

False Data Injection Threats in Active Distribution Systems: A Comprehensive Survey[★]

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ARTICLE INFO

Keywords:

False Data Injection Attack
Distribution System
Smart Meter
Advanced Metering Infrastructure
AMI
Smart Grid

ABSTRACT

With the proliferation of smart devices and revolutions in communications, electrical distribution systems are gradually shifting from passive, manually-operated and inflexible ones, to a massively interconnected cyber-physical smart grid to address the energy challenges of the future. However, the integration of several cutting-edge technologies has introduced several security and privacy vulnerabilities due to the large-scale complexity and resource limitations of deployments. Recent research trends have shown that False Data Injection (FDI) attacks are becoming one of the most malicious cyber threats within the entire smart grid paradigm. Therefore, this paper presents a comprehensive survey of the recent advances in FDI attacks within active distribution systems and proposes a taxonomy to classify the FDI threats with respect to smart grid targets. The related studies are contrasted and summarized in terms of the attack methodologies and implications on the electrical power distribution networks. Finally, we identify some research gaps and recommend a number of future research directions to guide and motivate prospective researchers.

1. Introduction

In this new global economy, adequacy of uninterrupted power supply to end-users has now become one of the main priorities of the critical energy infrastructure of several nations Husnoo, Anwar, Chakrabortty, Doss and Ryan (2021). In the past few years, traditional manually-operated distribution systems have shifted to smart distribution systems to cope up with the increased power consumption demands and operational reliability Pahwa (2015). Recently, the growing trend of integrating distributed renewable energy sources into power systems have also shifted focus from passive distribution systems into Active Distribution Systems (ADSs) in response to environmental concerns, power sustainability and energy market economics Radwan, Zaki Diab, Elsayed, Haes Alhelou and Siano (2020).

In line with the IEEE Grid Vision 2050, the main goal of a smart grid is to enable efficient and reliable bi-directional communication through control and automation processes applied through the different components of a power grid Simard (2013). This vision is being achieved by converting the static grid into intelligent cyber-physical systems through the integration of information and communication technologies. Modern technologies including Internet of Things (IoT),

and cloud computing are considered to be the foundations of ADSs, which take full advantage of such cutting-edge technologies to proactively coordinate the renewable energy generation, energy storage and other distributed units in view of achieving safe and economical operation of smart grids Yang (2019).

There has been a massive shift of research focus from transmission systems to distribution systems as the latter is highly influenced by socio-economic and environmental parameters given its close proximity to end-users Musleh, Chen and Dong (2020). However, the rush to integrate of a wide variety of technologies and components with distribution systems has neglected the security aspects of ADSs. Furthermore, the bi-directional communication within ADSs brings additional security and privacy challenges due to the large-scale complexity and resource limitations of deployments Jokar, Arianpoo and Leung (2016). Coupled with limited research done on distribution networks, there are growing concerns over massive threats potentially impacting its integrity, reliability and stability. One such notorious cyber-physical attack on distribution networks happened on 23rd December 2015 at Kiev, Ukraine, where perpetrators gained unauthorized access to the Supervisory Control and Data Acquisition (SCADA) system and tampered with circuit breakers which affected more than 225,000 customers for several hours Liang, Weller, Zhao, Luo and Dong (2017a).

1.1. Motivation & Scope

Attacks and countermeasures within the transmission network of power grids have been well studied in several previous literature Jokar et al. (2016); Liu, Xiao, Li, Liang and Chen (2012); Deng, Xiao, Lu, Liang and Vasilakos (2017). However, the major differences between transmission and

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distribution networks such as high R/X ratio hinder the extension of the previous works to ADSs Hammer, Fuhr, Hanson and Konigorski (2019). With the jump in the number of cyber-related incidents on smart grids such as the Ukraine 2015 outage Liang et al. (2017a), it is obvious that such attacks can have devastating consequences on ADSs. While current research is mainly focused on the active applications of cutting-edge technologies and the development of enhanced communications methods within distribution networks, the security risks introduced are seldom considered from the perspective of adversaries. At present, very little work have been done in relation to discovering the vulnerabilities of distribution systems which leads to urgent calls in ensuring the resilience of ADSs to zero-day attacks. Since scholars and researchers are now shifting their focus on improving the previously neglected security and privacy aspects of ADSs, the primary objective of this manuscript is to provide an early systematic literature review and insight into the security threats within active distribution systems to motivate future researchers into exploring some of the emerging areas within active ADSs.

1.2. Contributions

This manuscript covers a comprehensive survey of the existing publications and reference materials on cyber threats identified within the various domains of the smart grid distribution infrastructure. Our primary objective is to systematically and thoroughly analyze recent literature within the last decade, and assess and contrast each proposed attack methodology. In particular, the main contributions of our article are listed as follows:

1. We identify the essential cybersecurity goals of active distribution systems and provide some theoretical overview of stealthy False Data Injection (FDI) attacks.
2. Following a comprehensive review of the relevant existing literature, we highlight their contributions and identify the gaps as addressed by our survey. A detailed comparison of previous works against ours can be found in Table 1.
3. We develop and propose a detailed taxonomy of FDI attacks with respect to attack targets in active distribution systems as shown in Section 5.
4. We analyze the various state-of-the-art FDI threat modeling proposed by several independent studies, critically evaluate the approaches and summarize the results.
5. Lastly, we discuss some main research gaps in the existing FDI attack methodologies and provide some technical recommendations for future research directions within the related topic.

We strongly believe that an early systematic review of independently developed research will enable future researchers to get a clear picture of the neglected security aspects of AMI-based ADSs, thus contributing towards more resilient distribution systems of the future.

1.3. Paper Structure

Following a brief introduction of the subject of interest of this manuscript in Section 1, we discuss, compare and contrast previous related survey articles against ours in Section 2. The literature search methodology employed to gather, assess and select the relevant papers to our topic is presented in Section 3. Next, an overview of the cyber-physical security aspect of Active Distribution Systems along with some theoretical background of FDI attacks are highlighted in Section 4. Section 5 provides a brief overview of the several categories of attack targets within our proposed taxonomy. Sections 6-9 discuss the suggested taxonomy of FDI threats, mainly from the adversarial point of view with reviews of previously undertaken studies. In particular, Section 6 covers FDI attacks on the end user level, Section 7 explores similar attacks on field devices, Section 8 reviews those on the control center, while integrity threats on energy pricing and billing are covered under Section 9. Moreover, under Section 10, we identify some shortcomings of the current literature and provide some recommendations and directions for further research within this emerging field. Lastly, Section 11 concludes this survey article.

2. Related Works

Wang et al. Wang et al. (2013) reviewed some of the early works on cyber threats in smart meters. The work by Elmabet et al. Mrabet et al. (2018) surveyed the attacks on smart grids and proposed a novel classification of cyber threats to smart grids based on methods used by hackers or penetration testers while compromising the grid. Furthermore, the authors in Deng et al. (2017) conducted a survey of data integrity attacks with respect to three major security aspects namely the construction of FDI attacks, the impacts of FDI attacks on state estimations for real-time electricity markets and lastly, defense mechanisms against those attacks.

The work in Guan et al. (2015) comprehensively surveyed FDI attacks with respect to power flow models namely Alternating Current and Direct Current. Liu et al. Liu and Li (2017) reviewed the existing literature based on several attack models, financial attack impacts and countermeasures within the transmission, distribution and micro-grid network. Similarly, research works in Liang et al. (2017b) discuss the FDI attack models and their impacts on smart grid operations. Different to the previous work, Reda et al. Reda et al. (2021) surveyed and classified the related works on FDI attacks within all smart grids domains with respect to the attacks models, their attacks and the impacts of such attacks on grids.

As opposed to the existing related works, our manuscript attempts to present a thorough survey and review of the state-of-the-art data integrity attacks and develops a detailed taxonomy of aforementioned attacks with respect to points of attack across the modern distribution networks of power grids. A more detailed comparison of our paper against other surveys can be found in Table 1 above.

✓: Included , ✗: Not Included,
†: Partially Included

Comparison Attributes		Wang, Guan, Liu, Gu, Sun and Liu (2013)	Mrabet, Kaabouchet al. Ghazi and Ghazi (2018)	Deng (2017)	Guan, Sun, Xu and Yang (2015)	Liu and Li (2017)	Liang, Zhao, Luo, Weller and Dong (2017b)	Reda, Anwar and Mahmood (2021)	Our Paper
Attack Target	End User Level	-	-	-	-	-	-	-	-
	Energy Management	✗	✗	✗	✓	✗	✗	✗	✓
	Photo Voltaic Systems	✗	✗	✗	✗	✗	✗	✗	✓
	Smart Energy Management	✗	✗	✗	✗	✗	✗	✓	✓
	Advanced Metering Infrastructure	Communication Networks	✗	†	✗	✓	✗	✗	✓
	Smart Meters	✓	†	✗	✓	✓	✗	✓	✓
	Field Devices	-	-	-	-	-	-	-	-
	Voltage Regulators	✗	✗	✗	✗	✗	✗	✗	✓
	Micro-PMU	✗	✗	✗	✗	✗	✗	✗	✓
	Intelligent Field Devices	✗	✗	✗	✗	✗	✗	✓	✓
Control Center	Control Center	-	-	-	-	-	-	-	-
	Volt-var Control	✗	✗	✗	✗	✗	✗	✗	✓
	Distribution State Estimation	Balanced Single-phase	✗	✗	✓	✗	✗	†	✓
	Unbalanced Multi-phase	✗	✗	✓	✗	✗	†	†	✓
	Energy Pricing & Trading	-	-	-	-	-	-	-	-
	Distribution Locational Marginal Pricing	✗	✗	✗	✗	✓	✗	✗	✓
	Real-time Pricing (RTP)	✗	✗	✓	✗	✓	✗	✓	✓
	Transactive Energy Market	✗	✗	✗	✗	✗	✗	✗	✓
	Peer-to-peer Distributed Energy Trading	✗	✗	✗	✗	✗	✗	✗	✓
	System of Focus	Electrical Transmission System	✓	✓	✓	✓	✓	✓	✗
	Utility Distribution System	✗	✓	✓	✓	✓	✓	✓	✓

Table 1
Comparison of our survey against existing related surveys.



Figure 1: Survey Methodology employed

3. Literature Review Methodology

This work covers a comprehensive survey and review of several independent studies on FDI threats in active distribution systems. Therefore, within this section, we provide an overview of our systematic literature search and selection process.

3.1. Search Process

Finding the relevant literature is vital to perform a comprehensive analysis of the topic. Therefore, we tackle this tedious search process using a structured methodology proposed by Kitchenham and Charters Kitchenham and Charters (2007). Relevant keywords and year filters are used to perform backward and forward searches on the academic databases to systematically identify high quality publications.

Research databases used during our search process included IEEE Xplore, ACM Digital Library, Springer, Elsevier and others. The steps as shown in Figure 1 are then applied to each dataset using keywords such as "distribution system", "false data injection", "attacks", etc.

3.2. Literature Assessment & Selection

To ensure that our literature search does not consist of FDI articles related to other critical areas of research such as transportation, we restrict our search to smart grid distribution systems. Furthermore, all literature found from scholarly research sources deemed relevant to the subject in matter were manually evaluated against the scientific ranking platforms, namely SJR¹ Lab (2021) for journal articles and CORE² Education (2016) for conferences, to consider prestigious and high quality studies. Following the confirmation of high quality literature, steps 5 & 6 of Figure 1 were applied.

4. Background

As part of the smart grid paradigm, ADSs are threatened by FDI attacks by potential adversaries. Therefore, in this section, we briefly give an overview of the cybersecurity aspect of active distribution systems followed by a theoretical background of FDI attacks.

4.1. Cyber-physical Security of Active Distribution Systems

As mentioned earlier on, the growing trend in renewable energy sources, predominantly installed on the distribution level, is gradually transforming the operations of distribution networks to an active paradigm Ghiani, Pilo and Celli (2018). Contemporary innovative and intelligent technologies and devices are being used to revolutionize the once centralized, radial and "fit-and-forget" power distribution approach to a bi-directional automated scheme where efficiency and optimality of operations are guaranteed Pahwa (2015). During the last few years, power system researchers around the globe have been significantly contributing to the shift from passive distribution systems to active ones. However, due to the conflicting nature of the objectives to be simultaneously optimized, research is still lagging behind to design economical, reliable and yet, cyber-resilient ADSs of the future Lakshmi and Ganguly (2018). Therefore, throughout this section, we provide an overview of the main security goals and attacks on ADSs.

4.1.1. Security Goals of Active Distribution Systems

While utility operators are mainly focused on optimal and efficient distribution of energy to customers, security has taken the backseat and is now becoming a major concern. Therefore, it is important to extend and ensure the basic four NIST principles of smart grid cybersecurity Committee (2014) to ADSs, namely:



Figure 2: Order of Priority of four NIST Principles in relation to Active Distribution Systems

1. Availability: Availability is the most crucial security goal of ADSs to ensure uninterrupted supply of power to consumers at any given time. Countermeasures to protect ADSs against cyber-attacks must be within acceptable latency ranges while minimally impacting availability.
2. Integrity: Being the second highest prioritized goal of ADSs cybersecurity, integrity must ensure that data is not illicitly altered and is from verifiable sources.
3. Confidentiality: While confidentiality may seem to be of lesser importance in ensuring reliability of distribution networks, vulnerable Advanced Metering Infrastructure (AMI) must be protected against unauthorized leakage of private customer or proprietary information.
4. Accountability: The last security objective being accountability, relates to consumers being responsible for their actions such as during billing, consumption, etc.

4.1.2. Cyber-physical Attacks on Active Distribution Systems

While Distributed Generation (DG) is a viable solution to sustain the exponential growth in load demand, the integration of converter-based DG units including Photovoltaic (PV) generators deteriorates the power quality through the injection of harmonics to the distribution network Lakshmi and Ganguly (2018). Coupled with the integration of non-standardized DG units, the addition of contemporary technologies for efficient and automated power distribution management greatly increases the complexity of distribution networks Jokar et al. (2016). This opens up several security vulnerabilities which can be exploited by potential adversaries for both financial and political gains.

4.2. False Data Injection Threats

The concept of FDI attacks was first coined by Liu et al. Liu, Ning and Reiter (2009) and quickly became one of the stealthiest and devastating attacks on power systems. More specifically, during FDI attacks, an attacker attempts to compromise sensor readings stealthily such that gross errors are introduced into data or aggregation procedures while evading detection Ahmed and Pathan (2020). The objective of an attacker is to introduce an attack vector a into the data measurements while evading bad data detection by operators. This results in maliciously compromising the state variables across distribution networks. In simple words, during a FDI attack, an adversary manipulates the real measuring vector which can be mathematically denoted as in Equation

¹SJR: Scientific Journal Ranking (Scimago)

²CORE: Computing Research and Education Association of Australia

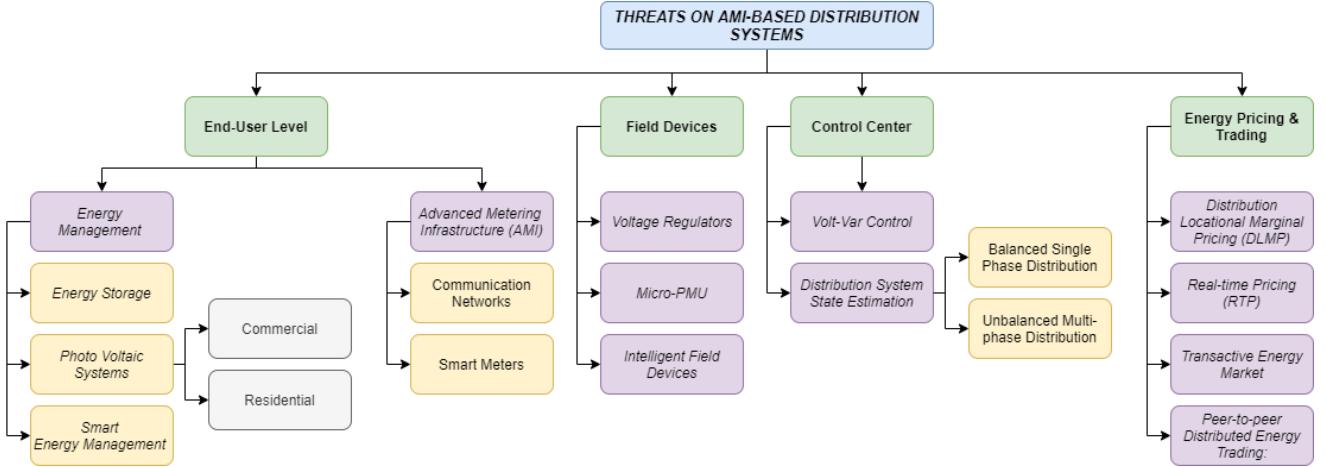


Figure 3: Taxonomy of threats on AMI-based distribution systems

1 below:

$$z_a = z + a \quad (1)$$

where z is the original sensor information, z_a is the corrupted measurement and a is the attack vector. In any case, corrupted information can be achieved by one of the following Ahmed and Pathan (2020):

- Deletion of data from the original measurement information, z .
- Change of data in the original measurement information, z .
- Addition of fake data to the original measurement information, z .

In addition to formulating an FDI attack to a generalized system, adversaries may be subject to several inequality constraints to simultaneously minimize the probability of detection of the launched attack and minimize the probability of detection of such attacks.

5. Proposed Taxonomy

Several studies on FDI threats to distribution systems have been conducted by researchers. In this survey, we propose a taxonomy to classify threats on ADSs with respect to attack targets as shown in Figure 3 below. The four major attack target levels are:

1. End-user Level: Edge devices based at the end-user side/customer side are often prone to several cyber-threats due to the lack of standardization and secure communication protocols. Therefore, we address the related FDI threats within this attack target level in Section 6.
2. Field Devices: The integration of IoT-based devices increases the complexity of the wireless field area networks which opens up security vulnerabilities and can impact the grid. We discuss the FDI threats relevant to this category in Section 7

3. Control Center: Network operation outsourcing and the complexity of connection and communication of Supervisory Control and Data Acquisition (SCADA) components within the power distribution control center are prone to FDI threats which can adversely impact the stable operation of smart grids. FDI threats targeting the control center are discussed in Section 8.
4. Energy Pricing & Trading: The shift to a modern decentralized supply and demand side management approach due to power system restructuring and the integration of renewable power sources threatens the energy billing and trading process for the adversaries' malicious financial gains. We therefore address this category in Section 9.

6. Threats on End-User Level

The increase in complexity along with the bi-directional communication provoked by renewable energy management systems and advanced metering infrastructure at the end-user level opens up several security vulnerabilities within ADSs Rashed Mohassel, Fung, Mohammadi and Raahemifar (2014). In this view, we present the FDI threats on end-user level as in Table 2.

6.1. Energy Management

The traditional power grid has shifted from a current centralized power generation paradigm to a distributed one resulting from the integration of local sustainable power generation systems Petinrin and Shaaban (2012). To balance the increasing demand for power, operators are deploying renewable energy sources from different vendors which increases the complexity of power grids Balezentis, Streimikiene, Mikalauskas and Shen (2021). Such increased complexity increases the distribution systems to severe attacks that may disrupt the operations of the grid. In this view, we present the state-of-the-art threats on energy manageme-

Main Category	Sub-Category	Ref No.	Year	Attack Target	Attack Type	Attack Mechanism
Energy Management	Energy Storage	Zhuang and Liang (2021)	2021	Battery Terminal Voltage	Sequential data injection	Constraint optimization based on Coulomb Counting Method to inject attack vectors post-attacking.
		Olowu, Dharmasena, Jafari and Sarwat (2020)	2020	Volt-VAR, Volt-Watt & Constant power factor of Smart Inverters	Short-term data injection	Gross data is injected to change the set-points based on smart inverter settings before and after the attack.
	Photo-voltaic Inverters (PVs)	Tertytchny, Karbouj, Had-jidemetriou, Char-alambous, Michael, Sazos and Maniatakos (2020)	2020	PV penetration levels data packets	MiTM and Short-term data injection	Analysis of collected packets in order to inject corrupted measurements which will overfeed the Smart Inverter and cause tripping.
		Barua and Faruque (2020)	2020	Hall sensor measurement	DoS	Non-invasive physical magnetic spoofing technique with adversarial control.
		Kandasamy (2020)	2020	Reactive Power information	Coordinated MiTM attack	Physical Tampering with the actuation command of inverters.
	Residential	Lindström, Sasahara, He, Sandberg and Johansson (2021)	2021	Power penetration data	Power Injection Attack	Constraint Optimization of cause maximal voltage deviation with an attack at one node in the finite time interval
		Anuebunwa, Rajamani, Abd-Alhameed and Pillai (2018)	2018	Load & Pricing data	DoS, Phishing attacks & short-term data injection	Genetic Algorithm Optimization to inject corrupted information into load profiles.
	Smart Energy Management System	Sajeev and Rajamani (2020)	2020	Price data	Long-term data injection	Genetic Algorithm Optimization for minimizing the total electricity cost drawn from grid.

		Sethi, Mukherjee, Singh, Misra and Mohanty (2020)	2020	Price data	MiTM long-term data injection	Bi-level linear programming Optimization
Advanced Metering Infrastructure	Smart Meters	Lo and Ansari (2013)	2013	Energy Profile	MiTM short-term data injection	Dynamic programming optimization of the attack formulation to a coin change problem.
		Khanna, Panigrahi and Joshi (2016)	2016	Smart meter energy generation data	Short-term data injection	Constraint Optimization to maximize the power injection of a bus.
		Fan, Li and Cao (2017)	2017	Load Profile	Privacy attack	Application signature extraction & identification
		Wu, Chen, Weng, Wei, Li, Qiu and Liu (2019)	2019	Energy Consumption Data	False load attack	Sending periodic circuit-OFF signals to the IGBT gate such that the circuit is switched off when the meter is sampling the current reading.
		Ismail, Shaban, Naidu and Serpedin (2020)	2020	Smart meter energy generation data	Short-term data injection	The adversary manipulates their readings to claim higher supplied energy to the grid and hence falsely overcharge the utility company.
	Communication Networks	Yi, Zhu, Zhang, Wu and Li (2014)	2014	Communication packets between smart meters and utilities.	Puppet DDoS attacks	An adversary floods a puppet node with data packets so as to exhaust the network communication bandwidth and node energy
		Boudko and Abie (2018)	2018	Communication messages	MiTM Short term data injection	Evolutionary game theory

Table 2: Comparative View of threats on End-User Level

nt within distribution systems on three sub-categories namely:

6.1.1. Energy Storage:

Renewable energy generated from decentralized production do not often provide immediate response to demand and therefore requires energy storage usually in the form of batteries. The integration with several state-of-the-art technologies including IoT and cloud computing is increasing the complexity of energy management systems in the distribution side. This increased complexity is however exposing energy management systems to severe cyber threats. Zhuang and Liang Zhuang and Liang (2021) proposed the static analytical injection of corrupted State-of-Charge (SoC) information with small magnitude into weighted least squares (WLS)-based state estimators. Experimental validations revealed that their formulated static sequential data integrity attack drastically affected the accuracy of the SoC estimation by 17% while still being able to circumvent state-of-the-art measurement residual-based bad data detection algorithms and innovation test.

6.1.2. Photovoltaic Inverters:

The rapid technological integration of smart photovoltaic inverters with Distributed Energy Resources (DERs) coupled with environmental sustainability objectives has led to the proliferation of inverter-based Distributed Energy Resources (IBDERs) in electric power grids Yazdaninejadi, Hamidi, Golshannavaz, Aminifar and Teimourzadeh (2019). However, the successful deployment of photovoltaic inverters is still prone to security and privacy breaches which may have devastating implications on distribution power systems Wankhede, Paliwal and Kirar (2020). In this view, we present the related recent state-of-the-art literature on threats against smart solar inverters within two application scenarios namely:

1. Commercial Domain: Olowu et al. Olowu et al. (2020) first investigated the impact of data integrity attacks to a commercial distribution feeder by injecting false data to the three most common Smart Inverters functionalities namely Volt-VAR, Volt-Watt and Constant Power factor (CPF). Experimental evaluation of their proposed attack revealed that the attacks severely impacted the voltage profile and the reactive power injection from the capacitor. Similarly, the authors in Tertytchny et al. (2020) proposed a man in the middle attack to overload a targeted feeder by injecting false data to all packets between the smart meter and the ancillary services controller. This trips the overcurrent protection relay and in turn leads to a regional blackout. After conducting further risk analysis, it was revealed that the efficacy of their proposed attack rose drastically with increasing solar photovoltaic inverter capacity. On the other hand, Barua and Faruque Barua and Faruque (2020) crafted a non-invasive DoS attack whereby an adversary injects false measurement data into hall sensors of solar inverters through magnetic spoofing. The data integrity attack further propagates to compromise the whole inverter eventually which

may cause grid instability and failures. As opposed to the works presented in Olowu et al. (2020) and Tertytchny et al. (2020), the false data injection in this case comes from physical domains by exploiting the external magnetic fields.

2. Residential Domain: Lindstrom et al. Lindström et al. (2021) investigated the consequences of a deceptive power injection attack against the physical layer of a smart distribution grid with radial topology. The adversary tends to maximize the voltage deviation which impacts the inverter and eventually shuts down part of a grid. Kandasamy Kandasamy (2020) demonstrated the effect of bias attacks in prosumer-based reactive power control. The goal of the attacker is to inject gross errors to the actuation commands of smart photovoltaic inverter which drastically reduces its voltage and increases the current flow. The over-current leads to thermal tripping of the inverter and as a result of which, a regional blackout occurs.

6.1.3. Smart Energy Management System

The wide use of smart residential components and integration of IT has revolutionized residential homes into smart ones. Further coupled with the incorporation of the two-way communication with smart grids and advanced intelligence in exchange for economic benefits, Smart Home Energy Management Systems (SHEMSs) can be considered as systems that provide optimal energy management services in view of efficiently monitoring and managing electricity generation, storage, and consumption in smart residential homes Son and Moon (2010); Han, Choi, Park and Lee (2011). However, SHEMSs are becoming more prone to cyber threats which may have devastating impacts. Anuebunwa et al. Anuebunwa et al. (2018) first investigated the effects of cyber attacks on SHEMSs by launching DoS and phishing attacks in view of modifying the load profile data and the dynamic pricing information. The researchers highlighted that such types of attacks can temporarily disrupt the scheduling operation and can adversely affect the energy pricing. Similarly, Sajeev et al. Sajeev and Rajamani (2020) proposed a pricing attack on smart homes under a third party aggregator system at different attack points. The authors concluded that the vulnerability of SHEMSs to pricing attacks will impede its adoption in smart homes. In similar line, Sethi et al. Sethi et al. (2020) proposed the injection of corrupted pricing data to disrupt scheduling and pricing operations. During this particular attack, the attacker, in perspective of a customer, plans to decrease the price of the electricity bill from being originally at \$2.11 to \$1.79 and the grid power import from 78.15kW to 76.99kW. While this difference in pricing seems slight, corrupting electricity bills may be profitable to a customer in the long run and cause financial losses for the electricity utilities. For instance, depending on how many households have increased their consumption, the collective energy consumption may be considerable particularly if it happens in an unwanted period of time such as peak consumption time.

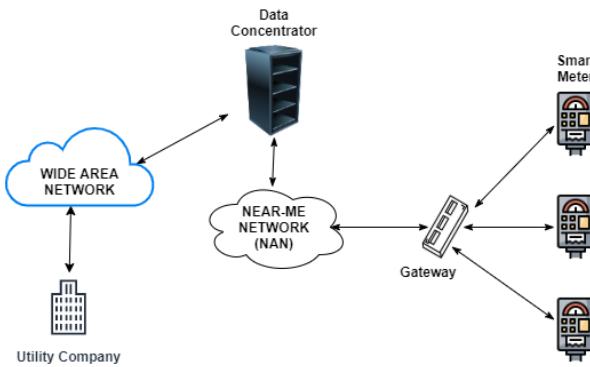


Figure 4: Overview of AMI components and networks

6.2. Advanced Metering Infrastructure (AMI)

Advanced Metering Infrastructure (AMI) is now regarded as the backbone of smart grids enabling real-time communications between utility providers and customers Mohassel, Fung, Mohammadi and Raahemifar (2014). However, the increasing complexity of AMIs has significantly resulted in a rise in the number of cyber-threats on AMIs in recent years. The highly sensitive data sensed and transmitted within the AMI has empowered adversaries to exploit the vulnerable points of an AMI. In this view, we present the related recent state-of-the-art literature on threats against AMIs at the two vulnerable points of entry namely:

6.2.1. Smart Meters:

Energy theft has always been a major concern faced by utility companies throughout the globe and dates as far as the late 1800s Monteiro (2020). Physical interventions through illegal connections and meter tampering contribute to significant revenue losses of utility providers Czechowski and Kosek (2016). While the introduction of smart meters has brought along an array of opportunities including accurate load forecasting, network controllability, etc., researchers have been investigating new attacks to compromise smart meters. Lo and Ansari Lo and Ansari (2013) proposed a combination sum of energy profiles (CONSUMER) attack whereby an adversary reduces its own energy consumption by injecting false data into its own smart meter. Furthermore, to lower the changes of fraud detection by the utility company, the attacker compensates the discrepancy in measurement by injecting corrupted data into least possible number of other smart meters within the neighborhood area network. The authors inferred that several machine learning detection schemes will indeed fail to detect such alterations, especially if the adversary injects corrupted data of small magnitude. Khanna et al. Khanna et al. (2016) developed a new attack for modifying the system state to portray false increased energy exports by injecting false data into smart meters at generator buses. The authors claim that their attacks were successful at enabling an adversary to gain momentary economic gains whilst attacking the least number of smart meters. The researchers in Fan et al. (2017) focus on the exploitation of reactive power data from smart meters to infer

power consumption of home appliances by initially extracting a one-minute window of the reactive power waveform to capture the essential characteristics of appliances, filtering deceptive events, detecting real events and lastly identifying the appliances. Evaluation results on real residential power consumption data revealed that such attacks are highly effective for violating the privacy of residents. The authors in Wu et al. (2019) proposed the closing and opening of a power main line (or its branch) synchronous to the rate of sampling of the smart meter by injecting corrupted signals to an insulated gate bipolar transistor. After validation, this attack is found to be immune to all standard security countermeasures as well as very effective in significantly reducing power consumption bills. The authors in Ismail et al. (2020) introduced a setting whereby the malicious customers hack their smart meters and increase the solar power generation readings using several types of cyber attacks namely partial increment attacks, minimum generation attacks and peak generation attack which resulted in the overcharging of utility companies.

6.2.2. Communication Networks:

Real-time two-way communication is of crucial importance in AMIs. As aforementioned, a high volume of extremely sensitive data is transmitted to and from the utility provider and the end-user Mohassel et al. (2014). Nonetheless, the numerous advantages brought about by the two-way communication also increases the vulnerability of an AMI network to malicious attacks. Yi et al. Yi et al. (2014) introduced a novel type of Denial-of-Service attack known as puppet attacks on AMI networks by flooding a puppet node with adversarial route request packets so as to exhaust the bandwidth of communication and the node energy. Experimental evaluations show that their proposed attack significantly decreases the performance of the AMI communication network and the packet delivery rate reduces from 20% to 10%. The authors in Boudko and Abie (2018) proposed a one-shot evolutionary game theoretical framework to model data integrity attacks on AMIs nodes to allow adaptive selection of strategies under resource constraints such that the node pay-offs are maximized. Results highlight that adversaries prefer nodes with higher aggregation and the attacker uses most of his budget to attack the Head-End System node.

7. Threats on Field Devices

With the increased deployment of field devices along distribution feeders and within substations, grids are now able to smartly and efficiently perform distribution automation, automatic load shedding, outage management, etc Chhaya, Sharma, Kumar and Bhagwatikar (2018). However, the implementation of several such IoT-based devices increases the complexity of the wireless field area networks and therefore, exposes several security vulnerabilities which can be exploited by adversaries. In this view, we survey the state-of-the-art threats on field devices as in Table 3:

Main Category	Ref No.	Year	Attack Target	Attack Type	Attack Mechanism
Voltage Regulators	Isozaki, Yoshizawa, Fujimoto, Ishii, Ono, Onoda and Hayashi (2014)	2014	Load ratio control switch sensor measurement data	Short term data injection	Constraint Optimization which enables the attacker to suppress/ induce tap changes.
	Teixeira, Pardari, Sandberg and Johansson (2015)	2015	Bus Voltage Measurement	Voltage reference attack & Voltage measurement routing attack	During the first attack, the adversary inputs corrupted information to the bus voltage measurements while during the routing attack, the perpetrator redirects voltage measurements to another receiving bus in the network.
	Ma, Teixeira, van den Berg and Palensky (2017)	2017	Bus Voltage Measurement	Short-term data injection	Multiplicative bounded scaling factor for crafting attacks to one node only.
Intelligent Electronic Devices (IEDs)	Radasky and Hoad (2012)	2012	Electromagnetic Field	Electromagnetic Threats	Electromagnetic Disturbances that may either be produced deliberately or is naturally occurring.
	Chattopadhyay, Ukil, Jap and Bhasin (2018)	2018	Faulty IEDs	Implementation attacks (malicious fault injection attacks & hardware Trojan)	—
Micro-Phasor Measurement Units (μ-PMU)	Santos and Orillaza (2018)	2018	Voltage & Angle measurements	Short-term data injection	High Value FDI attack
	Kamal, Farajollahi, Nazaripouya and Mohsenian-Rad (2021)	2021	Phase angle channel measurements	Unsynchronized & event-synchronized attacks	During the first attack, the attacker is unable to synchronize the FDI attack with the occurrence of pre-event and post-event measurements as opposed to during event-synchronized attacks.

Table 3
Comparative View of threats on Field Devices.

7.1. Voltage Regulators

The multi-directional power flow achieved from the integration of DERs along with the additional stress on voltage control devices caused by the stochastic and concentrated power profiles of Plug-in Electric Vehicles (PEVs) can lead to over voltages, under voltages, high system losses, excessive tap operations and so on Canha, Pereira, Milbradt, da Rosa Abaide, Kork Schmitt and de Abreu Antunes (2017). Therefore, grid operators employ voltage regulation devices such as on load tap changers (OLTC), ratio control transformers (LRTs), Step Voltage Regulators (SVRs) and shunt capacitors to mitigate the previously mentioned issues. However, the centralized nature of voltage regulation enables attackers to create bottom-to-top attacks propagation which can ultimately lead to severe outages Sun, Hahn and Liu (2018). Therefore, Isozaki et al. Isozaki et al. (2014) pro-

posed the falsification of a limited number of sensor measurements through suppressing or inducing tap changes at the LRT to maximize overvoltage or undervoltage violations by an adversary with full knowledge of the control algorithm. Simulation results on a distribution network with one feeder modeled at a smaller scale from a residential district in Japan with real-world data revealed comparable results with two upward tap changes each for cases with and without PVs which result in undervoltages between $1.00 \text{ to } 7.86 \times 10^5$ at some nodes. The work in Teixeira et al. (2015) considered two types of attacks known as Voltage Reference Attack (VRA) where an adversary injects false-data into the communication network and Voltage Measurement Routing Attack (VMRA) where an adversary redirects data to a wrong receiver bus within a network by manipulating reference signals. The impact of the attacks were further characterized

based on control-theoretic tools namely stability and input-output induced norm of linearized systems. Numerical simulations resulted in a step change in the voltage profile ranging between 0.5% to 8% at the buses during VRA and between -3% to 8% during VMRA. Ma et al. (2017) extended the work in Teixeira et al. (2015) by mostly focusing on the manipulation of sensor measurements with similar approaches to characterize the impact of the attacks. Experimental evaluations of an islanded four-bus power distribution network with a line topology reveals that the closed-loop system under attack is asymptotically stable and the voltage deviation relates to falsification ratio, δ , with an exponential decrease of 90% from $\delta = 0$ to $\delta = 0.5$ and a near linear increase of 30% from $\delta = 0.5$ to $\delta = 1$. Such attack whereby the adversary decreases the voltage measurement received by the droop controller has higher impacts on the neighboring nodes within a line network.

7.2. Intelligent Electronic Devices

Intelligent Electronic Devices (IEDs) are widely used to enhance automation within smart substations Hong and Liu (2019). However, the vast spatial complexity and the complex management hierarchy opens up potential vulnerabilities that can be easily exploited by adversaries Wang and Shi (2018). Radasky and Hoad Radasky and Hoad (2012) studied the impacts of three High Power Electromagnetic (HPEM) threats on IEDs namely Intentional Electromagnetic Interference (IEMI) whereby an adversary deliberately increases the electromagnetic disturbances, High Altitude Electromagnetic Pulse (HEMP) whereby an attacker creates a 30 km high-altitude nuclear burst that produces intense electromagnetic signals which reach the earth and lastly, Extreme Geomagnetic Storms which is a natural disaster that cause a significant rapid distortion of the geomagnetic field at the earth's surface. A fast rising and short 2.5/2.5 ns electric field pulse during Early-time HEMP results in levels of the order of 20kV to IEDs and can even trip protective relays at substations. Similarly, other types of attacks distort and damage IEDs present in sub-stations. Chattopadhyay et al. (2018) studied the effects of two types of implementation attacks namely malicious low-cost fault injection attack by underfeeding the micro-controller and hardware Trojan attack on protective distribution relays in smart sub-stations. Simulations on ARMv7-based micro-controller with 100 attack executions revealed a significant increase in the reaction time to a trip signal of up to 9 times. Such attacks may eventually cause delays in tripping part of a power distribution network. Any delays above a threshold may cause drastic damage to some equipment including power network assets such as power lines, transformers, etc.

7.3. Micro Phasor Measurement Units

The shift from a passive to an active distribution system has overseen rapid developments in Micro Phasor Measurement Units (μ -PMU) to guarantee real-time and accurate synchronized phasor data measurements of electricity including voltage, current, and frequency Shahsavar, Sadeghi-Mobarakeh, Stewart, Cortez, Alvarez, Megala and Mohsenian-

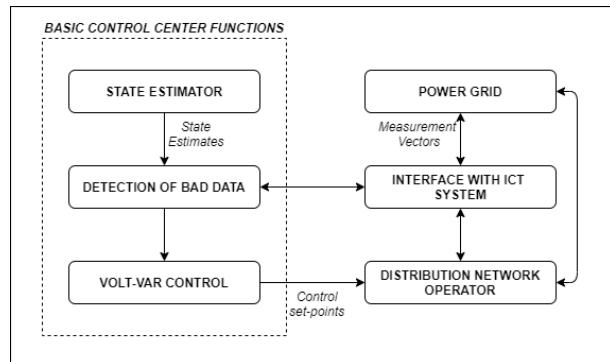


Figure 5: Block diagram depicting a typical distribution control center system

Rad (2017). However, the ubiquitous nature of μ -PMU increases the attack surface of ADSs to adversaries Shukla, Dutta and Sadhu (2021). Ren and Jordan Santos and Orillaza (2018) proposed the injection of corrupted high value data in μ -PMU measurements (voltage and angles) to assess the robustness of Weighted Least Absolute Value and Weighted Least Squares (WLS) estimators. Simulations on an IEEE 37 Node Test Feeder with μ -PMU buses revealed a stunning 96.7% error in the measurement which in turn results in the divergence of the WLS estimator. Furthermore, the study undertaken in Kamal et al. (2021) developed two types of false data injection threats namely event-unsynchronized attacks and event-synchronized attacks on μ -PMUs. During the event-unsynchronized attack, the attacker distorts the data at the magnitude channel or the phase angle channel of the micro-PMU while being unable to synchronize the attack with the pre-event phasor measurements and the post-event phasor measurements. On the other hand, during an event-synchronized attack, the adversary may compromise the pre-event phasor measurements and the post-event phasor measurements, separately which can easily bypass bad data detectors and be triggered only during event occurrences. Experiments on an IEEE-33 bus test system followed by geometric analysis revealed that event-synchronized attack require 20 times lesser injection of error measurements than their event-unsynchronized counterparts and causes higher impacts with a 50 times smaller fractional change in phasor angle and voltage magnitude while still remaining stealthy. Such a targeted attack could be limited in scope but result in a major impact on the operation of the power grid by highly deviating the outcome of the event-based methods.

8. Threats on Control Center

Following the Northeast blackout of 2003 Sweet (2003), traditional power grids have been revamped with the integration of latest technologies which enables grid operators to have more control and monitoring over the distribution system of Energy (2019). However, network operation outsourcing and the complexity of connection and communication of Supervisory Control and Data Acquisition (SCADA) components within power distribution control systems opens

Main Category	Sub Category	Ref No.	Year	Attack Target	Attack Type	Attack Mechanism
Volt-var Control		Teixeira, Dán, Sandberg, Berthier, Bobba and Valdes (2014)	2014	Voltage node measurements	MiTM Stealth attack	Addition of Arbitrary voltage while subtracting attack vector from capacitor configurations.
		Ju and Lin (2018)	2018	Reactive power of DER devices	Short Term Data Injection	Topology-agnostic approach with constraint optimization
		Choeum and Choi (2019)	2019	Distribution feeder voltage profile	Short Term Data Injection	Bilevel optimization problem using mixed integer linear programming
		Shen, Liu, Xu and Lu (2021)	2021	Volatge & load information	Load redistribution attack	Single-leader-multi-follower bi-level mixed-integer linear Optimization
State Estimation	Balanced Single-Phase Distribution	Deng, Zhuang and Liang (2019)	2019	Meter measurement information	Short Term data injection	Non-linear attack policy based on weighted least squares optimization
	Unbalanced Multi-phase Distribution	Zhuang, Deng and Liang (2019)	2019	Bus voltage measurements	Short Term data injection	Constraint optimization based on proposed local state-based linear DSSE
		Choeum and Choi (2021)	2021	Smart Meter Data	Load redistribution attack	Bi-level optimization problem transformation to a single-level optimization problem based on Karush-Kuhn-Tucker conditions of the lower level optimization problem

Table 4
Comparative View of threats on Control Center.

up security vulnerabilities which can be exploited for financial or political welfare Tom and Sankaranarayanan (2017). Therefore, we present a taxonomy of threats on the power distribution systems control center as in Table 4:

8.1. Volt-var Control

Distribution Automation Systems (DASs) have emerged as effective solutions to improve operational efficiency of distribution systems with Volt-Var Control (VVC) being the most cost-effective solution to maintain adequate balance of voltage and power factor Souran, Safa, Moghadam, Ghasempour, Razeghi and Heravi (2016). The use of heterogeneous equipment from several vendors to achieve a healthy balance of voltage and power within acceptable range raises several security issues which can be exploited by stealthy adversaries. As such, Teixeira et al. Teixeira et al. (2014) have proposed a white-box stealthy attack model whereby an adversary intercepts the communication between measurement devices and the central controller to inject false data measurements which successfully evades Bad data detectors such that the controller issues sub-optimal commands to the Load Tap Changer (LTC) and capacitors. Experimen-

tal results on an actual distribution model using GridLab-D revealed that VVC reduces voltage with an error rate of 2% which is significant enough to disrupt the grid operation. The work in Ju and Lin (2018) proposed the injection of corrupted reactive power measurements into a set of DER devices with the attacker having complete knowledge of the network topology in view of causing severe voltage mismatch within the distribution network. Simulations on a single-phase 12 kV 16-bus distribution feeder revealed that the proposed attack is not very sensitive to the step size and voltage disruptions fluctuating up to 200% are achieved. Furthermore, the authors concluded that a topology-agnostic attack can leverage legitimate buses' responses to further boost damages. Choeum and Choi's work Choeum and Choi (2019) focused on the manipulation of distribution feeder voltage profiles through the injection of measurement data with gross errors into smart meters which is formulated as an optimization problem using Mixed Integer Linear Programming (MILP). Evaluations on a modified IEEE 33-bus distribution test system with one On-LTC, nine Capacitor Banks (CBs), four PV systems and 32 smart meters highlight that there is a 1% increase in the voltage magnitude along with a

16% increase in the On-LTC tap position which results in abnormal feeder voltage profile in both the physical and cyber layers. Shen et al. Shen et al. (2021) extended the previous work by modeling a load redistribution attack on VVC as a single-leader-multi-follower bi-level mixed-integer linear programming (BMILP) model to maximize voltage profiles and increase load curtailment costs. Real-world experiments on a High-and-medium-voltage distribution system (HMVDS) in China demonstrate fluctuations on the reactive power support and voltage profiles by up to 83%.

8.2. State Estimation

While state estimation has been actively used within transmission system, the transition to sustainable energy sources introduced Distribution System State Estimation (DSSE) to estimate distribution system variables in real-time with highest possible accuracy and monitor the distribution feeder operations in power grids Primadianto and Lu (2017). However, extending traditional state estimation approaches to active distribution systems poses several operational challenges such as observability problem, unbalanced operations, etc. as well as cyber security concerns Dehghanpour, Wang, Wang, Yuan and Bu (2019). In this view, we present the state-of-the-art threats on DSSE based in the two state estimation phases namely:

8.2.1. Balanced Single-Phase Distribution:

While distribution networks are often unbalanced and single state estimations within such systems provide sub-optimal results Brinkmann, Bicevskis, Scott and Negnevitsky (2017), it is worth noting that distribution feeders have low x/r ratio which is a reason why data integrity attacks on DSSE have not much been explored Chihota and Gaunt (2018). However, Deng et al. Deng et al. (2019) proposed a practical non-linear false data injection on voltage measurements of nodes to compromise DSSE while also enabling an adversary to infer the system state from power flow or power injection measurements without much hindrance. Simulations on a single-phased balanced IEEE 56-node test feeder showed that the approximation of system state is very close to the accurate system state with a relative error of up to 7% for voltage magnitude and 0.6% for voltage phase angle. Furthermore, under the attack, the state estimation is successfully brought down by nearly 6% of its original value.

8.2.2. Unbalanced Multi-phase Distribution:

As earlier mentioned, unbalanced multi-phase distribution (more specifically three-phase distribution) is the most optimal state estimation solution. However, from the work proposed by Deng et al. in Deng et al. (2019), it can be seen how a simple corrupted measurement attack can negatively impact the state estimation in balanced single-phase distributions. Therefore, Zhuang et al. Zhuang et al. (2019) introduced a three-phased coupled corrupted measurement injection attack on a local state-based linear DSSE for multi-phase and unbalanced smart distribution systems which considers the weak couplings among phases to reduce the number of measurement modifications. After evaluation of the

proposed attack on an IEEE 13 and IEEE 37 Bus Test Feeders shows that the DSSE under the proposed attack results in approximately similar Largest Normalized Residual (LNR) as that without attacks under 100 Monte-Carlo simulations. However, the DSSE under simple attacks proves to be highly effective by projecting a LNR of 5 which is higher than the LNR threshold. On the other hand, Choeum and Choi Choeum and Choi (2021) proposed a load redistribution attack on a closed-loop conservation reduction in an unbalanced three-phase distribution network integrated with DERs using MILP to inject malicious measurements into smart meters communication in view of rising the three-phase active power flow at the substation. Simulations on an IEEE 12-node test feeder with 1 OLTC, 2 PVs, 2 CBs and 17 smart meters revealed the OLTC tap position increases by 4 after the attack which increases the feeder voltage profile and in turn increases customer energy consumption. Furthermore, at node 3, the voltage physical layer is 0.94 which slightly violates below the minimum voltage limit and can therefore result in premature breakdown of electrical appliances.

9. Threats on Energy Billing & Trading

Within the past two decades, traditional power systems have transitioned from a centralized supply side approach to a decentralized supply and demand side management due to power system restructuring and integration of smart distribution systems with renewable power sources Abidin, Aly, Cleempot and Mustafa (2018). However, such increased complexity exposes energy pricing and trading to cyber threats from several adversaries for their own revenue gains or for other malicious intentions Aitzhan and Svetinovic (2018). Therefore, we present a taxonomy of threats on the energy billing and trading process of smart grids as in Table 5.

9.1. Distribution Locational Marginal Pricing

Following the success of locational marginal pricing within transmission systems Liyanapathirane, Khorasany and Razzaghi (2021), the adoption of Distribution Locational Marginal Pricing (DLMP) enables reduction in end-user energy costs, efficient peak-demand stress management on utilities and enhanced system sustainability Papavasiliou (2018). However, degree of accuracy of DLMP is dependent on the integrity of the Distribution System State Estimation data Zhang et al. (2019b) which exposes DLMP to data integrity attacks. Zhuang and Liang Zhuang and Liang (2019) were the first to study the effects of directly injecting corrupted data of small magnitude to the bus voltage measurements of DLMP by formulating a non-convex optimization problem, which is solved by Dinkelbach's algorithm. Experimental validations on a modified multi-phase and unbalanced IEEE 13-bus test feeder revealed that an adversary can heavily benefit from a sharp decrease in pricing (from 10.07¢/kWh to 0.76¢/kWh) at the attacked bus while the total payment of all other customers increases from 34873 cents to 35078 cents.

Main Category	Ref No.	Year	Attack Target	Attack Type	Attack Mechanism
<i>Distribution Locational Marginal Pricing</i>	Zhang, Wang and Li (2019b)	2019	Bus voltage measurements	Short-term Data Injection	Dinkelbach non-convex optimization
<i>Real-time Pricing</i>	Tan, Badri-nath Krishna, Yau and Kalbarczyk (2013)	2013	Price Data Packets	Scaling/ Delay	Control-theoretic clock manipulation
	Mishra, Li, Pan, Kuhnle, Thai and Seo (2017)	2016	Price signals	Short-term Data Injection	Stackelberg game
	Zhang, Yang, Lin, Xu and Yu (2017)	2017	Smart meter data	Short-term Data Injection	Lagrangian Optimization
	Giraldo, Cárdenas and Quijano (2017)	2017	Price Signals	Long-term Scaling/ Delay/ Data Injection	Control-theoretic Linear Optimization
<i>Transactive Energy Market</i>	Krishnan, Zhang, Kaur, Hahn, Srivastava and Sindhu (2018)	2018	Cap price, Bid price, Demand & Breaker Operations	Proxy Attacks	Tampering with information from controller
	Jhala, Natarajan, Pahwa and Wu (2019)	2019	Electricity Prices	MiTM Short-term Data Injection	Simple least square approach for demand co-efficients Estimation
	Barreto and Koutsoukos (2019)	2019	Customer Bids	Fake Bidding Injection	Approximation of aggregate functions using market equilibrium information.
	Barreto, Neema and Koutsoukos (2020b)	2020	Customer Bids	Short-term Data Injection	Biased welfare function maximization using market equilibrium information.
<i>P2P Distributed Energy Trading</i>	Barreto, Eghtesad, Eisele, Laszka, Dubey and Koutsoukos (2020a)	2020	Gateway between prosumers and system	Discard/Delay/ DDoS	Approximation of aggregate cost function using quadratic optimization
	Islam, Mahmud and Oo (2018)	2018	Power generation and usage patterns	Short-term Data Injection	Constraint Optimization to minimize energy demand and sale.
	Mohammadi, Eliassen and Zhang (2020)	2020	Demand	Demand Data Manipulation	Game theory & Smart Meter Tampering

Table 5
Comparative View of Threats on Energy Billing & Trading.

9.2. Real-time Pricing

One of the key price response mechanisms of demand side management is Real-Time Pricing (RTP) which enables efficient power utilization and reduction in electricity costs Dai, Gao, Gao and Zhu (2017). Due to the complex closed-loop feedback control approach which is used to maintain grid stability and performance Gusrialdi and Qu (2019) along with market expansions for efficient Demand Response pro-

grams Cioara, Anghel, Bertoncini, Salomie, Arnone, Mammina, Velivassaki and Antal (2018), adversaries can easily affect energy markets through simple yet powerful attacks. Tan et al. Tan et al. (2013) demonstrated the impacts of modifying the incoming price signals to a group of customers during transmission via either a reduction of values during scaling attacks or providing old prices during delay attacks. Upon validation of their proposed attacks

on a normally-distributed Constant Elasticity of Own-price (CEO) model for each customer of New South Wales, Australia's half-hourly total demand load for 2013 as baseline load, the authors concluded that under scaling attacks, excessive distribution line overload events occurred and system volatility was directly proportional to the proportion of customers under attack and inversely proportional to amplification. Furthermore, delay attacks increased the distribution line overload which causes circuit breakers to open and eventually leads to marginal system instability and regional blackouts.

The work illustrated in Mishra et al. (2017) focuses on arbitrarily increasing the price signals from the electric provider to the smart meters with the aim of maximizing the mismatch between energy supply and demand. Using real-world Summer 2004 Polish power flow system dataset, Mishra et al. (2017) concluded that such attacks heavily impact load shifts and redistribution in the power grids which in turn overloads and heats up transmission lines to cause failures and catastrophic blackouts. Zhang et al. (2017) proposed two approaches known as Ex-ante attacks and Ex-post attacks by injecting false information into demand-users or supply-users before and after the price decision making process respectively for maximizing welfare on the real-time pricing schemes. Evaluations with 15 demand-users, 20 supply users and a traditional power system set-up, they concluded that such cyber-threats can effectively alter real-time prices to the benefit of the adversaries. The authors in Giraldo et al. (2017) extended the Tan et al.'s work Tan et al. (2013) by modeling a more realistic attack model whereby an adversary can compromise the integrity of price signals repeatedly over a long period of time and at any moment as opposed to being constrained to one-shot scaling or delay attacks in view of maximizing the gap between generated and consumed power. Experimental results highlight that their additive approach causes greater damage to the market stability and is more powerful while attacking sensed data by smart meters.

9.3. Transactive Energy Market

In recent years, transactive control Hu, Yang, Kok, Xue and Bindner (2017) has been extensively studied to enable the integration of DERs and Renewable Energy Sources (RES) with smart grids to ensure safety and efficient operability as it promises the flexibility of responsive assets in the grid and maintains a dynamic balance of energy supply and demand. However, experts fear that the participation of the prosumers at the edge Zhang, Eisele, Dubey, Laszka and Srivastava (2019a) can lead to several security and privacy concerns due to frauds, unfair welfare maximization, etc. In this view, Krishnan et al. Krishnan et al. (2018) studied the effects of three data integrity proxy attacks namely the manipulation of cap price from 3.78\$ to 0.01\$, manipulation of bid price and quantity on total demand, and lastly, the manipulation of the breaker operations by altering router at generator substation for a set-up of thirty houses. After testing their proposed attack models on TESP framework, the authors concluded

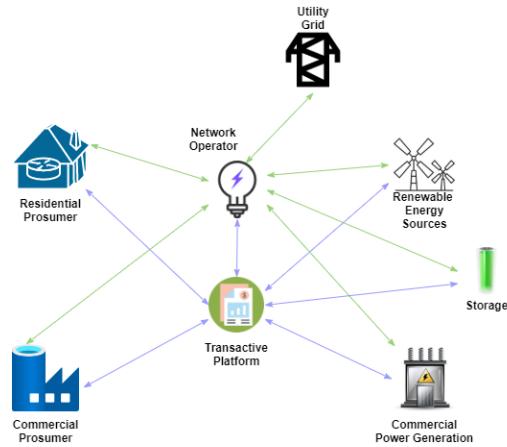


Figure 6: Conceptual Model of a Transactive Energy Market. Image adopted from Zia, Elbouchikhi, Benbouzid and Guerrero (2019)

that the manipulation of cap price as well as the alteration of bid price and quantity on total demand resulted in a spike in cooling set-point, fluctuations in the HVAC controller loads and eventually impacts overall demand on the feeder. Furthermore, the tripping of the breaker significantly affects the market price and may result in financial losses on behalf of the service provider. The work in Jhala et al. (2019) focused changing the integrity of electricity prices as a man-in-the-middle attack during communication or as the manipulation of sensed electricity usage data at smart meters within a transactive energy market. Simulations on the IEEE 69-bus test system revealed that attacks on electricity prices have higher implications than attacks on consumption data by resulting in higher demand fluctuations and hence, higher voltage violations. More specifically, a 10% reduction of electricity prices increases the magnitude of oscillation of energy demand and distribution system voltage. Barreto and Koutsoukos Barreto and Koutsoukos (2019) proposed the formulation of an adverse generator to manipulate the bids of other customers in the view of shifting the transactive market equilibrium to maximize welfare gains. Experimental validations on GridLAB-D and PNNL set-ups demonstrate the attack's success in increasing the adversary's monetary gains whilst also heavily impacting the social welfare of other customers if attack parameters are wrongly estimated. The authors in Barreto et al. (2020b) extended the same approach in Barreto and Koutsoukos (2019) by imposing restrictions on the adverse generator such that the adversary has to initially protect his own assets from operation states and to hide a successful attack as long as possible to maximize profit gains. After compromising 80% of the HVAC systems, the electricity prices and total energy traded increased significantly, and the positive gains are upped with increasing attack intensity causing financial losses of other customers. However, with increasing attack intensity comes a decrease in the adversary's marginal returns. Barreto et al. Barreto et al. (2020a) proposed three attack scenarios targeting the gateways between prosumers and the system within a transactive energy

market. During the first threat model, the attacker gains access to a gateway in order to delay or discard the bids based on bidding information, the second scenario involves discarding or delaying selected bids without complete information and thirdly, the adversary launches a Distributed Denial of Service (DDoS) attack. The authors concluded that such simple attacks can effectively alter the clearing price of a blockchain-based transactive market.

9.4. Peer-to-peer Distributed Energy Trading

The decentralization of energy market models enables local nodes to exchange surplus power in Peer-to-Peer (P2P) setting which results in major financial welfare for both the prosumers and the utility company Guerrero, Chapman and Verbić (2019). However, the complexity of such large scale decentralized energy trades within untrusted and non-transparent energy markets is highly vulnerable to several security and privacy concerns Li, Kang, Yu, Ye, Deng and Zhang (2018). In this view, Islam et al. Islam et al. (2018) developed an optimal false data injection attack to enable adversaries to peak at the power generation and usage patterns for extracting the maximum benefits from legitimate nodes while minimizing the gap between power sold and power purchased to avoid detection. Results after validation of the proposed attack approach on a residential micro grid with four households revealed that the proposed attack significantly impacts the profits of legitimate houses by 86% to 94%. The work in Mohammadi et al. (2020) proposed the manipulation of prosumers' demands by a malicious supplier acting as a participating prosumer to maximize their financial welfare which can be achieved either through smart meters tampering or communication network interception. Experimental evaluations with a real dataset from Austin, Texas revealed that attacking 70% of prosumers decreases the average utility for prosumers by 2.7% and the profits of the external energy supplies by 10.6%.

10. Main Research Gaps & Future Directions

Since the topic of FDI threats within active distribution systems is an emerging topic of research with very few related studies at the time of writing, we present the main existing research gaps and provide some recommendations for fueling future research within this field.

10.1. Existing Research Issues

In what follows, we discuss some of the main gaps in the current FDI attack studies within active distribution systems.

1. *Limited FDI threats studied in perspective of active distribution systems:* While most research on FDI threats on smart power grids have concentrated mostly on transmission networks, there is currently a considerable lack of FDI attacks proposed on ADSs. The literature surveyed within this manuscript tried to cover most or if not all of the integrity attacks on distribution networks. However, there are still several open challenges with respect to the scope. For instance, at the time

of writing, only Zhuang and Liang Zhuang and Liang (2021) assessed the impact of FDI attacks on energy storage infrastructure and SoC information. Hence, it is vital for researchers to extend the aforementioned work in the aim of exposing the subtle extreme vulnerabilities of energy storage systems. Similarly, our survey highlighted that not much studies have been undertaken which properly assess the impact of FDI threats on IEDs, μ -PMUs, DLMP, etc.

2. *Lack of realistic real-world experimentation:* The FDI threats on ADSs proposed by existing literature are produced and evaluated within laboratory confined settings with several assumptions such as linearity. However, industrial standards differ from those studies such that models may be non-linear and are alternating current based systems. Therefore, we believe that more realistic FDI attacks must be formulated against large-scale realistic industrial networks/systems with lesser assumptions.
3. *Lack of corroboration of FDI attack evaluations:* Even though the FDI attacks proposed within the existing related literature has successfully proven their impacts through numerical evaluations against bench-marked test cases, there is still a lack of experimental result validations on standardized testbeds. Testbeds are vital for assessing the performance of attacks on power grids which take into consideration the architectures, security concepts, etc. Hence, we believe that before researchers plan to carry further research on this emerging topic, it is of high priority to initially set some standardization which will enable easy comparison of studies.

10.2. Future Directions

With the number of cyber-threats constantly rising on smart grids, securing modern active distribution networks is becoming one of the top agendas of several nations. Within this section, we recommend some future research prospects in relevance to FDI threats on ADSs.

1. *Secure Communication & Aggregation Protocols:* Active distribution networks feature bi-directional flow of critical data and messages. Throughout this review, we have uncovered that AMI communications can easily be subverted to inject corrupted measurements into the data Siqueira de Carvalho, Kumar Sen, Nag Velega, Feksa Ramos and Neves Canha (2018). Furthermore, attackers are enable to actively participate in the data aggregation process to input falsified data into the network Wang and Lu (2013). The critical issue to be addressed is how to accurately identify subtle false data injection attacks and refrain adversaries from maliciously gaining access to the network. How to design strong data encryption and differentially private schemes with a healthy trade-off between data utility and accuracy along the aggregation path is also a challenging issue in smart grids.

2. *Privacy Preservation Consideration:* Most, if not all, of the FDI threats proposed within the emerging field of active distribution systems are mainly concerned about compromising the stable operations of grids. However, we believe that researchers should actively research on privacy breaching attacks and their countermeasures to expose and resolve the vulnerabilities of future active distribution networks. One such solution is the application of collaborative learning within the power distribution infrastructure.
3. *FDI attacks on Blockchain-based distribution system solutions:* Since the rise of blockchain paradigm, energy system researchers have been actively finding blockchain-based solutions for smart grids, more specifically in the field of distribution systems. While blockchain offers several promising benefits of security and complex interaction modeling, FDI attacks on blockchain-based solutions for distribution networks must be thoroughly studied as it is itself a very new research field.

11. Conclusion

Active distribution systems in smart grids are being threatened from an emerging class of cyber attacks known as False Data Injection attacks. Through the injection of corrupted measurement vectors, attackers can easily bypass bad data detection countermeasures and compromise the availability, integrity and confidentiality of the data within ADSs. Moreover, properly coordinated and executed FDI cyberattacks can have devastating impacts on not only the distribution system, but on the overall smart grid due to large-scale power system operation failures, regional blackouts, energy thefts, and so on.

Therefore, in this manuscript, we presented a survey of FDI attacks on active distribution systems and proposed a taxonomy to classify the studies with respect to four attack targets namely end-user level, field devices, control center and, energy pricing and trading. Finally, we identified some main gaps in the existing research and provided some future research directions for FDI attacks on active distribution systems.

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Robin Doss (Senior Member, IEEE) is a Professor and the Research Director of the Strategic Centre for Cyber Security Research & Innovation (CSRI) at Deakin University. In this role, he provides scientific leadership for this multidisciplinary research centre focused on the technical, business, human, policy and legal aspects of cybersecurity. In addition, he also leads the Next Generation Authentication Technologies theme for the Critical Infrastructure Security research program of the national Cyber Security Cooperative Research Centre (CSCRC). Prior to this role, he was the Deputy Head of School for the School of Information Tech-

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