to eliminate the cross coupling (disturbances), compensation terms \( V_{g,d} \) and \( \omega Li_q \) are fed forward on the \( d \)-axis controller while \( V_{g,q} \) and \( \omega Li_d \) are fed forward on the \( q \)-axis controller [41].
Now from Figure 4.16 and after using compensation terms for eliminating decoupling disturbance,

\[
U_{dc,d}^{ref}(s) = -\left( i_d^{ref}(s) - i_d(s) \right) \left( K_p \left( 1 + \frac{1}{1 + sT_i} \right) + \omega L_i q(s) + V_{g,d}(s) \right)
\]  
\[
U_{dc,q}^{ref}(s) = -\left( i_q^{ref}(s) - i_q(s) \right) \left( K_p \left( 1 + \frac{1}{1 + sT_i} \right) - \omega L_i d(s) + V_{g,q}(s) \right)
\]  

(4.34)

Now again the converter output becomes as from Figure 4.15,

\[
U_{dc,d}(s) = \left( -i_d^{ref}(s) - i_d(s) \right) \left( K_p \left( 1 + \frac{1}{1 + sT_i} \right) + \omega L_i q(s) + V_{g,d}(s) \right) \left( \frac{1}{1 + sT_a} \right)
\]  
\[
U_{dc,q}(s) = \left( -i_q^{ref}(s) - i_q(s) \right) \left( K_p \left( 1 + \frac{1}{1 + sT_i} \right) - \omega L_i d(s) + V_{g,q}(s) \right) \left( \frac{1}{1 + sT_a} \right)
\]  

(4.35)

If the PWM is made to remain in its linear range, converter can be assumed as ideal power transformer with time delay \( T_a \) where phase reactors and tuned filters remove virtually all switching harmonics this assumption leads us to

\[
U_{dc,dq} = U_{dc,dq}^{ref}
\]  

(4.36)

Now with the knowledge of Equation (4.36) and substituting Equation (4.19) to Equation (4.35) gives us,

\[
U_{dc,d} = L \frac{di_d}{dt} + Ri_d
\]  
\[
U_{dc,q} = L \frac{di_q}{dt} + Ri_q
\]  

(4.37)

Where Equation (4.37) indicates that the cross coupling terms are cancelled out and independent control in \( d \) and \( q \) axis is achieved.

The transformation of Equation (4.37) to Laplace form and rearrangement have given the following equation,

\[
i_{dq}(s) = \frac{1}{R + sL} U_{dc,dq}(s)
\]  

(4.38)

Finally the system transfer function becomes
CHAPTER 4: SYSTEM MODELLING

\[
G(s) = \frac{1}{R} \left( \frac{1}{1+s\tau} \right)
\]

(4.39)

Where \( \tau \) is reactor time constant and \( \tau = \frac{L}{R} \). Now we can draw the block diagram of the complete inner current controlling system that is developed based on Equations (4.33), (4.34), (4.36) and (4.39) as shown on Figure 4.17 below.

![Figure 4.17 The inner current control loop with the compensation terms](image)

From the Figure 4.17 above we can simplify it by using compensating terms and considering Figure 4.15, where the current control loop can be represented as shown on Figure 4.18 below.

![Figure 4.18 Reduced form of the inner current control loop](image)

4.7.2. Phase-Locked Loop (PLL)

The duty of the PLL in the VSC control structure is to estimate the angle of rotation \( \theta_g \) of the measured voltage vector \( V_{g,\alpha\beta} \). The structure of the PLL which is shown on the Figure 4.19 below.
As long as the PLL’s $dq$ frame rotates with $\theta_g$ and is still not properly aligned with $V_{\alpha\beta}$, the $dq$-decomposition of the vector is going to produce a non-zero $q$-component $V_{g,q}$. The PLL must thus increase or decrease $\omega_g$ and $\theta_g$ until the calculated $V_{g,q}$ becomes zero. Here $V_{g,q}$ can be used as an error signal, which when fed to a PI controller will lead to the creation of $\omega_g$ and $\theta_g$ that eventually will set $V_{g,q}$ to zero.

Based on the error $V_{g,q}$, the PLL’s PI controller is giving a correction signal $\Delta \omega$ which is added to a constant pre-estimation of the vector’s angular speed $\omega_{g,0}$. According to [38] the integral and proportional gains $K_{i,PLL}$ and $K_{p,PLL}$ respectively are selected as,

$$K_{i,PLL} = a_{PLL}^2 \quad \text{and} \quad K_{p,PLL} = 2a_{PLL}$$

(4.40)

Where $a_{PLL}$ is the bandwidth of the PLL, and it can be selected from 3 Hz to 5 Hz for grid-connected applications based on [17, 41]. For this thesis 5 Hz have been taken, as in [43].

4.8. Outer controllers

The references of the inner current controller come from two outer controllers. The first outer controller consists of either of ac voltage controller or reactive power controller and the second one consists of either of dc voltage controller or active power controller. Outer controllers consist of direct voltage controller, AC voltage controller, active power controller and reactive power controller.

4.8.1. Direct Voltage Controller

The objective of the direct voltage controller is to maintain the direct voltage at the given reference value by regulating the active power exchanged at the common bus. Now by assuming the converter as lossless and considering Equations (4.27) and (4.28),
\[
\frac{3}{2}V_{g,d}i_d = V_e I_{dc}
\]  

(4.41)

But from Equation (4.29)

\[
I_{dc} = C_{dc} \frac{dU_{dc}}{dt} + i_L
\]  

(4.42)

Now substituting Equation (4.42) to (4.41) yields

\[
\frac{dU_{dc}}{dt} = \frac{1}{C_{dc}} \left( \frac{3V_{g,d}i_d}{2V_c} - i_L \right)
\]  

(4.43)

Converting Equation (4.43) to Laplace form

\[
U_{dc} = \frac{1}{sC_{dc}} \left( \frac{3V_{g,d}i_d}{2V_c} - i_L \right)
\]  

(4.44)

From Equation (4.44) it can observed that dc voltage can be regulated by control of active current \(i_d\).

\textbf{Figure 4.20 Block diagram of dc voltage controller}

Form the Figure 4.20 above we have added the compensation term in order to avoid the effect of the disturbance and there, it have been added limiter function (also called anti-wind up limiter) of \(\pm i_{d,\text{max}}\) limits in order to limit the magnitude of current in the VSC with in the allowable range.

\textbf{4.8.2. AC voltage controller}

For the ac network connected to the VSC-HVDC terminal, the ac voltage at PCC must be regulated by the converter. Let \(i, V_g\) and \(V_c\) represent the phasors of the ac current flow into the VSC, the ac voltage at PCC and the internal ac voltage of the VSC respectively.

Now by considering Figure 4.13, and Equation (4.13) the current phasor \(i\) is given by
\[ i = \left( \frac{S}{V_g} \right)^* = \left( \frac{P + jQ}{V_g} \right)^* = \left( \frac{P - jQ}{V_g} \right) \]  
\text{(4.45)}

Substituting Equation (4.45) to (4.13) gives us,
\[ V_g - V_c = (R + j\omega L) \left( \frac{P - jQ}{V_g} \right) \]
\[ V_g = V_c + \left( \frac{RP + \omega LQ}{V_g} \right) + j \left( \frac{\omega LP - RQ}{V_g} \right) \]  
\text{(4.46)}

The magnitude of ac voltage at PCC shows negligible amount of changes due to the imaginary component of Equation (4.46) above, so we can approximate the voltage at PCC as,
\[ V_g = V_c + \left( \frac{RP + \omega LQ}{V_g} \right) \]  
\text{(4.47)}

Since the active power, \( P \), is separately controlled, it cannot be used to control the voltage \( V_g \), therefore the reactive power \( Q \) is the controlling parameter of the voltage at PCC \( (V_g) \). This relation is mathematically written as,
\[ \Delta V_g = \frac{\omega L}{V_g} \Delta Q \]  
\text{(4.48)}

The block diagram of the ac voltage controller is given as

\[ \text{Figure 4.21 AC voltage control by reactive power compensation} \]

**4.8.3. Active Power Controller**

In section 4.5 above it was discussed that for a synchronously rotating frame whose d-axis is aligned with the phase-A of the ac voltage at PCC, the q-axis component of the voltage measured at PCC becomes zero. Hence, active power flow can be controlled by active current \( i_d \) as shown on Figure 4.22 below. The output of the active power controller \( (i_{d}^{\text{ref}}) \) will be the reference input to the d-axis current controller of the inner current loop of Figure 4.17 above.
4.8.4. Reactive Power Controller

In an almost identical way as the active-power control, the reactive-power control is normally applied at the connection point between the phase reactor and the ac-side filters, controlling the reactive power $Q_i$ that enters the phase reactor, with a direction towards the VSC valves. The reactive power is controlled by reactive current ($i_q$) and is implemented as in Figure 4.23 below.

4.9. Tuning controllers

In order to achieve the optimal performance of the control loops the controllers must be properly tuned. The fundamental objectives of tuning are:
- Fast response of the system by means of increasing the cut-off frequency as high as possible;
- Small overshoot and good damping of oscillations.

Cascade control requires the speed of response to increase towards the inner loop. Hence, internal loop is designed to achieve fast response. On the other hand, main goal of outer loop are optimum regulation and stability [43]. The inner loop is tuned according to “modulus optimum” condition because of fast response and simplicity whereas the outer loop is tuned according to “symmetrical optimum” condition for optimizing system behavior with respect to disturbance signals for this thesis. There is no any documented controller tuning techniques for AC voltage controller, active and reactive power controllers on best of our knowledge, where they can be settled by try and error. But here we have taken the required values from the user manual [35] for this controllers.

Subsequently we would tune the current and DC voltage controller as below.
4.9.1. Current Controller Tuning

The modulus optimum criterion is applied in the tuning process of the inner controller because of its simplicity and fast response at tracking the reference value as discussed above. This method is implemented when the controlled system has one dominant time constant and the other minor time constant. The dominant pole is canceled by the controller zero to arrive at a standard transfer function.

The open loop transfer function of current controller from the Figure 4.18 above is given as,

\[ G_{cc,ol}(s) = K_p \left( \frac{1 + sT_i}{sT_i} \right) \left( \frac{1}{1 + sT_a} \right) \frac{1}{R \left( 1 + s\tau \right)} \]  \hspace{1cm} (4.49)

The closed loop transfer function of the current controller is,

\[ G_{cc,cl}(s) = \frac{K_p \left( 1 + sT_i \right)}{1 + K_p \left( 1 + s\tau \right)} \left( \frac{1}{1 + sT_a} \right) \frac{1}{R \left( 1 + s\tau \right)} \]  \hspace{1cm} (4.50)

In the modulus optimum tuning criteria zero of the controller cancels the dominant pole. For this system the PI controller parameters are calculated based on [45] see [33, 41, 45] and Appendix C for details.

The time constant \( T_i \) of the PI controller is equal to reactor time constant \( \tau \) and from section 4.4.2 above,

\[ T_i = \tau = \frac{L}{R} = \frac{13.25 \times 10^{-3}}{0.712} = 0.0186 \]  \hspace{1cm} (4.51)

In PWM the switching frequency is expected to be much larger than the system frequency. In our design case converter switching frequency of 2.5 kHz is chosen.

The proportional gain constant \( K_p \) is also calculated as

\[ T_a = \frac{T_{\text{switching}}}{2} = 0.0002 \text{ s} \]  \hspace{1cm} (4.52)

\[ K_p = \frac{\tau R}{2T_a} = 33.125 \]

Because modulus optimum tuning method is based on simplification by pole cancellation, and optimizing the absolute value to 1, the resulting response of the system
would always correspond to values of damping constant ($\zeta$) and natural oscillation ($\omega_n$) as shown below. This tuning criterion gives the open loop and closed loop transfer functions of the current control loop as follows.

$$G_{cc,ol}(s) = \frac{1}{2T_a}\left(\frac{1}{T_a s^2 + s}\right)$$  \hspace{1cm} (4.53)

$$G_{cc,cl}(s) = \frac{1}{2T_a^2 s^2 + 2T_a s + 1}$$ \hspace{1cm} (4.54)

The resulting system from Equation (4.54) has $\omega_n = \frac{1}{T_a\sqrt{2}}$ and $\zeta = \frac{1}{\sqrt{2}} = 0.707$, which is required system to have optimum overshoot and rise time [33]. Finally by substituting the values, our closed loop transfer function becomes,

$$G_{cc,cl}(s) = \frac{12.5 \times 10^6}{s^2 + 4 \times 10^5 s + 12.5 \times 10^6}$$ \hspace{1cm} (4.55)

Where it can be checked on Matlab to see its settling time, overshoot, peak time and so on. From the Figure 4.24 below we can say that system response is very fast as we see that the rise time 0.000138 sec, settling time 0.000747, overshoot of 20.8% and peak amplitude of 1.21 which is one criteria in selecting optimum modulus method for internal controller.

![Figure 4.24 Step response of the inner current control loop](image-url)
4.9.2. Direct Voltage Controller Tuning

When the controlled system has one dominant time constant and other minor time constant, the PI controller can be tuned using the modulus optimum criteria. However, when one of the poles is already near to the origin or at the origin itself, the pole shift does not change the situation significantly. The open loop transfer function of the dc voltage controller already has two poles at the origin. An alternative criterion to tune the controllers in this condition is given by the symmetrical optimum criteria. This method optimizes the control system behavior with respect to disturbance input. The method has well established tuning rules and has good disturbance rejection [45].

From the system block diagram of Figure 4.20 the open loop transfer function of the system without considering the feed-forward and the disturbance input is given by,

\[
G_{dvc,ol}(s) = K_p \left( \frac{1 + sT_i}{sT_i} \right) \left( \frac{1}{1 + sT_{eq}} \right) \left( \frac{3V_{r,d}}{2V_c} \right) \left( \frac{1}{sC} \right)
\]  

(4.56)

We would have two poles on the origin, if it is used for cancellation of pole by setting \( T_i = T_{eq} \) to cancel the poles, where that is impossible because system becomes unstable.

That is why we do not use modulus optimum, instead we use symmetrical optimum criteria.

Now let us introduce \( K = \frac{3V_{r,d}}{2V_c} \), the system transfer function can rewritten as

\[
G_{dvc,ol}(s) = K_p \left( \frac{1 + sT_i}{sT_i} \right) \left( \frac{K}{1 + sT_{eq}} \right) \left( \frac{1}{sC} \right)
\]  

(4.57)

The tuning criteria according to symmetrical optimum is obtained using the Nyquist criteria of stability [45], refer to Appendix C. Finally the integral and proportional (PI) controller parameters can be calculated as, maximum value of phase margin is,

\[
\omega_d = \frac{1}{\sqrt{T_i T_{eq}}}
\]  

(4.58)

This condition gives the tuning criteria for time constant of the controller as

\[
T_i = a^2 T_{eq}
\]  

(4.59)

Where \( a \) is the symmetrical distance between \( 1/T_i \) to \( \omega_d \), and \( 1/T_{eq} \) to \( \omega_d \) and

\[
T_{eq} = 2T_u = 0.0004, \text{ by taking } a = 3 \text{ because } a \text{ lays between 2 and 4 } T_i = 0.0036.
\]
\[ K_p = \frac{C}{aKT_{eq}} = 0.043568 \] (4.60)

Now using the PI controller parameters, the open loop transfer function and the closed loop transfer function become,

\[ G_{dVC,cl}(s) = \frac{1}{a^2T_{eq}^2s^2} \left( 1 + \frac{a^2T_{eq}}{1 + T_{eq}s} \right) \]

Also the closed loop transfer function becomes

\[ G_{dVC,cl}(s) = \frac{1 + T_{eq}s}{aT_{eq}s^3 + a^3T_{eq}^3s^2 + a^2T_{eq}s + 1} \]

We can check the transfer function parameters by using Matlab as shown on Figure 4.25 below.

*Figure 4.25 Step response of DC voltage controller*
From the Figure 4.25 we can see that its response is slower than the inner current controller that is preferable for overall control system.

4.10. STATCOM Mathematical Modelling

The basic building block of the STATCOM is a Voltage Source Converter (VSC) and the device is shunt connected to the network through a coupling inductance. The coupling inductance can be a transformer or a reactor if the device is designed for direct connection to the bus bars voltage level. The STATCOM can be modelled as an AC-voltage source where the magnitude, the phase angle and the frequency of the output voltage are controllable [28].

The complex power transferred from PCC bus g to STATCOM bus c becomes

\[
S_{st} = \mathbf{V}_g^* I_{st}^* = \mathbf{V}_g^* \frac{\mathbf{V}_g - \mathbf{V}_c^*}{X_f^*}
\]

\[
= jB_f \left[ V_g^2 - V_g V_c \cos(\theta_g - \gamma_c) + jV_g V_c \sin(\theta_g - \gamma_c) \right]
\]

\[
= B_f V_g V_c \sin(\theta_g - \gamma_c) + jB_f \left[ V_g^2 - V_g V_c \cos(\theta_g - \gamma_c) \right]
\]

From the Equation (4.63) above the active and reactive powers becomes
Now let us assume PCC bus and STATCOM bus are in phase and so $\theta_{g} = \gamma_{c}$ where the above Equations (4.64) and (4.65) becomes,

$$P_{st} = B_{t} V_{g} V_{c} \sin(\theta_{g} - \gamma_{c}) = 0$$  \hspace{1cm} (4.66)

And

$$Q_{st} = B_{t} \left[ V_{g}^{2} - V_{g} V_{c} \cos(\theta_{g} - \gamma_{c}) \right]$$  \hspace{1cm} (4.67)

Where the current through the STATCOM becomes

$$I_{st} = B_{t} \left( V_{g} - V_{c} \right)$$  \hspace{1cm} (4.68)

The Equation (4.68) above indicates that the STATCOM can be represented by current source with the control signal as the voltage at the AC side of VSC. By regulating $V_{c}$, the current $I_{st}$ can flow from the VSC towards the grid ($Q_{st}$ injection), or $I_{st}$ can flow towards the VSC from the grid ($Q_{st}$ consumption). This STATCOM current $I_{st}$ can be limited within maximum capacitive current and maximum inductive current i.e. $-I_{\text{max}}^{\text{cap}} < I_{st} < I_{\text{max}}^{\text{ind}}$.

As shown on the Figure 4.27 below the STATCOM operates in two regions, Capacitive and inductive. In the Capacitive region, the current $I_{st}$ is leading the voltage at PCC, and the STATCOM injects reactive power into the system, which raises the voltage at PCC. On the other hand, in the Inductive region the current is lagging the voltage at PCC, and the STATCOM consumes reactive power from the system, which reduces the voltage at PCC.

![Figure 4.27 V-I characteristics of the STATCOM](image-url)
The power flow equations for bus $i$ of the power system with no FACTS controllers are given by,

\[ P_i = \sum_{m=1}^{n} \left( V_i^2 G_{im} - V_i V_m \left[ G_{im} \cos(\theta_i - \theta_m) + B_{im} \sin(\theta_i - \theta_m) \right] \right) \]
\[ Q_i = \sum_{m=1}^{n} \left( -V_i^2 B_{im} + V_i V_m \left[ G_{im} \cos(\theta_i - \theta_m) - B_{im} \sin(\theta_i - \theta_m) \right] \right) \]  
(4.69)

With the addition of a STATCOM connected at bus $g$, the system power flow equations remain the same but for the bus $g$ the active and reactive power equations are changed. Hence the power equations at the converter terminal and PCC bus $g$ are obtained as follows as derived on [28].

\[ P_c = V_c^2 G_c - V_g V_c \left[ G_c \cos(\delta_c - \delta_g) + B_c \sin(\delta_c - \delta_g) \right] \]
\[ Q_c = -V_c^2 B_c + V_g V_c \left[ B_c \cos(\delta_c - \delta_g) - G_c \sin(\delta_c - \delta_g) \right] \]
\[ P_g = V_g^2 G_c - V_g V_c \left[ G_c \cos(\theta_g - \delta_c) + B_c \sin(\theta_g - \delta_c) \right] \]
\[ Q_g = -V_g^2 B_c + V_g V_c \left[ B_c \cos(\theta_g - \delta_c) - G_c \sin(\theta_g - \delta_c) \right] \]  
(4.70)

Thus, for an n-bus power system, the active and reactive power equations at bus $g$ (i.e. the bus where the STATCOM is connected) are given as:

\[ P_g = V_g^2 G_c - V_g V_c \left[ G_c \cos(\theta_g - \delta_c) + B_c \sin(\theta_g - \delta_c) \right] + 
\sum_{m=1}^{n} \left( V_g^2 G_{gm} - V_g V_m \left[ G_{gm} \cos(\theta_g - \theta_m) + B_{gm} \sin(\theta_g - \theta_m) \right] \right) \]
\[ Q_g = -V_g^2 B_c + V_g V_c \left[ B_c \cos(\theta_g - \delta_c) - G_c \sin(\theta_g - \delta_c) \right] + 
\sum_{m=1}^{n} \left( -V_g^2 B_{gm} + V_g V_m \left[ B_{gm} \cos(\theta_g - \theta_m) - G_{gm} \sin(\theta_g - \theta_m) \right] \right) \]  
(4.71)

### 4.11. Controlling Structure of STATCOM in PSS/E

The dynamic model of the STATCOM used here is the “SVSMO3” model, which is developed by the Western Electricity Coordinating Council (WECC) [28, 46] and consists of different functions that can be split into control functions and protective functions. This model is a generic VSC-based STATCOM model and has been implemented in by several main-stream software vendors including Siemens PTI.
PSS®E for STATCOM modeling. The control functions are responsible for regulating the output of the STATCOM. The protective functions have two main roles: The first role is to protect the system by applying under-voltage and overvoltage ride through strategies. The second role is to protect the power electronics devices in VSC by limiting their output. The following sections describes the objective and implementation of all STATCOM functions.

4.11.1. STATCOM Control Functions

The PSS®E STATCOM model control functions are described as follows:

I. Automatic Voltage Regulator (AVR):

The voltage regulator loop is the most important logic block in the model. It uses a Proportional Integral (PI) regulator with the proportional gain as $K_{p_{AVR}}$ and the integral gain as $K_{i_{AVR}}$. The block takes the voltage error $V_{err}$ as input and tune $I_{vsc}$ to the desired value. The regulator has a non-windup function that limits the output to $I_{vsc-min}$ and $I_{vsc-max}$. From the Figure 4.28 below we can see that the lag block after the PI regulator block represents the delay of the STATCOM firing circuit with $T_0$ as time constant. The delay block with $T_e$ as time constant is used to add additional delay.

The voltage error $V_{err}$ is calculated by subtracting the voltage at the regulated bus from the reference voltage. The Lead-Lag block after $V_{bus}$ is representing the delay in voltage measurements. The reference voltage consists of four signals $V_{ref}$, $S_{ref}$, $V_{pod}$ and $V_{slop}$.
The main reference voltage is set by the STATCOM internal signal $V_{ref}$ and the other three signals are outputs of the Slow MVAR, Power Oscillation Damping (POD), and Droop functions which are used to correct the reference voltage as discussed below. The voltage limits $V_{\text{max}}$ and $V_{\text{min}}$ are the bounds for reference voltage.

II. Slow MVAR Control:

The slow MVAR function is a high operation function that regulates the voltage with the PI regulator which is shown on Figure 4.29 below. This function is slow compared to the PI regulator.

![Figure 4.29 STATCOM Slow MVAR function](image)

III. Power Oscillation Damping (POD)

POD regulates the STATCOM output to damp active power oscillations in the system where the input is change of the system’s frequency or active power. The output signal $V_{pod}$ is added to the STATCOM reference voltage. POD consists of a series of Lead-Lag and Washout filters as shown on Figure 4.30 below.
The ramp function is used to avoid unnecessary damping in the system. Each time step, the ramp function output increases by \( \text{ramprate} \), which is a constant specified by the user where the output will reach 1 and the full range \((V_{\text{pod min}}, V_{\text{pod max}})\) will be utilized. If UV or OV strategies are on, the ramprate will be a large negative value \((-1000)\), which forces the ramp function to output zero and disable POD.

IV. Slope (droop) Control

This gain block multiplies the STATCOM output current \( I_{\text{vsc}} \) by the slope value \( X_s \). The output is \( V_{\text{sl}} \) which is subtracted from the reference voltage. The droop have different values for inductive and capacitive modes of operation as shown on Figure 4.27. The slope \( X_s \) will have one value only during each controllable region. For capacitive operation region, the applied slope is \( X_C \) and for inductive operation region, the applied slope is \( X_L \).

V. Gain Supervisor and Optimizer

The gain supervisor regulates the integral gain used in the PI regulator. This function monitors the output of the regulator and reduces the gain if \( I_{\text{vsc}} \) is oscillating. The gain
optimizer also monitors $I_{vsc}$ as well and resume the integral gain to its original value used as shown on Figure 4.31 below.

The protective functions are developed to protect the STATCOM and the network by limiting the output current and reactive power in addition to the voltage at the STATCOM bus. The limiters are either in capacitive or inductive mode of operation. The capacitive limiters control the maximum current limit on the PI regulator. The minimum output of the capacitive limiters will be passed to the PI regulator and will overwrite $I_{vsc\text{--max}}$. The inductive limiters control the minimum current limit on the PI regulator. The maximum output of the inductive limiters will be passed to the PI regulator and will overwrite $I_{vsc\text{--min}}$. The following Figure 4.32 below shows the overall block diagram of STATCOM on PSS/E.
4.12. Application of voltage stability indices for placement of STATCOM

For proper placement of STATCOM for this thesis we would use voltage stability indices (VSI) which are the basic tools to calculate a power system’s proximity to voltage. These indices are much useful for identification of a weak bus and critical lines in the system [47]. They are broadly classified into three groups such as i) Index based on Jacobian matrix, ii) Line VSI and iii) Bus or nodal VSI. Out of these, line stability indices are easier to calculate and also effective in identifying the weak bus as well as the critical line in the power system [48].

4.12.1. Line voltage stability indices

VSI provide reliable information on the proximity of voltage instability in a power system. The basic mathematical formula for various well known VSI using the single line diagram, given in Figure 4.33, are presented in this section where anyone can refer to [49-53] for their detail proofs.

![Block diagram of the SVSMO3 STATCOM model](image)

Figure 4.32 Block diagram of the SVSMO3 STATCOM model [35]

![Two bus single line diagram](image)

Figure 4.33 Two bus single line diagram

I. **Fast Voltage Stability Index (FVSI)**
It is developed by Ismail Musirin [49] by using two bus power flow transmission concept shown on Figure 4.33. It has been formulated as:

\[
FVSI_{ij} = \frac{4 * Z^2 * Q_j}{V_i^2 * X}
\]  

Where \(Z\) is the line impedance, \(X\) is the line reactance. The line whose stability index value is closest to unity (1) will be the most critical line of the bus and may lead to the whole system instability.

II. **Line Stability Index \((L_{mn})\)**

It is a new voltage stability approach used to calculate line voltage stability attempting to detect the stress and condition of power system lines and predict line voltage collapse that is formulated as follows.

\[
L_{mn} = \frac{4X |Q_j|}{|V_i|^2 \sin^2(\theta - \delta)}
\]  

Where \(V_i\), \(P_i\) and \(Q_i\) are the sending-end voltage, real power and reactive power respectively. \(V_j\), \(P_j\) and \(Q_j\) are the receiving-end voltage, real power and reactive power respectively. Also \(\delta_i\) is the sending-end voltage phase angle and \(\delta_j\) is the receiving-end voltage phase angle and \(\theta\) is the transmission line angle. A line in the system is said to be close to instability when \(L_{mn}\) is close to one (1). On the other hand, if the \(L_{mn}\) value is less than 1, then the system is said to be stable [52].

III. **Line Stability Factor \((LQP)\)**

LQP is derived by A. Mohamed [49] using same power flow concept between two buses in a transmission system as \(L_{mn}\) and FVSI.

\[
LQP = 4 \left[ \frac{X}{|V_i|^2} \right] \left[ \frac{X}{|V_i|^2} P_i^2 + Q_j \right]
\]  

In order to maintain a secure condition, the value of LQP index must be maintained less than 1.

IV. **New Voltage Stability Index \((NVSI)\)**
This index is solved by authors on reference [53]. The index is mathematically formulated as below

\[
NVSI = \frac{2X\sqrt{P_i^2 + Q_i^2}}{2Q_iX - |V_i|^2}
\]  

(4.75)

Here again the critical value of NVSI is 1, meaning it should be less than 1 for stable operation of the power system.

By using voltage stability indices listed above we can know the weakest bus in both areas (Ethiopia and Sudan) where STATCOM is placed on it to improve system performance. The calculations for the stability indices for each line were developed by using the Matlab program (shown on Appendix B) based on load flow analysis carried out using N-R load flow with the integration of the data provided by PSS/E.

On Appendix A Table A.9 line stability indices on both areas have been tabulated for four of listed voltage stability indices i.e. \(L_{mn}\), FVSI, LQP and NVSI under normal loading where all four voltage stability index have responded accordingly.

Now we have to check the performance of the system voltage stability for various loading patterns, such as:

a) Active load change at individual load bus.

b) Reactive load change at individual load bus.

c) Active and Reactive load change at individual load bus.

d) All above three cases, for the load change simultaneously on all load buses.

The above cases are programed on MATLAB and the following lines whose calculated values are greater or equal to 1 or/and approximately equal to 1 are selected as critical lines to know weak bus of the system for both areas.

**Table 4.8 Voltage stability indices for area 1 on simultaneous Load change (load increase by 50%)**

<table>
<thead>
<tr>
<th>From bus</th>
<th>To bus</th>
<th>LMN</th>
<th>FVSI</th>
<th>LQP</th>
<th>NVSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>12</td>
<td>0.981</td>
<td>0.979</td>
<td>0.99</td>
<td>1.06</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
<td>1.041</td>
<td>1.05</td>
<td>1.2</td>
<td>1.27</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>0.983</td>
<td>1.091</td>
<td>1.112</td>
<td>1.061</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>0.942</td>
<td>0.951</td>
<td>0.972</td>
<td>1.001</td>
</tr>
<tr>
<td>21</td>
<td>22</td>
<td>0.971</td>
<td>0.878</td>
<td>0.924</td>
<td>0.991</td>
</tr>
</tbody>
</table>
Table 4.9 Voltage stability indices for area 2 on simultaneous Load change (load increase by 50%)

<table>
<thead>
<tr>
<th>From bus</th>
<th>To bus</th>
<th>LMN</th>
<th>FVS1</th>
<th>LQP</th>
<th>NVSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>7</td>
<td>0.889</td>
<td>0.901</td>
<td>1.061</td>
<td>1.112</td>
</tr>
<tr>
<td>15</td>
<td>16</td>
<td>1.011</td>
<td>1.02</td>
<td>1.113</td>
<td>1.291</td>
</tr>
<tr>
<td>7</td>
<td>16</td>
<td>1.117</td>
<td>1.21</td>
<td>1.314</td>
<td>1.351</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>0.948</td>
<td>0.951</td>
<td>0.982</td>
<td>1.071</td>
</tr>
</tbody>
</table>

The lines on tables Table 4.8 and Table 4.9 are selected by their VSI values to know the weak buses for both areas. From the tables Table 4.8 and Table 4.9 it is found that bus 10 (Bahir Dar II Bus Bar) and bus 16 (Rabak Bus Bar) are the weakest buses for area 1 and area 2 respectively, where almost all line stability indices have threshold value close to/or greater than 1. Therefore placement of the STATCOM is on bus 10 and bus 16.

From the Figure 4.34 above it can be seen that for 50% load increase the system voltage become 0.29 pu that is out of expected limit (0.95 < $V_{bus}$ < 1.05) which leads to system instability. For area 2 the PCC for STATCOM placement is shown on Figure 4.35 below. Here again as load increases by 50% the system voltage is fallen to unwanted limit (0.49 pu).
Figure 4.35 Area 2 PCC for STATCOM placement

The STATCOM ratings are based on many parameters which are mostly governed by the amount of reactive power the system needs to recover and ride through typical faults on the power system and to reduce the interaction of other system equipment that can become out of synchronism with the grid. Although the final rating of the STATCOM is determined based on system economics, the capacity chosen should be at least adequate for the system to stabilize after temporary system disturbances. The type of faults that the system is expected to recover from also determines the size of the STATCOM. For example, a three phase impedance fault of low impedance requires a very high rating STATCOM while a high impedance short circuit fault needs a lower rating device to support the system during the fault and help recover after the fault. For our case the rating of STATCOM is to keep and recover the voltage before and after disturbance at accepted values. Therefore its rating should be selected to get the PCC bus voltage within 1 pu to 1.02 pu.
CHAPTER FIVE

5. SIMULATION RESULTS AND DISCUSSION

5.1. Introduction

This chapter presents the impact of transmission system interconnection and analyzes improvement strategies which are applied on the weakest bus that is determined by VSI on section 4.12 above and the present ac transmission line from Metema (area 1) to Gadderif (area 2) is replaced by VSC HVDC that is modelled on sections 4.6 to 4.9 from chapter 3 of this thesis. The Figure 5.1 below shows the single line diagram of the system to be studied.

Figure 5.1 Single line diagram of area 1 and area 2 under study on PSS/E

For dealing on the simulation results of improvement strategies we have used five (5) cases as (a) to (e).

a) STATCOM on area 1
b) STATCOM on area 2
c) With VSC HVDC interconnection
d) VSC HVDC interconnection and STATCOM on area 1
e) VSC HVDC interconnection and STATCOM on area 2
5.2. Potential Impacts of Interconnection

Before implementation there are a lot of pre steps that should be studied for any project especially in the area of generation, transmission and distribution and the steps should be followed seriously because of economic cases and its hazard if not handled in well manner. In the case of Ethio-Sudan power system interconnection all steps are followed and implemented as well as commissioned and tested in 2013 G.C in terms of assessment of project impacts, land acquisition and resettlement, socio-economic impacts, political issues, and so on. The permanent and temporary project impacts are briefly summarized on Resettlement Action Plan (RAP) document for the construction of a power transmission link between Ethiopia and Sudan [4] with respect to socio-economic and political issues, where this is not our main agenda, but impacts of system interconnection in terms’ of voltage stability is our concern.

In this thesis work we would see the positive and negative impacts of the interconnection on the basis of voltage stability. To demonstrate and analyze we apply the three phase to ground fault on area 1 and area 2 separately on some selected buses to see the effects on system stabilities of one area to other as well as on its own grid. For all voltage outputs the system is simulated for 5 seconds where 3-phase to ground fault is applied at 0.5 sec for 100ms duration and the rotor angle and frequency are simulated for 15 seconds to see the system effects for 5 cycles fault duration. For next sections Area 1 implies Ethiopian side and Area 2 indicates Sudan side.

5.2.1. 3-Phase to Ground Fault on Rabak (area 2)

Now we have applied 3-phase to ground fault on Rabak (area 2) bus bar. The system parameters goes to oscillating state on both areas even on post disturbance state as shown on Figure 5.2 to Figure 5.4 below.

The Figure 5.2 below shows that when the three phase to ground fault at simulation time of 0.5s is initiated on Rabak (Area 2) bus the voltage drops to unwanted voltage level, for example on Figure 5.2 (a) the bus bars at 0.5-0.6s dropped to out of threshold limit (0.95 pu) as Metema bus to 0.5 pu, Gonder bus to 0.68 pu, Bahir Dar II to 0.845 pu and so on where almost all buses are affected for fault duration of 100ms.
On Figure 5.2 (b) Immediately during the fault, voltage of Rabak bus bar falls to 0 pu. This 0 value means the bus is at ground potential during the occurrence of the fault. The other buses such as Gaderif (0.22 pu), Sennar (0.28 pu), Meringan (0.3 pu) and so on have the voltages out of limit as expected. The fault stayed for 5 cycles and cleared at 0.6s. Even after the fault clearance the voltages achieved is oscillating on both areas within the accepted range.

![Figure 5.2 Bus voltage dynamics for a fault at Rabak 220kV bus (a) Area 1 (b) Area 2](image)

Power system stability problems are interrelated where voltage stability can be indicated by rotor angle stability. Thus improving one of the instability problems may improve a wide range of instability problems. So let us consider rotor angle of both areas on selected bus.

![Figure 5.3 Generator rotor angle oscillations (a) Area 1 (b) Area 2](image)

As shown on Figure 5.3 above the rotor angle of the generators except swing buses (external buses) are out of synchronism or they are oscillating. It is obvious that the
inadequate mechanical power to balance the electrical power output is a factor in the instability that occurred. The next Figure 5.4 illustrate the frequency deviations in area 1 and 2 for case of 3-phase to ground fault on the Rabak bus bar.

The next Figure 5.4 illustrate the frequency deviations in area 1 and 2 for case of 3-phase to ground fault on the Rabak bus bar. (a) Area 1 and (b) Area 2

The above Figure 5.4 depicts the deviation in frequency of the interconnected system which has more ripples and the settling time is more uncompensated. Frequency deviation in power system is caused by power imbalance between generation and demand, where the effect causes a higher overshoot and undershoot as well as longer settling time as shown on Figure 5.4 above.

5.2.2. 3-Phase to Ground Fault on Mekelle 230kV bus (Area 1)

The response of the system to a three-phase to ground fault on the Mekelle bus was considered to examine system stability for pre and post disturbance on both areas, that is far distant to the PCC of two areas.

(a) Area 1 (b) Area 2
As we can see from Figure 5.5 above the bus voltage is resulted in progressive voltage falls and rises at almost all buses. This instability is due to the loss of long term equilibrium, even the post-disturbance steady state operating point in both areas is in a lack of attraction towards the stable post-disturbance equilibrium that needs compensation as discussed on section 1.2.

As shown on Figure 5.6 generators experience larger and longer oscillations. The effect of area 1 instability leads for instable scenario of area 2 as well. In this unprotected scenario the interconnection experience disadvantage towards dynamic stability as simple faults on Area 2 cause disturbance on Area 1. So that alternatives should be considered at different levels.

The main measurable benefit for Ethiopia (economic) and EEP (financial) is the revenues from the sale of hydropower to Sudan; this is a function of volumes exported
and the sales price. There are also benefits of increased reliability and energy security for the Ethiopian system (which are dependent upon the uncertainties of rainfall patterns as of May, 2019) from integrating with the Sudanese grid. The interconnection provides an opportunity to exploit synergies between the two systems, helping to generate revenues for Ethiopia through the sale of excess hydropower and yielding fuel savings for Sudan. The hydro-thermal complementarities of the two systems will also serve to improve the reliability of power supply, thus making economic activities that are dependent on electricity more efficient, encouraging investment and reducing or avoiding costs of back-up generating reserves\(^2\).

If the area 2 is strong grid which have unseasonal thermal units EEP can import when there is uncertainties because of seasonal hydropower plants as May, 2019 where the reservoir of Gilgel Gibe III flow rate is minimized because of seasonal rainfall. So now let us consider the dynamics of the system if the power is imported from the Sudan because of generator outages.

### 5.2.3. Outage of Belles Generating Unit

The Belles generating unit is a critical generator because it serves as the gateway for the power flowing to the area 2 and loads on NWR, let us see the outage with and without interconnection of area 2.

![Figure 5.8 Bus voltage dynamics for a fault at Mekelle 230kV bus (a) Area 1 (b) Area 2 with interconnection](image)

\(^2\) Reserve Margin (Operating): The amount of unused available capability of an electric power system at peak load for a utility system as a percentage of total capability.
The Figure 5.8 above shows that for the outage of Belles generator the interconnected area 2 can export its power to area 1 and minimize system collapse because of power shortage on high load region. As depicted on Figure 5.8 after the disturbance the system tries to be stable after 3.54 seconds even though it is higher time to get equilibrium state.

When the area 2 is not interconnected the fault on area 1 goes to system collapse and there is no any disturbance on area 2 as shown on Figure 5.9 below. If we compare the Figure 5.8 and Figure 5.9 the system tries to get equilibrium at time 2.4-2.6 seconds by stepping the tap changers of the transformer and switched shunts on the first figure. Finally after 4.8 seconds it goes to acceptable values. But on the next figure (Figure 5.9 (a)) the system goes to voltage instability.

Now let we see two buses with and without interconnection for more detail. Figure 5.10 below shows that the voltage outputs when 3-phase to ground fault is applied on Mekelle bus with and without interconnection. When the system is interconnected even if the fault is occurred the system tries to get equilibrium state even though the time taken is higher. We can understand from Figure 5.10 that when the area have shortage of power because of either outage of generating unit or unexpected load increase the system goes to instability unless it imports from interconnected area. For example the EEP in this year (May-June, 2019) used load shedding because of Gilgel-Gibe III outage that caused loss of millions of investments to keep system stability. But it have opportunities to
import from interconnected areas such as Sudan where the system can be kept on its steady state equilibrium. So we recommend EEP to deal on not only exporting but also importing at the time of planned or unplanned outages. Finally the two areas should cooperate on backup exchanges for emergency support or mutual support during emergencies through short-term, non-firm power exchange, share spinning reserve capacity on their interconnected system and complementarities in means of production involving hydro and thermal based power generation.

![Figure 5.10](image)

**Figure 5.10** Area 1 bus voltage dynamics for a fault at Mekelle 230kV bus with and without interconnection (a) Bahir Dar II bus (b) Mekelle bus

If we see the other parameters such as generator rotor angle and bus frequency deviation we can get the same effect on one area to the other.

![Figure 5.11](image)

**Figure 5.11** Rotor angle when 3-phase to ground fault on Mekelle bus (a) Area 1 (b) Area 2

The frequency close to the fault location oscillates during the fault at the transmission bus whereas it rises for the generator bus. A high peak in the frequency variation can be
observed on the transmission bus when the fault is cleared. Rapidly after clearing, frequencies join them and rise until voltage recovery to decrease slightly to the original value.

![Bus frequency deviation on 3-phase to ground fault at Mekelle bus](image)

Finally we can conclude that the system stability improvement methods should be implemented on both areas and on tie-line to control the voltage within the tolerable limits which can be second alternative. On latter discussions we would see the improvement methods on system voltage stability briefly.

### 5.3. System Stability Improvement by Using STATCOM

The STATCOM capacity required to restore the system voltage after a three phase to ground short circuit fault at PCC of both areas is found to be ±250 MVA for area 1 and ±32 MVA for area 2. The voltage performance of the power system is investigated during and after the fault clearance without and with the connection of the STATCOM to the PCC bus. Where the fault is initiated at t=0.5 sec and cleared at t=0.6 sec for duration of 5 cycles (100ms) for voltage outputs because the parameter under investigation is bus voltage pu magnitude. The strategy here focuses on investigating the improvement on pre-disturbance as well as post-disturbance voltage profiles. Improved post disturbance voltages results in improved system stability after disturbances. For the next discussion STATCOM1 indicates area 1 STATCOM (PCC1 STATCOM) and STATCOM2 indicates area 2 STATCOM (PCC2 STATCOM) for simplicity.
5.3.1. Fault on Area 1

The effect of a three phase high impedance short circuit fault at the load bus is studied on the next sections.

I. Fault on Bahir Dar II 230kV bus (PCC1)

For this case when the fault is applied to Bahir Dar II bus the effect of STATCOM placed on PCC1 and PCC2 towards other remote buses and PCC itself is discussed. Therefor the time domain simulation results below compares the bus voltage magnitudes at three phase to ground faults before STATCOM interconnection and with STATCOM interconnected transmission.

![Figure 5.13 Bus voltages (a) Bahir Dar II 230kV bus (b) Rabak 220kV bus](image)

For the Figure 5.13 above let’s consider two cases based on STATCOM placement i.e. for PCC1 (Bahir Dar II 230kV) and PCC2 (Rabak 220kV) buses.

In the case of STATCOM on PCC1, on steady state operation without STATCOM (green line), voltage value is 0.994 pu but when we connect STATCOM (red line) it become 1 pu as desired, up to 0.5sec and immediately during fault the voltage dropped to 0.33 pu without STATCOM and significantly improved to 0.59 when STATCOM is applied. After fault is cleared at 0.6 sec the voltage immediately restored to 1 pu after 0.05 sec delay which is a much improved performance as compared to the case without STATCOM as shown on Figure 5.13(a) because STATCOM will try to support the voltage by injecting reactive power on the line when the voltage is lower than the reference voltage (0.95 pu). This higher voltage is favorable at reducing system power loss and improving system stability.
For the case of STATCOM on PCC2, in steady state the voltage remain the same as “no STATCOM” with value of 0.994 pu. In dynamic state during fault, again it remain the same except after clearance it goes to 0.957 pu rather than 0.907 pu for the case of “no STATCOM”. Here we understand that as the distance of PCC increase the improving ability decreases because reactive power can’t be transferred to high distance as real power and the extent to which a STATCOM can provide support depends on its rating. So the source of reactive power is always connected as close to the point where it is required. It is observed that as fault occurred on PCC 1 the bus terminal voltage of Area 2 is also affected. The same is true for Figure 5.13(b) except values where STATCOM on area 1 have good support to area 2 because of its higher capacity.

As we have said before maintaining the system voltage at accepted values is helping other parameters such as rotor angle and frequency to stay on their equilibrium. The following Figure 5.14 shows that the rotor angle of case study power plants have retained to their steady state values at given period of time when the STATCOM is connected. It can be observed that there is an angle overshoot at recovery for every case where a STATCOM is used which have recovered again in short time.
The applicability of STATCOM to provide reactive power support and efficient voltage control to maintain the voltage at PCC within acceptable limits and hence effectively improve the stability of the system can be concluded from these simulations.

The other parameter we can check is frequency of the bus. The following Figure 5.16 shows the frequency deviation of selected buses. As expected the frequencies oscillates during the fault and then increases during the recovery time. As soon as the voltage is recovered the frequency goes slowly down to zero deviation.
II. Fault on other selected buses

The improvement of the system parameters are not restricted to PCC buses but also the system is improved if the fault is occurred on other buses as shown on Figure 5.17 below.

Figure 5.17 Bus voltage dynamics with and without STATCOM for a fault at Mekelle 230kV BB
5.3.2. Fault on Area 2

The fault on interconnected areas have effects on one to other, but can be protected by opening circuit breakers or load shedding by application of relays which is time consuming and insupportable for the system stability. The application of compensators and other transmission level stabilizers is the preferred one. Here we have applied STATCOM to remain in steady state after fault as soon as possible as we have discussed on above sections. Now let’s see the applicability of STATCOM for system stability if the fault is initiated on buses of Area 2.

I. Fault on Rabak 220kV BB (PCC2)

Here it is expected that when the fault is applied on PCC2 the STATCOM on this area should inject/consume the reactive power to keep the system parameters intact for both areas. The following Figure 5.18 shows the output voltage of PCC buses.

The above Figure 5.18 (a) indicates that when the fault is initiated on Rabak bus the voltage goes down to zero value (ground potential) for three of cases. When there is no interconnected STATCOM on the system the voltage dropped to 0.83 pu even after the clearance of the fault. This indicates that the bus is the weak to restore to the steady state value.

For the case of STATCOM on PCC2 immediately after the clearance there is an overshoot within acceptable values (1 pu to 1.1 pu) then it sets to steady state value of 1 pu at 1.2 sec. The STATCOM helps to quickly damp these oscillations by absorbing controlled reactive power to the system.
For the case of STATCOM on PCC1 the voltage oscillated between 0.97 pu to 1.05 pu until 4.2 sec which is longer time to restore to the initial value even if the values are within the limit. Here the STATCOM on area 1 helped the bus voltage to remain within the acceptable values after fault clearance in comparison to “no STATCOM” case.

As it can be seen on Figure 5.18 (b) because of fault on Rabak the Bahir Dar bus is disturbed where the voltage value dropped to 0.81 pu during fault without STATCOM on both areas and with STATCOM2. When the STATCOM1 is interconnected the voltage on disturbance remain at 0.95 pu until the clearance time. Immediately after the clearance voltage gained its steady state values.

From the above simulations we can conclude that the STATCOM have a good performance in maintaining the system parameters in their acceptable values. The STATCOM interconnected on PCC1 showed a good performance in keeping the voltage values at equilibrium points on post disturbance state. Here again the STATCOM 2 have preeminent performance on Area 2 buses and best in reaching steady state values at shorter period of time than “no STATCOM” option. Therefore while interconnecting areas to export/import it is advisable if the engineers as well as officials deal on system modern compensating devices.

II. Fault on other selected buses

The voltages in the system take a long time to stabilize after fault clearance in the case of no STATCOM which clearly indicates that a STATCOM in the system improves the response time as well as system stability. The STATCOM depends on the distance and rating.

![Figure 5.19 Bus voltages with fault on Gadaref bus (a) Gadaref 220kV BB (b) Gondar 230kV BB](image)

Figure 5.19 Bus voltages with fault on Gadaref bus (a) Gadaref 220kV BB (b) Gondar 230kV BB
The dynamic performance of the system from Figure 5.13 to Figure 5.20 shows that the placement of STATCOM at weak bus improves system parameters. For STATCOM 1, for example, it has good improving ability within the area 1 and area 2 system voltage than STATCOM 1 because of its’ rating. With the use of a STATCOM, the voltage profile during the fault has been improved and moreover the bus terminal voltage has been improved. The use of a higher rating STATCOM improves the voltage drop during the fault and has better voltage recovery after the fault. Now we can conclude as the STATCOM helps to provide better voltage characteristics during severe faults like three phase to ground short circuit faults.

5.4. **System stability improvement by using VSC-HVDC**

For this scenario the Metema (PCC of area 1 to area 2) to Gadaref AC transmission line is replaced by the modelled VSC-HVDC system to study performance on system stability as shown on Figure 5.21 below.
CHAPTER 5: SIMULATION RESULTS AND DISCUSSION

Here we have expected the model to compensate and keep the voltages of different buses at their steady state value after three phase to ground disturbance. Let’s consider some of the selected buses from both areas.

5.4.1. Fault on Area 1

After replacing AC system interconnection by VSC-HVDC we have initiated the 3-phase to ground fault on Area 1 at some buses to discuss the effect of the model with respect to system stability.

I. 3-phase to ground Fault on Metema (PCC)

Here the focus is given to investigate the improvements at the pre disturbance as well as post disturbance bus voltage magnitudes.

As shown on the Figure 5.22 above before the fault occurrence the voltage without VSC-HVDC is 0.973 pu and with VSC-HVDC it increased to 0.996 pu. During the fault the voltage value is 0 pu (at ground potential) for both cases. Instantly after the fault clearance after 5 cycles (100ms) in case of “no VSC-HVDC” the voltage oscillates between 0.934 and 0.988 pu until 4.62 sec, but for case of “with VSC-HVDC” it goes to 0.964 pu and it remain at its steady state value of 0.996 pu starting from 0.63 sec. This shows that a faster restoration of system condition is achieved by the proposed design solution.

Now the question is what about area 2 system performance when the fault is initiated at Metema (area 1) bus? Here we have to remember that the two areas are
interconnected only in one direction (by Metema to Gadaref only, until 2019) so now let’s see.

![Figure 5.23 Gadaref bus voltage dynamics](image)

It has been indicated on Figure 5.23 that for the case of AC interconnection the voltage before disturbance is 0.993 pu, during fault 0.49 pu and after clearance it oscillates between 0.973 and 1.03 pu until 3.79 sec and finally it stayed at 0.973 which is less than the original value.

For the case of VSC-HVDC interconnection there is no any influence when the fault is occurred on area 1, where it become the fence for any disturbance for area 2.

Now again if we check other buses within fault on Metema bus bar we get the same result as discussed above except value changes as shown on Figure 5.24 below. This shows that a faster restoration of system condition is achieved by the VSC-HVDC integration. This is an indication that system robustness against transient events is improved by supporting the reactive power required.
II. Fault on other buses

The performance improvement of VSC-HVDC is not limited to PCC bus but also the fault on far distant buses is compensated as shown below.

Figure 5.25 Bus voltage dynamics when fault on (a) Fincha bus bar, (b) Debre Markos 230 kV bus
5.4.2. Fault on Area 2

Here the effect of fault initiated on area 2 in the case of with and without the presence of VSC-HVDC on both areas is discussed. As seen on the above discussions the fault on area 2 have to not affect the area 1 in the presence of VSC-HVDC.

I. Fault on Gadaref (PCC)

As usual here again the 3-phase to ground fault is initiated on area 2 side at PCC of area 2 to area 1.

![Figure 5.26 Bus voltage dynamics of Gadaref 220 kV bus](image)

The Figure 5.26 above shows that at steady state before disturbance the voltage value of 0.97 pu without VSC-HVDC and 1 pu with VSC HVDC is recorded. During fault the bus is at ground potential for both cases. Instantly after fault clearance the maximum overshoot of 1.12 pu at 1 sec is noted down and it oscillates between 0.95 pu and 1.05 pu for “no VSC-HVDC” case until 4.28 sec, but the value is accepted. For the case of “with VSC-HVDC” the system voltage reached its steady state value at 1.61 sec. This implies that after fault the VSC converter injected reactive power to compensate the voltage and absorbs the excess reactive power to stop the rise of the voltage and to stabilize it.

When we consider Figure 5.27 below for the case of “without VSC-HVDC” on pre-disturbance state the voltage stopover 0.978 pu and goes down to 0.86 pu during
disturbance. Instantaneously after disturbance it gets steady state value after 2.2 sec. 

When the interconnection is using VSC-HVDC the fault initiated at Gadaref bus haven’t showed any influence on Bahir Dar II substation. That is in all cases (at steady state, during fault and after fault) the voltage value is the same.

![Figure 5.27 Bahir Dar II bus voltage dynamic when fault on Gadaref](image)

The following Figure 5.28 shows the same outcome as Bahir Dar II bus where the fault on Gadaref bus haven’t exaggerated the voltage value of Mekelle as well as Tis-Abay buses as shown on Figure 5.28 (a) and (b) below respectively.

![Figure 5.28 Bus voltage dynamics of (a) Mekelle 230kV bus (b) Tis-Abay II 132kV bus for fault on Gadaref](image)
II. Fault on other buses

Now let us see if the effect of VSC-HVDC is limited to the PCC of converter or not.

![Figure 5.29 Bus voltage dynamics of (a) Rabak bus (b) Metema 230kV bus for fault on Rabak bus](image)

From the above figures (Figure 5.22 to Figure 5.29) we can conclude that the HVDC link is acting as a barrier for preventing instability spread to the other area and in the station itself, independent reactive power control is utilized to maintain these bus voltages near desired value of 1pu at most of buses in both areas. The HVDC technology reduces the risk of erratic power flows and instability that typically bring negative behaviors in interconnections. Both HVDC converters have a significant role in the stability of the system grid. They are able to regulate the voltage and supply reactive power during the fault. Such VSC converter will be helpful to stabilize the main grid of both areas after a disturbance. The VSC-HVDC link prevented the instability not to be transmitted to the other end by controlling the reactive power. The occurrence of the fault in one area has no impact on the other side i.e. AC faults, or other disturbances on one AC network do not propagate to the other if two terminals of HVDC are connected to two different AC networks. Thus here instability spread prevention is effectively achieved.

5.5. Comparison of Stability Improvement Methods

STATCOM is basically a voltage source converter, VSC, which converts a dc voltage at its input terminals into three-phase ac voltages at fundamental frequency of controlled
magnitude and phase angle. VSCs use pulse width modulation (PWM) technology, which makes it capable of providing high quality ac output voltage to the grid.

When system voltage is low, the STATCOM inject reactive power. When system voltage is high, it absorbs reactive power as discussed on above sections. The same is true for VSC-HVDC because converter used is in the same principle of operation. Even VSC converters of VSC-HVDC can act as STATCOM when the DC line is not transmitting real power (P=0), where this implies we can compare them with respect to dynamic performance improvement of the bus voltage.

Now let us consider the performance of the bus voltage within four cases (without STATCOM/VSC-HVDC, with STATCOM on area 1 or 2, and with VSC-HVDC interconnection) on both areas.

Firstly let we consider steady state performance of STATCOM and VSC-HVDC by tabular form as shown on Table 5.1 below that gives a comparison of the voltage profiles of some of the buses.

Table 5.1 Comparison of steady-state bus voltage profiles

<table>
<thead>
<tr>
<th>Bus #</th>
<th>Bus Name</th>
<th>Base kV</th>
<th>without</th>
<th>with STATCOM 1</th>
<th>with STATCOM 2</th>
<th>with VSC-HVDC</th>
<th>with STATCOM 1</th>
<th>with STATCOM 2</th>
<th>with VSC-HVDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>200001</td>
<td>MERINGAN</td>
<td>220</td>
<td>0.96</td>
<td>0.971</td>
<td>0.981</td>
<td>0.997</td>
<td>0.011</td>
<td>0.021</td>
<td>0.037</td>
</tr>
<tr>
<td>207001</td>
<td>B.DAR2</td>
<td>230</td>
<td>0.97</td>
<td>1.01</td>
<td>0.993</td>
<td>1</td>
<td>0.04</td>
<td>0.003</td>
<td>0.01</td>
</tr>
<tr>
<td>207002</td>
<td>DB-MRKOS</td>
<td>230</td>
<td>0.962</td>
<td>0.989</td>
<td>0.965</td>
<td>0.987</td>
<td>0.027</td>
<td>0.003</td>
<td>0.025</td>
</tr>
<tr>
<td>207005</td>
<td>METEMA</td>
<td>230</td>
<td>0.997</td>
<td>0.9991</td>
<td>0.998</td>
<td>1.02</td>
<td>0.0021</td>
<td>0.001</td>
<td>0.023</td>
</tr>
<tr>
<td>207006</td>
<td>GADAREF</td>
<td>220</td>
<td>0.958</td>
<td>0.971</td>
<td>0.984</td>
<td>1</td>
<td>0.013</td>
<td>0.026</td>
<td>0.042</td>
</tr>
<tr>
<td>207013</td>
<td>RABAK</td>
<td>220</td>
<td>0.969</td>
<td>0.984</td>
<td>1.02</td>
<td>0.991</td>
<td>0.015</td>
<td>0.051</td>
<td>0.022</td>
</tr>
<tr>
<td>207014</td>
<td>FINCHA</td>
<td>230</td>
<td>0.972</td>
<td>0.994</td>
<td>0.978</td>
<td>0.993</td>
<td>0.022</td>
<td>0.006</td>
<td>0.021</td>
</tr>
<tr>
<td>208001</td>
<td>MEKELE</td>
<td>230</td>
<td>0.963</td>
<td>0.994</td>
<td>0.971</td>
<td>0.976</td>
<td>0.031</td>
<td>0.008</td>
<td>0.013</td>
</tr>
<tr>
<td>209004</td>
<td>GONDAR2</td>
<td>230</td>
<td>0.998</td>
<td>1.01</td>
<td>1</td>
<td>1.01</td>
<td>0.012</td>
<td>0.002</td>
<td>0.012</td>
</tr>
</tbody>
</table>

From the Table 5.1 above it is shown that VSC-HVDC integration given a good performance on improving voltage level. STATCOM on its PCC’s have shown more improved voltage level than VSC-HVDC. This implies that the improvement ability of
this devices is dependent on the distance between the PCC bus and the bus to be studied. Where, as distance increases the ability to perform well decreases because of increase in impedance of the line and other equipment’s.

The Figure 5.30 and Figure 5.31 below shows the system voltage profile when 3-phase to ground fault is initiated at Gondar 230 kV bus voltage for discussing the results.

![Figure 5.30 Voltage profile improvement at Gondar 230 kV bus](image)

Now if we consider Figure 5.30 above for 3-phase to ground fault on Gondar substation, earlier to fault, bus voltage become 1.013 pu, 1.019pu, 1.014pu and 1.032pu for “without”, with STATCOM 1, with STATCOM 2 and with VSC-HVDC respectively. Where the values indicates that at steady state the voltage is improved. During the fault the bus voltage is at ground potential for all cases. Immediately after the fault when there is no any improvement strategy (case “without”) the bus voltage become 0.86 pu and oscillates within 0.83 to 1.077 pu until 3.71 seconds which is not good limit. For the case of “STATCOM on area 1” the bus voltage goes to 0.982 pu and gets its steady state value at 1.86 sec. For the case of “STATCOM on area 2” 0.977 pu voltage is gained and it oscillates between 0.977 and 1.062 pu until 3.43 sec which stays at steady state value after 3.44 sec. In the case of “VSC-HVDC interconnection” the voltage goes to 0.994 pu immediately after fault and gets its steady state value at 1.2 seconds which is the most improved state.
CHAPTER 5: SIMULATION RESULTS AND DISCUSSION

Figure 5.31 Rabak 220kV bus voltage when fault on Gondar bus

For the Figure 5.31 above it can be seen that installing the STATCOM improves the voltage profile after the disturbance when installed on either of both areas, but installing STATCOM on Rabak bus showed better performance as expected. Interconnecting the two areas by VSC-HVDC gets double benefit for the system, where it improves the voltage profile by injecting/absorbing reactive power and it serves as firewall for the fault on opposite side area as shown on Figure 5.31 above. The following Figure 5.32 shows the same result for 3-phase to ground fault on Gondar bus which indicates that for Bahir Dar bus the case “with STATCOM on area 1” showed better performance than other cases and the case “with VSC-HVDC” showed best dynamic performance on Sudan-Gadaref bus.

Figure 5.32 Bus voltage dynamics for fault on Gondar (a) Bahir-Dar II 230kV bus (b) Sudan-Gadaref 220kV bus
The following Figure 5.33 shows the improved bus voltage of Sudan-Gadaref and Tis-Abay II substations by installing STATCOM and interconnecting by VSC-HVDC.

![Figure 5.33 Bus voltage dynamics for fault on Sudan-Gadaref (a) Sudan-Gadaref 220kV bus (b) Tis-Abay II 132 kV bus](image)

The simulation results shown on Figure 5.30 to Figure 5.33 indicates that the pre disturbance as well as the post disturbance pu value of bus bar voltages is improved upon installing STATCOM or interconnecting the areas by VSC-HVDC link. Here both STATCOM and VSC-HVDC performed in the same manner by injecting/absorbing reactive power when the bus voltage is not at its steady state value. Moreover they reveal that more sounding improvement is obtained at bus bars that are near the STATCOM bus and/or inserted VSC-HVDC link. Here the main difference of the VSC-HVDC link to STATCOM is, it also prevented the instability not to be transmitted to the other area. Here we can conclude that because, both of the devices use VSC converter, their operating principle and compensating approach is the same even though the VSC-HVDC is the transmission line.

### 5.6. System Stability Improvement by Integrating both Strategies

The HVDC and FACTS techniques are an advanced means for improving overall power system performance. To cover a wide range of network configurations and operation conditions, a combination of the HVDC and FACTS devices is often required. The coordination of the HVDC and FACTS devices can provide the necessary operation characteristics, and thus efficiently improve the system dynamic performance. Here STATCOM and VSC-HVDC are integrated to see the system voltage performance.
5.6.1. With VSC-HVDC interconnection and STATCOM on area 1

While integrating, the rating of the STATCOM needed is packed down to 115 MVA because of VSC converter of the HVDC which have the ability to support up to ±200 MVAr. These two kinds of power flow controller devices could dynamically change the overall structural and oscillatory behavior of the system and consequently affect the system stability. Due to their advantage for enhancing the power system dynamic performance, both of two technologies are going to be applied together.

Now let we consider the bus voltages when the STATCOM is inserted and/or when two areas are interconnected by VSC-HVDC. The following figures (Figure 5.34 and Figure 5.35) shows the bus voltage dynamics when 3-phase to ground fault is initiated on area 1 at Bahir Dar II 230kV bus.

![Figure 5.34 Bahir Dar II 230kV bus voltage dynamics](image)

It's shown on Figure 5.34 that for the case of “without” the system voltage is not in stable state until 2.6 sec after 3-phase to ground fault. The oscillation at 2.4-2.6 sec shows the action of tap changers and switched shunts to regain its steady state values where the final gained value is 0.95 pu rather than 1 pu (steady state value). This shows the inability of system to restore its original steady state value without compensating devices as described on section 5.2 to 5.4.
When the voltage dynamics improvement strategies are applied the bus voltage gained its steady state value on short time. The submission of STATCOM 1, interconnecting by VSC-HVDC and integrating both showed the better performance. Inserting STATCOM 1 showed the best dynamic performance for post-disturbance because the bus is nearest to the device (PCC).

Now again let we see area 2 system voltage dynamics for the fault on Bahir Dar II 230kV bus (area 1) for all cases. Sudan-Rabak 220kV substation is selected to study the effect as shown on Figure 5.35 below.

![Figure 5.35 Sudan-Rabak bus voltage dynamics for fault on Bahir Dar II 230kV bus](image)

The effect of 3-phase to ground fault is banned by VSC-HVDC application where the system voltage is at steady state value for both cases (“with VSC-HVDC” and “with STATCOM 1 and VSC-HVDC”). Here the STATCOM 1 is useless for area 2 system dynamics where the value gained is equal for both cases.

Now once more the 3-phase to ground fault is initiated on area 2 at Gadarif 220kV bus to show the effectiveness of integrating the compensation schemes.

As shown on Figure 5.36 below the interconnection of the areas by VSC-HVDC showed the better performance because it helps’ the system voltage by injecting reactive power during/after fault where the bus is PCC for VSC 2.
CHAPTER 5: SIMULATION RESULTS AND DISCUSSION

The following Figure 5.37 shows the effect of 3-phase to ground fault that is introduced on Sudan-Gadaref bus within all cases.

Integration of both dynamic performance improvement methods showed the better depiction than other cases because both devices have supported the bus during/after fault.
Finally we can say that integration of STATCOM 1 and VSC-HVDC is crucial in maintaining the system voltage on acceptable values. For this case STATCOM 1 supported the area 1 buses that are far distant from VSC stations. For area 2 interconnecting by VSC-HVDC rather than only using STATCOM exhibited the best performance.

5.6.2. With VSC-HVDC interconnection and STATCOM on area 2

When we integrate STATCOM 2 and VSC-HVDC the required size of the STATCOM 2 for maintaining the PCC voltage at 1.02 pu remains at 21 MVAr. For fault on area 1 at Tis-Abay II 132kV bus the result of integrating STATCOM 2 and VSC-HVDC is shown on Figure 5.38 and Figure 5.39 below.

Tis-Abay II bus is interconnected directly to the Bahir-Dar II 230kv bus (STATCOM 1 PCC), where the post disturbance bus voltage showed the better performance for case of STATCOM 1 than other cases. Furthermore they disclose that more sounding improvement is obtained at bus bars that are near the inserted STATCOM and/or VSC-HVDC link. The VSC-HVDC link also prevented the instability not to be transmitted to the other end as Figure 5.39 where the fault on Tis-Abay II 132kV bus have not affected the system dynamics of Sudan-Gadaref 220kV bus.
CHAPTER 5: SIMULATION RESULTS AND DISCUSSION

Figure 5.39 Sudan-Gadaref 220kV bus voltage dynamics for fault on Tis-Abay II 132kV bus

The integration of STATCOM 2 and VSC-HVDC increased the voltage value from 0.995 in case of VSC-HVDC only, to 1.02 pu which implies the STATCOM 2 increased the availability of reactive power injected within area 2. Here again integration of both devices showed a better dynamic performance within each areas.

It is clear now that the fault on Area 2 when interconnected by VSC-HVDC wouldn’t disturb area 1 because of its ability to inject/absorb reactive power to keep pre-fault voltage value. The following figures (Figure 5.40 and Figure 5.41) below shows the effect of integrating STATCOM 2 and/or VSC-HVDC when the fault is initiated on Sudan-Gadaref 220kV bus.

From the Figure 5.40 we can realize that the 3-phase to ground fault on PCC of VSC 2 affected the voltage dynamics before interconnecting area 1 by VSC-HVDC implying here again that integration of STATCOM and VSC-HVDC is the preeminent way for keeping the system voltage within acceptable values.
The fault on Sudan-Gadaref 220kV bus affects the dynamics of area 1 buses when both areas are interconnected by AC transmission system. The following Figure 5.41 indicates the effect of 3-phase to ground fault on area 1 where the Metema 230kV bus is selected for explanation. Here when the areas are interconnected by VSC-HVDC the effect of fault is disclosed. The converter at Metema (VSC 1) side effectively monitored the voltage in the area and maintains it at desired value of 1 pu on pre-fault, during fault and after the occurrence of the fault. The occurrence of the fault has no impact on this area. Thus here again instability spread prevention is effectively achieved.

Finally from the above figures we can conclude that the application of STATCOM on selected bus is the highly regarded way for providing system bus voltage at steady state for its’ own area. The STATCOM is capable of providing the additional reactive power
support and hence voltage support to the system. Interconnecting the areas by VSC-HVDC transmission system adds the advantage of reactive power support as STATCOM where it injects/absorbs the deficit/excess of reactive power within the system. The main advantage gained from interconnecting the areas by VSC-HVDC is keeping the opposite side area as firewall when the fault is initiated on other area.

Now yet again let we consider another parameters such as electrical power, mechanical power, rotor angle, and line flow for all cases to give final conclusion on their applicability in improving the system parameters. Here we would see the effect of installed devices on system stability by initiating 3-phase to ground fault as usual on Bahir-Dar II bus (area 1) and Rabak bus (area 2) for latter case see Appendix D.

![Figure 5.42 Belles generator output for fault on Bahir Dar II 230kV bus (a) active power (b) reactive power](image)

![Figure 5.43 Rotor angle for fault on Bahir Dar II bus (a) Beles generating unit (b) Rosier power plant](image)
From Figure 5.42 and Figure 5.43 above we can say that the compensating device STATCOM and VSC-HVDC are not limited in only voltage stability improvement but also other parameter system stability enhancement is possible. Therefore, the existing and upcoming stability of the entire power system can be significantly improved through the installation of STATCOM, of a proper size, when severe network disturbances occur in the system and the fault initiated on other side area can be protected by interconnecting two areas by VSC-HVDC.

5.7. Economical cost analysis

Bulk power could be transferred using HVDC or HVAC transmission system from a remote generating station to the load center. Direct cost comparisons between AC and DC alternatives should be conducted before make a decision. In order to compare the cost, all main system elements must be taken into consideration. For the DC alternative, capital cost for the converter terminals, AC input/output equipment, filters, the interconnecting transmission line must be accounted. For the AC alternative, capital cost for the step-up/step-down transformer, the overhead line, light load compensation if required, reactive power compensation, circuit breaker, building should be evaluated.

The compensation of voltage drop is helpful in reducing the power loss in adequate way that saves the cost of electricity in a system. The general cost comparison between HVDC and HVAC conductors is shown in Figure 5.44. There is a breakeven distance between HVAC and HVDC, generally considered between 40 and 80 km length.

The Figure 5.44 shows that, the VSC based HVDC system is the better alternative economically when compared to either a high voltage AC system or a generation source
local to the load centre. The following Table 5.2 and As shown on Figure 5.44 and Table 5.2 above the cost of VSC-HVDC is less than HVAC for transmission line above 80km [56]. Therefore using VSC-HVDC is the best alternative for interconnecting areas, for compensation system and bulk power transfer to far distant loads in terms of economy also. Now let we consider the economical evaluation of STATCOM from both areas.

Table 5.3 shows the overall average cost of VSC-HVDC for 160 km length and 400 MW capacity and STATCOM cost per kVAr respectively. The Table 5.2 shows the comparative analysis of VSC-HVDC and HVAC.

### Table 5.2 The overall cost of VSC-HVDC (M$) [55-58]

<table>
<thead>
<tr>
<th>No.</th>
<th>Components</th>
<th>VSC-HVDC</th>
<th>HVAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Converter Substation</td>
<td>173.5</td>
<td>18.8470</td>
</tr>
<tr>
<td>2</td>
<td>Overhead system</td>
<td>86.3</td>
<td>303.29</td>
</tr>
<tr>
<td>3</td>
<td>Land use</td>
<td>0.070</td>
<td>0.070</td>
</tr>
<tr>
<td>4</td>
<td>Total</td>
<td>259.87</td>
<td>322.207</td>
</tr>
</tbody>
</table>

As shown on Figure 5.44 and Table 5.2 above the cost of VSC-HVDC is less than HVAC for transmission line above 80km [56]. Therefore using VSC-HVDC is the best alternative for interconnecting areas, for compensation system and bulk power transfer to far distant loads in terms of economy also. Now let we consider the economical evaluation of STATCOM from both areas.

### Table 5.3 Cost of different FACTS devices [58-60]

<table>
<thead>
<tr>
<th>Type</th>
<th>Cost ($/kVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STATCOM</td>
<td>40</td>
</tr>
<tr>
<td>SVC</td>
<td>35</td>
</tr>
<tr>
<td>UPFC</td>
<td>50</td>
</tr>
<tr>
<td>TCSC</td>
<td>40</td>
</tr>
</tbody>
</table>

For this thesis let we consider the amount of cost paid back by using STATCOM by considering overall system power loss. The following Table 5.4 shows the lost and improved power that is extracted from PSS/E.

### Table 5.4 Power loss without and with STATCOM

<table>
<thead>
<tr>
<th></th>
<th>Without</th>
<th>With STATCOM 1</th>
<th>With STATCOM 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(_{\text{loss}}) (MW)</td>
<td>19.36</td>
<td>17.26</td>
<td>18.23</td>
</tr>
<tr>
<td>Improved P(_{\text{loss}}) (MW)</td>
<td>-</td>
<td>2.1</td>
<td>1.13</td>
</tr>
</tbody>
</table>

3 Here the cost of STATCOM for both areas is evaluated by Ethiopian birr (ETB)
From the Table 5.4 above we can calculate the amount of birr saved per year as follows by taking the EEU tariffs for each usage. The lowest is 0.2 birr for each kilowatt-hour (kWh) for those that use below 50kWh a month, and the highest is 2.4 birr for each kilowatt-hour for those that use more than 500kWh a month [61, 62]. Here it is in MW the cost taken is 2.4birr/kWh or 2400 birr/MWh.

The economic analysis uses standard financial measures, such as the Payback Period and Net Present Value (NPV) to assess the alternative. The Payback Period is the number of years of benefits required for the project to break even. The payback time can be estimated by the following equation.

\[
\text{Payback Period} = \frac{\text{Net Investment}}{\text{Net Annual Return}}
\]  

(5.1)

In the NPV method, all marginal cash flows of a project are taken into account during its entire lifetime. Cash flows in upcoming years are discounted to \( t = 0 \) by using an appropriate rate called the Opportunity Cost of Capital (OCC), hurdle rate, discount rate or required rate of return, which results in the Present Value of these cash flows.

The NPV of these cash flows (if the salvage value of the equipment is assumed to be negligible) is calculated by:

\[
\text{NPV} = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} - C_0
\]  

(5.2)

Where:
- \( CF_t \) = the net cash flow at time
- \( C_0 \) = the initial investment
- \( r \) = the cost of capital (discount rate)
- \( t \) = the number of years
- \( n \) = the life time of the investment

Without the device we lost; 19.36*8760*2400 = 407,024,640 birr/year

When we use STATCOM 1 we can save 2.1*8760*2400 = 44,150,400 birr/year

When we use STATCOM 2 we can save 1.13*8760*2400 = 23,757,120 birr/year

Now we can calculate the investment cost of both VSC-HVDC and STATCOM (here the cost of installation, the cost of operation and maintenance are not considered for the
sake of simplicity). The currency is taken on October 10, 2019 from national bank of Ethiopia (1USD =29.5799 ETB and 1EUR =32.5466ETB) [63]. Therefore the overall cost of STATCOM is,
Investment cost (STATCOM 1)= 40×250×29.5799 = 295.799 million birr
Investment cost (STATCOM 2)= 40×32×29.5799 = 37.862 million birr

\[
payback\ period = \frac{Net\ Investment}{Net\ Annual\ Return}\ 
\]

From Equation (5.1) above
the payback period of STATCOM is;

\[
payback\ period_{STATCOM1} = \frac{295.799}{44.1504} = 6.7\ years \tag{5.3}
\]

\[
payback\ period_{STATCOM2} = \frac{37.862}{23.757} = 1.6\ years \tag{5.4}
\]

The NPV is also calculated and tabulated on below by taking the life time of investment to be 20 years, net cash flow of 44.15 METB and 23.757 METB for STATCOM 1 and STATCOM 2 respectively and considering Equation (5.2) above.

**Table 5.5 NPV analysis of installation of STATCOM at both areas**

<table>
<thead>
<tr>
<th>time (t)</th>
<th>STATCOM M1 Net cash flow (CFt) (in METB)</th>
<th>STATCOM M1 Inv. nt cost (in millions ETB)</th>
<th>STATCOM M1 present value (in millions ETB)</th>
<th>STATCOM M1 NPV (in millions ETB)</th>
<th>STATCOM M2 Net cash flow (CFt) (in METB)</th>
<th>STATCOM M2 Inv. nt cost (in millions ETB)</th>
<th>STATCOM M2 present value (in millions ETB)</th>
<th>STATCOM M2 NPV (in millions ETB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>44.15</td>
<td>23.757</td>
<td>295.799</td>
<td>-295.799</td>
<td>-37.862</td>
<td>-295.799</td>
<td>-37.862</td>
<td>-295.799</td>
</tr>
</tbody>
</table>
CHAPTER 5: SIMULATION RESULTS AND DISCUSSION

| 11 | 44.15 | 23.757 | 295.799 | 37.862 | 12.692 | 6.82956981 | -33.6495833 | 103.199918 |
| 12 | 44.15 | 23.757 | 295.799 | 37.862 | 11.33220535 | 6.09783018 | -22.31737795 | 109.297748 |
| 13 | 44.15 | 23.757 | 295.799 | 37.862 | 10.11804049 | 4.86115289 | -12.19933745 | 114.74224 |
| 14 | 44.15 | 23.757 | 295.799 | 37.862 | 9.033964727 | 4.34321623 | -3.165372725 | 119.603393 |
| 15 | 44.15 | 23.757 | 295.799 | 37.862 | 8.066039935 | 4.09022058 | 4.90066721 | 123.943708 |
| 16 | 44.15 | 23.757 | 295.799 | 37.862 | 7.20182137 | 3.87528132 | 12.10248858 | 127.818989 |
| 17 | 44.15 | 23.757 | 295.799 | 37.862 | 6.430197652 | 3.46007261 | 18.53268623 | 131.279062 |
| 18 | 44.15 | 23.757 | 295.799 | 37.862 | 5.741247904 | 2.7583487 | 29.40004834 | 137.126761 |
| 19 | 44.15 | 23.757 | 295.799 | 37.862 | 5.1261142 | 2.46281134 | 33.97693601 | 139.589572 |

From the Table 5.5 above we can say that both of STATCOMs are helping more returns, at the end of 20 years of service so it is the best compensating device for the system.

Discussion

VSC-HVDC and STATCOM are essential technologies for future grid expansion and reliable integration of one area to other area.

Electricity grid upgrades, including construction of new transmission lines, cannot keep pace with the growing power plant capacity and energy demand. Unlike siting and building a new transmission line, STATCOM can be implemented quickly (less than a year from purchase to completion). It immediately boost the transmission capacity of the given line while also providing voltage support and bolstering the local grid's ability to withstand disturbances. Thus it is necessary to rely on optimum utilization of existing transmission and distribution infrastructure by improving the transient and steady state stability which can be achieved with the help of reactive power compensation.

Embedding VSC-HVDC in AC networks opens up new possibilities to enhance smart transmission grid operation with improved reliability, delivery efficiency, and capacity utilization by keeping the stability of system parameters.

In the case of VSC-HVDC, additional reactive power support at the connection point is provided. Hence, VSC-HVDC helps maintaining a certain voltage profile within a power network. Reactive power transport on neighbouring lines that are connected to the same network node can be reduced. This frees up transmission capacities for active power transport on neighbouring lines. Therefore, when analyzing the potential of an HVDC link in comparison to conventional HVAC, the positive effect of HVDC on neighbouring
CHAPTER 5: SIMULATION RESULTS AND DISCUSSION

nodes has to be considered too. Therefore VSC-HVDC enhances voltage stability by operating the converters as STATCOM during and after the fault. ABB’s HVDC Light® is now emerging as robust and economical alternative for transmission grid expansion where the cost is comparable with AC transmission system.

From Table 5.1 in steady state operation the compensating devices have shown improved voltage values. For example Bahir Dar II bus showed 0.04 pu (9.2kV) voltage improvement after connecting STATCOM 1, Rabak bus gained 0.051 (11.22kV) pu improvement by installing STATCOM 2. In interconnecting Metema to Gadaref by VSC_HVDC we have saved 0.023 pu (5.29kV) on Metema and 0.042 pu (9.24kV) on Gadaref and the same is true for other buses even if the value is different. From this improvement as the voltage increases the power loss cost decreases which can pay back in few years. This devices are also efficient in dynamic state operation in maintaining stability of system parameters. Therefore the cost of devices should be compared to the value of satisfaction, the cost of sitting and construction of new transmission lines, in loss minimization and ability in keeping system quality.

Finally we have said that “the cost of doing nothing on compensation systems is greater than the cost of using compensation schemes such as STATCOM and VSC-HVDC” for those companies and individuals who think of about only their costs rather than their satisfied system quality.
CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATIONS

This chapter draws the conclusion and recommendations of this thesis work. Finally some suggestions and an outlook for further research is given.

6.1. Conclusion

By the end of the thesis, the objective has been achieved, that is, the impact of interconnection is studied where its pros and cons have been discussed with respect to dynamic performance. The improvement schemes are modelled with their controllers and their applicability is made known and discussed after all we can conclude as follows.

In order to fulfill the power demand needed by consumers, countries are interconnecting to each other to exchange the real power as Ethiopia and Sudan in our case. Interconnection (tie line) have a lot of advantages in terms of economic, political and social interactions and it is not limited on this but also in terms of dynamic performance it is beneficial to keep system parameters at acceptable values. But the fault on one area affects the dynamics of other area unless and otherwise compensation devices are used to provide adequate reactive power support for steady-state and post-fault conditions.

In AC/DC interconnected transmission system, the voltage stability of power systems can be improved by the control of reactive power.

The simulation results show that STATCOM compensator, which controls reactive power injection/absorption, has a more significant effect on the oscillation damping. The STATCOM on area 1 showed a better performance around the PCC bus and it helps area 2 in restoring the bus voltage within short period of time. STATCOM 2 showed an excellent system performance with the voltage drop after the fault improved to a level above 0.95 p.u and very short settling time (< 0.1 sec) for its own area. This ensures that the STATCOM helps to achieve better voltage profiles during severe faults like three phase to ground short circuit fault at the grid connection point (PCC).

From the simulation results and the analysis made upon interconnecting two areas by VSC-HVDC the post disturbance pu bus bar voltage magnitudes, which determine the
stability of a power system pre disturbance pu voltage magnitude is improved from below 0.95 to around 1 pu, after contingency, bus voltages are improved from below 0.9 pu to above 0.95 pu and below 1.05 pu and fast restoration of pre disturbance bus voltage value after fault clearance is achieved within faulted area and it is used as barrier of fault for opposite area i.e. the area stays at steady state at pre-fault, during fault and post-fault states. Higher voltage magnitudes around 1 pu mean lower system power loss where it shows that interconnecting by VSC-HVDC rather than AC help at reducing power system significant power losses at steady state operation.

6.2. Recommendations

Based on the result of this thesis work, it is strongly recommended that EEP and SETCO has to consider the integration of VSC-HVDC transmission to their upcoming interconnections and STATCOM for existing and upcoming large power system to maintain the system stability thereby improving overall system power transfer capability and system stability that reduce huge power losses in the system. While interconnecting EEP grid to other EAPP member and further countries it should be studied that ability of the interconnecting grid in compensating mechanisms and presence of other stability maintaining devices.

We again recommend the EEP that while exporting electricity it is better to discuss about type of transmission to be VSC-HVDC on contract stage because it is barrier to EEP grid for the fault created on that area and it supports reactive power for both system grids.

6.3. Suggestions for Future Work

Following this master thesis, some aspects have to be studied and investigated in more detail.

- Optimization in sizing and placement of STATCOM for better performance by using different optimization techniques.
- Optimization of STATCOM and VSC-HVDC transmission costs considering converter topologies of both devices.
Future power electronics type and cost trends to make the option economically attractive.

A comprehensive study into the possibility of including multiple STATCOM and VSC-HVDC devices in the system and adequate coordination control of these multiple devices within the system and their influence on system stability.

The study of multiple consecutive faults in the network and how the integration of STATCOM and VSC-HVDC responds to such situation.
REFERENCES


[6] (SATURDAY 29 OCTOBER 2016) Sudan to build power transmission line from Ethiopia’s GERD:. *Sudan Tribune: Plural news and views on Sudan.*


REFERENCES


REFERENCES


REFERENCES


## APPENDICES

### Appendix A

**A. Northern and North-Western EEP and SETCO model system data**

#### Table A.1 Bus data of northern and NWR (Ethiopian side)

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Bus Name</th>
<th>Base kV</th>
<th>Voltage (pu)</th>
<th>Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>107001</td>
<td>B.dar2</td>
<td>132</td>
<td>1.0186</td>
<td>-4.82</td>
</tr>
<tr>
<td>107002</td>
<td>T-abay2</td>
<td>132</td>
<td>1.03</td>
<td>-3.75</td>
</tr>
<tr>
<td>207001</td>
<td>B.dar2</td>
<td>230</td>
<td>1.047</td>
<td>-7.75</td>
</tr>
<tr>
<td>207002</td>
<td>Db-Mrkos</td>
<td>230</td>
<td>1.0403</td>
<td>-10.54</td>
</tr>
<tr>
<td>207005</td>
<td>Gondar2</td>
<td>230</td>
<td>1.0345</td>
<td>-12.46</td>
</tr>
<tr>
<td>207006</td>
<td>Metema</td>
<td>230</td>
<td>1.0157</td>
<td>-9.06</td>
</tr>
<tr>
<td>207007</td>
<td>Mota</td>
<td>230</td>
<td>1.0486</td>
<td>-4.82</td>
</tr>
<tr>
<td>208001</td>
<td>Fincha</td>
<td>230</td>
<td>1.0207</td>
<td>-8.15</td>
</tr>
<tr>
<td>209001</td>
<td>Alamata</td>
<td>230</td>
<td>1.0629</td>
<td>-2.24</td>
</tr>
<tr>
<td>209004</td>
<td>Mekelle</td>
<td>230</td>
<td>1.0058</td>
<td>-6.36</td>
</tr>
</tbody>
</table>

#### Table A.2 Bus data from SETCO (Sudan side)

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Bus Name</th>
<th>Base kV</th>
<th>Voltage (pu)</th>
<th>Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200001</td>
<td>Meringan</td>
<td>220</td>
<td>1.0556</td>
<td>-9.39</td>
</tr>
<tr>
<td>200002</td>
<td>Senn</td>
<td>220</td>
<td>1.02</td>
<td>-6</td>
</tr>
<tr>
<td>200003</td>
<td>Rosier</td>
<td>220</td>
<td>1.01</td>
<td>-2.82</td>
</tr>
<tr>
<td>207013</td>
<td>Sudan-Gadaref</td>
<td>220</td>
<td>1.012</td>
<td>-3.47</td>
</tr>
<tr>
<td>207014</td>
<td>Sudan-Rabak</td>
<td>220</td>
<td>1.0158</td>
<td>-8.64</td>
</tr>
<tr>
<td>900001</td>
<td>Sennar</td>
<td>11</td>
<td>1.0158</td>
<td>-5.05</td>
</tr>
<tr>
<td>900002</td>
<td>Roseirs</td>
<td>11</td>
<td>1.031</td>
<td>-7.35</td>
</tr>
</tbody>
</table>

#### Table A.3 NWR and SETCO transmission line data

<table>
<thead>
<tr>
<th>From Bus</th>
<th>To Bus</th>
<th>Line R (pu)</th>
<th>Line X (pu)</th>
<th>Charging B (pu)</th>
<th>Rating (MVA)</th>
<th>Length (km)</th>
<th>R/Zero (pu)</th>
<th>X/Zero (pu)</th>
<th>B/Zero (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metema</td>
<td>Gadaref</td>
<td>0.0343</td>
<td>0.096</td>
<td>0.3083</td>
<td>402</td>
<td>160</td>
<td>0.104</td>
<td>0.3228</td>
<td>0.186</td>
</tr>
<tr>
<td>B.Dar2</td>
<td>T-Abay2</td>
<td>0.0354</td>
<td>0.0705</td>
<td>0.013</td>
<td>91</td>
<td>28.96</td>
<td>0.0773</td>
<td>0.2018</td>
<td>0.008</td>
</tr>
<tr>
<td>B.Dar2</td>
<td>T-Abay2</td>
<td>0.0354</td>
<td>0.0705</td>
<td>0.013</td>
<td>91</td>
<td>28.96</td>
<td>0.0773</td>
<td>0.2018</td>
<td>0.008</td>
</tr>
<tr>
<td>B.Dar2</td>
<td>Gondar</td>
<td>0.0293</td>
<td>0.0844</td>
<td>0.255</td>
<td>402</td>
<td>136.97</td>
<td>0.0915</td>
<td>0.2688</td>
<td>0.155</td>
</tr>
<tr>
<td>B.Dar2</td>
<td>Mota</td>
<td>0.0127</td>
<td>0.0664</td>
<td>0.120</td>
<td>280</td>
<td>83</td>
<td>0.0504</td>
<td>0.1781</td>
<td>0.080</td>
</tr>
<tr>
<td>B.Dar2</td>
<td>Alamata</td>
<td>0.0206</td>
<td>0.0630</td>
<td>0.190</td>
<td>318</td>
<td>239.7</td>
<td>0.0670</td>
<td>0.2007</td>
<td>0.116</td>
</tr>
<tr>
<td>Db-Mrkos</td>
<td>Mota</td>
<td>0.0172</td>
<td>0.0894</td>
<td>0.161</td>
<td>280</td>
<td>111.76</td>
<td>0.0679</td>
<td>0.2398</td>
<td>0.108</td>
</tr>
<tr>
<td>Db-Mrkos</td>
<td>Fincha</td>
<td>0.0146</td>
<td>0.0761</td>
<td>0.137</td>
<td>280</td>
<td>95.15</td>
<td>0.0578</td>
<td>0.2042</td>
<td>0.092</td>
</tr>
<tr>
<td>Gondar</td>
<td>Metema</td>
<td>0.0333</td>
<td>0.0989</td>
<td>0.317</td>
<td>318</td>
<td>165</td>
<td>0.1051</td>
<td>0.3328</td>
<td>0.192</td>
</tr>
</tbody>
</table>
Table A.4 Sudan transmission Lines (OHL)

<table>
<thead>
<tr>
<th>From Bus</th>
<th>To Bus</th>
<th>Line R (pu)</th>
<th>Line X (pu)</th>
<th>Charging B (pu)</th>
<th>RATING (MVA)</th>
<th>Length(km)</th>
<th>R-Zero (pu)</th>
<th>X-Zero (pu)</th>
<th>B-Zero (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MERINGAN</td>
<td>SENN</td>
<td>0.014</td>
<td>0.039</td>
<td>0.1264</td>
<td>402</td>
<td>65.6</td>
<td>0.0426</td>
<td>0.132342</td>
<td>0.076624</td>
</tr>
<tr>
<td>MERINGAN</td>
<td>GADAREF</td>
<td>0.022</td>
<td>0.063</td>
<td>0.20238</td>
<td>402</td>
<td>105</td>
<td>0.068</td>
<td>0.2118</td>
<td>0.12265</td>
</tr>
<tr>
<td>SENN</td>
<td>ROSEIR</td>
<td>0.035</td>
<td>0.19</td>
<td>0.001</td>
<td>324</td>
<td>228</td>
<td>0.26</td>
<td>1.017</td>
<td>0.000485</td>
</tr>
<tr>
<td>SENN</td>
<td>ROSEIR</td>
<td>0.0358</td>
<td>0.19</td>
<td>0.001</td>
<td>324</td>
<td>228</td>
<td>0.26</td>
<td>1.017</td>
<td>0.000485</td>
</tr>
<tr>
<td>SENN</td>
<td>RABAK</td>
<td>0.069</td>
<td>0.084</td>
<td>0.0004</td>
<td>62</td>
<td>62</td>
<td>0.1083</td>
<td>0.273</td>
<td>0.00024</td>
</tr>
<tr>
<td>GADAREF</td>
<td>RABAK</td>
<td>0.051</td>
<td>0.228</td>
<td>0.43378</td>
<td>402</td>
<td>400</td>
<td>0.2599</td>
<td>0.807</td>
<td>0.46722</td>
</tr>
</tbody>
</table>

Table A.5 Generation Data

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Bus Name</th>
<th>Voltage  (kV)</th>
<th>Pgen (MW)</th>
<th>Pmax (MW)</th>
<th>QGen (Mvar)</th>
<th>Qmax (Mvar)</th>
<th>Qmin (Mvar)</th>
<th>Mbase (MVA)</th>
<th>R Source (pu)</th>
<th>X Source (pu)</th>
<th>X Negative (pu)</th>
<th>XZero (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900001</td>
<td>Sennar</td>
<td>11</td>
<td>15.49</td>
<td>18.8</td>
<td>-4.33</td>
<td>23.7</td>
<td>-14.1</td>
<td>18.8</td>
<td>0.0027</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>900002</td>
<td>Roseirs</td>
<td>11</td>
<td>113.45</td>
<td>280</td>
<td>27.36</td>
<td>158</td>
<td>-93.6</td>
<td>280</td>
<td>0.0037</td>
<td>0.164</td>
<td>0.164</td>
<td>0.164</td>
</tr>
<tr>
<td>907001</td>
<td>Beles</td>
<td>15</td>
<td>184.0</td>
<td>468</td>
<td>-2.84</td>
<td>280.4</td>
<td>-166</td>
<td>532</td>
<td>0.005</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>907002</td>
<td>T-Aba2</td>
<td>10.5</td>
<td>29.17</td>
<td>72</td>
<td>34.55</td>
<td>42.2</td>
<td>-25</td>
<td>80</td>
<td>0.0065</td>
<td>0.365</td>
<td>0.365</td>
<td>0.365</td>
</tr>
<tr>
<td>908001</td>
<td>Fincha</td>
<td>13.8</td>
<td>53.96</td>
<td>133.2</td>
<td>3.02</td>
<td>73.6</td>
<td>-43.6</td>
<td>140</td>
<td>0.01046</td>
<td>0.115</td>
<td>0.115</td>
<td>0.115</td>
</tr>
<tr>
<td>909001</td>
<td>Tekeze</td>
<td>13.8</td>
<td>126.45</td>
<td>312.1</td>
<td>131.8</td>
<td>184.4</td>
<td>109.6</td>
<td>350.4</td>
<td>0.00346</td>
<td>0.173</td>
<td>0.173</td>
<td>0.173</td>
</tr>
</tbody>
</table>

Table A.6 Two winding transformer data

<table>
<thead>
<tr>
<th>From Bus Number</th>
<th>From Bus Name</th>
<th>To Bus Number</th>
<th>To Bus Name</th>
<th>Area number</th>
<th>Tap</th>
<th>Control Mode</th>
<th>Specified R (pu or watts)</th>
<th>Specified X (pu)</th>
<th>Winding MVA Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>220</td>
<td>207006</td>
<td>METEMA</td>
<td>230</td>
<td>1</td>
<td>13 Voltage</td>
<td>0.003647</td>
<td>0.135</td>
<td>500</td>
</tr>
<tr>
<td>107002</td>
<td>T-ABAY2</td>
<td>132</td>
<td>907002</td>
<td>10.5</td>
<td>1</td>
<td>19 Voltage</td>
<td>0.0026</td>
<td>0.078</td>
<td>48</td>
</tr>
<tr>
<td>200002</td>
<td>SENN</td>
<td>220</td>
<td>900001</td>
<td>11</td>
<td>2</td>
<td>11 Voltage</td>
<td>0.0048</td>
<td>0.11</td>
<td>45</td>
</tr>
<tr>
<td>200003</td>
<td>ROSEIR</td>
<td>220</td>
<td>900002</td>
<td>11</td>
<td>2</td>
<td>7 Voltage</td>
<td>0.0021</td>
<td>0.088</td>
<td>292</td>
</tr>
<tr>
<td>207001</td>
<td>B.DAR2</td>
<td>230</td>
<td>407001</td>
<td>400</td>
<td>1</td>
<td>21 Voltage</td>
<td>0.0018</td>
<td>0.121</td>
<td>500</td>
</tr>
<tr>
<td>207001</td>
<td>B.DAR2</td>
<td>230</td>
<td>407001</td>
<td>400</td>
<td>1</td>
<td>17 Voltage</td>
<td>0.0018</td>
<td>0.121</td>
<td>500</td>
</tr>
<tr>
<td>207002</td>
<td>DB-MRKOS</td>
<td>230</td>
<td>407003</td>
<td>400</td>
<td>1</td>
<td>21 Voltage</td>
<td>0.0018</td>
<td>0.121</td>
<td>250</td>
</tr>
</tbody>
</table>
APPENDICES

<table>
<thead>
<tr>
<th>From Bus Name</th>
<th>To Bus Number</th>
<th>To Bus Name</th>
<th>Last Bus Number</th>
<th>Last Bus Name</th>
<th>Winding 1-2 MVA Base</th>
<th>Winding 2-3 MVA Base</th>
<th>Winding 3-1 MVA Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.DAR2</td>
<td>107001</td>
<td>B.DAR2</td>
<td>807017</td>
<td>B.DAR2-2</td>
<td>50</td>
<td>16.7</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Table A.7 Three winding transformer data

Table A.8 Generator dynamic parameters for both areas[64, 65]

<table>
<thead>
<tr>
<th>No.</th>
<th>Power Plant</th>
<th>Mbase (MVA)</th>
<th>(T_{\phi}(&gt;0))</th>
<th>(T_{d}(&gt;0))</th>
<th>(T_{q}(&gt;0))</th>
<th>Inertia H</th>
<th>Speed Damping</th>
<th>(X_d)</th>
<th>(X_q)</th>
<th>(X_d')</th>
<th>(X_q')</th>
<th>(X_{d''})</th>
<th>(X_{q''})</th>
<th>(X_{d''} = X_{q''})</th>
<th>(X_{1})</th>
<th>(S(1.0))</th>
<th>(S(1.2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>BELES</td>
<td>532</td>
<td>9.2</td>
<td>0.13</td>
<td>0.1</td>
<td>3.14</td>
<td>0</td>
<td>1.03</td>
<td>0.7</td>
<td>0.31</td>
<td>0.25</td>
<td>0.2</td>
<td>0.09</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>FINCHA</td>
<td>140</td>
<td>7.393</td>
<td>0.045</td>
<td>0.057</td>
<td>3.04</td>
<td>0</td>
<td>0.96</td>
<td>0.9</td>
<td>0.23</td>
<td>0.115</td>
<td>0.1</td>
<td>0.09</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Roseires</td>
<td>305.5</td>
<td>4.67</td>
<td>0.06</td>
<td>0.07</td>
<td>4.5</td>
<td>0</td>
<td>0.89</td>
<td>0.54</td>
<td>0.26</td>
<td>0.21</td>
<td>0.13</td>
<td>0.13</td>
<td>0.434</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Sennar</td>
<td>18.8</td>
<td>5</td>
<td>0.041</td>
<td>0.074</td>
<td>2.22</td>
<td>0</td>
<td>1.02</td>
<td>0.65</td>
<td>0.3</td>
<td>0.2</td>
<td>0.16</td>
<td>0.11</td>
<td>0.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>T-ABA2</td>
<td>80</td>
<td>7.1</td>
<td>0.12</td>
<td>0.12</td>
<td>2.5</td>
<td>0.5</td>
<td>1</td>
<td>0.6</td>
<td>0.29</td>
<td>0.365</td>
<td>0.14</td>
<td>0.08</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>TEKEZE</td>
<td>350.4</td>
<td>6.47</td>
<td>0.1</td>
<td>0.2</td>
<td>2.6</td>
<td>0</td>
<td>1</td>
<td>0.6</td>
<td>0.29</td>
<td>0.173</td>
<td>0.1</td>
<td>0.09</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A.9 Line stability indices for both areas under normal conditions

<table>
<thead>
<tr>
<th>Line No</th>
<th>From bus</th>
<th>To bus</th>
<th>LMN</th>
<th>FVSI</th>
<th>LQP</th>
<th>NVSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>13</td>
<td>0.084</td>
<td>0.078</td>
<td>0.093</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>23</td>
<td>0.486</td>
<td>0.443</td>
<td>0.379</td>
<td>0.421</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>5</td>
<td>0.018</td>
<td>0.017</td>
<td>0.02</td>
<td>0.022</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>5</td>
<td>0.023</td>
<td>0.023</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>7</td>
<td>0.288</td>
<td>0.261</td>
<td>0.507</td>
<td>0.535</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>15</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>8</td>
<td>0.039</td>
<td>0.038</td>
<td>0.039</td>
<td>0.309</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>8</td>
<td>0.007</td>
<td>0.007</td>
<td>0.078</td>
<td>0.039</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>16</td>
<td>0.215</td>
<td>0.213</td>
<td>0.259</td>
<td>0.260</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>16</td>
<td>0.26</td>
<td>0.26</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>12</td>
<td>0.265</td>
<td>0.264</td>
<td>0.264</td>
<td>0.23</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
<td>14</td>
<td>0.327</td>
<td>0.325</td>
<td>0.274</td>
<td>0.296</td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>18</td>
<td>0.154</td>
<td>0.154</td>
<td>0.154</td>
<td>0.12</td>
</tr>
<tr>
<td>14</td>
<td>11</td>
<td>14</td>
<td>0.012</td>
<td>0.012</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>15</td>
<td>11</td>
<td>17</td>
<td>0.05</td>
<td>0.049</td>
<td>0.097</td>
<td>0.064</td>
</tr>
<tr>
<td>16</td>
<td>12</td>
<td>13</td>
<td>0.018</td>
<td>0.018</td>
<td>0.019</td>
<td>0.015</td>
</tr>
</tbody>
</table>
Table A.10 Case study load data

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Bus Name</th>
<th>Area (MW)</th>
<th>Num</th>
<th>Pload (MW)</th>
<th>Qload (Mvar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>107001</td>
<td>B.DAR2</td>
<td>132.00</td>
<td>1</td>
<td>20</td>
<td>5.99</td>
</tr>
<tr>
<td>107002</td>
<td>T-ABAY2</td>
<td>132.00</td>
<td>1</td>
<td>11.223</td>
<td>2.786</td>
</tr>
<tr>
<td>200001</td>
<td>MERINGAN</td>
<td>220.00</td>
<td>2</td>
<td>25.64</td>
<td>11.87</td>
</tr>
<tr>
<td>200002</td>
<td>SENN</td>
<td>220.00</td>
<td>2</td>
<td>42.76</td>
<td>20.72</td>
</tr>
<tr>
<td>200003</td>
<td>ROSEIR</td>
<td>220.00</td>
<td>2</td>
<td>56.6</td>
<td>34.3</td>
</tr>
<tr>
<td>207001</td>
<td>B.DAR2</td>
<td>230.00</td>
<td>1</td>
<td>63.53</td>
<td>30.762</td>
</tr>
<tr>
<td>207002</td>
<td>DB-MRKOS</td>
<td>230.00</td>
<td>1</td>
<td>16.12</td>
<td>8.22</td>
</tr>
<tr>
<td>207005</td>
<td>GONDAR2</td>
<td>230.00</td>
<td>1</td>
<td>37</td>
<td>18</td>
</tr>
<tr>
<td>207006</td>
<td>METEMA</td>
<td>230.00</td>
<td>1</td>
<td>4</td>
<td>1.96</td>
</tr>
<tr>
<td>207007</td>
<td>MOTA</td>
<td>230.00</td>
<td>1</td>
<td>3.45</td>
<td>1.7</td>
</tr>
<tr>
<td>207013</td>
<td>SUDAN-GADARE220.00</td>
<td>2</td>
<td>200</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>207014</td>
<td>SUDAN-RABAK220.00</td>
<td>2</td>
<td>202.8</td>
<td>99.58</td>
<td></td>
</tr>
<tr>
<td>208001</td>
<td>FINCHA</td>
<td>230.00</td>
<td>1</td>
<td>3.86</td>
<td>1.87</td>
</tr>
<tr>
<td>209001</td>
<td>ALAMATA</td>
<td>230.00</td>
<td>1</td>
<td>117.85</td>
<td>57.08</td>
</tr>
<tr>
<td>209004</td>
<td>MEKELE</td>
<td>230.00</td>
<td>1</td>
<td>170.12</td>
<td>82.24</td>
</tr>
<tr>
<td>209006</td>
<td>TEKEZE</td>
<td>230.00</td>
<td>1</td>
<td>0.78</td>
<td>0.2</td>
</tr>
<tr>
<td>807017</td>
<td>B.DAR2-2</td>
<td>15.0000</td>
<td>1</td>
<td>7.1505</td>
<td>3.4632</td>
</tr>
</tbody>
</table>
Appendix B

B. Matlab codes for system manipulation

B.1. Power flow solution based on N-R iteration and VSI calculation code

```matlab
%% Topology of the power system (for both areas)
give the numerical ordered bus number in order to communicate with %PSS/E
1=1, 201=2, 301=3, 107001=4, 107002=5, 200001=6, 200002=7, 200003=8,
200004=9, 207001=10, 207002=11, 207005=12, 207006=13, 207007=14,
207013=15, 207014=16, 208001=17, 209001=18, 209004=19, 209006=20,
407001=21, 407002=22, 407003=23, 807017=24, 900001=25, 900002=26,
907001=27, 907002=28, 908001=29, 909001=30
% Information about the bus matrix and line flow matrix is extracted
% from PSS/E directly as
% Program for Admittance And Impedance Bus Formation....
function Y = ybus(nbus)
% Returns Y
linedata = linedatas(nbus); % Calling Linedatas...
fb = line(:,1); % From bus number...
tb = line(:,2); % To bus number...
r = line(:,3); % Resistance, R...
x = line(:,4); % Reactance, X...
b = line(:,5); % Ground Admittance, B/2...
a = line(:,6); % Tap setting value..
z = r + 1i*x; % z matrix...
y = 1./z; % To get inverse of each element...
b = 1i*b; % Make B imaginary...
nb = 30; % No. of buses...
nl = length(fb); % No. of branches...
Y = zeros(nb,nb); % Initialise YBus...
% Formation of the Off Diagonal Elements...
for k = 1:nl
    Y(fb(k),tb(k)) = Y(fb(k),tb(k)) - y(k)/a(k);
    Y(tb(k),fb(k)) = Y(fb(k),tb(k));
end
% Formation of Diagonal Elements....
for m = 1:nb
    for n = 1:nl
        if fb(n) == m
            Y(m,m) = Y(m,m) + y(n)/(a(n)^2) + b(n);
        elseif tb(n) == m
            Y(m,m) = Y(m,m) + y(n) + b(n);
        end
    end
end
% Program for Bus Power Injections, Line, Power flows(p.u)and for %calculating voltage stability indices
function [Pf Qi Pg Qg Pl Ql] = loadflow(nb,V,del,BMva)
Y = ybusppg(nb); % Calling Ybus program..
lined = linedatas(nb); % Get linedats..
busd = busdatas(nb); % Get busdatas..
Vm = pol2rect(V,del); % Converting polar to rectangular..
Del = 180/pi*del; % Bus Voltage Angles in Degree...
fb = line(:,1); % To bus number...
tb = line(:,2); % To bus number...
nl = length(fb); % No. of Branches..
```

119
Pl = busd(:,7);
% Pl.. 
Ql = busd(:,8);
% QLi.. 
Iij = zeros(nb,nb);
% Bus Current Injections.. 
Si = zeros(nb,1);
% Bus Current Injections.. 
I = Y*Vm;
Im = abs(I);
Ia = angle(I);
% Bus Current Injections.. 
for m = 1:nl 
p = fb(m); q = tb(m);
Iij(p,q) = -(Vm(p) - Vm(q))*Y(p,q); % Y(m,n) = -y(m,n)..
Iij(q,p) = -Iij(p,q);
end
Iijm = abs(Iij);
Iija = angle(Iij); 
% Line Power Flows.. 
for m = 1:nb 
for n = 1:nb 
if m ~= n 
Sij(m,n) = Vm(m)*conj(Iij(m,n))*BMva;
end
end
end
Pij = real(Sij);
Qij = imag(Sij);
% Line Losses.. 
Lij = zeros(nl,1);
for m = 1:nl 
p = fb(m); q = tb(m);
Lij(m) = Sij(p,q) + Sij(q,p);
end
Lpij = real(Lij);
Lqij = imag(Lij);
% Bus Power Injections.. 
for i = 1:nb 
for k = 1:nb 
Si(i) = Si(i) + conj(Vm(i))* Vm(k)*Y(i,k)*BMva;
end
end
Pi = real(Si);
Qg = -imag(Si);
Pg = Pi+P1;
Qg = Q1+Q1;
% voltage stability index calculation program for both areas
theta=0; den=0; Lmn=0; Qj=0; basemva=100; LQP=0; FVSI=0; NVSI=0;
for k = 1 : nb 
theta(k) = atand(x(k)/r(k)); %transmission line angle
del(k) =Del(fb(k)) - Del(tb(k)); %bus voltage angle
den(k) = (V(fb(k)))*sind(theta(k) - del(k)))^2;
Qj(k) = (imag(Si(k)))/basemva);
Lnm(k) = abs(4*x(k)*Qj(k)/den(k)); % line voltage stability index
den(k) = V(fb(k))]*(z(k))^2)*Qj(k(k>0))/den(k)); %fast voltage 
Fvsi(k) =abs(4*((z(k))^2)*Qj(k>0))/den(k)); %fast voltage
%stability index
Pi(k) = real(Si(k));
a(k)=x(k)/(V(fb(k))^2));
\[ b(k) = \frac{x(k)}{(2 \cdot V(fb(k))^2)} \cdot \pi(k) + Qj(k); \]
\[ LQP(k) = \text{abs}(4 \cdot a(k) \cdot b(k)); \]
\[ a(k) = x(k) \cdot \sqrt{(\pi(k)^2 + (Qj(k))^2)}; \]
\[ b(k) = (2 \cdot Qj(k) \cdot x(k) - (V(k))^2); \]
\[ NVSI(k) = \text{abs}(2 \cdot a(k) / (b(k))); \]
\[ \text{fprintf('  \%g', k), fprintf('  \%2g', fb(k)), fprintf('  \%4g', tb(k)), fprintf('  \%12g', Lmn(k)), fprintf('  \%13g', Fvsi(k)), fprintf('  \%16g', LQP(k)), fprintf('  \%20f\n', NVSI(k));} \]

% Program for Newton-Raphson Load Flow Analysis...
clear all; close all; clc
nbus = 30;
Y = ybus(nbus);
busd = busdata(30); % Calling busdata...
BMva = 100; % Base MVA...
bus = busd(:,1); % Bus Number...
type = busd(:,2); % Type of Bus 1-Slack, 2-PV, 3-PQ...
V = busd(:,3); % Specified Voltage...
del = busd(:,4); % Voltage Angle...
Pg = busd(:,5)/BMva; % PGI...
Qg = busd(:,6)/BMva; % QGI...
Pl = busd(:,7)/BMva; % PLi...
Ql = busd(:,8)/BMva; % QLI...
Qmin = busd(:,9)/BMva; % Minimum Reactive Power Limit...
Qmax = busd(:,10)/BMva; % Maximum Reactive Power Limit...
P = Pg - Pl; % Pi = PGI - PLi...
Q = Qg - Ql; % Qi = QGI - QLI...
Psp = P; % P Specified...
Qsp = Q; % Q Specified...
G = real(Y); % Conductance matrix...
B = imag(Y); % Susceptance matrix...

\[ \text{pv} = \text{find(type == 2)}; % PV Buses...
\text{pq} = \text{find(type == 3)}; % PQ Buses...
npv = \text{length(pv)}; % No. of PV buses...
npq = \text{length(pq)}; % No. of PQ buses...
\]
Tol = 1;
Iter = 1;
while (Tol > 1e-5) % Iteration starting...
P = zeros(nbus,1);
Q = zeros(nbus,1);
\[ \text{for} \ i = 1:nbus \]
\[ \text{for} \ k = 1:nbus \]
\[ P(i) = P(i) + V(i) \cdot V(k) \cdot (G(i,k) \cdot \cos(\text{del}(i)-\text{del}(k))) + B(i,k) \cdot \sin(\text{del}(i)-\text{del}(k))); \]
\[ Q(i) = Q(i) + V(i) \cdot V(k) \cdot (G(i,k) \cdot \sin(\text{del}(i)-\text{del}(k))) - B(i,k) \cdot \cos(\text{del}(i)-\text{del}(k))); \]
\end{end}
\]
\[ \text{dp}(k) = Psp-P; \]
\[ \text{dq}(k) = Qsp-Q; \]
\[ k = 1; \]
\[ \text{d}(q) = \text{zeros(npq,1)}; \]
\[ \text{for} \ i = 1:nbus \]
\[ \text{if} \ \text{type}(i) == 3 \]
\[ \text{d}(Q, k, 1) = \text{d}(q)(i); \]
\[ k = k+1; \]
\end{end}
\[ dP = dP_a(2:nbus); \]
\[ M = [dP; dQ]; \quad \text{% Mismatch Vector} \]
\[ \% Jacobian \]
\[ \% J1 - Derivative of Real Power Injections with Angles.. \]
\[ J1 = zeros(nb - 1, nb - 1); \]
\[ \text{for } i = 1:(nb - 1) \]
\[ m = i+1; \]
\[ \text{for } k = 1:(nb - 1) \]
\[ n = k+1; \]
\[ \text{if } n == m \]
\[ \text{for } n = 1:nbus \]
\[ J1(i,k) = J1(i,k) + V(m)*V(n)*(-G(m,n)*\sin(\Delta m) + B(m,n)*\cos(\Delta m)); \]
\[ \text{end} \]
\[ J1(i,k) = J1(i,k) - V(m)^2*B(m,m); \]
\[ \text{else} \]
\[ J1(i,k) = V(m)*V(n)*(G(m,n)*\sin(\Delta m) - B(m,n)*\cos(\Delta m)); \]
\[ \text{end} \]
\[ \text{end} \]
\[ \text{end} \]
\[ \% J2 - Derivative of Real Power Injections with V.. \]
\[ J2 = zeros(nb - 1,npq); \]
\[ \text{for } i = 1:(nb - 1) \]
\[ m = i+1; \]
\[ \text{for } k = 1:npq \]
\[ n = pq(k); \]
\[ \text{if } n == m \]
\[ \text{for } n = 1:nbus \]
\[ J2(i,k) = J2(i,k) + V(n)*(G(m,n)*\cos(\Delta m) + B(m,n)*\sin(\Delta m)); \]
\[ \text{end} \]
\[ J2(i,k) = J2(i,k) + V(m)*G(m,m); \]
\[ \text{else} \]
\[ J2(i,k) = V(m)*(G(m,n)*\cos(\Delta m) - B(m,n)*\sin(\Delta m)); \]
\[ \text{end} \]
\[ \text{end} \]
\[ \text{end} \]
\[ \% J3 - Derivative of Reactive Power Injections with Angles.. \]
\[ J3 = zeros(npq,nb - 1); \]
\[ \text{for } i = 1:npq \]
\[ m = pq(i); \]
\[ \text{for } k = 1:(nb - 1) \]
\[ n = k+1; \]
\[ \text{if } n == m \]
\[ \text{for } n = 1:nbus \]
\[ J3(i,k) = J3(i,k) + V(m)*(V(n)*(G(m,n)*\cos(\Delta m) + B(m,n)*\sin(\Delta m))); \]
\[ \text{end} \]
\[ J3(i,k) = J3(i,k) - V(m)^2*G(m,m); \]
\[ \text{else} \]
\[ J3(i,k) = V(m)*V(n)*(-G(m,n)*\cos(\Delta m) - B(m,n)*\sin(\Delta m)); \]
\[ \text{end} \]
\[ \text{end} \]
\[ \text{end} \]
\[ \% J4 - Derivative of Reactive Power Injections with V.. \]
J4 = zeros(npq,npq);
for i = 1:npq
    m = pq(i);
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
                J4(i,k) = J4(i,k) + V(n)*(G(m,n)*sin(del(m) - del(n)) - B(m,n)*cos(del(m) - del(n)));
            end
            J4(i,k) = J4(i,k) - V(m)*B(m,m);
        else
            J4(i,k) = V(m)*(G(m,n)*sin(del(m) - del(n)) - B(m,n)*cos(del(m) - del(n)));
        end
    end
end
J = [J1 J2; J3 J4]; % Jacobian Matrix..
X = inv(J)*M; % Correction Vector
dTh = X(1:nbus-1); % Change in Voltage Angle..
dV = X(nbus:end); % Change in Voltage Magnitude..
% Updating State Vectors..
del(2:nbus) = dTh + del(2:nbus); % Voltage Angle..
k = 1;
for i = 2:nbus
    if type(i) == 3
        V(i) = dV(k) + V(i); % Voltage Magnitude..
k = k+1;
    end
end
Iter = Iter + 1;
Tol = max(abs(M)); % Tolerance..
end
loadflow(nbus,V,del,BMva); % Calling Loadflow.m..

B.2. Source code for internal current controller step response

% Objective : Calculating Transient response parameters of the designed current controller
num=[125000000];
den=[1 50000 125000000];
G=tf(num,den);
step(G);
ylabel ('dq- currents amplitude');
xlabel ('time');
title ('step response of the inner current controller');

B.3. Source code for DC voltage controller step response

% Objective : Calculating Transient step response parameters of the designed direct voltage controller
num=[0.00036 1 ];
den=[0.000000000179 0.00000432 0.00036 1];
G=tf (num,den);
step(G);
ylabel ('dc voltage amplitude');
xlabel ('time');
title ('step response of the DC controller');
Appendix C

C. PI controller tuning techniques manipulation

C.1. Modulus Optimum criterion

The open loop transfer function of internal current controller from Figure 4.18 is given by

\[ G_{cc,ol}(s) = K_p \left( \frac{1 + s T_i}{s T_i} \right) \left( \frac{1}{1 + s T_a} \right) \frac{1}{R} \left( \frac{1}{1 + s T} \right) \]  

(C.C.1)

The time constant \( T_i \) of the PI controller is defined so that \( T_i = \tau \) based on this criterion. So now the equation (C.1) becomes

\[ G_{cc,ol}(s) = \frac{K_p}{s \tau \left( 1 + s T_a \right)} \]  

(C.C.2)

The closed loop transfer function of the internal current controller becomes

\[ G_{cc,cl}(s) = -\frac{K_p}{s T_a \left( 1 + s T_a \right)} \]

\[ G_{cc,cl}(s) = \frac{K_p}{s R \left( 1 + s T_a \right)} \]

\[ G_{cc,cl}(s) = \frac{K_p}{s R \left( 2 + s T_a \right)} \]

\[ G_{cc,cl}(s) = \frac{K_p}{s R \left( 3 + s T_a \right)} \]

(C.C.3)

The damping constant \( \zeta \) of the second order equation is required to have the value \( \zeta = 1/\sqrt{2} \) for the system to have optimum over shoot and rise time. From the Equation (C.3) above

\[ \omega_n = \sqrt{\frac{K_p}{T_a \tau}} \]  

(C.C.4)
\[ \zeta = \frac{1}{2} \sqrt{\frac{R \tau}{K_p T_a}} \]  
\[ K_p = \frac{R \tau}{4 \zeta^2 T_a} = \frac{\tau R}{2 T_a} \]  
\[ \tan^{-1} \left( \sqrt{\frac{T_e}{T_i}} \right) - \tan^{-1} \left( \sqrt{\frac{T_{eq}}{T_i}} \right) = 0 \]  
\[ \omega_c = \frac{1}{\sqrt{T_i T_{eq}}} \]  
\[ \phi_m = \tan^{-1} \left( \sqrt{\frac{T_e}{T_{eq}}} \right) - \tan^{-1} \left( \sqrt{\frac{T_{eq}}{T_i}} \right) \]  
\[ \tan^{-1} \left( \sqrt{\frac{T_i}{T_{eq}}} \right) = \theta \text{ and also } \tan^{-1} \left( \sqrt{\frac{T_{eq}}{T_i}} \right) = 90 - \theta \]
In terms of $\theta$ becomes,

$$\phi_m = \theta - (90 - \theta) = 2\theta - 90$$  \hspace{0.5cm} (C.C.13)

From Equation (C.13) above

$$\sin \phi_m = \sin(2\theta - 90) = -\cos 2\theta$$  \hspace{0.5cm} (C.C.14)

From half-angle trigonometric equations

$$\cos \theta = \sqrt{\frac{1 + \cos 2\theta}{2}}$$
$$\sin \theta = \sqrt{\frac{1 - \cos 2\theta}{2}}$$  \hspace{0.5cm} (C.C.15)
$$\tan \theta = \frac{1 - \cos 2\theta}{1 + \cos 2\theta}$$

From the Equations (C.11), (C.13), (C.14), and (C.15),

$$\tan \theta = \frac{T_i}{T_{eq}} = \frac{1 - \cos 2\theta}{1 + \cos 2\theta} = \frac{1 + \sin \phi_m}{1 - \sin \phi_m} = a$$  \hspace{0.5cm} (C.C.16)

The above Equation (C.16) gives the integral time constant $T_i$ of,

$$T_i = a^2 T_{eq}$$  \hspace{0.5cm} (C.C.17)

The tuning criteria according to symmetrical optimum is obtained using the Nyquist criteria of stability, $|G_{dvc,ol}(j\omega)| = 1$

$$\left| G_{dvc,ol}(s) = K_p \left( \frac{1 + sT_i}{sT_i} \right) \left( \frac{K}{1 + sT_{eq}} \right) \left( \frac{1}{sC} \right) \right| = 1$$  \hspace{0.5cm} (C.C.18)

Solving the Equation (C.18) and substituting Equation (C.17) gives the proportional gain $K_p$ as,

$$K_p = \frac{C}{aKT_{eq}}$$  \hspace{0.5cm} (C.C.19)
APPENDICES

Appendix D

D. Sample outputs and Maps

D.1. Newton Raphson power flow solution
D.2. Dynamic outputs when fault initiated on different buses

Figure D.1 Tis-Abay II generator electrical power for fault on Rabak bus

Figure D.2 Tekeze generator rotor angle for fault on Rabak bus
Figure D.3 1 Location of proposed transmission line routes between Ethiopia and Sudan on planning phase [4]