Contents

Co Fo Pr	Contributors Foreword Preface			xi xiii xv	
1	Synchrophasors for improving the performance of power system <i>P.K. Agarwal</i>				
	11	Summ	larv	1	
	1.2	Evolu	tion of the power grid	2	
	1.3	Challe	enges of modern grid	3	
	1.4	SCAL	DA system	4	
	1.5	Synch	rophasor technology	6	
		1.5.1	Phasor measurement	7	
		1.5.2	Time synchronised measurements	7	
		1.5.3	Wide area measurement system	9	
	1.6	SCAL	DA vs WAMS	10	
	1.7	Word-wide deployment of WAMS		11	
		1.7.1	WAMS in Americas	11	
		1.7.2	WAMS in Europe	12	
		1.7.3	WAMS in Asia	12	
	1.8	Applications of synchrophasors data		13	
		1.8.1	Fault detection, classification and analysis	14	
		1.8.2	Low-frequency oscillations	17	
		1.8.3	Insight to coherency of generators	21	
		1.8.4	Remote detection of system separation	21	
		1.8.5	Synchronising two grids from remote	23	
		1.8.6	Improving power plant performance	24	
	1.9	1.9 Way-forward			
	Acknowledgement				
	References				

2	An optimal redundancy criterion index (ORC) for optimal placement of				
	phasor measurement units (PMU) for full observability of power grid	29			
	Ranganath Vallakati and Prakash Ranganathan				

2.1 Introduction

	2.2	Synchrophasors	30	
		2.2.1 Advantages of synchrophasors over SCADA measurements	32	
		2.2.2 Challenges with synchrophasor measurements	32	
	2.3	Optimal placement of phasor measurement units (PMU)	33	
		2.3.1 Need for OPP for synchrophasors	34	
	2.4	PMU placement problem formulation using		
		linear programming (LP)		
		2.4.1 Problem formulation	36	
		2.4.2 System with no zero-injection buses	36	
		2.4.3 System with zero-injection measurements	38	
	2.5	System observability redundancy index (SORI)	39	
	2.6	5 Optimal redundancy criterion (ORC)		
	2.7	OPP on standard test systems		
		2.7.1 Advanced Modeling and Programming Language (AMPL)	43	
		2.7.2 Zero-injection buses	44	
		2.7.3 Enforcing optimal redundancy criterion (ORC)	46	
		2.7.4 SORI	46	
		2.7.5 PMU placement costs	48	
		2.7.6 Justification of ORC index	49	
		2.7.7 Time computation using LP	52	
		2.7.8 Forecasting the scalability of OPP using linear regression	52	
	2.8	Conclusion	55	
	Acknowledgments			
	Refe	erences	56	
3	Wid	le-area measurement-based power network protection	59	
	Prai	tim Kundu, Saumendra Sarangi and Ashok Kumar Pradhan		
	3.1	Introduction	59	
		3.1.1 WAMS architecture	60	
		3.1.2 WAMS communication	61	
	3.2	Improved network protection during stressed conditions		
			62	
		3.2.1 Protection support during power swing	62 63	
		3.2.1 Protection support during power swing3.2.2 Improved zone 3 operation	62 63 69	
	3.3	3.2.1 Protection support during power swing3.2.2 Improved zone 3 operationOnline identification of protection element failure	62 63 69 75	
	3.3	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 	62 63 69 75 75	
	3.3	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 3.3.2 Component failure indices 	62 63 69 75 75 75	
	3.3	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 3.3.2 Component failure indices 3.3.3 Signal communication 	62 63 69 75 75 75 75 76	
	3.3	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 3.3.2 Component failure indices 3.3.3 Signal communication 3.3.4 The method 	62 63 69 75 75 75 75 76 77	
	3.3	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 3.3.2 Component failure indices 3.3.3 Signal communication 3.3.4 The method 3.3.5 Case study: relay underreaching 	62 63 69 75 75 75 75 76 77 78	
	3.3	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 3.3.2 Component failure indices 3.3.3 Signal communication 3.3.4 The method 3.5 Case study: relay underreaching Adaptive protection 	62 63 69 75 75 75 76 77 78 82	
	3.3 3.4	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 3.2 Component failure indices 3.3.3 Signal communication 3.3.4 The method 3.5 Case study: relay underreaching Adaptive protection 3.4.1 Series compensated line 	62 63 69 75 75 75 75 76 77 78 82 82	
	3.3 3.4	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 3.2 Component failure indices 3.3.3 Signal communication 3.3.4 The method 3.5 Case study: relay underreaching Adaptive protection 3.4.1 Series compensated line 3.4.2 Three terminal line 	62 63 69 75 75 75 75 76 77 78 82 82 82 85	
	3.33.43.5	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 3.2 Component failure indices 3.3.3 Signal communication 3.4 The method 3.5 Case study: relay underreaching Adaptive protection 3.4.1 Series compensated line 3.4.2 Three terminal line Conclusion 	62 63 69 75 75 75 76 77 78 82 82 82 85 94	
	3.3 3.4 3.5 Non	 3.2.1 Protection support during power swing 3.2.2 Improved zone 3 operation Online identification of protection element failure 3.3.1 Faulted line identification 3.2 Component failure indices 3.3.3 Signal communication 3.4 The method 3.5 Case study: relay underreaching Adaptive protection 3.4.1 Series compensated line 3.4.2 Three terminal line Conclusion 	62 63 69 75 75 75 76 77 78 82 82 82 85 94 94	

4	Synchrophasor-assisted visualization and protection of power systems Sukumar Brahma					
	4.1	4.1 Traditional visualization with SCADA				
	4.2 State monitoring with synchrophasors			100		
	4.3	Distur	bance monitoring and identification using synchrophasors	102		
		4.3.1	Feature extraction	104		
		4.3.2	Classification	105		
		4.3.3	Case study: disturbance identification using PMU-generated	107		
	44	Lise of	f synchronhasors for nower system protection	111		
	т.т	441	Real-time constraints of nower system protection	111		
		442	Suitability of PMU measurements for protection	111		
		4.4.3	Potential improvements in existing protection applications	113		
		4.4.4	Supervisory protection—potential use of synchrophasors	115		
			to supervise local protection	114		
		4.4.5	Case study: synchrophasor-assisted out-of-step	115		
	4.5	C 1	protection for generators	115		
	4.5	Concl	usion	121		
	Refe	erences		121		
5	Using PMU measurements for enhanced power grid					
	monitoring and protection 1					
	Xiar	igqing .	Jiao and Yuan Liao			
	5.1	Introd	uction	123		
	5.2	Monit	oring of power system operation: state estimation	123		
		5.2.1	Background	123		
		5.2.2	State estimation solution	124		
		5.2.3	Use of PMUs for state estimation	126		
	5.3	Monit	oring of power system model	127		
		5.3.1	Introduction	127		
		5.3.2	Online transmission line parameter estimation	129		
		5.3.3	Load model monitoring	136		
		5.3.4	System-level model monitoring	142		
	5.4	Wide-	area fault location based on PMU measurements	143		
		5.4.1	Introduction	143		
		5.4.2	Fault location algorithm	143		
	5.5	Concl	usion	145		
	Refe	erences		145		
6	Fau	lt moni	toring, detection, and correction using synchrophasor			
-	mea	sureme	ents in modern power systems	147		
	Anupam Mukherjee and Prakash Ranganathan					
	6.1	Cluste	ring methods and openPDC interface	147		

		6.1.1	openPDC setup and data extraction process	147		
		6.1.2	Application of <i>k</i> -means clustering	148		
		6.1.3	Application of density-based spatial clustering			
			of applications with noise clustering	152		
		6.1.4	Development of a novel method, multitier k-means			
			clustering method	154		
	6.2	Need	for a hybrid method	155		
		6.2.1	Development of multitier k-means method	155		
		6.2.2	Advantages of using proposed multitier			
			<i>k</i> -means method	160		
	6.3	Result	ts and discussions	161		
		6.3.1	Results obtained from data clustering algorithms	161		
	6.4	Concl	usion	175		
	Ack	nowled	gments	175		
	Refe	erences		175		
7	Tra	nsmissi	ion line fault detection, classification, and localization			
	in s	mart p	ower grids using synchrophasor measurements	177		
	Path	iirikkat	Gopakumar, Maddikara Jaya Bharata Reddy and			
	Dusmanta Kumar Mohanta					
	7.1	Introd	uction	177		
	7.2	Real-t	ime transmission line fault monitoring in power grids	177		
		7.2.1	Emerging methodologies for fault monitoring	178		
	7.3	EVPA	- and ECPA-based transmission line fault detection	179		
		7.3.1	Real-time estimation of EVPA and ECPA	179		
		7.3.2	Fault detection using EVPA and ECPA	182		
	7.4	EVPA	- and ECPA-based transmission line fault classification	191		
	7.5	EVPA	- and ECPA-based transmission line fault localization	194		
		7.5.1	Parent bus identification methodology			
			(bus to which faulty branch is connected)	195		
		7.5.2	Faulty branch discrimination methodology	195		
		7.5.3	Fault localization using ECPA in faulty branch	195		
	7.6	Concl	usion	209		
	Refe	erences		209		
8	PMU-based vulnerability assessment of power systems					
	Guanqun Wang, Chen-Ching Liu, Evangelos Farantatos and Navin Bhatt					
	8.1	Introd	uction	211		
		8.1.1	Cascaded events and vulnerability assessment	211		
		8.1.2	PMU-based monitoring of power systems	213		
	8.2	PMU-	based monitoring and assessment of rotor-angle stability	214		
		8.2.1	Maximum Lyapunov exponent (MLE) method	214		
		8.2.2	MLE calculation algorithm	215		

8	8.3 Observability for PMU-based monitoring of system dynamics	218
	8.3.1 Static observability	218
	8.3.2 Topology observability	219
	8.3.3 Dynamic observability	220
	8.3.4 PMU-based monitoring of power system dynamics	221
8	3.4 Example	222
8	3.5 Conclusion	225
1	Acknowledgment	226
I	References	226
9 9	Synchrophasor applications for load estimation and stability analysis Tushar, H. Lee, P. Banerjee and A. K. Srivastava	231
ç	P.1 Introduction	231
9	9.2 Voltage stability assessment using synchrophasor data	232
	9.2.1 Review of existing PMU-based voltage stability	232
	9.2.2 Industrial voltage stability application	233
	9.2.3 Decentralized voltage stability assessment	240
9	P.3 PMU-based load modeling	243
	9.3.1 Definition of load modeling	243
	9.3.2 Classification of load models	244
	9.3.3 Review of estimation of load model parameters	249
	9.3.4 Advantages of using synchronized phasor	
	measurements for load modeling	250
	9.3.5 Parameter identification techniques	250
	9.3.6 Estimation of static load parameters	252
9	9.4 Transient stability assessment using synchrophasor data	257
	9.4.1 Review of existing techniques for transient stability	258
	9.4.2 MLE-based transient stability assessment	262
9	9.5 Conclusion	269
I	References	270
10 5	State estimation in the presence of synchronized measurement Sanjeev Kumar Mallik, Saikat Chakrabarti and Sri Niwas Singh	277
1	10.1 State estimation	277
	10.1.1 SCADA measurements	278
	10.1.2 Phasor measurement unit	278
	10.1.3 State estimation functions	279
	10.1.4 Measurement model for static state estimation	279
	10.1.5 Assigning weights to the measurements	280
1	10.2 Conventional state estimation	282
1	10.3 Linear state estimation	284
1	10.4 Postprocessing sequential state estimation	286
1	10.5 Preprocessing hybrid state estimation	287
1	10.6 Regularization method	290
-		

		10.6.1	Selection of regularization parameter by L-curve method	292
		10.6.2	Regularized state estimation problem	293
	10.7	Case study		294
		10.7.1	Case I for IEEE 14-bus test system	296
		10.7.2	Case II for IEEE 14-bus test system	298
	10.8	Conclus	sion	300
	Refer	References		
11	PMU	-based v	vide-area security assessment	305
	S.R. S	Samantar	ay, Innocent Kamwa and Geza Joos	
	11.1	Introdu	ction	305
	11.2	System studied using wide area monitoring		307
	11.3	Wide-area severity indices		308
		11.3.1	WASI features	308
		11.3.2	Wide-area severity indices and stability condition	310
	11.4	Data-mining models		310
		11.4.1	Decision tree	310
		11.4.2	DT-induced fuzzy approach	312
		11.4.3	Ensemble decision trees	313
	11.5	Data-mining model-based catastrophe predictors		314
		11.5.1	Scenarios and data count generation	314
		11.5.2	Data-mining models for catastrophe predictor	314
		11.5.3	Performance assessment	314
		11.5.4	Accuracy vs transparency trade-off	324
	11.6	.6 Conclusion		
	References			328

Index

333