

**APPLICATION OF SYNCHROPHASOR MEASUREMENTS
FOR ENHANCED BACK-UP PROTECTION AND
SITUATIONAL AWARENESS**

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FOR ENHANCED BACK-UP PROTECTION AND
SITUATIONAL AWARENESS**

by

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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

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Dedicated

to

My Brother KrishNa

CERTIFICATE

This is to certify that the thesis entitled “**Application of Synchrophasor Measurements for Enhanced Back-up Protection and Situational Awareness**” submitted by **Mr. Manas Kumar Jena**, 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 him under our supervision. The contents of this thesis have not been submitted to any other institute or university for the award of any degree or diploma.



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Abstract

Inadequate situational awareness along with mal-operations of distance relays are found out to be primary causes behind most of the cascaded outages/ blackouts. Certainly, nowadays the operators have to manage a more stressed power system. Stressed system condition stimulates the risk of cascading outages. Thus, enhancing situational awareness is the need of the hour. In the last decade, synchrophasor technology has emerged as one of the enabling technology. This technology enables real-time monitoring of large power system with adequate accuracy. Phasor measurement units (PMUs) are considered as the heart of synchrophasor technology. Further, number of PMUs installed across the power grid are increasing day by day. This results in a large amount of data being sent to the control centers/system protection centers. However, translating available data into actionable information remains a major challenge. This thesis intends to extract information from the synchronized phasor measurements and assesses system dynamics as quickly as possible to enhance Wide Area Protection (WAP) and Wide Area Situational Awareness (WASA). Different schemes have been suggested using PMU information in order to achieve this objective. The schemes are as follows:

- 1) A new adaptive dependability-security based wide area back-up protection (WABP) scheme is suggested for power transmission system. The scheme uses limited PMU information to accomplish the task of stress assessment in power system and shifts the dependability-security bias of the back-up protection operation adaptively.
- 2) Positive sequence voltage and current information from both ends of a transmission line are used to derive a new relaying signal termed as the phase angle of positive sequence integrated impedance (PAPSII), which helps in differentiating internal faults from other no-fault situations.
- 3) A decentralized approach based WABP scheme is suggested.
- 4) Four different algorithms are reported which enhance WASA in power transmission system. The algorithms include online line outage detection, vulnerable relay identification, supervisory zone-1 operation and dynamic stress assessment in power system.

Keywords: Blackouts, Cascaded tripping, Distance relays, Power swing, Stress assessment, Vulnerable relay, Wide Area Measurement Systems, Wide Area Protection, Wide Area Situational Awareness.

सार

दूरस्थ रिले के माल-संचालन के साथ अपर्याप्त स्थितिगत जागरूकता को अधिकांश कैस्केड आउटेज / ब्लैकआउट के पीछे प्राथमिक कारण माना जाता है। निश्चित रूप से, आजकल ऑपरेटरों को एक अधिक तनावग्रस्त बिजली व्यवस्था का प्रबंधन करना है। तनावग्रस्त सिस्टम की स्थिति कैस्केडिंग आउटेज के जोखिम को उत्तेजित करती है। इस प्रकार, परिस्थिति जागरूकता बढ़ाने के लिए समय की आवश्यकता है। पिछले दशक में, सिंक्रोफैसर प्रौद्योगिकी सक्षम प्रौद्योगिकी में से एक के रूप में उभरा है। यह तकनीक पर्याप्त शुद्धता के साथ बड़ी शक्ति प्रणाली की वास्तविक समय की निगरानी को सक्षम बनाता है। फासर माप इकाइयों (पीएमयू) को सिंक्रोफैसर प्रौद्योगिकी का दिल माना जाता है। इसके अलावा, बिजली ग्रिड में स्थापित पीएमयू की संख्या दिन-प्रतिदिन बढ़ रही है। इसके परिणामस्वरूप नियंत्रण केंद्र / सिस्टम सुरक्षा केंद्रों को बड़ी मात्रा में डेटा भेजा जा रहा है। हालांकि, उपलब्ध डेटा को क्रियाशील जानकारी में अनुवाद करना एक बड़ी चुनौती बनी हुई है। यह थीसिस सिंक्रनाइज़ किए गए फासर माप से जानकारी निकालने का इरादा रखती है और वाइड एरिया प्रोटेक्शन (डब्ल्यूएपी) और वाइड एरिया स्थिति जागरूकता (डब्ल्यूएसए) को बढ़ाने के लिए जितनी जल्दी संभव हो सके सिस्टम गतिशीलता का आकलन करती है। इस उद्देश्य को प्राप्त करने के लिए पीएमयू सूचना का उपयोग करके विभिन्न योजनाओं का सुझाव दिया गया है। योजनाएं निम्नानुसार हैं:

- 1) बिजली ट्रांसमिशन सिस्टम के लिए एक नई अनुकूली निर्भरता-सुरक्षा आधारित व्यापक क्षेत्र बैक-अप सुरक्षा (डब्ल्यूएबीपी) योजना का सुझाव दिया गया है। यह योजना बिजली प्रणाली में तनाव मूल्यांकन के कार्य को पूरा करने के लिए सीमित पीएमयू सूचना का उपयोग करती है और बैक-अप सुरक्षा संचालन की निर्भरता-सुरक्षा पूर्वाग्रह को अनुकूली रूप से बदल देती है।
- 2) सकारात्मक अनुक्रम वोल्टेज और ट्रांसमिशन लाइन के दोनों सिरों से वर्तमान जानकारी का उपयोग एक नए रिलेइंग सिग्नल को प्राप्त करने के लिए किया जाता है जिसे पॉजिटिव अनुक्रम एकीकृत प्रतिबाधा (पीएपीएसआईआई) के चरण कोण के रूप में जाना जाता है, जो अन्य दोषों की स्थिति से आंतरिक दोषों को अलग करने में मदद करता है।
- 3) एक विकेन्द्रीकृत दृष्टिकोण आधारित डब्ल्यूएबीपी योजना का सुझाव दिया जाता है।

- 4) चार अलग-अलग एल्गोरिदम रिपोर्ट किए जाते हैं जो बिजली ट्रांसमिशन सिस्टम में स्थितिगत जागरूकता को बढ़ाते हैं। एल्गोरिदम में ऑनलाइन लाइन आउटेज डिटेक्शन, कमजोर रिले पहचान, पर्यवेक्षी क्षेत्र -1 ऑपरेशन और पावर सिस्टम में गतिशील तनाव मूल्यांकन शामिल है।

कीवर्ड: ब्लैकआउट, कैस्केड ट्रिपिंग, दूरी रिले, पावर स्विंग, तनाव मूल्यांकन, कमजोर रिले, वाइड एरिया मापन सिस्टम, वाइड एरिया प्रोटेक्शन, वाइड एरिया स्टेटस जागरूकता।

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LIST OF ABBREVIATIONS AND SYMBOLS

AC	:	Alternating Current
BCF	:	Bus closest to the fault
CB	:	Circuit Breaker
CLDC	:	Central load dispatch center
CPC	:	Central protection center
CT	:	Current Transformer
CTU	:	Central Transmission Utility
CWT	:	Continuous Wavelet Transform
dB	:	Decibel
DC	:	Direct Current
DFT	:	Discrete Fourier Transform
DT	:	Decision Tree
DWT	:	Discrete Wavelet Transform
ED	:	Event detection
EMD	:	Empirical mode decomposition
EMS	:	Energy management system
ER	:	Eastern Region
ETR	:	Expected tripped region
FFT	:	Fast Fourier Transform
FIA	:	Fault Inception Angle
FLI	:	Faulted line identification
Fps	:	Frames per second
FT	:	Fourier Transform
GB	:	Giga Bite
GIM	:	Gain in momentum
GOIRMSF	:	Generator outage induced relay margin shift factor
Hz	:	Hertz
HV	:	Highly vulnerable
ICCP	:	Inter-Control Center Protocol

IEDs	:	Intelligent Electronic Devices
IEEE	:	Institute of Electrical and Electronic Engineers
IMF	:	Intrinsic mode function
IP	:	Internet Protocol
KM	:	Kilometer
LPC	:	Local protection center
LODF	:	Line outage distribution factor
LOIRMSF	:	Line outage induced relay margin shift factor
MHz	:	Mega Hertz
MOV	:	Metal Oxide Varistor
MVA	:	Mega Volt-Ampere
MW	:	Mega Watt
NER	:	North Eastern Region
NLDC	:	National load dispatch centre
NN	:	Neural network
NR	:	Northern Region
NRPG	:	Northern Regional Power Grid
OOS	:	Out-of-step
PAPSII	:	Phase angle of positive sequence integrated impedance
PDC	:	Phasor data concentrator
PGCIL	:	Power Grid Corporation of India Limited
PL	:	Protection logic
PMU	:	Phasor Measurement Unit
PPS	:	Pulse-per-second
PSRC	:	Power system relaying committee
PSS/E	:	Power System Simulation for Engineering
PSVM	:	Positive sequence voltage magnitude
PT	:	Potential Transformer
PZ	:	Protection zone
RCOAPSR	:	Relative center of active power speed reference
RCORPVR	:	Relative center of reactive power voltage reference

RF	:	Random forest
RLDC	:	Regional Load Despatch Centre
RM	:	Relay margin
ROCOF	:	Rate of change of frequency
RPC	:	Regional protection center
RTDS	:	Real Time Digital Simulator
SA	:	State assessment
SCADA	:	Supervisory control and data acquisition
SCC	:	Short circuit capacity
SCV	:	Swing center voltage
SNR	:	Signal to Noise Ratio
SLDC	:	State Load Despatch Centre
SPC	:	System protection centre
SPS	:	Stable power swing
SR	:	Southern Region
STFT	:	Short Time Fourier Transform
ST	:	Stock well Transform
SVM	:	Support vector machine
TPP	:	Transient potential power
TVE	:	Total vector error
UPS	:	Unstable power swing
UTC	:	Coordinated universal time
VMD	:	Variational mode decomposition
VPZ	:	Vulnerable protection zone
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
WAEWS	:	Wide area early warning system
WAEPS	:	Wide area early prevention system

WR	:	Western Region
WSCC	:	Western System Coordinating Council
WT	:	Wavelet Transform
A_i	:	Amplitude of Signal
C	:	Capacitance
C_1	:	Positive Sequence Component of Capacitance
C_0	:	Zero Sequence Component of Capacitance
E_S	:	Sending End Voltage of Source
E_R	:	Receiving End Voltage of Source
f	:	Frequency
f_s	:	Sampling Frequency
I	:	Current
$\text{Im}(V_A)$:	:	Imaginary Part of Voltage V_A
L	:	Inductance
L_1	:	Positive Sequence Inductance
L_0	:	Zero Sequence Inductance
R	:	Resistance
$\text{Re}(V_A)$:	:	Real Part of Voltage V_A
R_1	:	Positive Sequence Component of Resistance
R_0	:	Zero Sequence Component of Resistance
V	:	Voltage
Z	:	Impedance
Z_{L1}	:	Impedance of the Line Segment-1

Z_0	:	Zero Sequence Impedance of Transmission Line
Z_1	:	Positive Sequence Impedance of Transmission Line
Z_2	:	Negative Sequence Impedance of Transmission Line
Z_s	:	Source Impedance of Sending end Source
Z_r	:	Source Impedance of Receiving end Source
Ω	:	Unit of resistance
θ	:	Phase Angle between Voltage and Current
δ	:	Load Angle
Φ_i	:	Phase Angle of Signal