

**STUDY OF DYNAMIC VOLTAGE RESTORER FOR  
DISTRIBUTION WITH DIFFERENT ENERGY  
STORAGE OPTIONS**

U. N. Sanjaya

(109253A)



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

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

Department of Electrical Engineering

University of Moratuwa  
Sri Lanka

May 2015

## Declaration, copyright statement and the statement of the supervisor

I declare that this is my own work and this thesis/dissertation 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 University of Moratuwa the non-exclusive right to reproduce and distribute my thesis/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).

.....

U.N. Sanjaya



University of Moratuwa, Sri Lanka  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

Date:

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

.....

Internal supervisor:

Date:

Prof. J.P. Karunadasa

.....

External supervisor:

Date:

Dr. H. M. Wijekoon

## Abstract

Present Power quality problems in distribution systems have been increased due to the increased utilization of sensitive and critical equipment in the system. Power quality issues may contain transient over voltages, voltage sags, voltage swells, under voltage, overvoltage, harmonics distortion, flicker and voltage imbalance, etc. One of the most severe power quality problems is voltage sag. Among the various solutions to overcome power quality problems, Dynamic Voltage Restorer (DVR) is one of the most effective solutions. The DVRs can be used to mitigate voltage sags/swells by injecting an appropriate voltage in series with the grid voltage, in order to avoid loss of power as it can maintain the load voltage at its nominal magnitude and phase by compensating the particular voltage sag/swell. The DVR consists of a series connected injection transformer, a Voltage Source Inverter (VSI), inverter output filter and a DC energy storage.

DC storage mainly decides the capability of DVR. This dissertation is based on study of the technical and economic aspects of various DC energy storage options on the performance of DVR in the Voltage restoration.

The most common DC energy storage such as Batteries, Conventional Capacitors and the recently developed storage technology “Super capacitors” have been discussed here. MATLAB Simulink platform was used for modeling and simulating the DVR and the energy storage options. Other than the standard DC energy storage models, a new model was built up for Super capacitor and validated through experiential results. Further economics of the above energy storage options in achieving the required energy storage levels have been investigated.

Based on the responses of DVR in different types of sags and swells for the above energy storage options, it can be concluded that for deeper and short duration sag mitigations, super capacitor performs better. But in mitigating longer duration sags, battery performs better. Conventional capacitor storages manufactured in the same scale of super capacitors can perform better than batteries, but in the economic point of view it is not appropriate.

## Acknowledgement

I would like to extend my sincere gratitude to my internal supervisor, Prof. J.P. Karunadasa for his great insight guidance in this study. Also, as the head of the department, he gave me all the helping hands for all the laboratory experiments carried out in the Department of Electrical Engineering. In addition, I must appreciate the coordinator of the Post Graduate Division of the Department of Electrical Engineering, Dr. Asanka Rodrigo for all the assistance given to me.

Further, I wish to thank my external supervisor Dr. H.M. Wijekoon who suggested this research concept and made me realized about the aims of this study.

In addition, I shall be grateful to the staff of the Department of Electrical Engineering who assisted me in the laboratory experiments and other documentation work.

Finally I should thank all my colleagues for who haven't been mentioned personally for making this study a success.



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

## TABLE OF CONTENTS

Declaration, copyright statement and the statement of the supervisor .....	i
Abstract.....	ii
Acknowledgement .....	iii
TABLE OF CONTENTS .....	iv
LIST OF FIGURES .....	vii
LIST OF TABLES.....	x
LIST OF ABBREVIATIONS .....	xi
Chapter 1 .....	1
1.0 INTRODUCTION.....	1
1.1 Power Quality of Distribution Network .....	1
1.2 Mitigating the Power Quality Issues.....	1
1.3 Objective of the study of Moratuwa, Sri Lanka.....	3
1.4 Scope of the Study .....	3
1.5 Literature review.....	4
Chapter 2 .....	5
2.0 STUDY OF THE DYNAMIC VOLTAGE RESTORER AND DC ENERGY STORAGE.....	5
2.1 Locating the DVR for line conditioning.....	5
2.2 Equation Related to DVR .....	6
2.3 Conventional System of DVR .....	6
2.4 Basic elements of DVR .....	7
2.4.1 Series booster/injection transformer.....	8
2.4.2 Passive filter .....	8
2.4.3 Voltage Source Converter .....	9
2.4.4 Control and Voltage injection Scheme.....	10
2.4.5 DC Energy Storage with charging mechanism .....	11

Chapter 3 .....	18
3.0 RESEARCH METHODOLOGY .....	18
3.1 Modelling the MV and LV distribution feeders .....	18
3.1.1 Modeling the 33kV Feeder bay and the MV line.....	18
3.1.2 Modeling the Distribution Transformer .....	18
3.1.3 Modelling the sensitive load.....	19
3.1.4 Creating the Voltage Sag and Swell.....	19
3.2 Modelling the DVR .....	19
3.2.1 Modeling the Series Injection Transformer.....	20
3.2.2 Modeling the IGBT converter .....	20
3.2.3 Modelling the LC filter.....	20
3.2.4 Modelling the control system.....	20
3.3 Testing the model for voltage compensation.....	21
3.3.1 Testing for Single phase voltage sags.....	23
3.3.2 Testing for 3-phase sags.....	24
3.3.3 Testing for voltage swells.....	25
3.4 Modeling the DC Energy Storage for DVR .....	29
3.4.1 Modeling the Battery Energy Storage .....	29
3.4.2 Modelling the Super capacitor Energy Storage.....	31
3.4.3 Modeling the conventional capacitor Storage .....	38
Chapter 4 .....	39
4.0 RESULTS AND DISCUSSION .....	39
4.1 Integration of the battery energy storage with the DVR.....	39
4.2 Integration of the super capacitor energy storage with the DVR .....	44
4.2.1 Harmonics of injected voltage.....	50
4.3 Integration of the conventional capacitor energy storage with the DVR	55
Chapter 5 .....	58

5.0	ECONOMIC ANALYSIS .....	58
5.1	Ni-MH battery storage .....	58
5.2	Super capacitor storage .....	58
5.3	Conventional capacitor storage.....	59
Chapter 6	.....	62
6.0	CONCLUSION .....	62
Reference List	.....	64



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

## LIST OF FIGURES

Figure 2.1: Location of DVR in LV side .....	5
Figure 2.2: Location of DVR in MV side .....	5
Figure 2.3: Circuit Model of DVR installed in a line.....	6
Figure 2.4: Simplified block demonstration of DVR.....	7
Figure 2.5: Passive LC filter .....	9
Figure 2.6: Six pulse Voltage Source Converter .....	9
Figure 2.7: Technical capabilities of the energy storage options.....	11
Figure 2.8: Power and Energy Density of Storage options.....	12
Figure 2.9: Equivalent Electrical Model of a Battery .....	13
Figure 2.10: Typical Discharge Characteristics of Battery Storage .....	13
Figure 2.11: Structure of a Conventional Capacitor .....	14
Figure 2.12: Charging and discharging characteristics of conventional capacitor .....	14
Figure 2.13: Micro Structure of Super capacitor Electrodes.....	15
Figure 2.14: Structure of Uncharged and Charged Super capacitor.....	16
Figure 2.15: Equivalent Electrical Model of a Super capacitor.....	16
Figure 2.16: Charging and discharging characteristics of Super capacitor .....	17
Figure 3.1: Control system of DVR .....	21
Figure 3.2: Complete DVR model for Sag .....	22
Figure 3.3: Voltage measured at Source side for single phase sag .....	23
Figure 3.4: Voltage Injected by DVR to Compensate the Sag .....	23
Figure 3.5: Voltage measured at sensitive load side for single phase sag.....	24
Figure 3.6: Voltage measured at Source side for three phase sag.....	24
Figure 3.7: Voltage Injected by DVR to Compensate the Sag .....	25
Figure 3.8: Voltage measured at sensitive load side for three phase sag .....	25
Figure 3.9: Testing the DVR model for voltage swells.....	26
Figure 3.10: Voltage measured at Source side for single phase swell.....	27
Figure 3.11: Voltage Injected by DVR to Compensate the Swell .....	27
Figure 3.12: Voltage measured at sensitive load side for single phase swell .....	28
Figure 3.13: Voltage measured at Source side for three phase swell .....	28
Figure 3.14: Voltage Injected by DVR to Compensate the Swell .....	28
Figure 3.15: Voltage measured at sensitive load side for single phase swell .....	29
Figure 3.16: Testing the charging characteristics of the battery .....	29
Figure 3.17: Constant current charging characteristics of battery.....	30
Figure 3.18: Battery charging characteristics manufacturer's data .....	30
Figure 3.19: Super capacitor MATLAB model .....	31
Figure 3.20: Testing the super capacitor charging characteristics .....	32



Figure 3.21: Super capacitor charging characteristics.....	32
Figure 3.22: Super capacitors used for the experiment .....	33
Figure 3.23: Test setup for monitoring super capacitor charging .....	33
Figure 3.24: Super capacitor charging waveform.....	35
Figure 3.25: Super capacitor constant current discharging model in MATLAB .....	35
Figure 3.26: Super capacitor constant current discharging monitored through MATLAB .....	36
Figure 3.27: Super capacitor voltage vs time at constant current discharge.....	37
Figure 3.28: Conventional capacitor charging MATLAB model .....	38
Figure 3.29: Conventional capacitor charging characteristics.....	38
Figure 4.1: DVR MATLAB model for testing battery storage.....	39
Figure 4.2: Variation of minimum battery voltage vs time to compensate sags .....	41
Figure 4.3: SOC of battery at the end of sag vs time .....	41
Figure 4.4: Variation of SOC of battery with time during 50% sag.....	42
Figure 4.5: Voltage at source side during 50% sag condition .....	42
Figure 4.6: Voltage at sensitive load side at 50% sag condition.....	43
Figure 4.7: Mean power variation of the battery .....	43
Figure 4.8: Variation of SOC of the battery with time under 30% swell.....	44
Figure 4.9: testing the DVR MATLAB model for super capacitor.....	45
Figure 4.10: Variation of SOC of supercapacitor during 3 phase sag condition .....	46
Figure 4.11: Mean Power variation of Super capacitor during sag .....	47
Figure 4.12: Voltage at source side during 3 phase 60% sag condition.....	47
Figure 4.13: Voltage at sensitive load side for 0.1F super capacitor at initial voltage of 160V during 60% sag.....	48
Figure 4.14: Voltage at sensitive load side for 0.25F super capacitor at initial voltage of 160V during 60% sag.....	48
Figure 4.15: Voltage at sensitive load side for 1F super capacitor at initial voltage of 160V during 60% sag.....	49
Figure 4.16: Variation of Capacitance of supercapacitor vs duration of sag compensating capability .....	50
Figure 4.17: THD of the injected voltage at the primary side of the injection transformer for battery storage .....	51
Figure 4.18: THD of the injected voltage at the primary side of the injection transformer for super capacitor storage.....	52
Figure 4.19: THD of the injected voltage at the primary side of the injection transformer for 0.1F super capacitor .....	53
Figure 4.20: THD of the injected voltage at the primary side of the injection transformer for 1F super capacitor .....	53

Figure 4.21: THD of the injected voltage at the primary side of the injection transformer vs. capacitance of the super capacitor.....	54
Figure 4.22: DVR MATLAB model with Conventional capacitor storage.....	55
Figure 4.23: SOC of super capacitor under 40% sag condition for 0.45s duration .....	56
Figure 4.24: SOC of electrolytic capacitor under 40% sag condition for 0.45s duration .....	56
Figure 4.25: THD level of the injected voltage at the primary side of the injection transformer for conventional capacitor storage .....	57
Figure 4.26: THD level of the injected voltage at the primary side of the injection transformer for super capacitor storage .....	57
Figure 6.1: Hybrid energy storage proposed for DVR .....	63



University of Moratuwa, Sri Lanka.  
 Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

## LIST OF TABLES

Table 1.1: Definitions of Voltage Magnitude Events as used in IEEE Std. 1159-1995 .....	1
Table 3.1: Super capacitor terminal voltage variation with time at constant current charging ....	34
Table 3.2: Super capacitor terminal voltage variation with time at constant current discharging	36
Table 4.1: Minimum Battery voltage required to compensate three phase to ground faults.....	40
Table 4.2: Minimum Battery voltage required to compensate single phase to ground faults .....	40
Table 4.3: SOC of the battery with time under 30% swell .....	44
Table 4.4: Mean power released by the battery and super capacitor with different sag levels.....	45
Table 4.5: Duration of sag compensating capability with super capacitor Capacitance .....	49
Table 4.6: Variation of THD for 10 cycles of the injected voltage at the primary side of the injection transformer for capacitance of the super capacitor.....	54
Table 5.1: Cost comparison for energy storage options .....	60
Table 5.2: Variation of energy density and total mass required for energy storage options .....	60
Table 5.3: Required volume of energy storage options.....	60
Table 5.4: Variation of power density and total mass required for energy storage options.....	61
Table 5.5: Cycle durability of energy storage options .....	61



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

## LIST OF ABBREVIATIONS

Abbreviation	Description
rms	root mean square
SCR	Silicon Controlled Rectifiers
DSTATCOM	Distribution Static Synchronous Compensators
SETC	Static Electronic Tap Changers
UPS	Static Electronic Tap Changers
DVR	Dynamic Voltage Restorers
MV	Medium Voltage
LV	Low Voltage
DC	Direct Current
PWM	Pulse Width Modulation
VSC	Voltage Source Converter
SLG	Single Line to Ground Fault
DLG	Double Line to Ground Fault
SPWM	Sinusoidal Pulse Width Modulation
HEV	Hybrid Electric vehicles
SoC	Status of Charge
ESR	Equivalent Series Resistance
EPR	Equivalent Parallel Resistance
IGBT	Insulated Gate Bipolar Junction Transistors
VSI	Voltage Source Inverter
Ni-MH	Nickel Metal Hydride
THD	Total Harmonic Distortion
FFT	Fast Fourier Transform



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lsh.moratuwa.lk](http://www.lsh.moratuwa.lk)