Contents

		P	age
Al	bstract	t	vii
Co	ontent	s	ix
Li	st of T	ables	xiii
Li	st of F	Tigures Tigures	xv
Li	st of A	Abbreviations	XX
1	Intro	oduction	1
	1.1	Historical Background	1
	1.2	Inverters in Electrical Power System	2
	1.3	Three-phase Inverter Modelling	4
		1.3.1 Failures in inverters and its causes	6
	1.4	Reliability, Availability, and Condition Monitoring (RACM)	8
	1.5	Need of RACM of Inverters	9
		1.5.1 Inverters in PV Systems	10
		1.5.2 Inverters in Wind Energy Systems	12
		1.5.3 Inverters in EVs and other drives systems	12
	1.6	Role of Signal Processing Techniques in RACM	13
	1.7	Role of Machine Learning Techniques in RACM	13
	1.8	Thesis Motivation	16
	1.9	Objectives of the Thesis	18
	1.10	Contributions of the Thesis	18
	1 11	Outlines of the Thesis	19

2	Lite	rature S	Survey	23
	2.1	Introdu	uction	23
	2.2	Layout	ts of Solar-PV Systems	25
	2.3	Reliab	ility and Availability Analysis	27
		2.3.1	System Decomposition	28
		2.3.2	Reliability Evaluation of Inverter System	29
		2.3.3	Reliability Modeling	30
		2.3.4	Data Collection	31
	2.4	Availal	bility Estimation	32
	2.5	RACM	I of Inverters of PV Systems	35
	2.6	OC Fa	ult Diagnosis of Inverters	38
	2.7	Summa	ary	42
3	RAC	CM of I	nverters: 2 Samples Approach	43
	3.1	Introdu	action	43
		3.1.1	Proposed Fault Diagnosis System	47
	3.2	Two Sa	amples-based Method for RACM	49
		3.2.1	Two-Samples based Fault Detection Technique	49
		3.2.2	Features Extraction Technique	52
	3.3	Simula	ation Studies	57
	3.4	Results	s and Discussion	59
		3.4.1	Fault Diagnosis using EWP-SVM Technique	60
		3.4.2	Comparison between Proposed Technique and Existing Techniques	65
	3.5	Summa	ary	68
4	RAC	CM of I	nverter: Wavelet Entropy Based PCA-SVM Technique	69
	4.1	Introdu	action	69
	4.2	EWP-I	PCA-SVM Method for RACM	72
		4.2.1	OC Fault Detection using PCA	74
		4.2.2	WPD	77
		4.2.3	Wavelet Entropy	79
	4.3	Results	s and Discussion	80
	4.4	Summa		88

5	RAG	CM of Inverters: Walsh Function based KNN Approach	91
	5.1	Introduction	91
	5.2	WFC-KNN Approach for RACM	94
		5.2.1 Walsh-Function Coefficients (WFC)	95
		5.2.2 OC Fault Detection using WFC	96
		5.2.3 WFC-SVM and WFC-KNN Techniques for Fault Diagnosis	103
	5.3	Results and Discussion	106
	5.4	Summary	120
6	Con	clusions and Scopes for the Future Work	121
	6.1	Conclusions	121
	6.2	Benefits of the Proposed Work	123
	6.3	Scopes for the Future Work	123
AĮ	pend	lix A Data Collection	125
Re	eferen	ices	129
Li	st of l	Publications	143



List of Tables

Chapter 2

2.1	Comparison of the proposed method with existing methods	25
2.2	Details of sub-assemblies of each component of PV system	33
2.3	Subsystem failure rate (YR^{-1}) estimated from Tables A.1 and A.2	33
2.4	Subsystem repair rate (YR^{-1}) estimated from Table 2.2	33
2.5	Comparison of fault detection time of proposed methods with existing techniques	41
Chapte	r 3	
3.1	Features extracted from three-phase currents under different conditions	56
3.2	Fault diagnosis results using Simple Entropy-SVM technique	67
3.3	Comparison of fault detection time of different techniques	67
Chapter	r 4	
4.1	Features extraction under different conditions	81
4.2	Different OC faults used to train and validate the classifier	84
4.3	Comparison of the accuracy of different fault diagnosis techniques	86
5.1	Training time for KNN and SVM classification techniques	110
Chapte	r 5	
5.2	Subsystem reliability of PV system for one year of operation (in %) (using eq	
	2.19)	112
5.3	Subsystem reliability of PV system for 20 years of operations (in %) (using eq	
	2.20)	112

5.4	Subsystem availability (in %)	114
5.5	Availability importance measures	114
5.6	Importance measures based on failure rates	115
5.7	Importance measures based on repair rates	115
5.8	Ranking of components affecting the availability of PV system	118
5.9	Comparison of the reliability values of PV system found from proposed method	
	and existing methods after one year of operation	119
5.10	Comparison of the reliability values of PV system found from proposed method	
	and existing methods after twenty years of operation	119
Appendi	ix A	
A.1	Gathered data of failure rate and repair rate from literature	126
A.2	Gathered data of failure rate and repair rate from literature	127

List of Figures

Cha	pter	1

1.1	Inverters used in electrical power system including wind generation, solar PV	
	panel, EVs, and ESS connected to the grid	3
1.2	Block diagram of three-phase inverter	7
1.3	Benefits of condition monitoring of system	10
1.4	Division of PV system into its components and sub-components and reliability	
	block diagram.	12
1.5	Features extraction from three-phase currents using signal processing technique	14
1.6	Features extraction from three-phase voltages using signal processing technique	14
1.7	Fault diagnosis using machine learning technique	16
Chapter	r 2	
2.1	Arrangement of components in PV system connected with grid	26
2.2	Division of PV system into its components and sub-components and reliability	
	block diagram.	31
2.3	The proposed methodology for RACM in PV systems	37
2.4	Flow chart of PCA-based condition monitoring algorithm	38
2.5	Condition monitoring output showing the data points lying in normal, warning,	
	and alarm range	39
Chapter	:3	
3.1	RACM using two samples and EWP-SVM based techniques	44
3.2	Flow chart of the proposed system	46
3.3	Schematic diagram for two-samples based fault detection algorithm	48

3.4	WPD of a signal into Approximate (A) and detail (D) coefficients up to 3 levels	49
3.5	Flow chart of two-samples based OC fault detection algorithm	50
3.6	Estimated current of phase-a of the inverter under multi-IGBTs OC faults at S1	
	and S5	51
3.7	Original current of phase-a of the inverter under multi-IGBTs OC faults at S1	
	and S5	52
3.8	OC fault detection by comparing estimated and original current signals	53
3.9	The difference of actual and estimated current signal, fault occurring and alarm	
	generation	53
3.10	Simulink model of the fault diagnosis system	58
3.11	Three-phase output currents of the 3-phase, 3-level inverter under normal con-	
	dition	59
3.12	Three-phase currents for single IGBT (S1) fault	60
3.13	OC fault detection for single IGBT (S1) fault	61
3.14	Three-phase currents for multiple IGBTs (S1, S2, S5) faults	61
3.15	OC fault detection for multiple IGBTs (S1, S2, S5) faults	62
3.16	OC fault detection output with current of phase-b under OC fault in S1	62
3.17	OC fault detection output with current of phase-b under OC faults in S1, S2,	
	and S5	63
3.18	OC fault detection output with current of phase-c under OC fault in S1	63
3.19	OC fault detection output with current of phase-c under OC faults in S1, S2,	
	and S5	64
3.20	Classification results using proposed EWP-SVM technique	64
3.21	Classification results using simple entropy as feature extraction	65
Chapter	• 4	
4.1	RACM using PCA-EWP-SVM technique	70
4.2	Process flow of the proposed algorithm	73
4.3	Data variance covered by the principal components individually and cumulatively.	74
4.4	Schematic diagram of PCA-based fault detection technique	75
4.5	OC fault detection output pattern under normal condition	76

4.6	PCA-based OC fault detector output pattern for single IGBT	76
4.7	PCA-based OC fault detector output pattern for multiple IGBTs	77
4.8	Decomposition of wavelet packets into Approximate and detail coefficients	78
4.9	Process flow of fault localization using WE feature	80
4.10	Three-phase currents of the inverter under normal condition	82
4.11	Three-phase currents of the inverter under OC fault in single IGBT (S1)	82
4.12	Three-phase currents of the inverter under OC faults in multiple IGBTs (S1, S5).	83
4.13	PCA-based OC fault detector output under S1 fault	83
4.14	Classification results using simple entropy	85
4.15	Classification results using WE of the current signal as feature	85
4.16	Accuracy of fault classification algorithm during training	87
4.17	Accuracy of fault classification algorithm during testing	88
4.18	Prototype for the proposed algorithm of fault detection and localization	89
4.19	Outputs of fault detection and localization algorithms under normal condition.	89
4.20	Outputs of fault detection and localization algorithms under fault condition in	
	switch S1	90
Chapter	5	
5.1	RACM using PCA-EWP-KNN technique	92
5.2	Process flow of the proposed algorithm	94
5.3	Line voltage V_{ab} under normal condition	97
5.4	Line voltage V_{ab} under fault condition at $S_1 \ldots \ldots \ldots \ldots \ldots$	97
5.5	WFCs of voltage signal under normal condition	98
5.6	Reconstruction of voltage signal using WFCs	98
5.7	WFCs of voltage signal under fault condition in S_1	99
5.8	WFCs of voltage signal under normal condition with second next sample com-	
	ing in	100
5.9	WFCs of voltage signal under normal condition with third next sample coming	
	in	100
5.10	in	100

5.11	WFCs of voltage signal under S_1 fault condition with second next sample com-	
	ing in	101
5.12	WFCs of voltage signal under S_1 fault condition with third next sample coming	
	in	102
5.13	WFCs of voltage signal under S_1 fault condition with forth next sample coming	
	in	102
5.14	Magnitude of WFCs of window of 11 samples of voltage signal under normal	
	condition	103
5.15	Phase of WFCs of window of 11 samples of voltage signal under normal con-	
	dition	104
5.16	Magnitude of WFCs of window of 11 samples of voltage signal under fault	
	condition at S_1	104
5.17	Phase of WFCs of window of 11 samples of voltage signal under fault condition	
	at S_1	105
5.18	Fault detection and generation of alarm under fault condition at S_1	105
5.19	Zoomed view of occurrence of fault, detection and generation of alarm under	
	fault condition at S_1	106
5.20	Fault classification result using SVM-algorithm	107
5.21	Fault classification result using fine KNN-algorithm	107
5.22	Fault classification result using weighted KNN-algorithm	108
5.23	Accuracy of SVM-based fault classification technique	108
5.24	Accuracy of KNN-based fault classification technique	109
5.25	Accuracy of MLP-based fault classification technique	109
5.26	Prototype for the proposed algorithm of fault detection and localization	110
5.27	Outputs of fault detection and localization algorithms under normal condition.	111
5.28	Outputs of fault detection and localization algorithms under fault condition in	
	switch S1	111
5.29	Percentage reliability of PV systems for one year of operation	113
5.30	Percentage reliability of PV systems for 20 years of operation	113
5.31	Sub-systems availability for the studied systems	115
5.32	Importance measures for PV module, converter and inverter	116
5 33	Sub-system availability for inverter	116

5.34	Overall system availability before inverter redundancy	117
5.35	Overall system availability after inverter redundancy	118