

**CYBER-PHYSICAL SECURITY OF SMART
GRID AND ADVANCED METERING
INFRASTRUCTURE**

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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by

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DEPARTMENT OF ELECTRICAL ENGINEERING

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Certificate

This is to certify that the thesis entitled “**Cyber-Physical Security of Smart Grid and Advanced Metering Infrastructure**” being submitted by **Mr. Sandeep Kumar Singh** to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is the record of bonafide research work carried out by him under my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other University or Institute for the award of any degree or diploma.

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Dedicated to my parents
Mr. Shiv Singh and Mrs. Vimla
and
my lovely wife
Mrs. Shaloo Yadav

Abstract

The power grid has become an essential part of the present-day society. People's day-to-day life will be affected dramatically without a reliable and stable power grid. Therefore, nations have been modernising their existing power system into the smart grid with advanced information system and communication technologies. The control and operation of the smart grid relies on complex cyberspace of communication and information technologies, computers, and software. Due to the integration and dependency on cyber infrastructure, the possibilities of cyber-physical threats also increases. Cyber attack is one of the key threat in the smart grid system. Advanced Metering Infrastructure (AMI) play an important role in the smart grid. AMI has modernized the electricity metering system by replacing mechanical and digital meters with smart meters. While some security mechanism has been developed for cyber threats in smart meters, they are not sufficient to prevent attacks. So there is a need of strong defence mechanism to detect cyber threats in smart meters.

In this thesis, we investigate cyber-physical security challenges in smart grid and AMI; and propose several defence algorithms for detecting cyber attacks. Our work includes three parts.

In the first part of the thesis, we address the cyber-physical security of the smart grid. We present a method to detect a relatively new type of cyber-attack called false data injection (FDI) attacks in smart grid. The FDI attacks are one of the most thoroughly researched cyber-attacks. Intelligently crafted, it can cause false estimation of states, which seriously affects the entire power system operation. We have introduced the state estimation process, bad data detection method and the formulation of FDI attacks. To detect FDI attacks, we propose a transformation-based method

by transforming the measurement variation, which enhances the resolution (scaling) of the probability distribution function, thereby, increasing the detection probability. In the proposed method, the probability distribution of measurement variations is obtained from the histogram plot of measurement variations. The chosen transformation techniques are computationally efficient and detect the FDI attacks without burdening the state estimation process. The proposed method is tested using IEEE 14 bus system considering attack on different state variables. The performance of the proposed transformation-based scheme is also tested under different topologies.

In the second part of the thesis, we address the problem of cyber-physical security of AMI. AMI, one of the prime components of the smart grid, has many benefits like the demand response and load management. Electricity theft is a key concern in AMI security since smart meters used in AMI are vulnerable to cyber-attacks. In the light of this problem, we have proposed a statistical distance based electricity theft detection scheme to detect theft attacks by tracking the dynamics of consumption variations of the consumers. Different statistical distances are used to compute the distance between probability distributions obtained from the consumption data. When electricity theft attacks are launched against AMI, the probability distribution of the consumption data deviates from historical consumption, thus leading to a larger statistical distance. To test the performance of the proposed method, we have used real smart meters consumption data. A wide range of attack patterns is generated using synthetic attack dataset. Extensive experiments on real dataset show the effectiveness of the proposed method.

In the third part of the thesis, we address the issue of large dimensional AMI data. Smart meters send consumption measurement data to the control center at predefined time intervals. Hence, large dimensional data is stored at the control center. To handle this large sized data, we have applied Principal Component Analysis (PCA) to the large dimensional AMI data, computed different Principal components (PCs) and transformed the data to the low dimensional AMI data. The first PC retains the maximum variance, the second PC retains the second largest variance and so on. To detect the electricity theft attacks, we propose three different detection methodologies. In the first method, we reconstruct the consumption data using PCs and compute Kullback-Leibler distance. In the second method, we propose an anomaly score based electricity

theft detection in which anomaly score at each time step is computed and threshold based detection is made. In the third method, we propose Mahalanobis distance based electricity theft detection. In this method, we project the AMI data on the PCs space and compute Mahalanobis distance of the test data from the historical data set. We have classified the testing data as malicious or true based on the computed Mahalanobis distance. We have tested the proposed detection methods for different attack scenarios using real smart meter data. The performance of the proposed schemes are compared with the existing SVM based theft detector.

सार

पावर ग्रिड आज के समाज का एक अनिवार्य हिस्सा बन गया है। लोगो का दिन-प्रतिदिन का जीवन एक भरोसेमंद और स्थिर पावर ग्रिड के बिना नाटकीय रूप से प्रभावित होगा। इसलिए, राष्ट्र उन्नत सूचना प्रणाली और संचार प्रौद्योगिकियों के साथ स्मार्ट ग्रिड में अपनी मौजूदा पावर सिस्टम का आधुनिकीकरण कर रहे हैं। स्मार्ट ग्रिड का नियंत्रण और संचालन संचार और सूचना प्रौद्योगिकी, कंप्यूटर और सॉफ्टवेयर के जटिल साइबर स्पेस पर निर्भर करता है। साइबरइन्फ्रास्ट्रक्चर पर एकीकरण और निर्भरता के कारण, साइबर-भौतिक खतरों की संभावनाएं भी बढ़ जाती हैं। स्मार्ट ग्रिड सिस्टम में साइबर हमला महत्वपूर्ण खतरा है। उन्नत मीटरिंग इंफ्रास्ट्रक्चर (एएमआई) स्मार्ट ग्रिड में एक महत्वपूर्ण भूमिका निभाते हैं। एएमआई ने यांत्रिक और डिजिटल मीटर की जगह स्मार्ट मीटर का उपयोग कर के बिजली मीटरिंग प्रणाली का आधुनिकीकरण किया है। जबकि स्मार्ट मीटर में साइबर खतरों के लिए कुछ सुरक्षा तंत्र विकसित किए गए हैं, वे हमलों को रोकने के लिए पर्याप्त नहीं हैं। इसलिए स्मार्ट मीटर में साइबर खतरों का पता लगाने के लिए मजबूत रक्षा तंत्र की आवश्यकता है।

इस थीसिस में, हम स्मार्ट ग्रिड और एएमआई में साइबर-भौतिक सुरक्षा चुनौतियों की जांच करते हैं; और साइबर हमलों का पता लगाने के लिए कई रक्षा एल्गोरिदम प्रस्तावित करते हैं। हमारे काम में तीन हिस्से शामिल हैं।

थीसिस के पहले भाग में, हम स्मार्ट ग्रिड की साइबर-भौतिक सुरक्षा को संबोधित करते हैं। हम स्मार्ट ग्रिड में झूठे डेटा इंजेक्शन (एफडीआई) हमलों नामक एक अपेक्षाकृत नए प्रकार के साइबर हमले का पता लगाने के लिए एक विधि प्रस्तुत करते हैं। एफडीआई हमले सबसे अच्छी तरह से शोध किए गए साइबर हमलों में से एक हैं। समझदारी से तैयार की गई, यह स्टेट्स के झूठे अनुमान का कारण बन सकती है, जो पूरे पावर सिस्टम ऑपरेशन को गंभीरता से प्रभावित करती है। हमने स्टेट्स अनुमान प्रक्रिया, खराब डेटा पहचान विधि और एफडीआई हमलों के निर्माण की शुरुआत की है। एफडीआई हमलों का पता लगाने के लिए, हम माप भिन्नता को बदलकर एक परिवर्तन-आधारित विधि का प्रस्ताव देते हैं, जो प्रोबेबिलिटी डिस्ट्रीब्यूशन फंक्शन के रिजॉल्यूशन (स्केलिंग) को बढ़ाता है, जिससे पता लगाने की संभावना बढ़ जाती है। प्रस्तावित विधि में, मापन भिन्नता का प्रोबेबिलिटी डिस्ट्रीब्यूशन फंक्शन मापन भिन्नता के हिस्टोग्राम से प्राप्त किया जाता है। चयनित परिवर्तन तकनीक कम्प्यूटेशनल रूप

से कुशल हैं और स्टेट्स अनुमान प्रक्रिया को बोज़ किए बिना एफडीआई हमलों का पता लगाती हैं। विभिन्न स्टेट्स पर हमले पर विचार करते हुए आईईईई 14 बस प्रणाली का उपयोग करके प्रस्तावित विधि का परीक्षण किया जाता है। प्रस्तावित परिवर्तन-आधारित योजना का प्रदर्शन विभिन्न टोपोलॉजीज के तहत भी किया जाता है।

थीसिस के दूसरे भाग में, हम एएमआई की साइबर-भौतिक सुरक्षा की समस्या का समाधान करते हैं। स्मार्ट ग्रिड के प्रमुख घटकों में से एक एएमआई में मांग प्रतिक्रिया और लोड प्रबंधन जैसे कई फायदे हैं। एएमआई सुरक्षा में विद्युत चोरी एक महत्वपूर्ण चिंता है क्योंकि एएमआई में इस्तेमाल होने वाले स्मार्ट मीटर साइबर हमलों के लिए कमजोर हैं। इस समस्या के प्रकाश में, हमने उपभोक्ताओं की खपत भिन्नताओं की गतिशीलता को ट्रैक करके चोरी हमलों का पता लगाने के लिए एक सांख्यिकीय दूरी आधारित बिजली चोरी पहचान योजना का प्रस्ताव दिया है। कंसम्पशन डेटा से प्राप्त प्रोबेबिलिटी डिस्ट्रीब्यूशन के बीच की दूरी की गणना करने के लिए विभिन्न सांख्यिकीय दूरी का उपयोग किया जाता है। जब एएमआई के खिलाफ बिजली चोरी हमले शुरू किए जाते हैं, कंसम्पशन डेटा का प्रोबेबिलिटी डिस्ट्रीब्यूशन ऐतिहासिक कंसम्पशन से विचलित हो जाता है, इस प्रकार एक बड़ी सांख्यिकीय दूरी की ओर अग्रसर होता है। प्रस्तावित विधि के प्रदर्शन का परीक्षण करने के लिए, हमने वास्तविक स्मार्ट मीटर कंसम्पशन डेटा का उपयोग किया है। सिंथेटिक अटैक डेटासेट का उपयोग करके अटैक पैटर्न की एक विस्तृत श्रृंखला उत्पन्न होती है। वास्तविक डेटासेट पर व्यापक प्रयोग प्रस्तावित विधि की प्रभावशीलता दिखाते हैं।

थीसिस के तीसरे हिस्से में, हम बड़े आयामी एएमआई डेटा के मुद्दे को संबोधित करते हैं। स्मार्ट मीटर पूर्ववर्ती समय अंतराल पर नियंत्रण केंद्र में कंसम्पशन माप डेटा भेजते हैं। इसलिए, नियंत्रण केंद्र पर बड़े आयामी डेटा संग्रहीत किया जाता है। इस बड़े आकार के डेटा को संभालने के लिए, हमने प्रिंसिपल कंपोनेंट एनालिसिस (पीसीए) को बड़े आयामी एएमआई डेटा पर लागू किया है, विभिन्न प्रिंसिपल घटकों (पीसी) की गणना की और डेटा को कम आयामी एएमआई डेटा में बदल दिया। पहला पीसी अधिकतम वैरिअन्स बरकरार रखता है, दूसरा पीसी दूसरा सबसे बड़ा वैरिअन्स बरकरार रखता है। बिजली चोरी हमलों का पता लगाने के लिए, हम तीन अलग-अलग पहचान पद्धतियों का प्रस्ताव देते हैं। पहली विधि में, हम पीसी का उपयोग कर कंसम्पशन डेटा का पुनर्निर्माण करते हैं और कुलबैक-लीबलर दूरी की गणना करते हैं। दूसरी विधि में, हम एक एनोमली स्कोर आधारित विद्युत चोरी का पता लगाने का प्रस्ताव करते हैं

जिसमें प्रत्येक समय चरण में एनोमली स्कोर गणना की जाती है और थ्रेसहोल्ड आधारित पहचान की जाती है। तीसरी विधि में, हम महालानोबिस दूरी आधारित बिजली चोरी पहचान का प्रस्ताव देते हैं। इस विधि में, हम पीसी स्पेस पर एएमआई डेटा प्रोजेक्ट करते हैं और ऐतिहासिक डेटा सेट से परीक्षण डेटा की महालानोबिस दूरी की गणना करते हैं। हमने गणना डेटा को गणना की गई महालानोबिस दूरी के आधार पर असत्य या सत्य डेटा के रूप में देखा है। हमने वास्तविक स्मार्ट मीटर डेटा का उपयोग करके विभिन्न हमले परिदृश्यों के लिए प्रस्तावित पहचान विधियों का परीक्षण किया है। प्रस्तावित योजनाओं का प्रदर्शन मौजूदा एसवीएम आधारित चोरी डिटेक्टर के साथ तुलना की जाती है।

Table of Contents

Certificate	i
Acknowledgements	ii
Abstract	iv
List of Figures	xvi
List of Tables	xxii
List of Algorithms	xxvi
List of Abbreviations	xxviii
1 Introduction	1
1.1 Background	1
1.2 Cyber-Physical Attacks in Smart Grid	1
1.3 Cyber-Physical Attacks in Advanced Metering Infrastructure	4

1.4	Thesis Organization and Contribution	7
1.4.1	Main Contributions in Thesis	10
2	Literature Survey	13
2.1	Cyber-Physical Security of Smart grid	13
2.1.1	Protection-based Defence	14
2.1.2	Detection-based Defence	14
2.2	Cyber-Physical Security of AMI	16
2.2.1	State-based Methods	16
2.2.2	Game theory-based Methods	17
2.2.3	Classification-based Methods	18
2.3	Research Gaps and Motivation	20
2.4	Research Objectives	22
2.5	Summary	23
3	Detection of False Data Injection Attacks in AC State Estimation in Smart Grid	25
3.1	Introduction	25
3.2	System Model	26
3.2.1	Network Model	26
3.2.2	Attack Model	27

3.2.3	Security Requirements and Design Goals	27
3.3	Formulation of FDI Attacks in AC state Estimation	28
3.3.1	State Estimation	28
3.3.2	WLS State Estimation Algorithm	33
3.3.3	Bad Data Detection	34
3.3.4	False Data Injection Attacks	36
3.3.5	Attack Formulation	37
3.4	Proposed Detection Methodology against FDI attacks	38
3.4.1	Transformation Schemes	38
3.4.2	Kullback-Leibler Distance	41
3.4.3	Threshold Selection	42
3.5	Test Setup	42
3.5.1	System Details	42
3.6	Results and Discussion	45
3.6.1	Without Considering Topology Changes	46
3.6.2	Scalability of the Proposed Method	49
3.6.3	Change in Network Topology	50
3.6.4	Parameter Selection	51
3.7	Summary	54

4	Statistical Distance based Electricity Theft Detection in AMI	57
4.1	Introduction	57
4.2	System Model	58
4.2.1	Network Model	58
4.2.2	Threat Model	60
4.3	Proposed Detection Methodology against Electricity Theft Attacks . .	64
4.4	Case Study	67
4.4.1	Measurement Variations	68
4.4.2	Statistical Distance Based Theft Detection	71
4.4.3	Threshold Selection	77
4.5	Results and Discussion	78
4.5.1	Synthetic Attack Patterns	78
4.5.2	Test Results	80
4.5.3	Effect of Threshold on Performance	84
4.5.4	Effect of α on Performance	86
4.5.5	Effect of Sampling Rate on Performance	88
4.6	Summary	88
5	Dimensionality Reduction of Large Dimensional AMI Data using Principal Component Analysis	93

5.1	Introduction	93
5.2	System Model	94
5.2.1	Network Model	94
5.2.2	Threat Model	95
5.3	Proposed Detection Methodology based on Low Dimensional AMI Data	95
5.3.1	Principal Component Analysis	95
5.3.2	Relative Entropy	99
5.4	Case Study	101
5.4.1	Dimensionality Reduction	101
5.4.2	Relative Entropy Based Detection	105
5.4.3	Threshold Selection	105
5.5	Results and Discussions	107
5.5.1	Synthetic Attack Patterns	107
5.5.2	Test Result	108
5.5.3	Effect of Threshold on Performance	110
5.5.4	Effect of β on Performance	112
5.5.5	Impact of Principal Components on Performance	112
5.6	Summary	113

6 Detection of Electricity Theft Attacks using Low Dimensional AMI

Data	115
6.1 Introduction	115
6.2 System Model	116
6.2.1 Network Model	116
6.2.2 Threat Model	117
6.3 Principal Component Analysis	117
6.4 Anomaly Score based Theft Detection	118
6.4.1 Smart Meter Data	120
6.4.2 Subspace Construction	120
6.4.3 Anomaly Score	121
6.4.4 Result and Discussion	123
6.5 Mahalanobis Distance based Theft Detection	127
6.5.1 Proposed Detection Framework	128
6.5.2 Case Study	130
6.5.3 Result and Discussion	131
6.6 Summary	139
7 Conclusions and Future Work	143
7.1 Summary of Contributions	143
7.2 Future Research Directions	145

Bibliography	149
List of Publications	161
Technical Biography of Author	165

List of Figures

2.1	Classification of electricity theft detection techniques.	16
2.2	Basic steps for classification-based methods.	18
3.1	System model.	27
3.2	Two-port π model.	30
3.3	Log transformation.	40
3.4	Power transformation.	40
3.5	IEEE 14 bus system.	44
3.6	NYISO map showing 11 load zones [1].	44
3.7	Histogram of KLD values using joint transformation (November, No At- tack).	47
3.8	Histogram of KLD values using joint transformation (December (θ_2 with IA = 90%)).	47
3.9	Detection rate for different values of Gamma (γ).	52
3.10	False positive rate for different values of Gamma (γ).	52
3.11	Detection rate for different values of parameter 'c'.	53

3.12	False positive rate for different values of parameter ‘c’.	53
4.1	Network model.	58
4.2	Single phase smart meter.	59
4.3	Adversary model	63
4.4	Histogram of the electricity consumption measurements in different months.	69
4.5	Histogram of the electricity measurements in different months.	70
4.6	Probability distribution of (a) Historical data (no attack) (b) Benign sample (no attack) (c) Malicious sample (with attack).	72
4.7	Histogram of relative entropy on August 2010 with no attack.	73
4.8	Histogram of relative entropy on September 2010 with attack.	73
4.9	Histogram of JSD with no attack (August 2010).	74
4.10	Histogram of JSD with attack (September 2010).	74
4.11	Histogram of HD with no attack (August 2010).	75
4.12	Histogram of HD with attack (September 2010).	76
4.13	Histogram of CBD with no attack (August 2010).	76
4.14	Histogram of CBD with attack (September 2010).	77
4.15	An example of the daily true electricity consumption pattern.	81
4.16	An example of the attacked electricity consumption pattern.	81
4.17	ROC curves for EBETD and SVM for A1 and A2.	84

4.18	ROC curves for EBETD and SVM for $A4$	85
4.19	ROC curves for EBETD and SVM for $A3$ and $A5$	85
4.20	ROC curves for JSD, HD, CBD and SVM.	86
4.21	Histogram of α	87
4.22	Detection rate for EBETD and SVM.	89
5.1	Network model.	94
5.2	Plot of 50 observations on two variables x_1, x_2	96
5.3	Plot of the 50 observations from Fig. 5.2 with respect to their PCs z_1, z_2	97
5.4	Example of daily electricity consumption of a typical consumer.	102
5.5	Histogram of weekly electricity consumption.	102
5.6	Variance captured by PCs.	103
5.7	Histogram of relative entropy (No Attack).	104
5.8	Histogram of relative entropy (With Attack).	104
5.9	ROC curves for SVM and the proposed method.	109
5.10	Effect of threshold on the performance of the proposed method (For $A2$ attack).	110
6.1	Network model.	116
6.2	Histogram of weekly consumption of a typical consumer.	119
6.3	Variance captured by principal components.	119

6.4	An example of daily electricity consumption.	124
6.5	An examples of attack consumption patterns for the three type of attacks.124	
6.6	Receiver Operating Characteristics curve for anomaly score based theft detection scheme.	126
6.7	Effect of threshold on the performance of anomaly score based theft detection method (For $A1$ attack).	127
6.8	Histogram of weekly electricity consumption of a typical consumer. . .	131
6.9	Variance captured by PCs.	132
6.10	Histogram of Mahalanobis distance (No Attack).	134
6.11	Histogram of Mahalanobis distance (Attack $A1$).	134
6.12	ROC curves for PCBTD and SVM.	136
6.13	Effect of threshold on the performance of the Mahalanobis distance based theft detector (For $A1$ attack).	137
6.14	Effect of τ on the performance of the Mahalanobis distance based theft detector (For $A2$ attack).	138

List of Tables

1.1	Comparative analysis of the traditional power grid and the smart grid.	2
2.1	Advantages and research gaps in defence techniques against FDI attacks.	21
2.2	Advantages and research gaps in defence techniques against electricity theft attacks in AMI.	22
3.1	Comparison of the proposed joint transformation based scheme with Ref. [42].	48
3.2	Variation of KLD considering attack on multiple state variables.	49
3.3	Computational time measurement	50
3.4	Undetected percentage considering topology changes ⁴	51
4.1	Summary of different electricity theft techniques in AMI	62
4.2	Summary of test results for energy theft attacks (For relative entropy case).	82
4.3	Summary of test results for energy theft attacks (For JSD, HD and CBD).	83
4.4	Effect of threshold on detection performance (For the case of relative entropy based theft detection).	87

4.5	Effect of α on detection performance (For the case of relative entropy based theft detection).	88
4.6	Effect of sampling rate on detection performance (For the case of relative entropy based theft detection).	89
5.1	Summery of test results for energy theft attacks.	108
5.2	Effect of threshold on detection performance of the proposed method.	111
5.3	Effect of β on detection performance of the proposed method.	111
5.4	Impact of PCs on detection performance of the proposed method.	112
6.1	Summary of test results for electricity theft attacks (Using Anomaly score based theft detection method).	126
6.2	Summery of test results for energy theft attacks (Using Mahalanobis distance based theft detection scheme).	135
6.3	Effect of threshold on detection performance of the Mahalanobis distance based theft detection scheme.	138
6.4	Effect of β on detection performance of the Mahalanobis distance based theft detection scheme.	139

List of Algorithms

3.1	WLS state estimation algorithm	34
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List of Abbreviations

AMI	Advanced metering infrastructure
CBD	Cumulative distribution function based distance
CDF	Cumulative distribution function
DR	Detection rate
EE	External entity
EMS	Energy management system
FDI	False data injection
FPR	False positive rate
GA	Genetic algorithm
GLRT	Generalized likelihood test
HD	Hellinger distance
IoT	Internet of Things
ISSDA	Irish Social Science Data Archive
JSD	Jensen-Shannon distance
KLD	Kullback-Leibler distance
LSE	Linear system of equations
MITM	Man in the middle
NN	Neural network
NTL	Non technical loss
NYISO	New York independent system operator
PC	Principal component
PCA	Principal component analysis
PMU	Phasor measurement unit
P2P	Peer to peer
RFID	Radio frequency identification

ROC	Receiver operating characteristic
RTU	Remote terminal unit
SCADA	Supervisory control and data acquisition
SE	State estimation
SVM	Support vector machine
TL	Technical loss
WLS	Weighted least square