SMART IOT-ENABLED MONITORING AND CONTROL OF MODERN POWER GRID NETWORKS

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SMART IOT-ENABLED MONITORING AND CONTROL OF MODERN POWER GRID NETWORKS

by

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I dedicate this dissertation to my maa, bapi, bunu, and dadu

Certificate

This is to certify that the dissertation entitled **Smart IoT-Enabled Monitoring and Control of Modern Power Grid Networks**, submitted by **Mr. Akash Kumar Mandal**, 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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Akash Kumar Mandal

Abstract

The growth of power systems, influenced by rising demands and industrialization has led to complex challenges. The integration of renewables alongside traditional sources has introduced unpredictability in the generation, transmission, and distribution processes, resulting in wideband disturbance generation and propagation in modern grids. The integration of modern communication technologies into grid monitoring emphasizes the need for rigorous surveillance for ensuring a reliable power supply. Leading the transition to modern grid systems are Internet-of-Things (IoT) devices such as smart meters, digital relays, and notably, phasor measurement units (PMUs). PMUs offer accurate, time-stamped readings of essential system metrics, allowing for remote monitoring and potential real-time control via phasor data concentrators (PDCs). However, the voluminous PMU data presents processing challenges at PDCs.

While wireless connectivity offers adaptability and cost-effectiveness, it faces unique electromagnetic interference, especially in high-voltage scenarios. Phenomena like 'corona discharge' significantly impact wireless performance, making it essential to undertake its mathematical characterization. Characterizing these disturbances requires a broader perspective, encompassing electromagnetic spectra, emphasizing the significance of real-time communication and wideband impedance understanding. This dissertation research aims to fill this gap, wherein it investigates and proposes novel strategies for stability and control of perturbation-prone power networks by using smart IoT-based grid monitoring and control. Throughout the study it explores the relationship between power system-specific noise and wireless IoT node communication essential for real-time monitoring and control of such grids. Using PMU-to-PDC communication as an example, the study aims to address challenges and potential solutions in this domain.

Specifically, the study focuses on: 1) analyzing perturbation-prone power networks, 2) optimal placement of grid monitoring nodes, 3) analysis of wireless communication in smart grid environment, and 4) analysis of real-time data from grid monitoring IoTs. The research starts with modeling wideband power network disturbances and understanding their propagation. A novel device design for identifying harmonic sources in perturbed power networks is proposed. The high sampling rate requirement by these devices for capturing the precise perturbation characteristics, motivated the need to develop a real-time multivariate data pruning framework. The proposed data pruning strategy is validated on real-time data from field deployed PMUs. The proposition of node-level data

pruning is extended to develop a network-level data pruning framework in optimally deployed PMUs in a network-wide setup. The PMU placement optimization is revisited in the process to ensure efficient communication bandwidth utilization while attaining a optimal power network observability. Analysis of IoT data transfer over smart grid wireless communication channels is undertaken and methods to mitigate the smart grid specific performance deterioration are suggested. To implement the channel state-aware solutions proposed through the aforementioned performance analysis, a channel estimation strategy for smart grid impulse noise-ridden channels is introduced. Finally, the received data from the grid monitoring IoTs is utilized in characterizing the wideband disturbance profile in modern-day perturbed power networks. Consequently, a novel optimization formulation is proposed for the grid monitoring IoT nodes, which can ensure a real-time reliable control of perturbed power networks. All the optimizations and their solutions are validated on standard IEEE test systems of various capacity, network size, and architecture.

सारांश

बढ़ती माँगों और औद्योगीकरण से प्रभावित बिजली प्रणालियों के विकास ने जटिल चुनौतियों को जन्म दिया है। पारंपरिक स्रोतों के साथ नवीकरणीय ऊर्जा के एकीकरण ने उत्पादन, पारेषण और वितरण प्रक्रियाओं में अप्रत्याशितता ला दी है, जिसके परिणामस्वरूप आधुनिक ग्रिडों में वाइडबैंड गड़बड़ी उत्पन्न और प्रसार हुआ है। ग्रिड निगरानी में आधुनिक संचार प्रौद्योगिकियों का एकीकरण विश्वसनीय बिजली आपूर्ति सुनिश्चित करने के लिए कठोर निगरानी की आवश्यकता पर जोर देता है। आधुनिक ग्रिड प्रणालियों में परिवर्तन का नेतृत्व करने वाले इंटरनेट-ऑफ-थिंग्स (IoT) उपकरण जैसे स्मार्ट मीटर, डिजिटल रिले और विशेष रूप से, चरण माप इकाइयाँ (PMU) हैं। पीएमयू आवश्यक सिस्टम मेट्रिक्स की सटीक, समय-मुद्रांकित रीडिंग प्रदान करते हैं, जिससे चरण डेटा कंसंट्रेटर (पीडीसी) के माध्यम से दूरस्थ निगरानी और संभावित वास्तविक समय नियंत्रण की अनुमति मिलती है। हालाँकि, भारी मात्रा में पीएमयू डेटा पीडीसी में प्रसंस्करण चुनौतियाँ प्रस्तुत करता है।

जबकि वायरलेस कनेक्टिविटी अनुकूलनशीलता और लागत-प्रभावशीलता प्रदान करती है, यह विशेष रूप से उच्च-वोल्टेज परिदृश्यों में अद्वितीय विद्युत चुम्बकीय हस्तक्षेप का सामना करती है। 'कोरोना डिस्चार्ज' जैसी घटनाएं वायरलेस प्रदर्शन पर महत्वपूर्ण प्रभाव डालती हैं, जिससे इसका गणितीय लक्षण वर्णन करना आवश्यक हो जाता है। इन गड़बड़ियों को चित्रित करने के लिए एक व्यापक परिप्रेक्ष्य की आवश्यकता होती है, जिसमें विद्युत चुम्बकीय स्पेक्ट्रा शामिल होता है, जो वास्तविक समय संचार और वाइडबैंड प्रतिबाधा समझ के महत्व पर जोर देता है। इस शोध प्रबंध अनुसंधान का उद्देश्य इस अंतर को भरना है, जिसमें यह स्मार्ट IoT-आधारित ग्रिड निगरानी और नियंत्रण का उपयोग करके गड़बड़ी-प्रवण बिजली नेटवर्क की स्थिरता और नियंत्रण के लिए नई रणनीतियों की जांच और प्रस्ताव करता है। पूरे अध्ययन के दौरान यह ऐसे ग्रिडों की वास्तविक समय की निगरानी और नियंत्रण के लिए आवश्यक बिजली प्रणाली-विशिष्ट शोर और वायरलेस IoT नोड संचार के बीच संबंधों का पता लगाता है। उदाहरण के तौर पर पीएमयू-टू-पीडीसी संचार का उपयोग करते हुए, अध्ययन का उद्देश्य इस क्षेत्र में चुनौतियों और संभावित समाधानों का समाधान करना है।

विशेष रूप से, अध्ययन इस पर केंद्रित है:

1) गड़बड़ी-प्रवण बिजली नेटवर्क का विश्लेषण,

2) ग्रिड मॉनिटरिंग नोड्स का इष्टतम स्थान,

3) स्मार्ट ग्रिड वातावरण में वायरलेस संचार का विश्लेषण, और

4) ग्रिड मॉनिटरिंग IoTs से वास्तविक समय डेटा का विश्लेषण।

अनुसंधान वाइडबैंड पावर नेटवर्क गड़बड़ी के मॉडलिंग और उनके प्रसार को समझने के साथ शुरू होता है। अव्यवस्थित विद्युत नेटवर्क में हार्मोनिक स्रोतों की पहचान के लिए एक नवीन उपकरण डिज़ाइन प्रस्तावित है। सटीक गड़बड़ी विशेषताओं को पकड़ने के लिए इन उपकरणों द्वारा उच्च नमूना दर की आवश्यकता ने वास्तविक समय बहुभिन्नरूपी डेटा प्रूनिंग ढांचे को विकसित करने की आवश्यकता को प्रेरित किया। प्रस्तावित डेटा प्रूनिंग रणनीति को क्षेत्र में तैनात पीएमयू से वास्तविक समय के डेटा पर मान्य किया गया है। नेटवर्क-वाइड सेटअप में इष्टतम रूप से तैनात पीएमयू में नेटवर्क-स्तरीय डेटा प्रूनिंग ढांचे को विकसित करने के लिए नोड-स्तरीय डेटा प्रूनिंग का प्रस्ताव बढ़ाया गया है। इष्टतम पावर नेटवर्क अवलोकन प्राप्त करते समय कुशल संचार बैंडविड्थ उपयोग सुनिश्चित करने के लिए प्रक्रिया में पीएमयू प्लेसमेंट अनुकूलन पर दोबारा गौर किया गया है। स्मार्ट ग्रिड वायरलेस संचार चैनलों पर IoT डेटा ट्रांसफर का विश्लेषण किया जाता है और स्मार्ट ग्रिड विशिष्ट प्रदर्शन में गिरावट को कम करने के तरीके सुझाए

जाते हैं। उपर्युक्त प्रदर्शन विश्लेषण के माध्यम से प्रस्तावित चैनल राज्य-जागरूक समाधानों को लागू करने के लिए, स्मार्ट ग्रिड आवेग शोर-ग्रस्त चैनलों के लिए एक चैनल अनुमान रणनीति पेश की गई है। अंत में, ग्रिड मॉनिटरिंग IoTs से प्राप्त डेटा का उपयोग आधुनिक समय के परेशान बिजली नेटवर्क में वाइडबैंड गड़बड़ी प्रोफ़ाइल को चिह्नित करने में किया जाता है। नतीजतन, ग्रिड मॉनिटरिंग IoT नोड्स के लिए एक उपन्यास अनुकूलन फॉर्मूलेशन प्रस्तावित है, जो परेशान बिजली नेटवर्क का वास्तविक समय विश्वसनीय नियंत्रण सुनिश्चित कर सकता है। सभी अनुकूलन और उनके समाधान विभिन्न क्षमता, नेटवर्क आकार और वास्तुकला के मानक IEEE परीक्षण प्रणालियों पर मान्य हैं।

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$X, R; R', L', G', C'$	Power line parameters
ω	Objective frequency, e.g., grid, signal, statistical, based on context
$A_w(f)$	Amplitude attenuation
v_p	Phase velocity
$\tau_{d,m}(f)$	Delay in the fth frequency component for the mth path
$L(f,t), g_m(f)e^{-\phi_{g_m}(f)}$	Number of multipaths, complex gain
z_i, κ_i	Transient impedance, spike impedance
N, a_k	Filter order, filter coefficients
$\boldsymbol{\mu}_r, \boldsymbol{\Sigma}_r, \boldsymbol{\omega}_r$	Mean vector, covariance matrix, LDA projection vector
$A_i = \{A_i^1, \cdots, A_i^n\}^T$	ith sample of n attributes from the PMU dataset
ω_{A_i}, Φ_{A_i}	SVR weight matrix, nonlinear mapping from input to feature space
$e_B, e_{NB}, \varepsilon_{th,\nu}$	Error in base attributes, error in non-base attributes, error threshold
c_i, o_i	Current channels in the PMU installed at node i, order of node i
$\tilde{x}_{i,D_j}^t, x_{i,D_j}^t, \Delta x_{i,D_j}^t$	Reconstructed value, true value, reconstruction error
$Pr(\mathcal{Z})$	Probability of monitoring line $L_{i,j}$
$\boldsymbol{\theta}_\nu$	Spatial error propagated in the νth pseudo-measurement
$\mathbf{C}_P, \mathbf{G}(\mathbf{U})$	PMU cost matrix, observability constraint matrix
$\mathbf{V}, \mathbf{F}(\mathbf{U})$	PMU observability weight matrix, bandwidth saving matrix
$E_i, I_{i,j}$	Voltage of bus i, current in transmission line i-j
$\tau_{\alpha_c,\beta_c}, \Lambda_{\alpha_c}, T_{\alpha_c,\beta_c}$	Reference duration, impulse duration, pulse arrivals process
A_c	Total number of time varying CIN sources
B_{α_c}	Total number of impulse states, $\alpha_c \in [1, A_c]$, $\beta_c \in [1, B_{\alpha_c}]$
d_{α_c}	Distance of α_c-th CIN source from receiver
η	Power path loss exponent, $\eta \in [2, 4]$
$h_{\alpha_c,\beta_c}e^{\theta_{\alpha_c,\beta_c}}$	Channel impulse response at receiver
$F_{\alpha_c,\beta_c}e^{j\phi_{\alpha_c,\beta_c}}$	Receiver narrow-band filtering
$T_{\alpha_c,\beta_c}, \tau_{\alpha_c,\beta_c}$	Duration of β_c-th impulse from α_c-th

$\nVdash(\cdot)$	Indicator ensuring activity of the impulse
T	Observation time frame for CIN modeling
ω_I, ω_Q	Moment generating variables for in-phase and quadrature components
$(\lambda_s, \mu_s), (\lambda_I, \mu_I)$	Rate of generation (ROG) and mean life couple
p, q	Number of interferer clusters and interferers per cluster
D, Q_p	Random number of active clusters and active interferer/cluster
$g_{p,q}, X_{p,q}$	i.i.d. random fast fading, random emission
$\lambda, \lambda_p, \mu_p, r_e$	ROG of CCI sources, impulses/source, mean life, cluster radius
P_t, P_r, P_I, P_n	Transmit power, received signal, impulse noise, and receiver noise
$\hat{H}_{LS}$	Least square estimate of channel H
$R_{H_sH_s}$	Channel auto-correlation matrix
f_t, i_t, o_t	Forget gate, input gate, output gate of LSTM
$\mathbf{F}_{\mathrm{S}}, \mathbf{F}_{\mathrm{I}}$	System matrix, input matrix
$\mathbf{G}_{\mathrm{S}}, \mathbf{G}_{\mathrm{I}}$	Output matrix, feed-forward matrix
$\mathfrak{Z}$	Hypotheses
$\mathbf{A}_l$	Average line observability reward matrix
$\mathbf{A}$	Grid incidence matrix
$\gamma, \overline{\gamma}$	Signal-to-noise-ratio (SNR), average SNR
f_m	Fade margin
f_D	Doppler frequency
T_P	Average throughput