WIDE AREA MONITORING AND PROTECTION FOR STRESSED POWER SYSTEMS

SAYARI DAS

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 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

<u>CERTIFICATE</u>

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.

Dated: 29.10.2020 Sayari Das

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 (डब्ल्यूएएमएस) 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 इंटीग्रिटी 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

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

AC	:	Alternating Current
ANFIS	:	Adapative 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
EI_{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	:	Statibility 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
Im(A) :	:	Imaginary Part of quantity 'A'
L	:	Inductance
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