## Contents

Docla	ration	pag
Certif	ration ficate	i
Abstr		
Conte	owledgements ents	v i
	f Figures	xi
	f Tables	xi
	f Symbols f Abbreviations	XX XX
LISCO	1 Nobi eviduolis	XX
Chap	oter 1: Introduction	
1.1	Power Quality Renewable Energy Sources	
1.2	1.2.1 Wind Energy Conversion System	
	1.2.2 Solar PV System	
	1.2.3 RE Sources Based Hybrid Power System	
1.3	Power Quality Events in the Utility Grid with RE Sources 1.3.1 Recognition of Power Quality Disturbances	
	1.3.2 Power Quality Improvement	1
1.4	Objective of the Thesis	1
1.5	Contributions of the Thesis	1
	1.5.1 Recognition of Standard PQ Disturbances 1.5.2 Recognition of PQ Disturbances Associated with the Renewable Energy Penetration in	1
	the Distribution Utility Network	1
	1.5.3 Power Quality Improvement Using DSTATCOM in Distribution System with RE Penetration	1
1.6	Thesis outline	1
Chan	oter 2: Review of Literature	1
2.1	Introduction	1
2.2	Detection of PQ Disturbances	2
	2.2.1 Power Quality Events Classifier 2.2.2 Effect of Noise on PQ Event Classifier	2
2.3	Detection of Power Quality Disturbances with Renewable Energy Sources	2
2.4	Power Quality Improvement	2
	2.4.1 Power Quality Improvement Using Filters	2
	2.4.2 Power Quality Improvement Using UPQC 2.4.3 Power Quality Improvement Using FACTS Devices	2
	2.4.4 Power Quality Improvement using PACTS Devices 2.4.4 Power Quality Improvement using Distribution Static Compensator	2
	2.4.5 Selection Criteria of PQ Improvement Techniques Based on Applications	
	2.4.6 Techno-Economical Considerations of PQ Improvement Techniques	3 3 3 3
2.5 2.6	Power Quality Improvement in Utility Grid Integrated with RE Sources Identified Research Gaps	ა ვ
2.7	Conclusions	$\frac{3}{3}$
<b>6</b> 1		
3.1	oter 3: Recognition of Standard Power Quality Disturbances Introduction	<b>4</b> 4
3.2	Proposed PQ Events Recognition Methodology	4
	3.2.1 Single Stage Power Quality Disturbances	4
	3.2.2 Complex Power Quality Disturbances	<b>4</b> 4
3.3	Analysis of Single Stage PQ Disturbances Using S-Transform 3.3.1 Pure Sine Wave	4
	3.3.2 Voltage Sag	4
	3.3.3 Voltage Swell	4
	3.3.4 Momentary Interruption	4
	3.3.5 Harmonics 3.3.6 Flicker	4
	3.3.7 Oscillatory Transient	4 4
	3.3.8 Impulsive Transient	4

	3.3.9 Multiple Notches	47				
	3.3.10 Multiple Spikes	<b>48</b> 48				
3.4	S-Transform Based Feature Extraction of Single Stage PQ Disturbances					
3.5	Classification of Single Stage PQ Disturbances 3.5.1 Classification Using Rule Based Decision Tree	51				
	3.5.2 Classification Using Decision Tree Initialized Fuzzy C-Means Clustering	51 52				
3.6	Performance Comparison of Results of Single Stage PQ Events Recognition with the Methods	)2				
٠.٠	Reported in Literature	58				
3.7	Analysis of Complex PQ Disturbances Using S-Transform	59				
	3.7.1 Second Order Complex PQ Disturbances	60				
	3.7.2 Third Order Complex PQ Disturbances	66				
- O	3.7.3 Fourth Order Complex PQ Disturbances	69				
3.8	S-Transform Based Feature Extraction of Complex PQ Disturbances Classification of Complex PQ Disturbances Using Rule-Based Decision Tree	70 71				
3.9 3.10	Performance Comparison of Results of Complex PQ Events Recognition with the Methods	11				
٠.٠٥	Reported in Literature	75				
3.11	Testing of Algorithms in Real Time Using RTDS	76				
	3.11.1 Single Stage PQ Disturbances	78				
	3.11.2 Complex PQ Disturbances	78				
3.12	Conclusions	78				
Chan	stor 4. Power Quality Assessment in Utility Crid with Wind and Solar Energy Pene					
Chap	oter 4: Power Quality Assessment in Utility Grid with Wind and Solar Energy Pene- tration: An Experimental Approach	81				
4.1	Introduction	81				
4.2	Proposed S-transform Based PQ Analysis Methodology	82				
1	4.2.1 Power Quality Index	82				
4.3	Experimental Set-up and Data Acquisition System of DFIG Based Wind Energy System	83				
4.4	Power Quality Assessment With Wind Energy Penetration: Case Studies	85				
	4.4.1 No Load at PCC	86				
	4.4.2 Resistive Load at PCC	86				
	4.4.3 Resistive-Inductive Load at PCC 4.4.4 Induction Motor Load at PCC	87 88				
	4.4.5 Non Linear Load at PCC	88				
4.5	Case Studies: Comparison (Wind Energy)	89				
4.6	Experimental Set-up and Data Acquisition System of Solar PV System	89				
4.7	Power Quality Assessment With Solar Energy Penetration: Case Studies	93				
	4.7.1 No Load at PCC	93				
	4.7.2 Resistive Load at PCC	94				
	4.7.3 Resistive-Inductive Load at PCC 4.7.4 Induction Motor Load at PCC	94				
	4.7.5 Non-linear Load at PCC	95 96				
4.8	Case Studies: Comparison (solar energy)	97				
4.9	Conclusions	98				
Chap	oter 5: Power Quality Recognition in Distribution System with Renewable Energy					
	Penetration: Simulation Approach	99				
5.1	Introduction Proposed Test System	99				
5.2	Proposed Test System 5.2.1 IEEE-13 Bus Test Feeder	100 100				
	5.2.2 Wind Energy Generation System	100				
	5.2.3 Solar Photovoltaic System	105				
5.3	Proposed Methodology for Detection of Operational Events	106				
5.4	Proposed Methodology for Detection of Power Quality Disturbances Associated with Oper-					
	ational Events	108				
5.5	Recognition of Power Quality Disturbances With Wind Energy: Case Studies	109				
	5.5.1 Grid Synchronization of Wind Generator 5.5.2 Outage of Wind Generator	109 109				
	5.5.3 Islanding	112				
	5.5.4 Wind Speed Variations	113				
5.6	Recognition of Power Quality Disturbances with Solar Energy Penetration: Case Studies	114				
	5.6.1 Grid Synchronization of Solar PV Plant	115				
	5.6.2 Outage of Solar PV Plant	117				
	5.6.3 Sudden Change in Solar Insolation	118				
5.7	Recognition of Power Quality Disturbances in Hybrid Power System: Case Studies	119				
	5.7.1 Islanding in the Presence of Wind Power Generation 5.7.2 Islanding in the Presence of Solar PV Power Generation	120 120				
	5.7.3 Islanding in the Presence of Wind Power and Solar PV Power Generations	120				
	5.7.4 Outage of Wind Generator in the Presence of Solar PV system	121				
	5.7.5 Outage of Solar PV system in the Presence of Wind Power Generation	122				

×

	5.7.6 Simultaneous Outage of Solar PV System and Wind Generator	123
	5.7.7 Grid Synchronization of Wind Generator in the Presence of Solar PV System	124
	5.7.8 Grid Synchronization of Solar PV System in the Presence of Wind Power Generation	125
	5.7.9 Simultaneous Grid Synchronization of Solar PV system and Wind Generator	126
5.8	Detection of Operational Events: Case Studies	129
	5.8.1 Islanding	131
	5.8.2 Outage of RE Generators	131
	5.8.3 Grid Synchronization of RE Generators	132
5.9	Testing of Results in Real Time Using RTDS	133
	5.9.1 Wind Energy System	133
	5.9.2 Solar PV System	133
	5.9.3 Hybrid Power System	133
5.10	Conclusions	1 <b>33</b> 135
Chan	oter 6: Power Quality Improvement in Distribution Network with Renewable En-	
	ergy Sources using DSTATCOM with Battery Energy Storage System	139
6.1	Introduction	139
6.2	Proposed Test System	140
6.3	Mathematical Modelling of Proposed DSTATCOM and Operational Principle	140
	6.3.1 DC Link Capacitor	140
	6.3.2 AC Inductor	141
	6.3.3 Ripple Filter	142
	6.3.4 Battery Bank	142
	6.3.5 Principle of Operation	142
6.4	Proposed DSTATCOM Controller	143
6.5	Proposed PQ Improvement Strategy	144
6.6	Mitigation of Power Quality Disturbances Using DSTATCOM: Case Studies	145
	6.6.1 Grid Disturbances	145
	6.6.2 Wind Energy Penetration	149
	6.6.3 Solar Energy Penetration	152
	6.6.4 Hybrid Power System	154
6.7	Testing of Results in Real Time Using RTDS	159
	6.7.1 Grid Disturbances	159
	6.7.2 Wind Energy Penetration	160
	6.7.3 Solar Energy Penetration	160
	6.7.4 Hybrid Power System	161
6.8	Conclusions	161
Chap	oter 7: Summary and Conclusions	163
7.1	Summary	163
7.2	Concluding Remarks	163
/•-	7.2.1 Detection of PQ Disturbances	163
	7.2.2 Mitigation of PQ Disturbances	165
7.3	Closing Comments	165
1.5	Closing Comments	100
Refe	rences	167