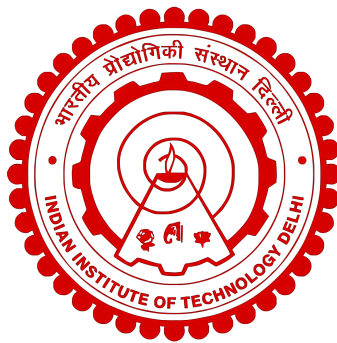


IMPACT ANALYSIS OF SOLAR PHOTOVOLTAIC ARRAY FAULTS ON POWER NETWORK

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JUNE 2025**

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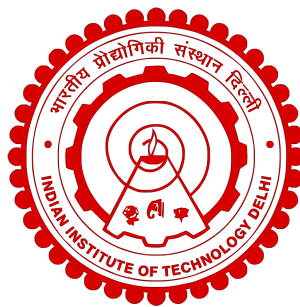
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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2025

I dedicate this dissertation to my parents

Certificate

This is to certify that the dissertation entitled **Impact Analysis of Solar Photovoltaic Array Faults on Power Network**, submitted by **Mr. Utkarsh Kumar**, a Research Scholar, in the *Department of Electrical Engineering, Indian Institute of Technology Delhi, New Delhi, India*, for the award of the degree of **Doctor of Philosophy**, is a record of an original research work carried out by him under my supervision and guidance. The dissertation fulfills all requirements as per the regulations of this Institute and in my opinion has reached the standard needed for submission. Neither this dissertation nor any part of it has been submitted for any degree or academic award elsewhere.

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— Utkarsh Kumar

Abstract

Solar photovoltaic (SPV) arrays can experience electrical issues like line-to-line (LL), open circuit (OC), and line-to-ground (LG) faults, leading to reduced efficiency, output power drops, voltage instability, and potential fire risks. To maintain stability in power distribution networks, particularly in the face of high impedance faults and low solar insolation, it is crucial to accurately pinpoint and identify these faults. Quantifying the power injection during high impedance array faults and faults under low insolation is challenging due to the maximum power point tracking control and the associated blocking and bypass diodes. Hence, this thesis focuses on elucidating the impact of these SPV array faults to develop efficient control, operation, and planning strategies for a renewable-integrated power system. In the initial phase, the work introduces an innovative approach using data-driven multi-modal transformation (MMT) to detect and classify such events. It also presents an MMT-aided support vector machine that uses only voltage magnitude data to identify SPV array faults and load variations. It incorporates a multi-class classification scheme for distinguishing between different types of SPV array faults. Additionally, a co-analysis method is outlined for precise fault location within a distribution system, along with a strategy for assessing the impact of SPV faults at various points across the network. The proposed method is efficient in terms of data usage. It has been validated through simulations on the modified IEEE 33-bus and CIGRE low-voltage benchmarks using PSCAD/EMTDC, demonstrating an enhanced accuracy and scalability compared to existing methods.

Later, the research extends to the panel-level diagnosis of SPV array faults. Changes in environmental conditions and nonlinear characteristics of solar cells make it challenging to identify faults by conventional protection schemes. Existing learning-based fault diagnosis approaches require voluminous data and sensors, making them costly and challenging to integrate with existing SPV systems. Moreover, the lack of panel-level monitoring in existing approaches renders them incapable of pinpointing the precise location of the faulty panel. To address these issues, this work proposes a methodology for detecting faults, localizing the exact faulty panel, and accurately classifying faults in SPV arrays. The methodology involves a sensorless electronic circuit using a bipolar junction transistor and Zener diode for fault detection, an IoT-based web application for monitoring individual solar panels for fault localization, and a deep autoencoder-based semi-supervised learning module followed by a hybrid support vector machine and logistic regression

for fault classification. The proposed methodology is a low-cost and less data-intensive solution that results in precise fault detection, exact faulty panel localization, and fault classification with an overall accuracy of 99.67%. The methodology is validated in a laboratory-scale, real-time setup of a grid-connected SPV system under varying electrical and environmental conditions.

Further, the thesis proposes a global sensitivity analysis (GSA) of output power to random SPV array faults to study the impact of the aforementioned SPV array faults. A data-driven approach based on the polynomial chaos Kriging method is proposed for the GSA. Four different state-of-the-art topologies of SPV array, namely, series-parallel, total-cross-tied, honey-comb, and bridge-linked, have been analyzed to determine power sensitivity to various electrical faults at different fault resistances. A sparse set of orthonormal polynomials approximate the global behavior, whereas analysis of variance kernel-based Kriging analyzes the local variability of the system output. This creates a hybrid metamodel that reflects the global relationship between the output power and random SPV array faults. With the developed metamodel, Sobol indices are calculated analytically to assess the sensitivity of outputs to the input variations, thus determining the severity of faults for array topology.

सार

सौर फोटोवोल्टिक (SPV) एरे में लाइन-टू-लाइन (LL), ओपन सर्किट (OC), और लाइन-टू-ग्राउंड (LG) जैसे विद्युत समस्याएं हो सकती हैं, जो दक्षता में कमी, आउटपुट पावर ड्रॉप, वोल्टेज अस्थिरता, और आग लगने के संभावित जोखिम का कारण बनती हैं। उच्च प्रतिबाधा दोषों और कम सौर विकिरण की स्थिति में बिजली वितरण नेटवर्क की स्थिरता बनाए रखने के लिए, इन दोषों को सटीक रूप से पहचानना और उनका स्थान निर्धारित करना अत्यंत आवश्यक है। उच्च प्रतिबाधा दोष और कम विकिरण स्थितियों में अधिकतम पावर प्वाइंट ट्रैकिंग नियंत्रण और संबंधित ब्लॉकिंग और बाईपास डायोड्स के कारण पावर इंजेक्शन को मात्रात्मक रूप से आंकना चुनौतीपूर्ण होता है। इसलिए, यह शोध SPV एरे दोषों के प्रभावों को स्पष्ट करने पर केंद्रित है, जिससे नवीकरणीय ऊर्जा से जुड़े पावर सिस्टम के लिए कुशल नियंत्रण, संचालन, और योजना रणनीतियां विकसित की जा सकें।

शुरुआती चरण में, यह कार्य डेटा-ड्रिवन मल्टी-मॉडल ट्रांसफॉर्मेशन (MMT) का उपयोग करते हुए इन घटनाओं का पता लगाने और वर्गीकृत करने के लिए एक अभिनव दृष्टिकोण प्रस्तुत करता है। यह वोल्टेज मैग्निट्यूड डेटा का उपयोग करके SPV एरे दोषों और लोड विविधताओं की पहचान के लिए एक MMT-सहायता प्राप्त सपोर्ट वेक्टर मशीन को प्रस्तुत करता है। इसमें SPV एरे दोषों के विभिन्न प्रकारों को अलग करने के लिए एक मल्टी-क्लास वर्गीकरण योजना भी शामिल है। इसके अतिरिक्त, वितरण प्रणाली के भीतर दोषों का सटीक स्थान निर्धारण और नेटवर्क के विभिन्न बिंदुओं पर SPV दोषों के प्रभाव का आकलन करने की एक रणनीति भी प्रस्तुत की गई है। प्रस्तावित पद्धति डेटा उपयोग के मामले में कुशल है। इसे PSCAD/EMTDC का उपयोग करके संशोधित IEEE 33-बस और CIGRE लो-वोल्टेज बेंचमार्क पर सिमुलेशन के माध्यम से मान्य किया गया है, जिससे मौजूदा विधियों की तुलना में सटीकता और मापनीयता में सुधार दिखाया गया है।

बाद में, शोध SPV एरे दोषों की पैनेल-स्तरीय निदान तक विस्तारित है। पर्यावरणीय परिस्थितियों में बदलाव और सोलर सेल्स की गैर-रेखीय विशेषताओं के कारण पारंपरिक सुरक्षा योजनाओं द्वारा दोषों की पहचान करना चुनौतीपूर्ण होता है। मौजूदा लर्निंग-आधारित दोष निदान दृष्टिकोणों को अधिक मात्रा में डेटा और सेंसर की आवश्यकता होती है, जो इन्हें महंगा और मौजूदा SPV सिस्टम के साथ एकीकृत करने में चुनौतीपूर्ण बनाता है। इसके अलावा, मौजूदा दृष्टिकोणों में पैनेल-स्तरीय निगरानी की कमी के कारण दोषपूर्ण पैनेल के सटीक स्थान का पता लगाने में अक्षमता होती है। इन समस्याओं के समाधान के लिए, यह कार्य दोषों का पता लगाने, सटीक दोषपूर्ण पैनेल का स्थान निर्धारित करने, और SPV एरे में दोषों का सटीक वर्गीकरण करने के लिए एक पद्धति प्रस्तुत करता है।

इस पद्धति में दोष का पता लगाने के लिए एक बाइपोलर जंक्शन ट्रांजिस्टर और जेनर डायोड का उपयोग करने वाला एक सेंसर-रहित इलेक्ट्रॉनिक सर्किट, व्यक्तिगत सोलर पैनेलों की निगरानी के लिए एक IoT-आधारित वेब एप्लिकेशन, और गहरे ऑटोएन्कोडर-आधारित अर्ध-पर्यवेक्षित लर्निंग मॉड्यूल शामिल है। इसके बाद हाइब्रिड सपोर्ट वेक्टर मशीन और लॉजिस्टिक रिग्रेशन का उपयोग दोष वर्गीकरण के लिए किया जाता है। प्रस्तावित पद्धति एक कम लागत और कम डेटा-गहन समाधान है, जो सटीक दोष पहचान, दोषपूर्ण पैनेल का सटीक स्थानीयकरण, और 99.67% समग्र सटीकता के साथ दोष वर्गीकरण सुनिश्चित करती है। इस पद्धति को विभिन्न विद्युत और पर्यावरणीय परिस्थितियों के तहत ग्रिड से जुड़े SPV सिस्टम के एक प्रयोगशाला स्तर के वास्तविक-समय सेटअप में मान्य किया गया है।

इसके अलावा, शोध SPV एरे दोषों के प्रभाव का अध्ययन करने के लिए आउटपुट पावर का वैश्विक संवेदनशीलता विश्लेषण (GSA) प्रस्तावित करता है। GSA के लिए बहुपद अराजकता क्रिगिंग विधि पर आधारित एक डेटा-ड्रिवन दृष्टिकोण प्रस्तुत किया गया है। SPV एरे की चार अलग-अलग अत्याधुनिक टोपोलॉजी, अर्थात्, श्रृंखला-समानांतर, पूर्ण-क्रॉस-बंधित, हनीकॉम्ब, और ब्रिज-लिंकड का विश्लेषण विभिन्न विद्युत दोषों के लिए आउटपुट पावर की संवेदनशीलता का निर्धारण करने के लिए किया गया है। ऑर्थोनॉर्मल बहुपदों के एक विरल सेट का उपयोग करके वैश्विक व्यवहार का सन्निकटन किया गया है, जबकि प्रणाली आउटपुट की स्थानीय भिन्नता का विश्लेषण करने के लिए वेरिऐंस कर्नल-आधारित क्रिगिंग का उपयोग किया गया है। यह एक हाइब्रिड मेटामॉडल

बनाता है, जो आउटपुट पावर और रडम SPV एर दाषा क बाच वाश्वक सबध का दशाता है। विकासत मटामाडल क साथ, इनपुट भिन्नताओं के प्रति आउटपुट की संवेदनशीलता का मूल्यांकन करने के लिए सोबोल इंडेक्स का विश्लेषणात्मक रूप से आकलन किया गया है, जिससे एरे टोपोलॉजी के लिए दोषों की गंभीरता का निर्धारण किया जा सके।

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List of Symbols

$\mathbf{X}_{\text{MMT},i}$	MMT spectrum of different transients
$\bar{\mathbf{X}}$	Column-wise data normalization
$\hat{\mathbf{X}}$	Outlier removal in the normalized dataset
$\dot{\mathbf{X}}$	Difference filter to capture event instants
$\bar{\bar{\mathbf{X}}}$	Regularization to neutralize data irregularities
\mathbf{X}_d	Convolutional de-noising to remove remnant noise
\mathbf{X}_Q	Data quantization for event vector
\mathbf{X}_F	Savitzky-Golay filtering for absolute instant record
$\mathbf{X}(\mathbf{O}_{n,i})$	Switch-over dataset
i_{pv}	SPV array current
V_C	Collector voltage
v_{pv}	SPV array voltage
BJT	Bipolar junction transistor
BL	Bridge-linked
DAE	Deep autoencoder
$FDEC$	Fault detection electronic circuit
$FMDAS$	Fault monitoring and data acquisition system
GSA	Global sensitivity analysis
HC	Honey combed
IoT	Internet of things
LC	Load change
LG	Line to ground
LL	Line to line
LR	Logistic regression
$LSTM$	Long short-term memory
$MPPT$	Maximum power point tracking
MMT	Multimodal transform

<i>OC</i>	Open circuit
<i>OCPD</i>	Over current protection device
<i>PCE</i>	Polynomial Chaos Expansion
<i>PCK</i>	Polynomial Chaos Kriging
<i>PSC</i>	Partial shading condition
<i>SPV</i>	Solar photovoltaic
<i>SP</i>	Series parallel
<i>SAF</i>	SPV array fault
<i>HISAF</i>	High impedance SPV array fault
<i>ZISAF</i>	Zero impedance SPV array fault
<i>SVM</i>	Support vector machine
<i>TCT</i>	Total cross tied