

LB/TH/46/2025
TH6051

**HYBRID VOLTAGE SAG MITIGATION FOR RENEWABLE
INTEGRATED WEAK DISTRIBUTION SYSTEMS USING A
LOAD MANAGEMENT AND ROBUST INVERTER CONTROL
APPROACH**

Kurukulasuriya Tharindu Stephan Fernando

(218945K)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

January 2024

**HYBRID VOLTAGE SAG MITIGATION FOR RENEWABLE
INTEGRATED WEAK DISTRIBUTION SYSTEMS USING A
LOAD MANAGEMENT AND ROBUST INVERTER CONTROL
APPROACH**

Kurukulasuriya Tharindu Stephan Fernando

(218945K)

Dissertation submitted in partial fulfilment of the requirements for the degree Master
of Science

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

January 2024

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 dissertation, 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: 28-06-2024

The above candidate has carried out research for the Masters dissertation under my supervision.

Name of Supervisor: Prof.Lidula N.Widanagama Arachchige

Signature of the Supervisor:

Date:

Name of Supervisor: Dr. H. M. Wijekoon Banda

Signature of the Supervisor:

Date:

DEDICATION

To my parents, my siblings, and my beloved wife

ACKNOWLEDGEMENT

First and foremost, I extend my sincere gratitude to Prof. Lidula N. Widanagama Arachchige, my internal supervisor, for her unwavering guidance and encouragement during the entire research.

Secondly, I express my sincere appreciation for the support given by my external supervisor, Dr. H. M. Wijekoon Banda. I would like to acknowledge his expertise and guidance, which significantly contributed to the success of this research.

I would like to express my gratitude to the academic staff of the Department of Electrical Engineering, Faculty of Engineering, the University of Moratuwa, Sri Lanka. Their insightful comments and unwavering support during the presentations have been invaluable and greatly appreciated.

I express gratitude to the CEB management for allowing me to use the data. Special thanks to Eng. Dinesh Dissanayake – CE (CPCDP-CEB), Eng. Isuru Kumarasinghe - PM (CPCDP-CEB), Eng. Dimuthu Wijewickrama - EE (CPCDP-CEB), and Eng. Dimalka Karunajeewa - EE (CPCDP-CEB) for their unwavering support.

Finally, I express my heartfelt thanks to my wife, Dr. Omalka Fonseka, my parents, and family members for their understanding and support in numerous ways, enabling me to consistently reach and surpass my research goals.

ABSTRACT

The world is rapidly transitioning towards renewable energy sources, with Inverter-Based Resources (IBRs) emerging as key power sources for future distribution systems. The electrification of rural and remote areas is progressing rapidly, bringing power to previously underserved locations. However, remote distribution networks face challenges, with one significant issue being lower fault levels.

Weak distribution networks in these remote areas give rise to several problems, with voltage sag being a primary concern. Voltage sag, often caused by sudden changes in load or faults on the grid, poses a particular threat to process controllers, PLCs, variable speed drives, robots, data processing and control equipment, in particular, are highly sensitive to voltage sags, risking potential data loss. The simultaneous operation of large machines can further exacerbate the challenges associated with low fault levels.

In the context of IBR-based distribution systems, vulnerability to unbalanced voltage sag is a specific concern. The Synchronous Reference Frame-Phase Locked Loop (SRF-PLL) may incorrectly estimate the positive sequence voltage component, resulting in a loss of controllability for the three-phase inverter. A grid-connected power converter, in particular, is sensitive to voltage disturbances, as its control system may lose controllability under such distorted operating conditions. This may lead to damage the inverter, as it is unsuitable for injecting unbalanced currents and lacks a specific control loop for negative-sequence current components. The abrupt disconnection of inverters can result in voltage collapse, frequency instability, and synchronous angle instability.

This research has addressed these challenges by developing a voltage sag mitigation technique for weak distribution systems. A robust inverter control system capable of maintaining connectivity during voltage sag events and a pre-assigned priority load management scheme to effectively mitigate voltage sag were designed. Performance evaluation revealed the success in mitigating voltage sag by applying the proposed techniques when integrating IBR to weak grids.

Keywords: Inverter-Based Resources, Large Machine Operation, Voltage Sag, Weak Distribution Grid.

TABLE OF CONTENTS

HYBRID VOLTAGE SAG MITIGATION FOR RENEWABLE INTEGRATED WEAK DISTRIBUTION SYSTEMS USING A LOAD MANAGEMENT AND ROBUST INVERTER CONTROL APPROACH.....	1
DECLARATION	i
DEDICATION	ii
ACKNOWLEDGEMENT	iii
ABSTRACT	iv
Table of Contents	v
List of Figures	viii
List of Tables.....	x
List of Abbreviations.....	xi
List of Appendices	xii
Chapter 1	1
1. INTRODUCTION	1
Leveraging Inverter-Based Resources for Sustainability.....	1
Voltage Sag	1
Main Causes of Voltage Sag	2
1.1.1 Connection of Large Inductive Loads.....	2
1.1.2 Sudden Overloading of Circuits.....	3
1.1.3 Network Faults	3
Low Fault Level Grid Characteristics	3
1.1.4 Large Inductive Machine Operation	4
1.1.5 Simultaneous Operation of Machines	5
Problem Statement	5
Scope	6
Objectives.....	6
Chapter 2	8
2. LITERATURE REVIEW.....	8
Conventional Phase Locked Loop	8
Conventional Inverter Control System Drawbacks.....	10

Decoupled Double Synchronous Reference Frame -Phase Locked Loop (DDSRF-PLL)	12
Flexible Positive and Negative Sequence Control (FPNSC)	13
Inverter Controller during Voltage Sag	14
Estimation of Over Current Limits	14
Removal of Coupling Effects in DDSRF-PLL	16
Loads Behaviour during Voltage Sag	16
Equipment Sensitivity for Voltage Sag.....	18
Chapter 3	21
3. METHODOLOGY.....	21
General Illustration.....	21
Chapter 4	23
4. MODELING APPROACH	23
Inverter Unbalanced Operation	23
4.1.1 Decoupled Double Synchronous Reference Frame -Phase Locked Loop (DDSRF-PLL).....	23
4.1.2 Flexible Positive and Negative Sequence Control (FPNSC)	26
Load Management System.....	26
4.1.3 Sag Detection for Load Management Scheme.....	26
4.1.4 Load Prioritization Scheme.....	27
4.1.5 Load Shedding Scheme.....	31
4.1.6 Typical Response Time.....	32
4.1.7 Restoration Scheme.....	33
Integrated System Operation.....	34
Chapter 5	36
5. UNBALANCED INVERTER OPERATION.....	36
Unbalanced Inverter Operation	36
Summary	38
Chapter 6	39
6. COST OF IMPLEMENTATION.....	39
Typical Implementation Cost.....	39
Chapter 7	41

7. IMPLEMENTATION OF THE PROPOSED METHOD.....	41
Case Study 1.....	41
7.1.1 Summary	45
7.1.2 Techno-Economic Analysis	46
Case Study 2.....	48
7.1.3 Load Management Scheme Operation	48
7.1.4 Inverter Unbalanced Operation	51
Chapter 8	55
8. CONCLUSION	55
Future Improvements	57
9. REFERENCES.....	59

Appendix - A: ETAP simulation reports for Case Study 1 with various loading on the distribution system

LIST OF FIGURES

Figure 1-1 Voltage sag due to large machine operation [2]	2
Figure 1-2 Different type of voltage sags due to faults, (a) Three-phase to ground fault through an impedance, (b) Phase to phase fault, (c) Single phase to ground fault, (d) Phase to phase to ground fault.	4
Figure 1-3 Voltage sag change with PCC fault level	5
Figure 2-1 Unbalanced Voltage	9
Figure 2-2 Sequence components of unbalanced voltage [8]	9
Figure 2-3 Phase angle during the unbalanced period [8].	9
Figure 2-4 Incorrectly analyzed sequence components [8]	10
Figure 2-5 The magnetic flux of 5.5 kW induction motor with 85% rated load. The magnetic flux of normal operation [16]	17
Figure 2-6 The magnetic flux at half cycle since the 30% voltage sag [16].	18
Figure 2-7 Old CBEMA and ITIC curves [17]	19
Figure 2-8 New ITI (CBEMA) curve (2000) [18]	20
Figure 3-1 Flowchart of Inverter operation mode to mitigate unbalanced voltage sag	21
Figure 3-2 Flowchart of Load Management System	22
Figure 4-1 Positive sequence component during the unbalanced voltage sag	23
Figure 4-2 Negative sequence component during the unbalanced voltage sag	24
Figure 4-3 Grid voltages during unbalance	24
Figure 4-4 Phase angle during the unbalance	25
Figure 4-5 Detected dq signals for the positive sequence component	25
Figure 4-6 Detected dq signals for the negative sequence component	25
Figure 4-7 Block diagram of grid voltage decomposition	26
Figure 4-8 Load management scheme detection technique	27
Figure 4-9 Load prioritization scheme	28
Figure 4-10 Implementation of proposed load management scheme	29
Figure 4-11 Implementation of proposed load management scheme	29
Figure 4-12 Load priority level selector interface	30
Figure 5-1 Unbalanced fault	36
Figure 5-2 Matlab model for the general system	37

Figure 5-3 The unbalance occurrence with absent inverter support	37
Figure 5-4 The unbalance occurrence with inverter support	38
Figure 7-1 ETAP model for case study 1	41
Figure 7-2 Operating a large induction machine within a distribution system under light load condition	42
Figure 7-3 Operating a large induction machine within a distribution system under 50% load condition	42
Figure 7-4 Load management scheme operation	43
Figure 7-5 Load restoration execution	44
Figure 7-6 Without load management scheme	46
Figure 7-7 Geographical view of the distribution system (Location: Pahala Bomiriya)	48
Figure 7-8 Matlab model of the selected distribution system	50
Figure 7-9 Voltage at the load PCC	50
Figure 7-10 Voltage recovery by using the LMS	51
Figure 7-11 Unbalanced fault at the selected distribution system	51
Figure 7-12 Inverter 1 terminal voltage without inverter support	52
Figure 7-13 Phase voltages during the voltage sag with unbalanced support from the inverter 1	52
Figure 7-14 RMS phase voltages during the voltage sag without unbalanced support from the inverter 1	52
Figure 7-15 RMS phase voltages during the voltage sag with unbalanced support from the inverter 1	53
Figure 7-16 Inverter current injection during voltage unbalance	54

LIST OF TABLES

Table 4-1 Load shedding scheme	32
Table 4-2 Typical latencies of communication protocols [25]	33
Table 4-3 Restoration Plan	33
Table 6-1 Typical System Implementation Component Cost	39
Table 7-1 Load shedding scheme operation	43
Table 7-2 Load restoration execution	44
Table 7-3 Economic analysis for case 1	47
Table 7-4 System data	48
Table 7-5 Consumer details of the selected system	49

LIST OF ABBREVIATIONS

Abbreviation	Description
DDSRF	Decoupled Double Synchronous Reference Frame
PLL	Phase Locked Loop
SRF	Synchronous Reference Frame
LMS	Load Management Scheme
BESS	Battery Energy Storage System
IBRs	Inverter Based Resources
PLC	Programmable Logic Controllers
SCR	Short Circuit Ratio
PCC	Point Of Common Coupling
AC	Alternative Current
DC	Direct Current
PWM	Pulse Width Modulation
CBEMA	Computer and Business Equipment Manufacturers Association
ANSI	American National Standards Institute
LVRT	Low Voltage Ride Through
FPNSC	Flexible Positive and Negative Sequence Control
rms	root mean square
HVAC	Heat Ventilation Air Conditioning
IoT	Internet of Things
MV	Medium Voltage
LV	Low Voltage

LIST OF APPENDICES

Appendix	Description
Appendix - A	ETAP simulation reports for Case Study 1 with various loading on the distribution system