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

Muhammad Akbar Husnoo, Adnan Anwar, Nasser Hosseinzadeh, Shama Naz Islam, Abdun Naser Mahmood and Robin Doss

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 many 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. 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 cybersecurity research done on distribution networks, there are growing concerns over massive threats potentially impacting its integrity, reliability and stability. From a cyber-physical perspective, the success of distribution systems is heavily reliant on its physical components which is the power network infrastructure, and its cyber components which includes information sensing, data analytics, etc Bienstock and Verma (2009). As earlier mentioned, attacks on transmission systems have been well-studied in the past Dán and Sandberg (2010). An interesting attack proposed by Soltan, Yannakakis and Zussman (2018) that considers physical tampering by disconnecting some power lines as well as cyber manipulation by blocking the information flow was used to disrupt the grid operability. Indeed, such attacks concepts may eventually be extended to distribution systems Bernstein, Bienstock, Hay, Uzunoglu and Zussman (2014). 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). Figure 1 shows a timeline of the well-known attacks that have occurred on power grid systems throughout the recent years.

1.1. Motivation & Scope

With the integration of IoT-based devices into power grid systems, cybersecurity is now a prominent aspect of smart grids due to the wide array of security attacks. Attacks and countermeasures within the transmission network of power grids have been well studied in several previous literature e.g. works conducted by the authors in Jokar et al. (2016); Liu, Xiao, Li, Liang and Chen (2012); Deng, Xiao, Lu, Liang and Vasilakos (2017). With the rise 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 has been done in relation to discovering the vulnerabilities of distribution systems which leads to urgent calls in ensuring the resilience of ADSs to different types of emerging threats and zero-day attacks.

In recent years, False Data Injection threats (FDI) have surfaced as one of the most critical threats faced by distribution systems whereby an adversary deliberately introduces corrupted noisy information into sensor measurements while being as stealthy as possible. As earlier mentioned, FDI threats in transmission systems have been studied and some countermeasures have been proposed. Indeed, the security aspects of ADSs have been previously neglected. Since scholars and researchers are now shifting their focus on improving the emerging security and privacy aspects of ADSs, it is critical to have an understanding of the characteristics of distribution systems which emphasise the needs and motivation of ongoing research on FDI threats and countermeasures:

1. Lack of proper security mechanisms: Power distribution networks consist of several field devices including power transformers, voltage regulators, remote terminal units and so on. Such types of field devices lack proper cyber and physical security mechanisms Otuoze, Mustafa and Larik (2018). Indeed, without strong security measures, adversaries can easily gain access and construct data integrity threats, specifically FDI attacks.

2. Communication Protocols: In a distribution system, Supervisory Control And Data Acquisition (SCADA) and/or Industrial IoT (IIoT) protocols such as ZIGBEE, Modbus, etc. are widely used for substation communication or communication between substation and field devices Anwar, Mahmood, Tari and Kalam (2022). These protocols are vulnerable to security threats. IEEE, IEC and other standard organisations who have been involved in the development of protocols are actively researching on increasing the resiliency of these protocols against cyber threats. However, widely used protocols, e.g. Modbus or Zigbee, still lack proper security mechanisms. As a result, messages sent without proper strong encryption or authentication mechanisms can be exposed to FDI threats McLaughlin, Friedberg, Kang, Maynard, Sezer and McWilliams (2015).

3. Distribution System Characteristics: As earlier highlighted, power distribution systems have different characteristics as compared to transmission systems such as high R/X ratio, etc Hammer, Fuhr, Hanson and Konigorski (2019). Therefore, the formulation of FDI threats on transmission systems will work differently in a distribution system. The assumption of DC power flow formulation is not valid for distribution systems. Moreover, the AC formulation for distribution systems need to consider multi-phase power flow models and distribution state estimations Giraldo, Vergara, López, Nguyen and Paterakis (2021). Hence, it is very important to investigate the both the attack construction and the detection of FDI threats on distribution systems.

4. Heterogeneity: The wide array of IoT devices in modern power distribution system e.g. smart homes, SCADA, field devices, sub-station devices, etc. along with the different communication protocols and different stakeholders within a single network increases the complexity of the network. For maintenance and monitoring purposes, third party companies need to connect to the proprietary networks through internet, which also introduces more vulnerabilities He, Chen,
Bu, Chan, Zhang and Guizani (2012); Renugadevi, Saravanan and Naga Sudha (2021). Eventually, with increasing complexity, the window of opportunities for FDI attacks increases.

Therefore, the primary objective of this manuscript is to provide an early systematic literature review and insight into the FDI 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 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 2.

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 2.2. 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.

| Terminologies                        | Definitions                                                                 |
|--------------------------------------|-----------------------------------------------------------------------------|
| Active Distribution System (ADS)     | Distribution system with operation and control capabilities coupled with distributed decentralized energy resources. |
| Advanced Metering Infrastructure (AMI) | Network of smart meters and data management systems that allows bidirectional communication between the utility providers and the consumers. |
| Control Center                       | Consists of monitoring systems and applications to ensure efficient and reliable power delivery operations. |
| Cyber-physical System                | System in which entities (e.g. sensors, etc.) are connected to each other and to the internet through wired or wireless solutions. |
| Man-in-The-Middle Attack (MiTM)      | Cyber-attack during which a perpetrator eavesdrops the communication channel between two parties and often relays messages. |
| Smart Grid                           | Modern power grid system with control and automation which enables bidirectional flow of electricity and communication in real-time. |
| Supervisory control and data acquisition (SCADA) | Control system consisting of technological resources which enable high-level supervision of the power grid. |
| Zero-day Vulnerability                | Broad terminology describing a newly discovered form of vulnerability which is exploited by black hats to attack systems. |

Table 1 Terminology Description

Sections 6-9 discuss the suggested taxonomy of FDI threats, mainly from the adversarial point of view with review 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

During the past couple of years, numerous amounts of work have surfaced on FDI threats in power systems. In this view, we first present related works in terms of FDI threats on power grids and how it can as well be extended to other fields. Secondly, we present a comparison of existing literature against ours to highlight the need for a new review.
2.1. False Data Injection Threats

The concept of FDI attacks was first coined by Liu, Ning and Reiter (2009) and quickly became one of the stealthiest and devastating attacks on power systems. Due to the shift in paradigm from traditional power systems to smart grids, a complex system of interconnected sensors continuously gather data which are useful to ensure the safe and reliable operation of the grids. However, in recent years, the energy critical infrastructure has become an attractive attack target for malicious adversaries whereby they attempt to corrupt sensor readings to either disrupt the integrity or the availability of the system for their illicit gains Chaojun, Jirutitijaroen and Motani (2015). Traditionally, Bad Data Detectors (BDDs) have been employed to observe for corrupted information in power grid systems by comparing residual thresholds Sayghe, Hu, Zografopoulos, Liu, Dutta, Jin and Konstantinou (2020). However, the speed of ongoing research throughout this field has brought about increasing stealthiness of such FDI attacks which tends to easily bypass BDDs. Following Liu et al. (2009)’s research, throughout the last decade, a vast array of FDI attacks have been proposed in relation to disrupting several facets of the smart grid system. For instance, Xie, Mo and Sinopoli (2010) presented a stealth FDI attack on state estimation in a deregulated energy market setting which successfully bypassed BDDs and led to financial gains of the adversary during virtual energy bids. Another work by Rahman and Mohsenian-Rad (2012) took a step further by proposing a more realistic FDI attack whereby the adversary conducted a gray-box attack with limited information in view of having similar impacts on the power systems. An interesting work proposed by Kosut, Jia, Thomas and Tong (2011) enable adversaries to optimize their attacks by balancing the trade-off between increasing corruption of data and decreasing the probability of detection of the attack such that energy is leaked. Furthermore, Jia, Kim, Thomas and Tong (2014) investigated the effects of FDI attacks on real-time Locational Marginal Price (LMP). While, throughout the previous decade there has been several interesting FDI attacks proposed, within this manuscript, we will be mostly reflecting on FDI threats on Active Distribution Systems.

2.1.1. FDI Threats in other fields

Albeit the terminology of FDI attacks initially surfaced from smart grid use-cases Liang, Zhao, Luo, Weller and Dong (2017b), it is inherently pertinent to any other types of IoT-based systems as FDI attacks generally focus on the manipulation of data to impact the integrity of a system. While in the past, researchers have mostly concentrated on crafting FDI attacks and developing countermeasures in the power grid domain, some few recent literature Gu, Yu, Guo, Qiao and Guo (2021); Yang, Feng, Zhang, He and Shi (2018) have extended FDI studies to other fields. For example, the work in Yang et al. (2018) proposed a novel attack construction and defense mechanism against FDI threats in Networked Radar Systems. Indeed, FDI attacks are relevant to critical healthcare infrastructure Newaz, Sikder, Babun and Ulug (2020). Corrupted information injected in medical devices and sensors can pose imminent dangers to the health of individuals and can also cripple the healthcare industry of a particular region. For instance, medical devices consist of sensors that gather readings and health information about patients. The injection of corrupted sensor readings may lead to wrong medical diagnosis and thus jeopardize the well-being of a patient. Similarly, within the transportation infrastructure Almalki and Sheldon (2021), the imputation of wrong information to sensor-based readings can eventually lead to several consequences such as traffic delays, accidents, etc. Furthermore, FDI attacks stand out as being one of the most aggressive threats on Industrial IoT (IIoT) systems where gross errors in sensor measurements can affect operations of machinery, etc Huang, Tao, Wang, Guo, Yang and Gui (2022). Moreover, there could be other instances and fields where FDI attacks could have potentially severe consequences such as in the finance sector whereby the manipulation of data could lead to misleading credit scores, in the military sector where drones can be hacked to inject false information which can trigger attacks to false targets, so on and so forth Newaz et al. (2020). Overall, it can be said that FDI threats, even though it has been mostly studied in the context of power systems, can be extended to several critical infrastructures and may cause adverse impacts in systems, all while remaining undetected for very long times. Therefore, it is highly necessary to have a better understanding of FDI attacks in the view of developing effective countermeasures. However, as aforementioned, within this manuscript, we shall be reflecting entirely on the threats targeting AMI-based distribution systems.

2.1.2. FDI Threats vs Other Types of Deception Threats

Cybersecurity has now become a prominent aspect of Internet of Things due to the wide array of security attacks on IoT-based critical infrastructure. The wide array and heterogeneity of sensors present in IoT-based systems with each simultaneously sensing different types of data increases the complexity of the systems. Furthermore, due to the increased use of sensing devices in critical infrastructure, IoT-based devices are often produced at mass extent without taking into consideration security as a highest priority. Producers of Industrial IoT solutions in recent years have focused more on meeting demands rather than implementing strict digital doors to prevent unauthorized access which enables hackers with illicit intentions to carry out several types of deception attacks such as FDI attacks with devastating impacts. Deception attacks can be of several types e.g. Denial-of-Service (DoS) attacks, Trojan Attacks, Identity Deception, covert attacks and other miscellaneous deception threats Rowe and Custy (2017). False Data Injection attack is one form of deception attack which targets data integrity issues. However, different types of deception threats have their own characteristics and impacts on a distribution system. For instance, DoS attacks target availability of systems while FDI threats are mostly related to data integrity issues.
sary’s perspective, based on the CIA triad, an FDI attack tries to destabilize the integrity aspects of a distribution system while other deception attacks may have varying natures based on their own characteristics. To compare with a covert deception attack, FDI attacks attempt to disrupt the system within a short time interval for momentary gains while a covert attack allows an adversary to feed false data into a system such that the attack effects usually happen in the long-term de Sá, Carmo and Machado (2017). On the other hand, the main difference between other types of deception attacks is that deception threats may or may not be stealthy (e.g., DoS attacks are not stealthy) while FDI threats are categorized as stealthy attacks.

### 2.2. Literature Review

The authors in Wang et al. (2013) reviewed some of the early works on cyber threats in smart meters. The work by 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 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.

### Table 2

| Comparison Attributes | Wang, Guan, Liu, Gu, Sun and Liu (2013) | Mrabet, Kaabouch, Ghazi and Ghazi (2018) | Deng et al. (2017) | Guan, Sun, Xu and Yang (2015) | Liu and Li (2017) | Liang et al. (2017b) | Reda, Anwar and Mahmood (2021) | Our Paper |
|-----------------------|----------------------------------------|----------------------------------------|-------------------|-----------------------------|------------------|---------------------|------------------------|-----------|
| **End User Level**    | -                                      | -                                      | -                 | -                           | -                | -                   | -                      | -         |
| **Energy Management** | -                                      | -                                      | -                 | -                           | -                | -                   | -                      | -         |
| Energy Storage        | X                                      | X                                      | X                 | ✓                           | X                | X                   | ✓                      | ✓         |
| Photo Voltaic Systems | X                                      | X                                      | X                 | X                           | X                | X                   | ✓                      | ✓         |
| Smart Energy Management | X                                       | X                                      | X                 | X                           | X                | X                   | ✓                      | ✓         |
| **Advanced Metering Infrastructure** | -                                      | -                                      | X                 | X                           | ✓                | ✓                   | ✓                      | ✓         |
| Communication Networks | X                                      | X                                      | X                 | ✓                           | X                | ✓                   | ✓                      | ✓         |
| Smart Meters          | ✓                                      | ✓                                      | X                 | ✓                           | ✓                | ✓                   | ✓                      | ✓         |
| **Field Devices**     | -                                      | -                                      | -                 | -                           | -                | -                   | -                      | -         |
| Voltage Regulators    | X                                      | X                                      | X                 | X                           | X                | X                   | ✓                      | ✓         |
| Micro-PMU             | X                                      | X                                      | X                 | X                           | X                | X                   | ✓                      | ✓         |
| Intelligent Field Devices | X                                      | X                                      | X                 | X                           | X                | X                   | ✓                      | ✓         |
| **Control Center**    | -                                      | -                                      | -                 | -                           | -                | -                   | -                      | -         |
| Volt-var Control      | X                                      | X                                      | X                 | X                           | X                | X                   | ✓                      | ✓         |
| **Distribution State Estimation** | Balanced Single-phase                   | X                                      | X                 | ✓                           | X                | ✓                   | ✓                      | ✓         |
| Unbalanced Multi-phase | X                                      | X                                      | ✓                 | ✓                           | ✓                | ✓                   | ✓                      | ✓         |
| **Energy Pricing & Trading** | Distribution Locational Marginal Pricing | X                                      | X                 | X                           | ✓                | ✓                   | ✓                      | ✓         |
| Real-time Pricing (RTP) | X                                      | X                                      | ✓                 | ✓                           | ✓                | ✓                   | ✓                      | ✓         |
| Transactive Energy Market | X                                      | X                                      | X                 | X                           | X                | X                   | ✓                      | ✓         |
| Peer-to-peer Distributed Energy Trading | X                                      | X                                      | X                 | X                           | X                | X                   | ✓                      | ✓         |
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 2 above.

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 as shown in Figure 2.

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 (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 2 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 SJR\textsuperscript{1} Lab (2021) for journal articles

\textsuperscript{1}SJR: Scientific Journal Ranking (Scimago)

and CORE\textsuperscript{2} Education (2016) for conferences, to consider prestigious and high quality studies. Following the confirmation of high quality literature, steps 5 & 6 of Figure 2 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 (refer to Figure 3 of smart grid cybersecurity Committee (2014) to ADSs, namely:

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.

\textsuperscript{2}CORE: Computing Research and Education Association of Australia

---

\textsuperscript{1}SJR: Scientific Journal Ranking (Scimago)

\textsuperscript{2}CORE: Computing Research and Education Association of Australia
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. The alteration and/or destruction of the true data leads to a loss of data integrity. Indeed, as data integrity degrades, it negatively impacts the reliability and stability of the distribution system.

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

Dubbed as one of the most critical malicious cyber-threats in power systems, an adversary tends to deliberately compromise sensor readings by orchestrating injection of false information into sensor measurements. 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. 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 $z_a = z + a$ 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: 1) Deletion of data from the original measurement information, $z$. 2) Change of data in the original measurement information, $z$. 3) Addition of fake data to the original measurement information, $z$. Furthermore, adversaries may be subject to several inequality constraints that simultaneously minimize the probability of detection of the launched attack and minimize the probability of detection of such attacks.

Based on the security goals discussed earlier, integrity is the second most prioritized security goal whereby a distribution system must ensure the accuracy of its information.

$$z_a = z + a, z_{\text{min}} \leq z_a \geq z_{\text{max}}$$

where $z_{\text{min}}$ and $z_{\text{max}}$ is assumed to be known by the adversary Mode, Calyam and Hoque (2019).

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 5 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 Tables 3 and 4.

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 management 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...
| Category                        | Ref No                                      | Attack Target                  | Attack Type                        | Attack Mechanism                                                                 |
|--------------------------------|---------------------------------------------|--------------------------------|------------------------------------|----------------------------------------------------------------------------------|
| Energy Storage                 | Zhuang and Liang (2021)                     | Battery Terminal Voltage       | Sequential data injection          | Constraint optimization based on Coulomb Counting Method to inject attack vectors post-attacking. |
| Photovoltaic Inverters         | Olowu, Dharmasena, Jafari and Sarwat (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. |
|                                | Tertytchny, Karbourj, Hadjidemetriou, Charalambous, Michael, Sazos and Maniatakos (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)                    | Hall sensor measurement        | DoS                                | Non-invasive physical magnetic spoofing technique with adversarial control.        |
| Residential                    | Kandasamy (2020)                            | Reactive Power information     | Coordinated MiTM attack            | Physical Tampering with the actuation command of inverters.                       |
|                                | Lindström, Sashara, He, Sandberg and Johanson (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 |
| Smart Energy Management System | Anuebunwa, Rajamani, Abd-Alhameed and Pillai (2018) | Load & Pricing data            | DoS, Phishing attacks & short-term data injection | Genetic Algorithm Optimization to inject corrupted information into load profiles. |
|                                | Sajeev and Rajamani (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) | Price data                     | MiTM long-term data injection      | Bi-level linear programming Optimization                                           |

Table 3
Comparative View of threats on End-User Level - Energy Management

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 (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 so-
lar inverters within two application scenarios namely:

1. **Commercial Domain**: 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, Tertychny 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 (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 Tertychny et al. (2020), the false data injection in this case comes from physical domains by exploiting the external magnetic fields.

2. **Residential Domain**: 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 (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 overcurrent 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. (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 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. (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.

### 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 (as depicted in Figure 6 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
| Category             | Ref No                     | Attack Target               | Attack Type               | Attack Mechanism                                                                 |
|----------------------|----------------------------|-----------------------------|---------------------------|----------------------------------------------------------------------------------|
| Smart Meters         | Lo and Ansari (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) | Smart meter energy generation data | Short-term data injection | Constraint Optimization to maximize the power injection of a bus. |
|                      | Fan, Li and Cao (2017)     | Load Profile                | Privacy attack            | Application signature extraction & identification.                                 |
|                      | Wu, Chen, Weng, Wei, Li, Qiu and Liu (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, Shaaban, Naidu and Serpedin (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) | 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)     | Communication messages      | MiTM Short term data injection | Evolutionary game theory. |

Table 4
Comparative View of threats on End-User Level - Advanced Metering Infrastructure

load forecasting, network controllability, etc., researchers have been investigating new attacks to compromise smart meters. 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. (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. 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. 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. (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 to nodes to allow adaptive selection of strategies under resource constraints such that the node payoffs 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 5:

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 et al. (2018). Therefore, Isozaki et al. (2014) proposed 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 to 7.86 $\times 10^3$ at some nodes. The work in Teixeira et al. (2015) considered two types of attacks on 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, $\delta$, 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 create 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 (PMU) to guarantee real-time and accurate synchronized phasor data measurements of electricity.
| Main Category | Ref No. | Attack Target | Attack Type | Attack Mechanism |
|---------------|---------|---------------|-------------|------------------|
| Voltage Regulators | Isozaki, Yoshizawa, Fujimoto, Ishii, Ono, Onoda and Hayashi (2014) | Load ratio control switch sensor measurement data | Short term data injection | Constraint Optimization which enables the attacker to suppress/induce tap changes. |
| | Teixeira, Paridari, Sandberg and Johansson (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) | 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) | Electromagnetic Field Threats | Electromagnetic Disturbances that may either be produced deliberately or is naturally occurring. |
| | Chattopadhyay, Ukil, Jap and Bhasin (2018) | Faulty IEDs | Implementation attacks (malicious fault injection attacks & hardware Trojan) | |
| Micro-Phasor Measurement Units (µ-PMU) | Santos and Orillaza (2018) | Voltage & Angle measurements | Short-term data injection | High Value FDI attack |
| | Kamal, Farajollahi, Nazaripouya and Mohsenian-Rad (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 5: Comparative View of threats on Field Devices.

Including voltage, current, and frequency Shahsavari, Sadeghi-Mobarakeh, Stewart, Cortez, Alvarez, Megala and Mohsenian-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 inte-
| Main Category | Sub Category | Ref No. | Attack Target | Attack Type | Attack Mechanism |
|---------------|--------------|---------|---------------|-------------|-----------------|
| Volt-var Control | | Teixeira, Dán, Sandberg, Berthier, Bobba and Valdes (2014) | Voltage node measurements | MiTM Stealth attack | Addition of Arbitrary voltage while subtracting attack vector from capacitor configurations. |
| | | Ju and Lin (2018) | Reactive power of DER devices | Short Term Data Injection | Topology-agnostic approach with constraint optimization |
| | | Choeum and Choi (2019) | Distribution feeder voltage profile | Short Term Data Injection | Bilevel optimization problem using mixed integer linear programming |
| | | Shen, Liu, Xu and Lu (2021) | Voltage & 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) | 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) | Bus voltage measurements | Short Term data injection | Constraint optimization based on proposed local state-based linear DSSE |
| | | Choeum and Choi (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 6
Comparative View of threats on Control Center.

Figure 7: Block diagram depicting a typical distribution control center system. (The figure represents the basic functionalities performed by a control centre as well as the flow of information within a distribution system.)

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. (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. Experimental 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 systems control center as in Table 6:
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 (2019)’s work 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. (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 (BMLP) 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 suboptimal 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. (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. (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. (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 (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, Cleemput 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 7.

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.

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 programs Cioara, Anghel, Bertoncin, Salomie, Arnone, Maminia, Velivassaki and Antal (2018), adversaries can easily affect energy markets through simple yet powerful attacks. 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 Tan et al. (2013)’s work 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 et al. (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. (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 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 (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 PNRL 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. (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 et al. (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 et al. (2018)]. In this view, 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 (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 1EDs, 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 nonlinear 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.

4. Lack of state-of-the-art methods to detect FDI attacks: Over the years, several techniques have been proposed to overcome the threats imposed by FDI attacks on smart grids. For instance, Kullback-Leibler distance method, fast go-decomposition, unscented Kalman filter (UKF), Bayesian formulation, etc. have been previously proposed as effective countermeasures against FDI attacks Sayghé et al. (2020). However, with the increasing strength and stealthiness of recent FDI attacks, several of the previously proposed solutions have become ineffective and outdated. In this view, we believe that state-of-the-art computer science techniques must be applied to enable effective detection of FDI threats. Some of the recent works in the field FDI counter defenses that have recently surfaced include the use of state-of-the-art computer science techniques such as:

- AI-based solutions: Artificial Intelligence has proven its success in several fields and disciplines and has emerged as one of the most successful technologies of the 21st century. Traditional BDDs that usually calculate the norm of the residuals between an attacked state and a normal state tend to fail in presence of stealthy FDI attacks. In order to overcome the FDI attack detection limitations posed by the use of traditional BDDs Sayghé et al. (2020), researchers have also developed several solutions by leveraging machine learning and deep learning techniques to effectively detect such cyber threats. For instance, authors in Ozay, Esnaola, Yaşar, Kulkarni and Poor (2016), which is among one of the earliest works, investigated the use of supervised machine learning algorithms for FDIA detection. The authors proposed the utilization of popular supervised and semi-supervised learning algorithms to detect FDI attacks with better performance than traditional BDDs. In response, other works Mohammadmourfard, Sami and Weng (2018); Kumar, Saxena and Choi (2021); Mohammadmourfard, Sami and Seifi (2017); Tabakhpour and Abdelaziz (2019) have followed which employed several machine learning and deep learning techniques for similar tasks. For instance, Kumaur et al. Kumar...
et al. (2021) similarly employed various machine and ensemble learning mechanisms for FDI attack detection. Several milestones have been achieved in developing FDI detection mechanisms through the use of machine learning technologies. However, throughout the past decade, there has been increased interests and applications of deep learning neural networks in several domains which have shown improved accuracy rates over traditional machine learning algorithms. Massaoudi, Abu-Rub, Refaat, Chihi and Oueslati (2021). Indeed, researchers within the field of FDI attack detection followed in the same footsteps. The work in Wei and Mendis (2016) is one of the earliest to employ the use of deep learning networks to analyze real-time measurements from the geographically sparse PMUs. Another work proposed by Haftu et al. Reda, Anwar, Mahmood and Chilamkurti (2022) developed a deep learning model for detection of false data injection attacks using a new using a new data-driven State Estimation model. Similarly, several other works Niu, Li, Sun and Tomsovic (2019); Zhang, Wang and Chen (2021); Mode, Calyam and Hoque (2020); Ashrafuzzaman, Chakchoukh, Jillepalli, Tosić, de Leon, Sheldon and Johnson (2018) have been proposed with improved deep neural networks.

- **Graph Signal Processing-based solutions**: While machine learning and deep learning techniques have been studied for FDI detection, the main prevailing issue with such approaches is the need for historic datasets that also contain attacked states which is extremely hard to obtain. Therefore, to overcome such problem, recent trends in literature have highlighted the use of graph signal processing techniques to detect FDI anomalies in power grid systems. Graph signal processing is an emerging field where classical signal processing tools developed in the Euclidean domain have been generalised to irregular domains such as graphs. Drayer and Routtenberg (2020) first proposed the use of anomaly filtering using Graph Fourier Transform to detect stealth FDI threats. Similarly, the authors in Ramakrishna and Scaglione (2019) developed a countermeasure to FDI threats in synchrophasor measurements through empirical evidence that PMU information are low-pass graph signals and the use of the features of the PMU graph signal. Similarly, Boyaci, Umunnakwe, Sahu, Narimani, Ismail, Davis and Serpedin (2022)’s study utilized a scalable Graph Neural Network (GNN) for FDI attack detection. While most of the work is based on transmission systems where the graphs are connected in nature, it would be great to investigate the extension of the work more from a distribution system perspective where the topology is radial or tree like. As very few studies have been undertaken within this area, we believe that this is a very interesting research gap that can be further explored.

- **Hybrid solutions**: Since real-time smart grid systems have become highly susceptible to real-time FDI attacks, researchers have began implementing hybrid countermeasures by leveraging hybrid solutions that enhances the chance of FDI attack detection. Data-driven solutions tend to leverage spatio-temporal correlations among multi-time-instant sensor measurements to detect FDI outliers. A few works including Chen, Wang, Cui, Zhao, Bi, Chen and Zhang (2022); Chen, Chen, Zhao, Zhang, Ni and Ren (2021); Deb Roy, Debbarma and Guerrero (2022) on data-driven FDI attack detection have been proposed in literature. For instance, the work in Chen et al. (2022) design an unsupervised detection scheme to detect the stealthy attack by employing a deep auto-encoding Gaussian mixture model which also means the data imbalance tolerance. While data-driven-based FDI defense mechanisms have been studied in the recent past, a new hybrid approach, namely physics-based solutions, has surfaced amongst researchers within this topic. Jevtic, Zhang, Li and Ilic (2018) is a pioneering work that uses a hybrid physics-based deep learning approach for FDI threat detection in power systems. In similar line, Trevizan, Ruben, Nagaraj, Ibukun, Starke, Bretas, McNair and Zare (2019); Chamanbaz, Dabbene and Bouffanais (2019); Xu, Higgins, Wang, Jaimoukha and Teng (2022) are among the few works that employed the use of physics-based methods for FDI attack detection.

5. **Lack of investigation of FDI threats in black-box settings**: Traditionally, the crafting of FDI threats by an adversary requires complete knowledge of the system. However, in practice, it is extremely hard to obtain topologies and other valuable characteristics of power systems as they are usually secured and encrypted to prevent unauthorized access. As prior knowledge for crafting FDI attacks is difficult to obtain in real-life scenarios, researchers have been motivated to contribute towards data-driven blind attack strategies based on black-box modelling for smart grids. In that regard, some few works Rahman and Mohsenian-Rad (2012); Zhang, Chu, Sankar and Kosut (2018); Deng and Liang (2019); Zhang, Chu, Sankar and Kosut (2016); Li and Wang (2019); Jiao, Xun, Liu and Yan (2021) have demonstrated that even with limited amount of information, successful FDI attacks have been implemented on transmission systems. Furthermore, the works in Anwar and Mahmood (2016); Anwar et al. (2022); Anwar, Mahmood and Pickering (2016) contributed significantly towards the development of blind FDI attacks in black-box based settings. Specifically, in a black-box setting as shown in Figure 9, an attacker is able to construct stealthy attack vectors which are based on the measurement subspace of the sensor information, thus eliminating the need of prior “known” system information. However, the mentioned studies have mostly been undertaken on transmission systems. Therefore, due to the major differences in characteristics between power transmission and distribution systems, transmission-based FDI attack construction mechanisms may not be extended to distribution systems. Very limited studies including Guihai and Sikdar (2021) have been undertaken to investigate the crafting of black-box FDI attacks in distribution systems. Thus, we believe that there exists a very critical gap in the existing state-of-the-art to be addressed by researchers as in the real world, adversaries often need to craft black-box attacks as they lack valuable insights of a particular system.
False Data Injection Threats in Active Distribution Systems: A Comprehensive Survey

(a) Demonstration of an FDI attack with known prior information. (An adversary constructs a FDI attack using known system information which produces a residual norm similar to a normal behaviour scenario)

(b) Demonstration of an FDI attack without prior information. (An adversary constructs a blind FDI attack using subspace information of the measurement data.

Figure 9: Comparison between FDI attack construction with prior information vs. in a black-box setting (referred from Anwar (2017)).

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 Velaga, 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.

4. FDI threats on Distributed Energy Management: DERs are changing the way of producing and managing electricity in several countries. Rather than the generation of electricity by centralized power stations, it is currently being generated through renewable energy units or systems that are commonly located at homes or businesses. Distributed Energy Management is an emerging topic within the grid research community and therefore, it is vital to study the emerging FDI risks in its relation.

5. Lightweight security mechanisms: Within the smart grid ecosystem, there are several resource-limited sensor devices (e.g. smart meters, etc.) which consistently gather valuable data. Therefore, due to the lack of computational resources, conventional security mechanisms are not suitable for sensor nodes in the smart grid system. Therefore, to defend against FDI threats, researchers must focus on developing light-weight defense solutions to overcome the resource-limitation of sensor devices.

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 OFDI 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 OFDI attacks on active distribution systems.

**References**

Abidin, A., Aly, A., Cleemput, S., Mustafa, M.A., 2018. Secure and privacy-friendly local electricity trading and billing in smart grid. arXiv:1801.08354.

Aitzhan, N.Z., Svetinovic, D., 2018. Security and privacy in decentralized energy trading through multi-signatures, blockchain and anonymous messaging streams. IEEE Transactions on Dependable and Secure Computing 15, 840–852.

Almalki, S.A., Sheldon, F.T., 2021. Deep learning to improve false data injection attacks in power grids using deep learning, in: 2018 IEEE Power and Energy Society General Meeting (PESGM), IEEE, Portland, OR, USA, pp. 1–5.

Anwar, A., 2017. Data-Driven Stealthy Injection Attacks on Smart Grid. Ph.D. thesis. The University of New South Wales, Australia. URL: https://www.researchgate.net/profile/Adnan-Anwar/publication/328128183_Data-Driven_Stealthy_Injection_Attacks_on_Smart_Grid/links/5bb950ba92851c7fde2fb8d6/Data-Driven-Stealthy-Injection-Attacks-on-Smart-Grid.pdf.

Anwar, A., Mahmood, A.N., 2016. Stealthy and blind false injection attacks on scada ems in the presence of gross errors, in: 2016 IEEE Power and Energy Society General Meeting (PESGM), pp. 1–5. doi: 10.1109/PES.2016.7741557.

Anwar, A., Mahmood, A.N., Pickering, M., 2016. Data-Driven Stealthy Injection Attacks on Smart Grid with Incomplete Measurements. Springer International Publishing, Cham. volume 9650. p. 180–192. URL: http://link.springer.com/10.1007/978-3-319-31863-9_13.

Anwar, A., Mahmood, A.N., Tari, Z., Kalam, A., 2022. Measurement-driven blind topology estimation for sparse data injection attack in energy system. Electric Power Systems Research 202, 107593. URL: https://linkinghub.elsevier.com/retrieve/pii/S0378779621005745. doi: 10.1016/j.epsr.2021.107593.

Ashrafuzzaman, M., Chakhchouk, Y., Jillepalli, A.A., Tosic, P.T., de Leon, D.C., Sheldon, F.T., Johnson, B.K., 2018. Detecting stealthy false data injection attacks in power grids using deep learning, in: 2018 14th International Wireless Communications & Mobile Computing Conference (IWCMC), pp. 219–225. doi: 10.1109/IWCMC.2018.8450487.

Balezentis, T., Streimikiene, D., Mikaluskas, I., Shen, Z., 2021. Towards carbon free economy and electricity: The puzzle of energy costs, sustainability and security based on willingness to pay. Energy 214, 119081.

Barreto, C., Eghtesad, T., Eisele, S., Laszka, A., Dubey, A., Koutsoukos, X., 2020a. Cyber-attacks and mitigation in blockchain based transactive energy systems, in: 2020 IEEE Conference on Industrial CyberPhysical Systems (ICPS), pp. 129–136.

Barreto, C., Koutsoukos, X., 2019. Attacks on electricity markets, in: 2019 57th Annual Allerton Conference on Communication, Control, and Computing (Allerton), pp. 705–711.

Barreto, C., Neema, H., Koutsoukos, X., 2020b. Attacking electricity markets through iot devices. Computer 53, 55–62.

Barua, A., Faruque, M.A.A., 2020. Hall spoofing: A non-invasive dos attack on grid-tied solar inverter, in: 29thUSENIXSecuritySymposium(USENIXSecurity20),USENIXAssociation,USA.pp.1273–1290.URL:https://www.usenix.org/conference/usenixsecurity20/presentation/barua.

Bernstein, A., Bienstock, D., Hay, D., Uzzunoglu, M., Zussman, G., 2014. Power grid vulnerability to geographically correlated failures — analysis and control implications, in: IEEE INFOCOM 2014 - IEEE Conference on Computer Communications, pp. 2634–2642. doi:10.1109/INFOCOM.2014.6848211.

Bienstock, D., Verma, A., 2009. The n-k problem in power grids: New models, formulations and numerical experiments (extended version). URL: https://arxiv.org/abs/0912.5233. doi:10.48550/ARXIV.0912.5233.

Boudlo, S., Abie, H., 2018. An evolutionary game for integrity attacks and defenses for advanced metering infrastructure, in: Proceedings of the 12th European Conference on Software Architecture: Companion Proceedings, ACM, Madrid, Spain, p. 1–7. URL: https://dl.acm.org/doi/10.1145/3241483.3241463.

Boyaci, O., Umunnakwe, A., Sahu, A., Narimani, M.R., Ismail, M., Davis, K.R., Serpedin, E., 2022. Graph neural networks based detection of stealth false data injection attacks in smart grids. IEEE Systems Journal 16, 2946–2957. doi:10.1109/JSYST.2021.9109802.

Brinkmann, B., Bicevski, K., Scott, R., Negnevitsky, M., 2017. Evaluation of single-and three-phase state estimation in distribution networks, in: 2017 Australasian Universities Power Engineering Conference (AUPEC), pp. 1–5.

Canha, L.N., Pereira, P.R., Milbradt, R., da Rosa Abaide, A., Kork Schmitt, K.E., de Abreu Antunes, M., 2017. Intelligent voltage regulator to distributed voltage control in smart grids, in: 2017 52nd International Universities Power Engineering Conference (UPEC), pp. 1–6.

Siqueira de Carvalho, R., Kumar Sen, P., Nag Velaga, Y., Feksa Ramos, L., Neves Canha, L., 2018. Communication system design for an advanced metering infrastructure. Sensors 18, 3734.

Chamanzabz, M., Dabbenbe, F., Boughn, M., 2019. A physics-based attack detection technique in cyber-physical systems: A model predictive control co-design approach, in: 2019 Australian & New Zealand Control Conference (ANZCC), pp. 18–23. doi:10.1109/ANZCC47149.2019.8945588.

Chaojun, J., Jiruttijaroen, P., Motani, M., 2015. Detecting false data injection attacks in ac state estimation. IEEE Transactions on Smart Grid 6, 2476–2483. doi:10.1109/TSG.2015.238545.

Chattopadhyay, A., Ukil, A., Jap, D., Bhasin, S., 2018. Toward threat of implementation attacks on substation security: Case study on fault detection and isolation. IEEE Transactions on Industrial Informatics 14, 2442–2451.

Chen, C., Chen, Y., Zhao, J., Zhang, K., Ni, M., Ren, B., 2021. Data-driven resilient automatic generation control against false data injection attacks. IEEE Transactions on Industrial Informatics 17, 8092–8101. doi:10.1109/TII.2021.3058413.

Chen, C., Wang, Y., Cui, M., Zhao, J., Bi, W., Chen, Y., Zhang, X., 2022. Data-driven detection of stealthy false data injection attack against power system state estimation. IEEE Transactions on Industrial Informatics, 1–10doi:10.1109/TII.2022.3149186.

Chihota, M., Gaunt, C., 2018. Transform for probabilistic voltage computation in smart grid. Electric Power Systems Research 202, 107593. URL: https://linkinghub.elsevier.com/retrieve/pii/S0378779621005745. doi: 10.1016/j.epsr.2021.107593.

Chulkyu, L., Sharma, P., Kumar, A., Bhagwatikar, G., 2018. Iot-based implementation of field area network using smart grid communication infrastructure. Smart Cities 1, 176–189.

Chung, Y., Gaunt, C., 2018. Transform for probabilistic voltage computation on distribution feeders with distributed generation, in: 2018 Power Systems Computation Conference (PSCC), pp. 1–7.

Choeun, D., Choi, D.H., 2019. Oltc-induced false data injection attack on distribution feeders with distributed generation, in: 2018 Power Systems Computation Conference (PSCC), pp. 1–7.

Choeun, D., Choi, D.H., 2021. Vulnerability assessment of conservation voltage reduction to load redistribution attack in unbalanced active distribution networks. IEEE Transactions on Industrial Informatics, 1–10doi:10.1109/TII.2022.3149186.

Chow, T., Anghel, I., Bertoncini, M., Salomie, I., Arnone, D., Mammina, M., Velivassaki, T.H., Antal, M., 2018. Optimized flexibility management enabling data centres participation in smart demand response programmes. Future Generation Computer Systems 78, 330–342.
Guilhai, Z., Siddik, B. 2021. Adversarial machine learning against false data injection attack detection for smart grid demand response. in: 2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), pp. 352–357. doi:10.1109/SmartGridComm51999.2021.9632316.

Gusrialdi, A., Qu, Z., 2019. Smart Grid Security: Attacks and Defenses. Springer International Publishing, Cham, Switzerland. p. 199–223. URL: https://link.springer.com/10.1007/978-3-319-88318-3_13.

Hammer, F., Fuhr, C., Hanson, J., Konigorski, U., 2019. Differences of power flows in transmission and distribution networks and implications on inverter droop control, in: 2019 International Conference on Clean Electric Power (ICCEP), pp. 46–54.

Han, J., Choi, C.S., Park, W.K., Lee, I., 2011. Green home energy management system through mixed energy usage between the same kinds of home appliances, in: 2011 IEEE 15th International Symposium on Consumer Electronics (ISCE), IEEE, Singapore. pp. 1–4.

He, D., Chen, C., Bu, J., Chan, S., Zhang, Y., Guizani, M., 2012. Secure service provision in smart grid communications. IEEE Communications Magazine 50, 53–61. doi:10.1109/MCOM.2012.6257527.

Hong, J., Liu, C.C., 2019. Intelligent electronic devices with collaborative intrusion detection systems. IEEE Transactions on Smart Grid 10, 271–281.

Hu, J., Yang, G., Kok, K., Xue, Y., Bindner, H.W., 2017. Transactive control: a framework for operating power systems characterized by high penetration of distributed energy resources. Journal of Modern Power Systems and Clean Energy 5, 451–464.

Huang, K., Tao, Z., Wang, C., Guo, T., Yang, C., Gui, W., 2022. Cloud-edge collaborative method for industrial process monitoring based on error-triggered dictionary learning. IEEE Transactions on Industrial Informatics 1, 1–1doi:10.1109/2945.2022.3161640.

Islam, S.N., Mahmud, M., Oo, A., 2018. Impact of optimal false data injection attacks on local energy trading in a residential microgrid. ICT Express 4, 30–34.

Ismael, M., Shaaban, M.F., Naidu, M., Serpedin, E., 2020. Deep learning detection of electricity theft cyber-attacks in renewable distributed generation. IEEE Transactions on Smart Grid 11, 3428–3437.

Isozaki, Y., Yoshizawa, S., Fujimoto, Y., Ishii, H., Ono, I., Onoda, T., Hayashi, Y., 2014. On detection of cyber attacks against voltage control in distribution power grids, in: 2014 IEEE International Conference on Smart Grid Communications (SmartGridComm), pp. 842–847.

Jevtic, A., Zhang, F., Li, Q., Ilic, M., 2018. Physics- and learning-based detection and localization of false data injections in automatic generation control. IFAC-PapersOnLine 51, 702–707. URL: https://linkinghub.elsevier.com/retrieve/pii/S2405896318335088. doi:10.1016/j.ifacol.2018.11.787.

Jhala, K., Natarajan, B., Pahwa, A., Wu, H., 2019. Stability of transactive energy market-based power distribution system under data integrity attack. IEEE Transactions on Industrial Informatics 15, 5541–5550.

Jia, L., Kim, J., Thomas, R.J., Tong, L., 2014. Impact of data quality on real-time locational marginal price. IEEE Transactions on Power Systems 29, 627–636. doi:10.1109/TPWRS.2013.2286992.

Jiao, R., Xun, G., Liu, X., Yan, G., 2021. A new ac false data injection attack method without network information. IEEE Transactions on Smart Grid 12, 5280–5289. doi:10.1109/TSG.2021.3182325.

Ju, P., Ariapoo, N., Leung, V.C.M., 2016. A survey on security issues in smart grids: A survey on security issues in sgs. Security and Communication Networks 9, 262–273.

Ju, P., Lin, X., 2018. Adversarial attacks to distributed voltage control in power distribution networks with ders, in: Proceedings of the Ninth International Conference on Future Energy Systems, Association for Computing Machinery, New York, NY, USA, p. 291–302. URL: https://doi.org/10.1145/3208903.3208912.

Kamal, M., Farajollahi, M., Nazarijouya, H., Moshensian-Rad, H., 2021. Cyberattacks against event-based analysis in micro-pmus: Attack models and counter measures. IEEE Transactions on Smart Grid 12, 1577–1588.

Kandasamy, N.K., 2020. Prosumer site power interruption attacks: exploiting the reactive power control feature in smart inverters. IET Generation, Transmission & Distribution.
Yang, C., Feng, L., Zhang, H., He, S., Shi, Z., 2018. A novel data fusion algorithm to combat false data injection attacks in networked radar systems. IEEE Transactions on Signal and Information Processing over Networks 4, 125–136. doi:10.1109/TSPIN.2018.2790361.

Yang, T., 2019. ICT technologies standards and protocols for active distribution network. Elsevier. p. 205–230. URL: https://linkinghub.elsevier.com/retrieve/pii/B9780128121542000109.

Yazdaninejadi, A., Hamidi, A., Golshannavaz, S., Aminifar, F., Teimourzadeh, S., 2019. Impact of inverter-based ders integration on protection, control, operation, and planning of electrical distribution grids. The Electricity Journal 32, 43–56.

Yi, P., Zhu, T., Zhang, Q., Wu, Y., Li, J., 2014. A denial of service attack in advanced metering infrastructure network, in: 2014 IEEE International Conference on Communications (ICC), IEEE, Sydney, NSW. p. 1029–1034. URL: http://ieeexplore.ieee.org/document/6883456/.

Zhang, J., Chu, Z., Sankar, L., Kosut, O., 2016. False data injection attacks on power system state estimation with limited information, in: 2016 IEEE Power and Energy Society General Meeting (PESGM), pp. 1–5. doi:10.1109/PESGM.2016.7741928.

Zhang, J., Chu, Z., Sankar, L., Kosut, O., 2018. Can attackers with limited information exploit historical data to mount successful false data injection attacks on power systems? IEEE Transactions on Power Systems 33, 4775–4786. doi:10.1109/TPWRS.2018.2818746.

Zhang, X., Yang, X., Lin, J., Xu, G., Yu, W., 2017. On data integrity attacks against real-time pricing in energy-based cyber-physical systems. IEEE Transactions on Parallel and Distributed Systems 28, 170–187.

Zhang, Y., Eisele, S., Dubey, A., Laszka, A., Srivastava, A.K., 2019a. Cyber-physical simulation platform for security assessment of transactive energy systems, in: 2019 7th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), pp. 1–6.

Zhang, Y., Wang, J., Chen, B., 2021. Detecting false data injection attacks in smart grids: A semi-supervised deep learning approach. IEEE Transactions on Smart Grid 12, 623–634. doi:10.1109/TSG.2020.3010510.

Zhang, Y., Wang, J., Li, Z., 2019b. Uncertainty modeling of distributed energy resources: Techniques and challenges. Current Sustainable/Renewable Energy Reports 6, 42–51.

Zhuang, P., Deng, R., Liang, H., 2019. False data injection attacks against state estimation in multiphase and unbalanced smart distribution systems. IEEE Transactions on Smart Grid 10, 6000–6013.

Zhuang, P., Liang, H., 2019. Fdi attacks against real-time dlmp in cps-based smart distribution systems, in: 2019 IEEE Global Communications Conference (GLOBECOM), IEEE, Waikoloa, HI, USA. p. 1–6. URL: https://ieeexplore.ieee.org/document/8814295/.

Zhuang, P., Liang, H., 2021. False data injection attacks against state-of-charge estimation of battery energy storage systems in smart distribution networks. IEEE Transactions on Smart Grid 12, 2566–2577.

Zia, M.F., Elbouchikhi, E., Benbouzid, M., Guerrero, J.M., 2019. Microgrid transactive energy systems: A perspective on design, technologies, and energy markets, in: IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, pp. 5795–5800.