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

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

***by***

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

**to the**

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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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Dated: Manas Kumar Jena

# 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 (डब्ल्यूएएसए) 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।

# Content

## LIST OF FIGURES

## LIST OF TABLES

# 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 |
| $Im(V_A)$: | : | Imaginary Part of Voltage $V_A$ |
| L | : | Inductance |
| $L_1$ | : | Positive Sequence Inductance |
| $L_0$ | : | Zero Sequence Inductance |
| R | : | Resistance |
| $Re(V_A)$: | : | 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 |
| $\Omega$ | : | Unit of resistance |
| $\theta$ | : | Phase Angle between Voltage and Current |
| $\delta$ | : | Load Angle |
| $\Phi_i$ | : | Phase Angle of Signal |