

**ACHIEVING FREQUENCY STABILITY THROUGH
CONTROLLED ACTIVE POWER INJECTION USING
ENERGY STORAGE SYSTEMS**

Chamindu Devin Aluthge

198131A

Degree of Master of Science by Research

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

November 2021

**ACHIEVING FREQUENCY STABILITY THROUGH
CONTROLLED ACTIVE POWER INJECTION USING
ENERGY STORAGE SYSTEMS**

Chamindu Devin Aluthge

198131A

Thesis submitted in fulfilment of the requirements for the degree of Master
of Science by Research

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

November 2021

Declaration

I declare that this is my own work, and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to the University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature:

Date:

The above candidate has carried out research for the Masters/MPhil/PhD thesis/ Dissertation under my supervision.

Name of the supervisor: Prof. K T M U Hemapala

Signature of the supervisor:

Date

Name of the supervisor: Prof. J R Lucas

Signature of the supervisor:

Date

Abstract

As solar Photovoltaic solar generation increases in the power system the conventional generators are being replaced or lose their dominance. Therefore, the resultant inertia of the system reduces. Due to this reason, in case of a large machine tripping in the system, or a line being tripped, the frequency deviation in a unit time increases compared to the frequency deviation in a system without high solar penetration. By using a fast active power injector to the system, such frequency deviation could be mitigated in a high solar power penetrated system. An energy storage system of such magnitude is not economically possible in the Sri Lankan context.

During a fault in the system, Under Frequency Load Shedding (UFLS) occurs in the feeders and 33 kV feeders are disconnected from the grid. A control mechanism has been developed to be used as an Uninterrupted Power Supply for the feeder. so that the feeder's voltage and frequency are kept intact until the system is restored. By incorporating the said method, the selected feeder will not undergo any power interruptions during UFLS, as the fast active power injector which has been developed will cater to supplying the required power to the feeder. The fast active power injection method has been developed by combining both the virtual synchronous generator concept and the indirect current control pulse width modulation technique.

Further, the research also addresses the selection criteria of the Battery Energy Storage System (BESS) to be implemented when developing the fast active power injector.

The study has shown that a unity power factor 50 MW BESS can stop UFLS occurring in case of the tripping of a medium scale power plant or line tripping. and other common system faults. As such a BESS would not be economical, it also shows that a 13.7 MW, 3.88 MWh of BESS would be sufficient to prevent UFLS operating 90% of the time at night peak and day peak, with the UFLS operating probability during the off peak being less than 0.1%. Thus, the study has also shown that depleting the energy storage during the day to account for solar fluctuations would be to great advantage, with building up the battery energy reserves before night time.

Keywords: Battery Energy Storage System, Solar power penetration, Fast active power injection, Under frequency load shedding, Low inertia power system, Virtual synchronous generator.

Acknowledgment

Foremost, I would like to express my gratitude to my supervisors Prof. Udayanga Hemapala and Prof. Rohan Lucas for their guidance and support throughout my research. It's my pleasure to acknowledge all the other academic staff members of the Electrical Engineering Department of the University of Moratuwa for their valuable advice and support which were valuable in achieving project goals.

My special thanks go to Eng. Channa Kulasekara for enlightening me on the current Sri Lankan power system and PSS/E. The knowledge which I gained helped me greatly throughout the research.

I extend my special gratitude to my father Eng. Janaka Aluthge for providing with me with necessary data and information to make my research a success. Furthermore, I am very much thankful for his insight of the national Power System which was a great benefit when identifying the problems at hand within the Power System.

Furthermore, I would like to extend my gratitude to my mother, Dr. Kumudini Gonsalkorale and my sister Dinara Aluthge for their encouragement, understanding and patience throughout my academic pursuit.

Content

Declaration.....	ii
Abstract.....	iii
Acknowledgment.....	iv
Content.....	v
List of Figures.....	vii
List of Tables.....	x
List of Abbreviations.....	xi
Chapter 1. Introduction.....	1
1.1. Project Objectives and Scope.....	1
1.2. Motivation.....	2
1.3. Terms and Definitions.....	3
1.4. Thesis Outline.....	3
Chapter 2. Literature Review.....	5
2.1. Installed BESS around the world.....	5
2.2. Li-Ion Battery Energy System Storage Characteristics.....	7
2.3. Grid Tied Inverters.....	11
2.4. Virtual Synchronous Generator (VSG).....	16
2.5. Methods of Fast Power Injection.....	19
2.6. Cost and Capacity Selection Methods of BESS.....	22
2.7. Research gap from Literature Review.....	25
Chapter 3. Methodology.....	27
3.1. Simulations conducted on the Sri Lankan Power System.....	27
3.1.1. Simulations on the National System with Solar Power penetration and rejection of 275 MW.....	28
3.1.2. Simulations on the National System with Solar Power penetration, rejection of 275 MW and 50 MW of fast active power generation.....	29
3.1.3. Simulations on the National System with Solar Power penetration, rejection of 60 MW and 50 MW of fast active power generation.....	31
3.1.4. PSS/E 50 MW BESS model parameters.....	33
3.2. Modelling a 33 kV feeder with fast active with fast active power injection.....	34
3.2.1. BESS modeled as DC Voltage source with VSI.....	39
3.2.2. Sinusoidal PWM inverter connected with VSG.....	39
3.2.3. Indirect current controlling PWM with VSG.....	40
3.2.4. Indirect current controlling PWM with VSG after amending.....	41
3.2.5. Proposed Active Power Injector to the 33 kV feeder.....	42

3.3.	Determination of BESS capacity and cost	43
Chapter 4.	Analysis.....	45
4.1.	Simulations conducted on the Sri Lankan Power System.....	45
4.1.1.	Simulations on the National System with Solar Power penetration and rejection of 275 MW.....	45
4.1.2.	Simulations on the National System with Solar Power penetration, rejection of 275 MW and 50 MW of fast active power generation	50
4.1.3.	Simulations on the National System with Solar Power penetration, rejection of 60 MW and 50 MW of fast active power generation	51
4.1.4.	Simulation and calculations analysis	52
4.2.	Modelling a 33 kV feeder with fast active power injection	53
4.2.1.	BESS model as DC voltage source with VSI	55
4.2.2.	Sinusoidal PWM inverter connected with VSG	57
4.2.3.	Indirect current controlling PWN with VSG	63
4.2.4.	Indirect current controlling PWM with VSG after amending	66
4.2.5.	Proposed Active Power Injector to the 33 kV feeder	69
4.2.6.	Summary of the simulation results	70
4.3.	Determination of BESS cost and Capacity	70
Chapter 5.	Conclusions.....	78
References	80

List of Figures

Figure 2-1 BESS voltage model	10
Figure 2-2 Discharging Characteristics of a Battery.....	10
Figure 2-3 The number of months of usage vs. SOH in different temperatures.....	11
Figure 2-4 Control system block diagram for the proposed indirect current control algorithm.	12
Figure 2-5 Conventional Grid tied inverter schematic	12
Figure 2-6 Vector notation.....	13
Figure 2-7 Geometric relationship between dq0 and alpha-beta-0.....	15
Figure 2-8 Increase in frequency changes in Electricity Reliability Council of Texas (ERCOT) connection due to generation loss	16
Figure 2-9 VSG Anatomy.....	18
Figure 2-10 System configuration Supercapacitor energy storage design.....	21
Figure 2-11 Methods of Frequency response in RES	22
Figure 2-12 Four-hour BESS cost projection	23
Figure 2-13 Inflation rate in the USA.....	23
Figure 2-14 Algorithm for selecting the optimal BESS.....	24
Figure 3-1 Summary of the methodology	27
Figure 3-2 Sri Lankan Transmission Network.....	28
Figure 3-3 National grid showing tripped power station and particular generator.....	29
Figure 3-4 Orientation of the BESS in the National Grid.....	30
Figure 3-5 – Kolonnawa Grid Substation showing the placement of BESS	30
Figure 3-6 National Grid with 60MW Generation rejected.....	31
Figure 3-7 Samanalawewa Power Station with 2 × 60MW generators	31
Figure 3-8 Algorithm to determine angle deviation with solar power replaced by conventional generation.....	32
Figure 3-9 Generator model for PSS/E simulation.....	33
Figure 3-10 Model of auxiliary system of battery equivalent generator	33
Figure 3-11 Modelling of system downstream of national grid	34
Figure 3-12 Map of Ratmalana Grid showing outgoing feeders	37
Figure 3-13 PSCAD model developed for the system studied	38
Figure 3-14 PWM signal generator model on PSCAD.....	39
Figure 3-15 Model of the developed Virtual Synchronous Generator	40

Figure 3-16 VSG orientation initially developed for fast active power injection.....	40
Figure 3-17 Proposed Indirect current controlling PWM with VSG.....	41
Figure 3-18 Amended Indirect current controlling PWM with VSG	42
Figure 3-19 Algorithm to determine the cost and capacity of the BESS.....	43
Figure 3-20 Ampere-load report for a particular date.....	44
Figure 4-1 Simulation results of hydro maximum, balanced and thermal maximum scenarios	45
Figure 4-2 Recovery of the frequency in the system	46
Figure 4-3 frequency response when 275 MW of generation is rejected	50
Figure 4-4 Frequency response with rejection of 60 MW and 50 MW of unity power factor generator	51
Figure 4-5 Power at the Kolonnawa grid with battery bank is installed.....	52
Figure 4-6 Response of 33 kV feeder with fast active power injection.....	53
Figure 4-7 Output power of the BESS	54
Figure 4-8 (a). Phasor voltage (11 kV) fluctuation during the transition. (b). Phasor voltage (11 kV) fluctuation during steady state. (c). Phasor voltage (400 V) fluctuation during transition.	56
Figure 4-9 Frequency response of the feeder during transition between the grid and the BESS	56
Figure 4-10 Frequency fluctuation when VSG incorporated with the Voltage Source Inverter	57
Figure 4-11 Frequency obtaining method PSCAD.....	57
Figure 4-12 Fast Fourier Transformation algorithm to determine the frequency response.....	59
Figure 4-13 Frequency response obtained by DFT.....	59
Figure 4-14 Change of Voltage Harmonic Amplitudes throughout the simulation.....	60
Figure 4-15 Fundamental Voltage amplitude of the three phases	61
Figure 4-16 Voltage waveforms after the reduction of inductance	61
Figure 4-17 Frequency response	62
Figure 4-18 Voltage harmonics amplitude variation	62
Figure 4-19 Fundamental phasor Voltage amplitude fluctuation.....	63
Figure 4-20 Total Harmonic Distortion percentage of the three phases	63
Figure 4-21 Voltage fluctuation throughout the simulation	64
Figure 4-22 Angular Velocity response	64
Figure 4-23 Voltage fluctuation during the transition period	65

Figure 4-24 Parameters of the integral block of the MATLAB simulink.....	66
Figure 4-25 Phasor Voltage waveform	67
Figure 4-26 Angular Frequency of the feeder.....	67
Figure 4-27 Enlarged Voltage waveform during transition.....	68
Figure 4-28 Voltage fluctuation without the VSG.....	68
Figure 4-29 33 kV Phasor Voltage fluctuation	69
Figure 4-30 33 kV Enlarged voltage waveform during transition.....	69
Figure 4-31 The graphs are associated with discharging the BESS to 100% (a). Chosen BESS capacity vs the installation cost recovery time period. (b). Chosen BESS capacity vs remaining cycles after the cost is recovered.	74
Figure 4-32 Unserved Energy Probability	75
Figure 4-33 The graphs are associated with discharging the BESS to a minimum of 3882 kWh (a). Chosen BESS capacity vs the installation cost recovery time period. (b). Chosen BESS capacity vs remaining cycles after the cost is recovered.....	76
Figure 4-34 Earnings from BESS installation	77

List of Tables

Table 2-1 DoD vs. Discharge life cycles of Li-Ion Batteries	9
Table 2-2 Modes of VSGs and their features.....	18
Table 3-1 Inputs used in the REECAU1 and REPCAU1 models.....	33
Table 3-2 Distribution of solar integration to feeder	35
Table 3-3 Bulk customers, their capacity and solar hosting capacity	35
Table 3-4 Parameters used for substations in the model.....	36
Table 3-5 Places where var compensators are located.....	42
Table 4-1 Summary of dispatch prior to the fault.....	48
Table 4-2 Summary of bulk solar generation	49
Table 4-3 Changes when BESS is not placed.....	53
Table 4-4 Changes in the presence of BESS	53
Table 4-5 Feeder interruptions with load shed and unserved energy	55
Table 4-6 All UFLS occurred in the Ratmalana Grid Substation.....	71
Table 4-7 Details of the recently occurred Total Failures in Sri Lanka since the Commissioning of Lakvijaya Power Station	72
Table 4-8 Comparison between the chosen BESS.....	73

List of Abbreviations

BESS	:	Battery Energy System Storage
CEB	:	Ceylon Electricity Board
DoD	:	Depth of Discharge
DFT	:	Discrete Fourier Transformation
ESS	:	Energy System Storage
FFT	:	Fast Fourier Transformation
PV	:	Photovoltaic
PWM	:	Pulse Width Modulation
SoC	:	State of Charge
UFLS	:	Under Frequency Load Shedding
VSG	:	Virtual Synchronous Generator