

WIDE AREA MONITORING AND PROTECTION FOR STRESSED POWER SYSTEMS

SAYARI DAS



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

OCTOBER 2020

© Indian Institute of Technology Delhi (IITD), New Delhi, 2020

WIDE AREA MONITORING AND PROTECTION FOR STRESSED POWER SYSTEMS

by

SAYARI DAS

Department of Electrical Engineering

Submitted

in the fulfilment of the requirements of the degree of Doctor of Philosophy

to the



Indian Institute of Technology Delhi

October 2020

Dedicated

to

My Mother

CERTIFICATE

This is to certify that the thesis entitled “**Wide Area Monitoring and Protection for Stressed Power Systems**” submitted by **Ms. Sayari Das**, to Indian Institute of Technology Delhi for the award of degree of **Doctor of Philosophy (Ph.D.)** is a bonafide record of research work carried out by her under my supervision. The contents of this thesis have not been submitted to any other institute or university for the award of any degree or diploma.

Dr. Bijaya Ketan Panigrahi

Professor

Department of Electrical Engineering

Indian Institute of Technology Delhi

New Delhi-110016, India.

Date:

Acknowledgements

I am very much grateful to my Supervisor, **Prof. B.K. Panigrahi** whose supervision, encouragement and personal support from the preliminary to the concluding level enabled me to develop an understanding of the subject. It is an honor for me to have been working under his supervision and being part of his working group.

I express my indebtedness to Prof. N. Senroy and Prof. A.R. Abhyankar whose lectures on “Power System Dynamics” and Power System Analysis”, respectively have been instrumental in my research work.

I acknowledge my deep sense of gratitude to the members of doctoral research committee Prof. N. Senroy, Prof. A R. Abhyankar and Prof. Ashu Verma for their valuable suggestions and scrutiny of this work. I am also grateful to Prof. Sukumar Mishra for his co-operation and help in my research. I would like to express my sincere gratitude to Prof. S. P. Singh, who played an instrumental role in introducing me to the world of research.

I am indebted to all my seniors, especially, Dr. Rahul Dubey, Mr. Deep Kiran, Mr. Deepak Pullagurram, Mrs. Snigdha Rani Behera, Ms. Sirin Duttachoudhury, Mr. Ganesh P Prajapat, Mr. Pratyasa Bhui, Mr. Dushyant Sharma for providing a warm research atmosphere, sharing knowledge and personal support. I am also thankful to my friends and juniors, specially, Mr. Manas Kumar Jena, Mr. Abdul Saleem Mir, Ms. Ayesha Firdaus, Mr. Pankaj, Mr. Debasis Mishra, Mrs. Astha Chawla, Mrs. Vibhuti Nougain, Mr. Diptak Pal, Mr. Siva Raman, Mr. Rajiv Jha, Mrs. Parul Arora, Mr. Mudassir Maniar, Mr. Rishi Sharma, Mr. Subham Sahoo, Mr. Surya Prakash, Ms. Shruti, Ms. Tabia Ahmed, Ms. Megha Gupta, Ms. Shaziya Rashid and others who have helped me and made my life in IIT Delhi very exciting and a pleasant memory. I am also thankful to the technical and laboratory staff of the department, Mr. Anand Sansanwal and Mr. Gaurav Kumar for their support.

I owe my deepest gratitude to my mother Lopamudra Das, who has been my greatest strength, father, Bibhuti Bhusan Das, brother, Sayok Das and grandparents for their love, affection, care and constant encouragement throughout the research work. Finally, I wish to mention a very special acknowledgment to my parents-in-law, for their continuous support and co-operation.

Last but not the least, I deeply acknowledge the sacrifice and the moral support of my husband Mr. Rakesh Mohanty throughout my research work and I am very much thankful to him.

Sayari Das.
Sayari Das

Dated: 29.10.2020

Abstract

Maloperation of distance relay and lack of real-time visualization have been the primary reason of many power system blackouts. Modern power systems are highly interconnected for economics and reliability concerns, which has made them more vulnerable to stressed conditions. Stressed conditions in power systems often lead to these cascading outages. Identification of such stressed conditions by enhancing situational awareness has emerged as a research challenge. Invention of synchrophasor technology has facilitated precise monitoring of power system in real-time. In the recent years, the transmission sector is witnessing a boom in the installation of Phasor Measurement Units (PMU) which has led to an exponential growth in the amount of data available for use at the control centers or Phasor Data Concentrators (PDC). This thesis focuses on extraction of essential features from the data obtained from Wide Area Measurements (WAMS) and dynamic assessment of health of the system in order to enable the system operator to initiate remedial action schemes for preventing events capable of endangering the integrity of the system. In order to achieve these objective, schemes employing PMUs have been proposed for enhancing Wide Area Protection (WAP), Situational Awareness (SA) and suggesting appropriate System Integrity Protection Schemes (SIPS) for retaining system stability. The schemes are as follows:

- 1) A new intelligent philosophy based wide area protection (WABP) scheme is suggested for power transmission system. It uses PMU information for stress assessment in power system and accordingly enhances the security aspect. It also includes out of step protection.
- 2) Qualitative assessment on the impact of Thyristor controlled series capacitor (TCSC) on power swing and distance relay is studied. A new index is derived for secured operation of distance relay during power swings in TCSC compensated lines.
- 3) Enhancement of wide area SA in power transmission systems by using PMU measurements for devising indices in order to identify events by visualizing the underlying dynamics in power systems through Dynamic State Estimation (DSE).
- 4) Two different algorithms are reported as SIPS for enhancing transient stability and preventing voltage instability using WAMS information.

Keywords: Blackouts, Distance relays, Stress assessment, Power swing, Voltage instability, Wide Area Measurement Systems, Wide Area Protection, Wide Area Situational Awareness, Zone-3 supervision.

सार

दूरी रिले की खराबी और वास्तविक समय दृश्य की कमी कई बिजली प्रणाली ब्लैकआउट का प्राथमिक कारण रही है। आधुनिक पावर सिस्टम अर्थशास्त्र और विश्वसनीयता चिंताओं के लिए अत्यधिक परस्पर जुड़े हुए हैं, जिसने उन्हें तनावपूर्ण परिस्थितियों के लिए अधिक संवेदनशील बना दिया है। बिजली प्रणालियों में तनाव की स्थिति अक्सर इन कैस्केडिंग आउटेज की ओर ले जाती है। स्थितिजन्य जागरूकता को बढ़ाकर ऐसी तनावपूर्ण स्थितियों की पहचान एक शोध चुनौती के रूप में सामने आई है। सिंक्रोफासोर प्रौद्योगिकी के आविष्कार ने वास्तविक समय में बिजली व्यवस्था की सटीक निगरानी की सुविधा दी है। हाल के वर्षों में, ट्रांसमिशन सेक्टर में फेजर मेजरमेंट यूनिट्स (पीएमयू) की स्थापना में तेजी देखी जा रही है, जिसके कारण नियंत्रण केंद्रों या फेजर डेटा कंसेंट्रेटर (पीडीसी) में उपयोग के लिए उपलब्ध डेटा की मात्रा में तेजी आई है। यह थीसिस वाइड एरिया माप (डब्ल्यूएमएस) से प्राप्त डेटा से आवश्यक सुविधाओं के निष्कर्षण और सिस्टम के स्वास्थ्य के गतिशील मूल्यांकन पर केंद्रित है ताकि सिस्टम ऑपरेटर को सिस्टम की अखंडता को खतरे में डालने वाली घटनाओं को रोकने के लिए सुधारात्मक कार्रवाई योजनाओं को शुरू करने में सक्षम बनाया जा सके। । इन उद्देश्यों को प्राप्त करने के लिए, वाइड एरिया प्रोटेक्शन (डब्ल्यूएपी), सिचुएशनल अवेयरनेस (एसए) को बढ़ाने और सिस्टम स्थिरता बनाए रखने के लिए उपयुक्त सिस्टम इंटीग्रेटी प्रोटेक्शन स्कीम्स (एसआईपीएस) का सुझाव देने के लिए पीएमयू को नियोजित करने वाली योजनाओं का प्रस्ताव किया गया है। योजनाएं इस प्रकार हैं:

- 1) बिजली पारेषण प्रणाली के लिए एक नया बुद्धिमान दर्शन आधारित व्यापक क्षेत्र सुरक्षा (WABP) योजना का सुझाव दिया गया है। यह बिजली व्यवस्था में तनाव मूल्यांकन के लिए पीएमयू सूचना का उपयोग करता है और तदनुसार सुरक्षा पहलू को बढ़ाता है। इसमें आउट ऑफ स्टेप प्रोटेक्शन भी शामिल है।
- 2) पावर स्विंग और दूरी रिले पर थायरिस्टर नियंत्रित श्रृंखला संधारित्र (टीसीएससी) के प्रभाव पर गुणात्मक मूल्यांकन का अध्ययन किया जाता है। टीसीएससी मुआवजा लाइनों में बिजली झूलों के दौरान दूरी रिले के सुरक्षित संचालन के लिए एक नया सूचकांक प्राप्त होता है।
- 3) डायनामिक स्टेट एस्टीमेशन (डीएसई) के माध्यम से बिजली प्रणालियों में अंतर्निहित गतिशीलता की कल्पना करके घटनाओं की पहचान करने के लिए पीएमयू मापों का उपयोग करके बिजली पारेषण प्रणालियों में व्यापक क्षेत्र एसए की वृद्धि।

- 4) दो अलग-अलग एल्गोरिदम को क्षणिक स्थिरता को बढ़ाने और WAMS जानकारी का उपयोग करके वोल्टेज अस्थिरता को रोकने के लिए SIPS के रूप में सूचित किया जाता है।

कीवर्ड: ब्लैकआउट, दूरी रिले, तनाव मूल्यांकन, पावर स्विंग, वोल्टेज अस्थिरता, वाइड एरिया मापन सिस्टम, वाइड एरिया प्रोटेक्शन, वाइड एरिया सिचुएशनल अवेयरनेस, जोन -3 पर्यवेक्षण।

Content

Certificate	i
Acknowledgements	ii
Abstract	iii
Contents	vi
List of Figures	x
List of Tables	xiii
List of Abbreviations and Symbols	xiv
CHAPTER 1	1
1.1 General	1
1.2 State-of-Art & Research Motivation	2
1.3 Enhancing Wide Area Protection under stressed condition	3
1.3.1 Secured Zone 3 operation of distance relay	3
1.3.2 Prediction of Generator Out of Step (OOS)).....	5
1.4 Impact of Series Compensation on Power Swing Characteristic and Distance Relay Behavior	6
1.5 Situational awareness enhancement in power systems	8
1.6 System Integrity Protection Schemes (SIPS)	9
1.6.1 Enhancing Transient Stability	9
1.6.2 Prevention of Voltage Instability	11
1.7 Thesis Objective	12
1.8 Brief Overview of Work Done.....	13
1.9 Major Contributions from This Thesis Work.....	16
1.10 Thesis Organization.....	17
CHAPTER 2	19

2.1	General	19
2.2	Wide Area Measurement Systems	20
2.2.1	Phasor Measurement Units.....	20
2.2.2	Phasor Data Concentrator.....	21
2.2.3	Communication Platform	21
2.3	Potential Applications	22
2.3.1	Adaptive Relaying.....	22
2.3.2	Instability Prediction	23
2.3.3	State Estimation.....	24
2.3.4	System Integrity protection Schemes	24
2.4	Synchrophasor Technology	25
2.4.1	IEEE Standards	25
2.4.2	Reporting rate and Latency	26
2.5	Conclusion.....	26
CHAPTER 3		28
3.1	General	28
3.2	Secured Zone 3 Operation of Distance Relay	28
3.2.1	General	28
3.2.2	Proposed Methodology	29
3.2.3	Online Sequential-Extreme Learning Machine (OSELM).....	34
3.2.4	Result Analysis and Discussion	36
3.2.5	Final Remarks	46
3.3	Prediction of Generator Out of Step (OOS)).....	46
3.3.1	General	46
3.3.2	Proposed methodology	47
3.3.3	Results and Discussion.....	52
3.3.4	Final Remarks	63

3.4	Conclusion.....	64
CHAPTER 4		65
4.1	General	65
4.2	TCSC Compensated Transmission Lines.....	65
4.2.1	Basic TCSC module	65
4.2.2	Apparent impedance seen by the distance relay in an uncompensated line:	68
4.2.3	Apparent impedance seen by the distance relay in transmission line compensated by a TCSC:	69
4.3	Proposed Scheme	71
4.3.1	Empirical Wavelet Transform:.....	71
4.3.2	Application of EWT for discriminating power swing and fault.....	74
4.4	Results and Discussion.....	75
4.4.1	Influence of TCSC on apparent impedance trajectory during power swing	77
4.4.2	Impact of different values I_{ref} for TCSC on the impedance circles during power swing	78
4.4.3	Failure of the double blinder scheme for PSB	81
4.4.4	Differentiating fault and power swing using EWT	83
4.4.5	Performance of proposed technique (EI_{HF}) for faults during power swings:	86
4.4.6	Performance in the presence of noise in the measurement data.....	86
4.5	Conclusion.....	88
CHAPTER 5		89
5.1	General	89
5.2	Proposed Scheme	89
5.3	Cubature Kalman Filter-Unknown Input (CKF-UI)	94
5.4	Simulation results and case studies	100
5.4.1	Performance of the CKF-UI based DSE	100

5.4.2	Sensitivity to measurement errors:	102
5.4.3	Case Studies	102
5.4.4	Validation On Real-World PMU Data	106
5.5	Conclusion.....	107
CHAPTER 6		109
6.1	General	109
6.2	Enhancing Transient Stability	109
6.2.1	General	109
6.2.2	Proposed Methodology	110
6.2.3	Result Analysis.....	118
6.2.4	Final Remarks	122
6.3	Prevention of Voltage Instability	124
6.3.1	General	124
6.3.2	Proposed Scheme	124
6.3.3	Result and discussions.....	129
6.3.4	Final Remarks	134
6.4	Conclusion.....	135
CHAPTER 7		136
7.1	Summary of the Work	136
7.2	Scope of Future Work	137
Appendix A		150
Appendix B		152
Publications from the Thesis		156
Bio-Data		157

LIST OF FIGURES

Figure 2.1 Hierarchical structure in a typical WAMS infrastructure.....	20
Figure 2.2 A Generic PMU	22
Figure 3.1 Conceptual block Diagram for ensuring system security under stressed conditions ..	30
Figure 3.2 Flowchart of the proposed scheme	34
Figure 3.3 Learning Algorithm of Online Sequential Extreme Machine Learning.....	36
Figure 3.4 Schematic of the WSCC-9 bus system.....	37
Figure 3.5 Instantaneous Phase Voltage at bus 7 and Current on line 7-5	38
Figure 3.6 Impedance trajectory as seen by relay R ₇₅	38
Figure 3.7 RMS voltage at bus 5 and Q_{loss} in line connecting buses 5 and 7	39
Figure 3.8 Impedance trajectory as seen by relay R ₇₅	39
Figure 3.9 Mean Decrease Accuracy Plot and Mean Decrease Gini Plot	41
Figure 3.10 Correlation Plot of the input features for the proposed classifier.....	41
Figure 3.11 OSELM: No of neurons vs Classification accuracy.....	42
Figure 3.12 Active Power Flow for symmetrical fault during power swing	44
Figure 3.13 Real-time performance of the proposed classifier (a) Voltage (b) Current (c) Output of the Classifier	46
Figure 3.14 Suggested Framework for Secured and Alert System.....	48
Figure 3.15 Flowchart for the proposed technique	49
Figure 3.16 Opal-RT based testbed for testing the proposed scheme.....	53
Figure 3.17 Decision Tree for Decision Logic 1	55
Figure 3.18 Rotor Angle of the Generators	57
Figure 3.19 Out of Step Predictor (OS_g) at generator buses during out of step condition	58
Figure 3.20 Out of Step Predictor (OS_g) at generator buses during a stable swing.....	58
Figure 3.21 Decision Tree for Decision Logic 2	59
Figure 3.22 Impedance trajectory seen by relay R ₇₈ for fault	60
Figure 3.23 Performance of the DL1 for Power Swing.....	60
Figure 3.24 Voltage at relay location following a fault on line 7-8.....	61
Figure 3.25 Performance of the DL1 under Voltage Instability condition	61
Figure 3.26 Performance of two blinder scheme for a stable swing.....	62
Figure 4.1 Basic TCSC module	66

Figure 4.2 Conventional TCSC Constant Current control developed in RSCAD.....	67
Figure 4.3 Schematic of power system transmission line without compensation	68
Figure 4.4 Impedance circle diagrams for (a) uncompensated system (b) TCSC compensated system	69
Figure 4.5 Schematic of power system transmission line with TCSC.....	70
Figure 4.6 Architecture of the EWT algorithm.....	72
Figure 4.7 Flowchart for estimation of EI_{HF} using EWT	76
Figure 4.8 WSCC 9 bus system on RSCAD.....	77
Figure 4.9 (a) Relay voltage (b) Relay line current (c) Voltage across the series capacitor branch	78
Figure 4.10 Impedance seen by the relay R on line 6-9 in presence of TCSC	79
Figure 4.11 (a) $I_{ref}=0.21kA$ (b) $I_{ref}=0.22kA$ (c) $I_{ref}=0.23kA$ (d) $I_{ref}=0.24kA$	80
Figure 4.12 Influence of I_{ref} on firing angle-reactance characteristics.....	81
Figure 4.13 Performance of the Double Blinder scheme in blocking power swing	82
Figure 4.14 Detected Fourier supports for voltage signal during (a) Fault (b) Power Swing in EWT	84
Figure 4.15 Performance of EI_{HF} for fault and power swing.....	84
Figure 4.16 Entropy of high-frequency components for fault and power swing.....	85
Figure 4.17 Comparison of the proposed index EI_{HF} for different types of faults and power swing	85
Figure 4.18 Performance of the proposed index EI_{HF} for inception of fault during power swing.....	86
Figure 4.19 Performance of the proposed technique with noise in the measurements.....	87
Figure 5.1 PMU data (Freq. and ROCOF) for Indian Grid during certain events (a) Line fault (b) Generation event (c) Load event.....	90
Figure 5.2 Architecture of the system and overview of the methodology.....	91
Figure 5.3 Actual and simulated power flow in the California-Oregon tie line on Aug 10, 1996 [127].....	92
Figure 5.4 Schematic of IEEE 39 bus system.....	101
Figure 5.5 Performance of the CKF-UI	101
Figure 5.6 Performance of the CKF-UI with measurement noise	103
Figure 5.7 Performance of W_{PE1} for power system events.....	104

Figure 5.8 Performance of W_{PE2} for power system events.....	104
Figure 5.9 Performance of W_{PE3} for power system events.....	105
Figure 5.10 Performance of W_{PE4} for power system events.....	106
Figure 5.11 Section of the affected western grid	106
Figure 5.12 Frequency measurements from the PMUs in the affected western grid.....	107
Figure 5.13 Performance of W_{PE3} for real PMU data from the western grid	107
Figure 6.1 Framework for the proposed SIPS	111
Figure 6.2 Single machine infinite bus system: (a) Single Line diagram (b) EAC for stable case (c) EAC for unstable case (d) Timing diagram	112
Figure 6.3 Flowchart for the proposed SIPS.....	117
Figure 6.4 Generator Rotor angle for stable and unstable swing.....	119
Figure 6.5 Performance of SAS for a stable swing.....	119
Figure 6.6 Performance of SAS for unstable swing	119
Figure 6.7 ROCOVA($d\delta'/dt$) (a) Gen. 3 (stable) (b) Gen. 2(unstable)	121
Figure 6.8 Generator rotor angles for (a) Gen 2 and 3 for an unstable swing (b) Gen 2 with and without GS	123
Figure 6.9 Flowchart of the proposed methodology	128
Figure 6.10 IEEE 39 bus system.....	129
Figure 6.11 Voltage profile of the buses under voltage instability condition.....	130
Figure 6.12 Apparent impedance seen by the relay R_{26-29}	130
Figure 6.13 (a) Reactive power fed to load at bus 26 (b) Reactive power output of gen. 8 and 9 during VI.....	131
Figure 6.14 Performance of the proposed Voltage Instability Index.....	132
Figure 6.15 Voltage magnitude at buses after remedial action.....	134

LIST OF TABLES

Table 3.1 Performance evaluation of OSELM on the basis of chunk size	42
Table 3.2 Performance of different techniques for Classifier 1 with differential data	43
Table 3.3 Performance of the models in classifying Power Swing and Voltage instability	43
Table 3.4 Performance of Classifier 2	44
Table 3.5 Performance of the proposed Classifier for the series compensated system	45
Table 3.6 Confusion matrix generated after testing period.....	56
Table 3.7 Truth table for the proposed framework	56
Table 4.1 Output of timer for double blinder scheme.....	83
Table 6.1 Amount of Generator Shedding required to prevent transient instability.....	123
Table 6.2 Injection shift factors for loads on the IEEE 39 bus system	133

LIST OF ABBREVIATIONS AND SYMBOLS

AC	:	Alternating Current
ANFIS	:	Adaptive neuro fuzzy inference system
ARMA	:	Autoregressive moving average
CB	:	Circuit Breaker
CCT	:	Critical clearing time
CEA	:	Critical equivalent acceleration
CKF	:	Cubature Kalman filter
CT	:	Current Transformer
CTU	:	Central Transmission Utility
CWT	:	Continuous Wavelet Transform
dB	:	Decibel
DC	:	Direct Current
DFT	:	Discrete Fourier Transform
DSE	:	Dynamic state estimation
DT	:	Decision Tree
DWT	:	Discrete Wavelet Transform
EAC	:	Equal area criterion
ED	:	Event detection
El_{HF}	:	Entropy index for high frequency
EKF	:	Extended Kalman filter
EMD	:	Empirical mode decomposition
EMS	:	Energy management system
ER	:	Eastern Region
ETR	:	Expected tripped region
EWT	:	Empirical Wavelet Transform
FACTS	:	Flexible AC transmission systems
FFT	:	Fast Fourier Transform
Fps	:	Frames per second
FT	:	Fourier Transform

GB	:	Giga Bite
GPS	:	Global positioning systems
HVDC	:	High Voltage Direct Current
IEDs	:	Intelligent Electronic Devices
IEEE	:	Institute of Electrical and Electronic Engineers
IMF	:	Intrinsic mode function
KM	:	Kilometer
MHz	:	Mega Hertz
MOV	:	Metal Oxide Varistor
MVA	:	Mega Volt-Ampere
MW	:	Mega Watt
NLDC	:	National load dispatch centre
NN	:	Neural network
NR	:	Northern Region
NRPG	:	Northern Regional Power Grid
OOS	:	Out-of-step
OSELM	:	Online sequential extreme learning machines
PDC	:	Phasor data concentrator
PGCIL	:	Power Grid Corporation of India Limited
PMU	:	Phasor Measurement Unit
PPS	:	Pulse-per-second
PSRC	:	Power system relaying committee
PT	:	Potential Transformer
PZ	:	Protection zone
PS	:	Power Swing
PSB	:	Power swing blocking
RF	:	Random forest
RLDC	:	Regional Load Despatch Centre
ROCOF	:	Rate of change of frequency
ROCOVA	:	Rate of change of voltage angle
RTDS	:	Real Time Digital Simulator

SA	:	Situational awareness
SAS	:	Stability assessment scheme
SCADA	:	Supervisory control and data acquisition
SCV	:	Swing center voltage
SIPS	:	System integrity protection schemes
SMIB	:	Single machine infinite bus
SNR	:	Signal to Noise Ratio
SPEF	:	Structure preserving energy function
SPA	:	Synchronized phase angle
SPS	:	Stable power swing
SR	:	Southern Region
STFT	:	Short Time Fourier Transform
SVM	:	Support vector machine
TCSC	:	Thyristor controlled series capacitor
TVE	:	Total vector error
UKF	:	Unscented Kalman filter
UPS	:	Unstable power swing
UTC	:	Coordinated universal time
VI	:	Voltage instability
VII	:	Voltage instability index
WABP	:	Wide area back-up protection
WAMS	:	Wide Area Measurement Systems
WAP	:	Wide Area Protection
WAMPAC	:	Wide area monitoring, control, and protection
WASA	:	Wide Area Situational Awareness
WR	:	Western Region
WSCC	:	Western System Coordinating Council
WT	:	Wavelet Transform
C	:	Capacitance
f	:	Frequency

f_s	:	Sampling Frequency
I	:	Current
$\text{Im}(A)$	:	Imaginary Part of quantity 'A'
L	:	Inductance
$\text{Re}(A)$	:	Real Part of quantity 'A'
V	:	Voltage
Z	:	Impedance
Ω	:	Unit of resistance
δ	:	Phase angle
ω	:	Rotor speed
ω_s	:	Synchronous speed