

Cyber-Physical System Security of Distribution Systems

Chen-Ching Liu, *Life Fellow, IEEE*, Juan C. Bedoya, *Member, IEEE*,
 Nitasha Sahani, *Student Member, IEEE*, Alexandru Stefanov *Member, IEEE*,
 Jennifer Appiah-Kubi, *Student Member, IEEE*, Chih-Che Sun, *Member, IEEE*,
 Jin Young Lee, *Student Member, IEEE*, Ruoxi Zhu, *Student Member, IEEE*

Abstract—The Information and Communications Technology (ICT) for control and monitoring of power systems is a layer on top of the physical power system infrastructure. The cyber system and physical power system components form a tightly coupled Cyber-Physical System (CPS). Sources of vulnerabilities arise from the computing and communication systems of the cyber-power grid. Cyber intrusions targeting the power grid are serious threats to the reliability of electricity supply that is critical to the society and economy. In a typical Information Technology (IT) environment, numerous attack scenarios have shown how unauthorized users can access and manipulate protected information from a network domain. The need for cyber security has led to industry standards that power grids must meet to ensure that the monitoring, operation, and control functions are not disrupted by cyber intrusions. Cyber security technologies such as encryption and authentication have been deployed on the cyber-power systems. Intrusion or anomaly detection and mitigation tools developed for power grids are emerging. This survey paper provides the basic concepts of cyber vulnerabilities of distribution systems and cyber-physical system security. The important ICT subjects for distribution systems covered in this paper include Supervisory Control And Data Acquisition (SCADA), Distributed Energy Resources (DERs), including renewable energy and smart meters.

I. INTRODUCTION

THE threats of cyberattacks targeting the electric power grid have been increasing in recent years [1][2]. The consequence of cyber incidents on the power grid includes equipment damage, cascading events, large-scale power outages, and disruption of market functions [3][4][5]. Government and industry have made a significant effort to strengthen the protection of the power infrastructure against cyber threats by setting standards and guidelines, e.g., [6][7][8][9][10][11].

- Critical Infrastructure Protection, Presidential Directive PDD-63, 1998.
- Cyber Security Roadmap for Energy Delivery Systems, Department of Energy (DOE), 2011.

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C.C. Liu, J. C. Bedoya, N. Sahani, R. Zhu, J. Appiah-Kubi are with the Power and Energy Center of the Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg VA 24060 (email: ccli@vt.edu; bedojuan@vt.edu; nitashas@vt.edu; ruoxi@vt.edu; jennifera@vt.edu). A. Stefanov is with TU Delft, The Netherlands (email: A.I.Stefanov@tudelft.nl); C.C. Sun and J. Y. Lee were with the School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA 99164 (email: csun@eecs.wsu.edu; jinyoung.lee@wsu.edu).

- Guidelines for Smart Grid Cyber Security, National Institute of Standards and Technology (NIST) Report 7628.
- Critical Infrastructure Protection (CIP) Standards, Cyber Security CIP 002-014, North American Electric Reliability Corporation (NERC).
- National Electric Sector Cybersecurity Organization Resource (NESCOR), Electric Power Research Institute (EPRI).
- European Programme for Critical Infrastructure Protection (EPCIP) resulting from the European Commission's directive EU COM (2006).

As power systems become more complex and dependent on ICT, the cyber system and physical system are highly connected and, therefore, the threat of cyberattacks on the power grid also increases. Intruders seeking to cause damages to the grid can compromise the communication systems to launch an attack on the power grid.

In December 2015, the power grid in Ukraine experienced a cyberattack by hackers [12][13]. The damage caused by the sophisticated attack was a power outage affecting about 225,000 customers for about 6 hours. The hacker implemented malware using phishing email to obtain the VPN credential. From this attack, the hacker launched remote control actions through the control center computers. Denial of Service (DoS) attacks jammed phone reports of the outage to the call center. Furthermore, the data destruction software, KillDisk, was used to erase the reboot software in the workstation, causing a delay in power system restoration. Further observations can be made concerning the Ukraine attack scenario: 1) First, the hackers were knowledgeable about the operation of the targeted grid, 2) The hackers were able to manipulate the cyber-power system from the Distribution System Operator (DSO) control center, and 3) The hackers had knowledge of critical control and operation devices. The in-depth information was obtained by penetrating the SCADA system and staying undetected for at least six months. After observing for six months, the hackers gained sufficient knowledge about the operation and critical information of the power system. With the information garnered, the hacker(s) conducted an attack through the SCADA system to operate circuit breakers in the substations, causing a power outage.

As demonstrated by the real-world cyberattack, it is critical to fully understand the vulnerabilities of the cyber-power system to develop the capabilities for detecting cyber intrusions and take timely mitigation actions. Although cyber intrusions

can be launched by compromising control center computers, damages could also be caused by man-in-the-middle attacks on the communication system between the control center and field devices. Therefore, defense of the communication system is a critical issue for power systems.

Cyber security issues arise when power system components are provided with remote monitoring and control capabilities over public communication infrastructures. Remote monitoring and control for power grids has been the industry practice. This would not be a problem if the utility communication networks are private and isolated from the Internet. The problem is that the utility private communication networks, Operational Technology (OT) systems, for substation and control center communications may be connected with the general IT systems used for other purposes [14] such as electricity trading and these IT systems are in turn connected to the Internet. While there are firewalls between IT and OT systems, the firewalls may have vulnerabilities. Furthermore, some distribution system operators use public communication networks for their distribution networks [14] such as 3G/4G/5G for the pole-mounted devices. They also communicate with the control centers.

Development of the Smart Grid in recent years by large-scale deployment of ICT leads to fast-increasing connectivity of devices and systems in the power grid. Smart grid development in the U.S. is primarily concerned with Phasor Measurement Units (PMUs) for the transmission system as well as remote control switches and voltage/var control devices in the distribution systems. The remote monitoring and control capabilities are also created for millions of smart meters at the customer locations and DERs, including renewable energy, energy storage, and responsive load. Indeed, Advanced Metering Infrastructure (AMI) has been installed for communication and control between the utility company and numerous smart meters. As a result of the DERs, the architecture of the power grid is rapidly evolving from a centralized utility service to a distributed or decentralized structure [15]. For example, Hawaii reached 23% of renewable electricity while California has 26% renewable [16][17] and targets a 50% level by 2030. Deployment of DERs is often conducted by non-utility parties and, therefore, the utility system may not have full control of the devices. AMI also brings new communication and control features through smart meters. As a result, additional risks emerge due to the large number of devices and non-controllable access points [18][19][20][21].

This survey paper is intended to serve as a module in senior level undergraduate as well as graduate courses in power engineering. The objective of this paper, therefore, is to provide fundamental concepts of cyber security for the distribution system as a cyber-physical system. To meet the objective, vulnerabilities of cyber intrusions and mitigation strategies are discussed. The remaining sections are organized as follows. The evolution of the ICT for the power grid, sources of vulnerabilities, and cyber security measures are presented in Section II. Sections III and IV describe the ICT in the power system environment. Section V focuses on the cybersecurity issues of a distribution system, while section VI discusses smart

grid communication standards and protocols. In Section VII detection of cyber intrusions in distribution systems is considered. Mitigation strategies are provided in Section VIII. Computer simulation cases based on the cyber-power system model are presented in Section IX, and the paper is concluded in Section X.

II. POWER GRID VULNERABILITIES AND SECURITY MEASURES

A. Age of Information Technology

Low-cost computer peripherals help to create an Internet-based computer communication environment. Deployment of the new information and communications technology (ICT) improves system performance, interoperability, and reliability. However, cyber security issues also arise from the fast-increasing connectivity. The cyber-physical system technology brings:

- Standardized communication protocols,
- Widely adopted technologies with known vulnerabilities,
- Connectivity of control systems to other networks,
- Use of existing security technologies and practice,
- Insecure remote connections, and
- Widespread availability of information about control systems.

Security flaws and malicious activities (hackers/worms) can damage cyber and physical components of the distribution system. Significant efforts are required to identify and isolate malicious actions and secure the cyber-power system. A cyberattack taxonomy is shown in Figure 1.

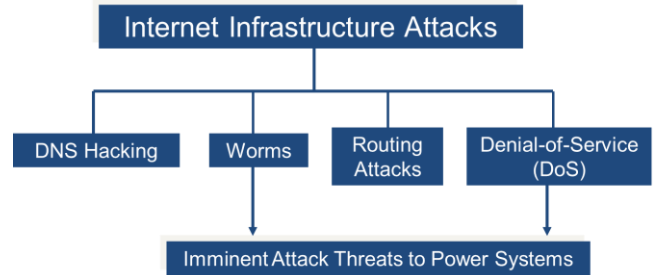


Figure 1. Cyber attack Taxonomy.

B. Typical Power Grid Vulnerabilities and Mitigation Actions

In Denial-of-Service (DoS), an attacker aims to deny authorized users access to the target system. One way to do this is to flood the target system (for instance, SCADA communication system) with a large number of requests so as to consume server resources and make the system unresponsive to genuine instructions. Viruses/Worms are malware that install themselves in cyber components of the power system and infect critical system components to cause abnormal behaviors. Usually, these packets are injected by hackers who initiate packet sniffing using the same network as the system operator. Hackers may also maliciously modify or inject packets in the network by accessing corporate firewalls. Software bugs can be exploited to gain (unauthorized) access to control center networks and SCADA systems. Additional sources of vulnerabilities are unauthorized access points from which it is possible to send false information through the SCADA system. Disgruntled employees are also a potential source of

vulnerability. Finally, there is a risk in power system control software using publicly available documentation.

The NERC Critical Infrastructure Protection (CIP) standards, CIP- 002 through 014 [22], among others, propose the following mitigation practice to overcome cyber-physical system vulnerabilities:

- Define cyber security policies for all organizations.
- Identify critical cyber assets to safeguard.
- Demarcate an electronic security perimeter.
- Implement electronic access control mechanisms.
- Monitor electronic access periodically.
- Define electronic incident response actions.
- Develop secure password management system and periodically modifications.
- Review authorization and access rights periodically.
- Disable unauthorized, invalidated, expired or unused computer accounts.
- Disable unused network ports and services.
- Secure dial-up connections, install, and manage firewall applications.
- Setup intrusion detection/prevention systems (IDS/IPS).
- Enable auto-updates and patch management.
- Install and keep up to date on anti-virus software.
- Retain and review operator logs, application logs, and IDS logs.
- Track computer system vulnerabilities and effective responses.
- Install secure VPN connections.
- Separate corporate and control networks as much as possible.

III. ICT IN CYBER-TRANSMISSION SYSTEMS

A. ICT Model of Power Systems

Power generation resources are connected to numerous consumers through transmission and distribution networks. The ICT system enables real time monitoring and control of the power system [8].

Figure 2 shows the communication systems and devices at the transmission level of power system operation. A transmission system operator coordinates the operation of a number of power systems, each with its own control center. Substations are connected to the control center of the power system through the SCADA system, which enables data acquisition and remote control.

B. Substation Automation System (SAS)

Monitoring and control at the substation level depends on communication and computation systems. The architecture of an IEC 61850 [2] based SAS is shown in Figure 3. Data and measurements are collected by CT and PT and transmitted to the control center through SCADA facilities at the substation. Remote control commands from the control center are delivered to the physical devices through Intelligent Electronic Devices (IEDs). The automation system has several advantages:

(1) **Installation cost reduction:** IEDs at a substation are connected through a Local Area Network (LAN) using Ethernet-based interaction. Traditional copper-based communication networks are replaced by new technology, e.g., optical fibers, that offer reduced latency. Lower cost is achieved by integration of massive data, measurements, and control commands in a single line for communication.

(2) **IED interoperability:** All devices based on IEC 61850, such as substation IEDs, are provided with import/export capabilities (Substation Configuration Language - SCL). SCL is represented in files that contain from/to interconnection information and are transmitted via ICT to the master server. Smart devices are designed with auto-configuration features that allow integration of IEDs from different vendors within the same substation.

(3) **Impact reduction of topology changes:** Engineers at a substation can connect IEDs into the Substation Automation System (SAS). Components of the ICT can be used to send SCL files to field IEDs and update the configuration information.

Modern substations at the transmission level are remotely controlled. System operators use different technologies to access the Substation Communication Network (SCN). Figure 3 presents a typical SCN architecture. The mechanism used by system operators to access the SCN can also be used by attackers to gain access to substation information and control.

Attackers explore different tactics (e.g., cracking the password) to access a SCN. Once access is granted, critical data is exposed (e.g., measurements, topology, maintenance records, historian data, and circuit breaker status). Furthermore, attackers are able to send control commands (e.g., opening circuit breakers). Once access is granted, attackers can log on multiple substation networks, if the communication system is vulnerable. A worst case cyberattack scenario leading to catastrophic outages may be caused by an attacker triggering a sequence of cascading events on the power grid.

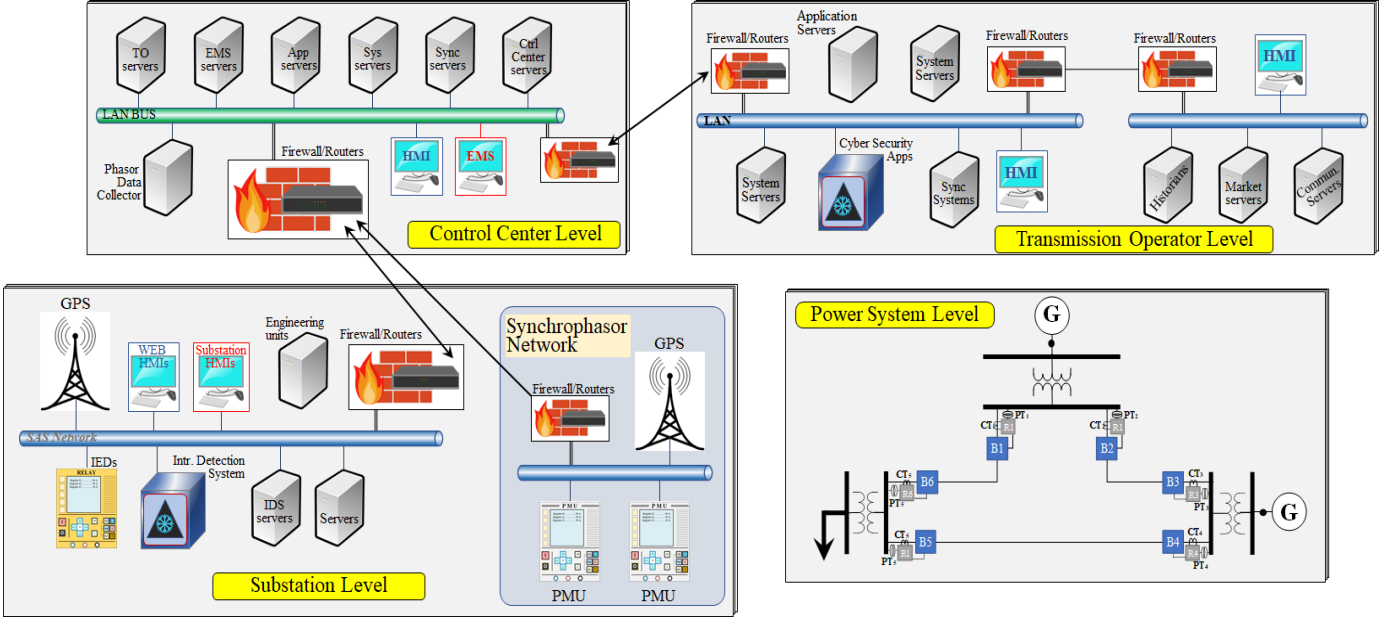


Figure 2. ICT model at the transmission system level.

remote sites, Programmable Logic Controllers (PLCs) or Remote Terminal Units (RTUs) are the functional devices for remote monitoring and control. However, PLCs are deployed for local control, whereas RTUs are used for wide area telemetry. Analytical software tools in an Energy Management System (EMS) or Distribution Management System (DMS) use the measurements to estimate the system states and the operators take appropriate actions based on the operating conditions. As shown in Figure 4, major components of a SCADA system are: communication system (LAN/WAN), software systems (e.g., EMS/DMS), Sensors (CT/PT), HMI, protective devices (relays), and control devices (circuit breakers) [23].

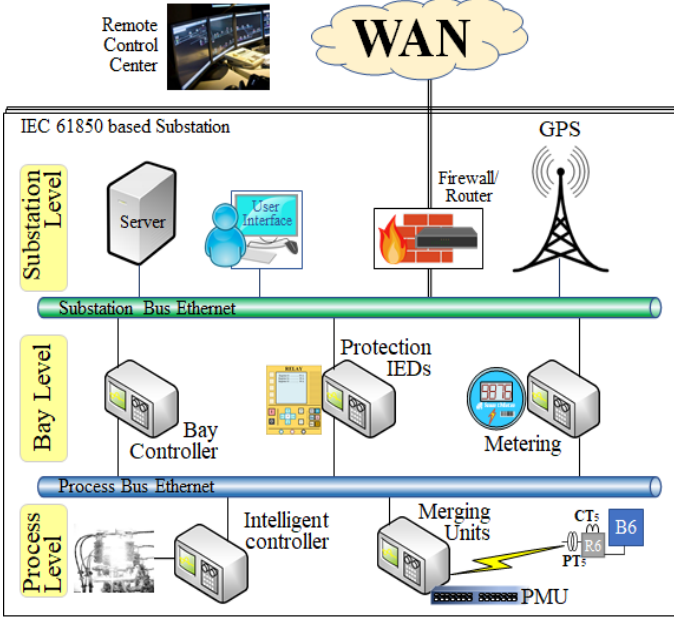


Figure 3. Architecture of an IEC 61850 based substation.

IV. ICT IN CYBER-DISTRIBUTION SYSTEMS

A. Supervisory Control And Data Acquisition (SCADA)

SCADA systems have been widely deployed in various industries, e.g., oil/gas, water, and power, for online monitoring and control. For power systems, SCADA is utilized for collecting measurements (e.g., voltage, current) and sending control commands from a control center to switching devices at substations. The Wide Area Network (WAN) is used as the communication system for the SCADA. In a control center or substations, the devices communicate with each other and access data through the Local Area Network (LAN). At the

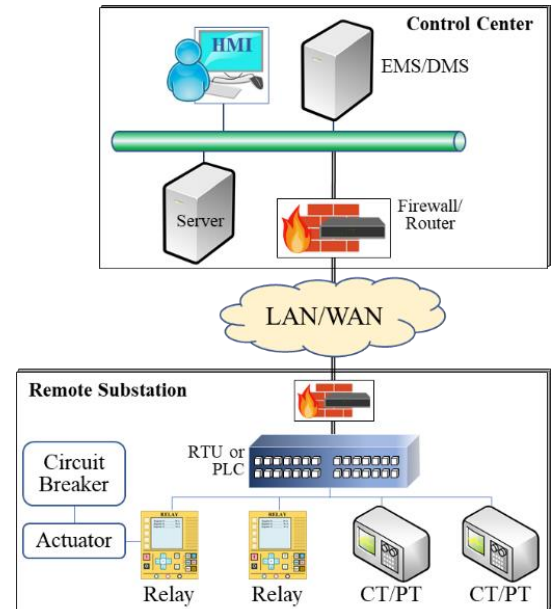


Figure 4. Major components of a SCADA system.

B. Advanced Metering Infrastructure (AMI)

With recent advancements in smart meter technology, AMI is used to collect power consumption data at customers' locations. Unlike the Automatic Meter Reading (AMR) system, AMI provides high rates for data exchange and is equipped with duplexed modules for communication in order to send/receive measurements and control commands (e.g., connect or disconnect service) [24].

Conventional meters were used to keep track of users' power usage and must be read on site by meter readers. Smart meters, however, provide new capabilities to record energy flow *in* and *out* [25] (when consumers produce surplus energy from rooftop solar panels or wind). Recent applications using energy storage capabilities from plug-in hybrid electric vehicles (PHEVs), make it possible to charge the battery when electricity price is low and inject power back to the grid when electricity price is high during peak hours [26]. Typical components of a smart meter include current/voltage sensors, communication module, data storage, microprocessor, and RAM.

Vulnerabilities exist for smart meters and AMI. Since smart meters collect the users' electricity consumption data, cyber attackers may be able to steal electricity or gain access to users' private information [27][28][29]. Also, smart meters send measurements to the control center every 5 to 60 minutes, depending upon configuration and network traffic [30]. AMI communication network is characterized by users' devices, local data aggregators, and Meter Data Management Systems (MDMSs).

Figure 5 shows a typical communication system. IEEE 802.15.4 wireless communication protocols [31] allow an extended communication distance between a local data aggregator and smart meters using point-to-multipoint configurations [30].

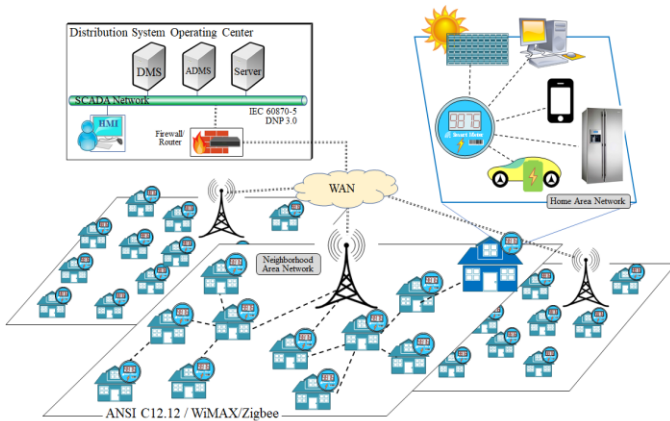


Figure 5. Architecture of an AMI system

Finally, the deployment of AMI opens new opportunities for reliability improvement. Two examples are:

- **Demand Response (DR):** In the DR mechanism, peak load is reduced by shifting energy consumption from peak to off-peak hours. Peak shaving helps to prevent line overloading and avoid the need to invest in costly generation resources [32].

- **Outage Management System (OMS):** AMI automatically reports power outage events allowing the Distribution System Operator (DSO) to determine the outage areas if multiple devices reporting the outage condition. Compared to traditional trouble calls, AMI allows operators to respond faster and reduce the outage duration [33].

C. Distributed Energy Resources

The high penetration of solar PVs in distribution systems significantly changes the operation and control. Smart inverters with the reactive power capability can support the voltage profile in distribution systems. Comparing with the traditional inverters, smart inverters with digital communication interface can provide the remote-control capability in an online environment. In the electricity market [34], DERs, include distributed generators, energy storage, renewable energy devices, and flexible load, are owned by utilities or third parties. At the third quarter of 2018, the installed solar energy has reached 60 GW in the U.S. [35]. To be connected through SCADA, smart inverters are equipped with a two-way communication interface. Smart inverters are critical devices for Voltage/VAR support and fault ride-through capabilities. However, these devices may not be secure because the consumers who own the devices may connect to unsecured network devices, e.g., a home Wi-Fi router. To manage a group of DERs in a utility, the facilities DER energy management systems are deployed via WAN/LAN [36].

As far as cyber security is concerned, the most critical devices in a DER network are smart inverters. Grid-tied renewable energy resources, such as wind turbines and PV panels, need a power inverter to change DC to AC and interface with a power grid. Smart inverters are monitored and controlled via a communication system from a control center. To regulate interconnected DER devices, certain standards have been proposed. These are discussed in a later section. Among the standards, is Rule 21 [37][38], which was formulated by the Smart Inverter Working Group (SIWG). Communication configurations between a utility and remote devices in a DER system that are included Rule 21 are shown in Figure 6 and Figure 7.

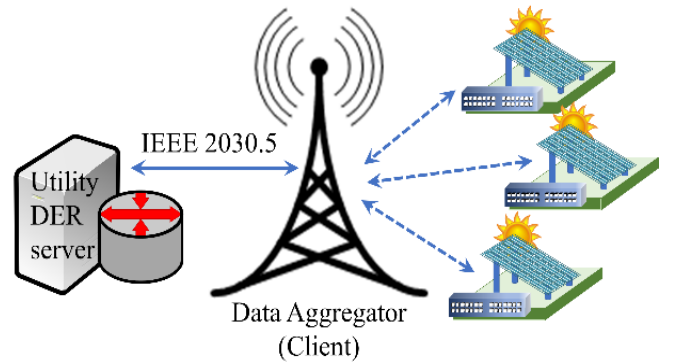


Figure 6. Communication structure of a DER system. System with carrier Data Aggregator.

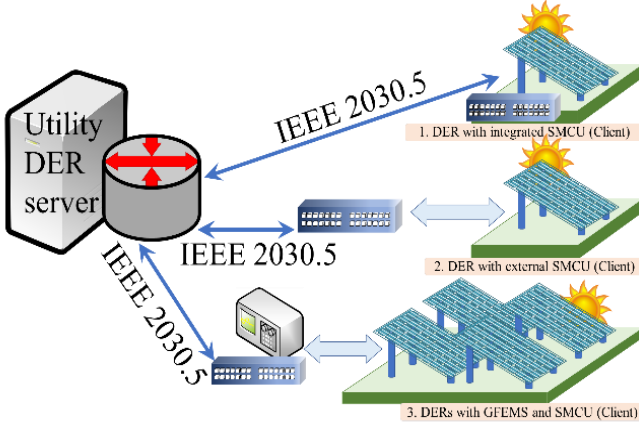


Figure 7. Communication structure of a DER system. Decentralized integration. DER with either generating facility energy management system (GFEMS) or smart inverter control unit (SMCU).

V. CYBER SECURITY OF A DISTRIBUTION SYSTEM

Cyber intrusions are a serious threat to the reliable operation of a smart grid. From the energy section of the National Cybersecurity and Communications Integration Center (NCCIC) annual report [39], most of the reported cyberattacks target the IT system of utilities and vendors. According to the U.S. Department of Energy (DOE), the attempted cyberattack figures are higher than actually reported [40]. Thus, it is important to identify cyber vulnerabilities and develop the detection and mitigation strategies for potential cyber intrusions into a smart grid.

Regulatory and technical issues must be addressed to achieve a secure environment for a distribution system in transformation. The main challenges are: 1) fast evolving distribution systems; 2) vulnerabilities of communication systems and integration with new communication technologies; 3) trust from different active/passive interacting parties; 4) heterogeneous protocols/technologies; 5) proprietary systems; and 6) privacy of the participants.

Availability means that authorized parties should have privileges to access required data without compromising the system's security. *Confidentiality* refers to data disclosure to only authorized individuals or systems. For instance, confidentiality should be maintained for metering data; privacy includes patterns of individual behaviors and can be used against customers at the meter locations, similarly for the pricing information which can be used to manipulate electricity markets. *Integrity* is the assurance that accuracy and consistency of data is maintained without unauthorized modifications, destruction, or loss of data. *Authentication* is concerned with verifying that users' identity in the communication systems matches a valid user account.

A. Common Cyber Attacks in Distribution System Infrastructure

Cyber-physical threats exist in transmission systems, which depend on communication systems for monitoring and control. Similarly, distribution systems also have vulnerabilities associated with the cyber-distribution system infrastructure. Common threats and attack models at the distribution system

level include:

- *Man in the Middle Attacks*: Unauthorized access to a communication channel that can be exploited to adversely alter the data from communication devices, compromising the availability and integrity of power system data [41] [42]. They include false data injection and replay attacks:
 - *False Data Injection (FDI)*: FDI attacks result from injecting (corrupting) measurements or data, with the goal of triggering damaging control actions to the system. For example, falsified low voltage measurements from the substations may mislead system operators in a control center to take actions to raise the voltages, causing high voltages in the power system.
 - *Replay Attack*: A replay attack with a malicious intent is launched by intercepting the valid data packet and re-transmitting it at a later time.
- *Rogue Devices*: Field devices that replace legitimate signals with falsified data. Vulnerability arises when an attacker gains physical access to field devices such as sensors and metering units.
- *Denial of Service*: Compromising data availability by attempting to delay/block critical communication links, flooding them with falsified packets [43]. At the distribution system communication level, two main DoS attacks are described next:
 - *Channel Jamming*: It is usually performed with "radio jammer" equipment that blocks wireless communication of the field physical devices.
 - *Medium Access Control (MAC) DoS*: Attackers modify MAC layer parameters and pretend to be trustworthy sources. Once access is granted, data theft/modification, malware spread, parameter changes, can be performed. This cyberattack approach is also known as spoofing attack, which can be launched in different forms, such as email, website, and text messages.

B. Vulnerabilities in Cyber Infrastructures

Firewalls, as a front-line defense, are installed at the access point (router or gateway) to prevent unauthorized access. By parsing the properties of incoming traffic, i.e., time delay, IP address, and port numbers, firewalls are designed to filter unauthorized packets. However, the pre-defined rule set of commercial grade firewalls can conflict in many cases [44][45]. It is challenging to develop accurate firewalls that satisfy all cyber assets for the authorized network. Furthermore, the proprietary software platform used by the power grid is usually inaccessible for the public, which complicates the rule setting for the firewalls. Identification approaches for anomalies in firewalls have been proposed [46][47][48]. To mitigate threats to a control system, the America National Standards Institute (ANSI)/International Society for Automation (ISA) proposes ANSI/ISA 62443-1-1 as a high-level security policy. However, firewalls cannot detect particular spoofed packets or malicious software that can bypass the rule set.

Integrity of data communication in a smart grid is critical. However, cryptographic protection mechanisms are not commonly deployed by the power industry as cyber security was not a serious threat when these protocols were developed. Also, considering the communication latency, MODBUS, and Distributed Network Protocol 3.0 (DNP3) used in SCADA, DER, PMU, SAS systems [49][50] have no cryptographic protection, which may cause security concerns. For example, DNP3 interfaces with WAN network, increasing the vulnerabilities as WAN is publicly accessible [51]. Therefore, MODBUS authentication frameworks have been proposed to secure the data communication[52][53]. Also, Security Authentication (SA) in DNP3 has been proposed [54][55][56].

SCADA, as a critical component of the cyber system in a distribution system, has security risks. Information exchange between LANs and WANs is vulnerable [57]. In distribution systems, SCADA is a cyber system to support the DMS. It may also be integrated with smart grid subsystems, e.g., AMI, Distribution Automation (DA) and DERs. As a result, it is damaging if an adversary gains access to SCADA [58][59][60][61][62][63].

The substation automation system plays an important role for power system operations. IEC 61850 introduces multiple multicast messages, i.e., Generic Object-Oriented Substation Event (GOOSE) and Sampled Values (SV) protocols, for various functions of substation automation. Unfortunately, cyber security mechanisms are not taken into account in the traditional design. Thus, data traffic inside a substation is vulnerable to false data injection attacks. The authentication proposed in IEC 62351 intends to protect IEC 61850 based communication protocols; however, multiple weaknesses have been exposed in the protocol's specification standard [64]. One of the weaknesses is an intentional reset of the parameter "stNum," which is a counter that increases by one each time a package is sent. It is used in the GOOSE protocol to provide timestamps for packages that are received/sent. This parameter can be increased up to 2^{32} before it is reset to zero. Under normal conditions (i.e., 30 packages per second), it would take more than four years to reach the reset limit. However, the parameter can be reset when a single GOOSE package is delayed for longer than the parameter, "timeAllowedToLive" (i.e., lifetime of the messages). This attack targeting GOOSE packets may trip circuit breakers maliciously [65]. If coordinated cyber-attacks are launched to compromise critical substations, a cascading sequence of events may be triggered.

Other vulnerabilities are related to the network of advanced metering infrastructure. When these networks are deployed in multiple user wireless networks, they can be adversely accessed through various nodes. Meter data modification and unauthorized remote load control can be launched by intruders, causing economic losses. Cyber-attacks targeting AMI include false data injection, leakage of the customer information, and energy theft [66][67][68][69].

C. Assessment of Vulnerabilities

Most common assessment of distribution system vulnerabilities related with voltage, current, and other power

measurements are related to Bad Data Detection Algorithms (BDDAs). Common BDDAs are based on power flow relation, state estimation, and most recently, artificial intelligence pattern recognition techniques that use historic data. BDDAs are included as part of the Distribution Management Systems that are used by the Distribution System Operator (DSO) for real-time operation purposes. The configuration of distribution state estimation-based (DSS-based) for bad data detection, as part of DMS modules, is shown in Figure 8.

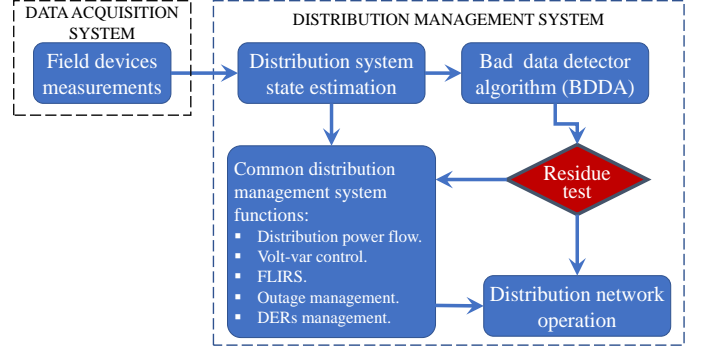


Figure 8. Bad data detection algorithm in distribution management systems.

Results of the power system states (voltage phasors at all nodes), estimated based on least squared errors, are evaluated in a residual test. Depending upon a pre-established threshold, bad data alarms can be triggered. System estimation results can also be used for other DMS functions such as volt-var control.

VI. SMART GRID COMMUNICATION AND CYBERSECURITY STANDARDS

Standard requirements and guidelines for data communication in power systems have been proposed [70]. Several Standard Development Organizations, including International Electrotechnical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), National Institute of Standards and Technology (NIST), and American National Standards Institute (ANSI), have developed standards to serve as guidelines for the smart grid.

Transmission system standards mainly concern SASs. Among SAS standards, IEC 61850 [2] set of standards is designed to meet the requirements of reliable communication. It includes Manufacturing Message Specification (MMS), Generic Object Oriented Substation Event (GOOSE), and Sampled Measured Values (SMV). While the MMS standard addresses real-time data transmission, the GOOSE protocol offers a publisher-subscriber messaging system for substation devices. The SMV standard provides for the transmission of high speed measured data points. The IEC 61850 standard, however, does not provide certain cybersecurity guarantees such as integrity, confidentiality, and authenticity. Therefore, the IEC 62351 standard is introduced to provide cybersecurity measure against attacks [71]. Other standards, recommendations, and guidelines to secure SAS network include:

- NERC: Critical Infrastructure Protection (CIP) standards, CIP- 002 through 014, "provides a cyber security

framework for the identification and protection of critical cyber assets to support reliable operation of the bulk electric system” [22].

- IEEE C37.111 (IEC 60255-24): Defines file format of measurement from IEDs.
- ESCSWG: “Roadmap to Achieve Energy Delivery System Cyber Security” is developed by Energy Sector Control Systems Working Group (ESCSWG) [72].

Due to the diversity of the distribution system, distribution system standards tend to be more wide-ranged. To regulate interconnected DER devices, the IEC TC Committee 57, WG 17 has released IEC 61850-90-7 providing specific object models for power converters in DER systems, while IEC 61850-7-420 provides abstract information models for general data exchange. The Smart Inverter Working Group (SIWG) has updated Rule 21 to California Public Utilities Commission (CPUC) in 2014, providing a three-phase approach to regulate DER systems [37]. IEEE 2030.5, also known as Smart Energy Profile 2.0 (SEP 2), is suggested to be the default protocol that should be supported by three types of individual DER communication devices, including:

1) Generating Facility Energy Management Systems (GFEMS), 2) Data aggregators, and 3) Smart inverter Control Unit (SMCU). According to the latest implementation guide for smart inverters [38], IEEE 2030.5 application layer protocol [73] implements “A client/server model based on a Representational State Transfer architecture utilizing the core HTTP methods of GET, HEAD, PUT, POST, and DELETE”. The IEEE 2030.5 profile supports smart inverter functionalities such as changing Volt-Var setpoints, and regulating real power output.

The ANSI C12.18 – C12.22 series provides a data object framework and an application layer protocol for smart meter communication [74].

Certain standards apply generically to SCADA systems and the smart grid in general. They are therefore applicable at both transmission and distribution levels. These are listed in Table 1.

TABLE I. Major standards for operating smart grids in distribution systems [8]

Subsystem Name	Standard	Applied System
SCADA	IEC 60870-6	Monitoring and control over a WAN
	IEEE 1815-2012 (DNP3)	Application layer protocol for SCADA communication
	DNP3 Secure Authentication	Address cybersecurity issues of DNP3 (authentication, integrity)
PMU	IEEE C37.118	Phasor data exchange
ICS	IEC 62443	Providing a framework to address the cybersecurity vulnerabilities of industrial control systems (ICSs)
Smart Grid	NIST 7628	Guidelines for smart grid cyber security

VII. MODELLING AND DETECTION OF CYBER INTRUSIONS

Firewalls serve as a first line of defense against intrusions. All traffic, both incoming and outgoing, is checked according to the set of rules. Anomalous events are subsequently flagged.

This is the most prevalent type of firewalls. Other applications for cyber intrusion detection at the firewall level include Deep Packet Inspection (DPI) tools, which inspect the data being sent over a computer network and take action by blocking, re-routing, or logging it accordingly. However, DPIs are known to be slow and require complex validation rules and, therefore, they may not work for all application layer protocols.

Intrusion Detection Systems (IDSs) may be employed as an additional layer of security. IDSs detect intrusions in the network and flag them accordingly. Mitigation steps may then be implemented. An IDS may be classified according to the detection technique and style, method of decision making, and source of the data used in intrusion detection. Table II highlights the types of classification. The following subsections discuss each type of classification.

TABLE II. Structure of cyber protection systems [8]

Detection Technique	Source of Intrusion Data	Detection Style	Method of Decision Making
Knowledge-based	Network-based	Passive	Centralized
Behavior-based	Host-based	Active	Decentralized

A. Source of Data

An IDS may be installed to monitor and protect a network or host. Consequently, data for performing intrusion detection may be gathered from the network, or from the subject host. An IDS may therefore be network-based [75][76][77], or host-based [18][78][79][80][81][82][83][84][85]. It may also be both network-based and host-based, in which case the IDS is referred to as an integrated or hybrid IDS [65][86][87]. An integrated IDS therefore leverages both cyber and physical properties of the system.

A Network-based IDS (NIDS) is configured to inspect network traffic. While it may look for indications such as frequency and intensity of network traffic as well as properties such as the port and IP addresses of packets, a NIDS may also perform a deep packet inspection, checking for malformed packet headers, or harmful payload, even at the application layer level.

On the other hand, a Host-based IDS (HIDS) is installed to monitor a specific device and is limited to that device. Hence, the data used in performing intrusion detection is collected from the subject device. The data may be readily available in the system logs. Information such as the frequency of system crash, usage of memory, temperature of device may be used in classifying an event as an attack.

B. Detection Techniques

An IDS may use a whitelist approach or a blacklist approach towards intrusion detection. The knowledge-based (or signature-based) IDS makes use of a blacklist. In other words, there is a database of attack patterns, called signatures. By comparing traffic or host features to the defined signature, an event may be classified as an attack or not. A classic example is an anti-malware software. By virtue of this, the knowledge-based IDS is highly accurate in identifying attacks whose

signatures have been uploaded in its database. However, it suffers a critical flaw of being unable to detect attacks not known in the database.

Using the whitelist approach [88], network traffic or host parameters are compared to a pre-established normal profile and once a deviation from this is significant, an anomaly is flagged. Thus, this type of IDS is also called an Anomaly Detection System (ADS). Nevertheless, the exact definition of normal behavior for a network or host can be a difficult task. Examples of network activities that can be difficult to manage in whitelisting approaches are: 1) Software upgrading; 2) New application requirements; 3) Unplanned servers' maintenance; 4) Triggered even alerts; and 5) Workstations and connection IPs identification. Thus, this type of IDS may be characterized by a high false positive ratio. The profile may be updated regularly to include new users, or new observations about the system at normal operating conditions. Table III summarizes the types of IDS according to detection technique.

TABLE III. Major standards for operating smart grids in distribution systems

Detection Technique	Feature	Defects
Blacklist	Identify and block malicious traffic	Security offered is minimal.
		Requires frequent update to rules.
		High false negative ratio.
Whitelist	Identify and pass benign traffic	Requires frequent update to rules.
		High false positive ratio.

C. Detection Style

While some IDSs flag intrusions and delegate mitigation to the human operator, others may be configured to take mitigation actions on their own. The former is called passive IDS, while the latter is called active IDS, or Intrusion Detection and Prevention System (IDPS), or Intrusion Prevention System (IPS). IDPSs reduce the impact of attacks in a shorter time.

An IDPS monitors network traffic searching for indications of potential attacks. When plausible dangerous activities are detected, actions to stop the attack are taken, i.e., dropping malicious packets, blocking traffic, or re-establishing connections [89]. Network administrator can also receive alert signals from IDPS about potential malicious activities.

Network-based IDPS (NIPS) solutions can be installed at the firewall level. A host-based intrusion prevention system, i.e., HIPS, sits on an endpoint (user terminals), looking for malicious traffic at the host level. A wireless intrusion prevention system (WIPS) looks for unauthorized access to Wi-Fi networks. NIPS activities are similar to firewalls, but there are some differences. A firewall deals with all incoming traffic and allows it to pass through if some security criteria are met. NIPS looks at traffic that is already on the network and only blocks traffic that looks suspicious.

D. Method of Decision Making

While an IDS may be a single system that detects and/or mitigates attacks, it may also comprise several autonomous software (called agents) which interact for the same purpose [41][42][90]. In the former, a centralized architecture is formed, whereas a decentralized technique is employed in the latter. In the centralized architecture, one detection system is installed at

the point of interest to detect and/or mitigate attacks. This approach tends to suffer from single point of failures. In certain cases, there are several IDSs installed at different points within the network of interest and these report to a central system which correlates alerts generated by the dispersed IDS to detect coordinated cyberattacks [90]. In the case of the decentralized technique, several agents interact with one another, forming a multi-agent system. In a multi-agent system, a form of consensus protocol is typically employed for communication among agents. The multi-agent approach may be deployed for collaborative detection [42], or for collaborative correlation and mitigation [41].

E. Other Categories of Classification

Although an IDS may fit into one or several of the aforementioned broad categories, there are other categories into which it may fall. First, it may be data-driven. In data-driven techniques [91], relevant operation data are collected from the system of interest. Data-driven techniques tend to be machine-learning-based or statistical [91][92]. Machine-learning-based IDSs have become prevalent over the years, with supervised [92][93], unsupervised [94] and reinforcement learning techniques [95] applied in different scenarios and for different purposes. In supervised learning, labeled data is used to train a neural network to identify features of interest. Unsupervised learning is mainly used for classification. Therefore, by nature, it is more suitable for anomaly detection [94]. In reinforcement learning, a reward scheme is used to incite the algorithm to learn optimal actions over a series of trial-and-error attempts. Reinforcement learning tends to be applied for mitigation purposes. An IDS may also be model-based; models of attack patterns (signature-based) or expected behavior (behavior-based) are created for intrusion detection. The model may be formed from data collected from the system of interest, in which case the IDS is also data-driven.

F. Attack Modeling

Intrusion detection based on attack models is a hybrid signature- and model-based detection technique. An attack model is first formulated using attack signatures. The model may be in the form of attack trees [96], Bayesian graphs [97], Petri nets [60], Markov decision processes [98], among others. In the event that suspicious behavior is detected, the trajectory and next steps of the attacker may be predicted with some accuracy. Attack models provide guidance for both reactive and proactive mitigation.

VIII. ATTACK MITIGATION IN DISTRIBUTION SYSTEMS

Mitigation is key to ensure reliability and security of the power grid, following a cyberattack. As already mentioned, an IDS alerts the operator in the event that an intrusion is detected. If the IDS is an active IDS, certain mitigation steps may be implemented. Considering that the smart grid is a cyber-physical system, mitigation steps may be taken at both the cyber and physical levels. The essence of cyber level mitigation may be to identify the attackers, disconnect them, and take back control of the power grid. At the physical level, mitigation is aimed at steering the power grid to a normal operating condition.

At the cyber level, the response taxonomy in [89] is useful.

Cyber mitigation strategies are grouped into learning actions and modifying actions. Learning mitigation actions could be active, such as tracing connections and starting analysis tools, or passive, such as generating alarms and reports. Modifying actions may be blocking, or recovery. Blocking includes limiting network access [41] and restarting affected system, while recovery includes renewing cryptographic keys, and distributing new attack signatures.

On the other hand, at a physical level, the preferred approach is dependent on the application. In [99], a game theoretic model is provided for the attacker and utility. In this model, the attacker seeks to disrupt the stability of the system. The utility (defender) mitigates this by controlling a select set of DERs in order to prevent system collapse and restore stability. Reference [100] proposes a mitigation framework as a response to switching attacks. When a malicious action results in tripping of smart grid switch(es), system stability may be compromised. This mitigation technique proposes a practical smart grid stabilizing controller and uses a game-theoretic approach to model DSO and attacker strategies under potential cyberattacks. Reference [96] presents a comprehensive cybersecurity analysis for critical infrastructure. As the main mitigation strategies, it includes remedial actions such as periodic control of user role privileges, and continuous monitoring of overloaded lines and buses with voltage conditions. As a remedial action, it contemplates suspending suspicious network users and relief of overloaded lines when current/voltage problems occur in the physical system.

In the following sub-sections specific cases of SCADA attack mitigation and smart meter attack mitigation are provided respectively.

A. SCADA Attack Mitigation

The SCADA attack mitigation is explained using a two-substation system, where each of them communicates with each other using two protocols: DNP 3.0 over TCP/IP and Inter-Control Center Communications Protocol (ICCP). A testbed application has been used in this demonstration [101]. In the substation, the communication among IEDs is based on IEC 61850. A Human Machine Interface (HMI) has been implemented to enable the operator to control and monitor the substation facilities. In the testbed implementation, it uses power system simulation tools to calculate voltage, power, frequency, and current signals. The HMI acquires from the simulation tool using Object Linking and Embedding for Process Control (OPC) communication. Remote access points are implemented via dial-up, VPN, and wireless technology, which serves, for the purpose of simulation, as intrusion paths.

An attacker attempts to access a substation from remote. The attacker tries to access substation ICT network by targeting firewalls, HMI control, or IEDs. If the attacker successfully completes the access task with user extended privileges, it will be able to retrieve sensitive information, control breakers, transformer taps, causing damages to grid operation.

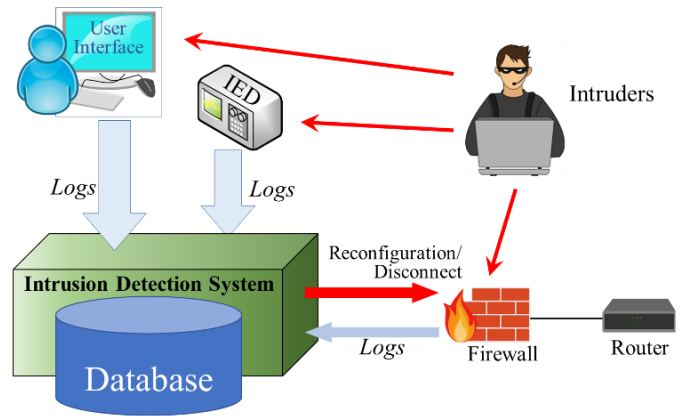


Figure 9. Intrusion detection system implemented in the testbed.

In Figure 9, the developed intrusion detection system is installed on the computer with user interface on the testbed. IDS reads the log of activities performed in the substation systems, including HMI, IEDs, and firewall. When the logs are transmitted to the IDS database, an algorithm explores for anomalies. If an anomaly is detected, for instance unauthorized changes made to critical parameters of the system and/or untrusted packages injected by intruders, a disconnect control signal is sent to the firewall to block intruder's connection.

As previously discussed, the impact of a cyberattack on the physical layer of a power system is modeled by power flow and dynamic analysis simulation tools. To demonstrate the impact of the attack on system operation, a small power system model is developed, as shown in Figure 10. This system includes 3 hydro plants (150 MW each), six 110 kV transmission lines, and six loads. Simulated real-time measurements are sent to the OPC server. Using a default user ID and password, HMI is connected to the OPC client and reads data from the simulation tool and substation IEDs. DNP 3.0 protocol is used to send the information to the control center that triggers alarms in case anomalies are detected. Operator's commands are sent via SCADA to the simulation tool which performs real-time power system analysis.

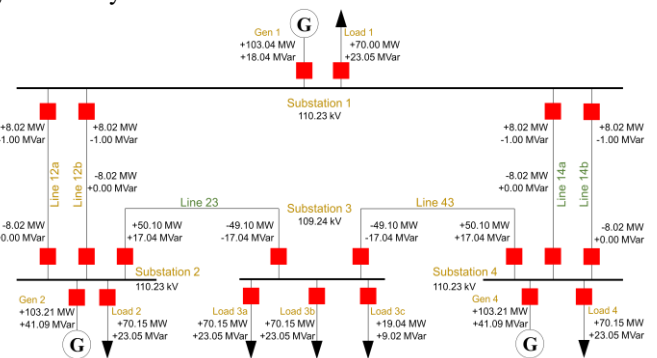


Figure 10. Control center SCADA display

An attack mitigation method to stop cyber-attacks and disconnect the intruder is presented. The proposed algorithm not only intends to detect anomaly access attempts but also helps to avoid cascading events after cyberattacks. The simulated scenario is as follows:

The intruder compromises the substation computer by obtaining user IDs/passwords via VPN communication to gain

access to substation HMI remote desktop connection and field devices. Since passwords have been cracked, the firewall views as legitimate the connection attempts and the attacker gains access to the network. Attacks are launched from the substation HMI. OPC client-server communication is used to acquire measurements of the power system. Cyberattacks are aimed at multiple locations (substations 2, substation 3, and hydro power plant 2). At substations 2 and 3, the attacks trigger the opening of circuit breakers and, as a result, two transmission lines and a hydro plant are disconnected. Attack results are reported via DNP 3.0 to the control center. Alarms at the control center indicate major disturbances in the system. The cyberattack mitigation mechanism is triggered to disconnect lines 43 and 12b. The delivery paths to loads 2, 3a, 3b, and 3c rely on line 12a. See Figure 11.

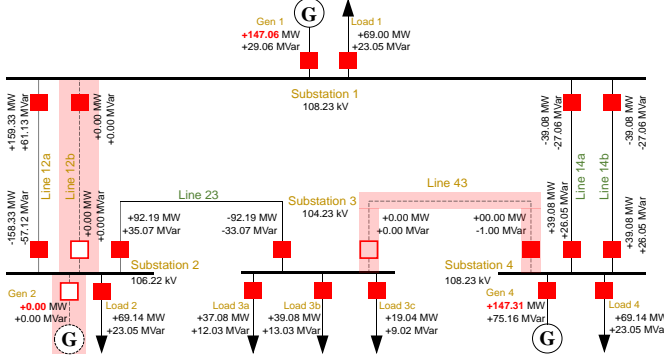


Figure 11. Test system after cyberattacks. Control center SCADA display.

Under these conditions, the remaining energy resources are at full capacity but still not possible to serve the total demand in the system. Hence, the system frequency falls below 48 Hz (Figure 12a). With the generator out of service, load shedding becomes necessary to maintain the system operating condition. First, intruders are disconnected by collaboration between the IDS and firewall in the substation network. Then, emergency control actions are taken to mitigate the effects of the cyberattacks as an attempt to restore a normal condition [102]. Next, an Optimal Power Flow (OPF) algorithm, with an objective function that minimizes load shedding, is run to determine the necessary actions to maintain system operability.

The results of the OPF show load shedding of 100% and 71% for loads 1 and 2, respectively. Figure 12b and Figure 12c indicate that it is possible to steer the voltage and frequency levels to within the allowable limits. Frequency oscillations are shown in Figure 12b. Note that after 15 s, when the cyberattack has been launched (opening breakers), the system frequency is maintained between secure operation limits. Next, 5 seconds afterward, once the hydro plant is disconnected, the frequency suddenly drops to 49.4 Hz. IDS mitigation action sheds the load and reconnects lines 12b and 43 at 60 and 65 s, respectively. The system is steered back to a stable operative condition.

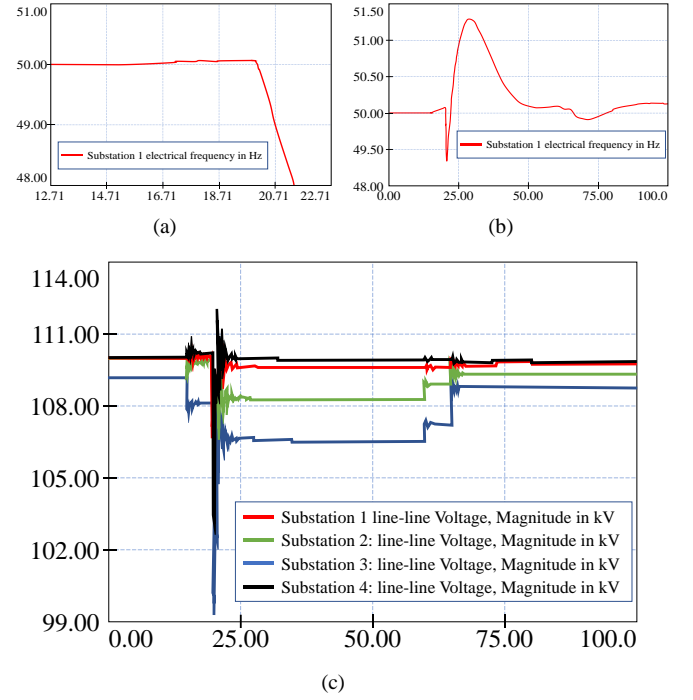


Figure 12. Frequency and voltages of simulated system. a) Electrical Frequency measured at substation 1 (Hz). b) Frequency after attack mitigation. c) Line to line voltage at each substation in the simulated event.

B. Attack Mitigation for Smart Meters

Since most of AMI devices are not installed in a monitored environment, attackers may study the weaknesses of both wireless communication and physical devices and then launch cyber-attacks. Figure 13 shows five primary compartments in a smart meter: (i) Central Processing Unit (CPU), (ii) Random Access Memory (RAM), (iii) communication module, (iv) flash memory (EEPROM), and (v) energy sensors. Since software/hardware components of smart meters are similar to other ICT devices, cyber attackers may adapt intrusion techniques from those employed in other software systems. In a smart meter, firmware controls the critical functions that handle low-level sensor data, data conversion, and data reporting. Since most functionalities are accomplished through software, new functions can be added on the field by performing updates. Firmware upgrades can be deployed using over the air mechanisms, or manually uploaded by using the onboard optical port. Firmware-based attacks can hinder the device's ability to operate multiple hardware components.

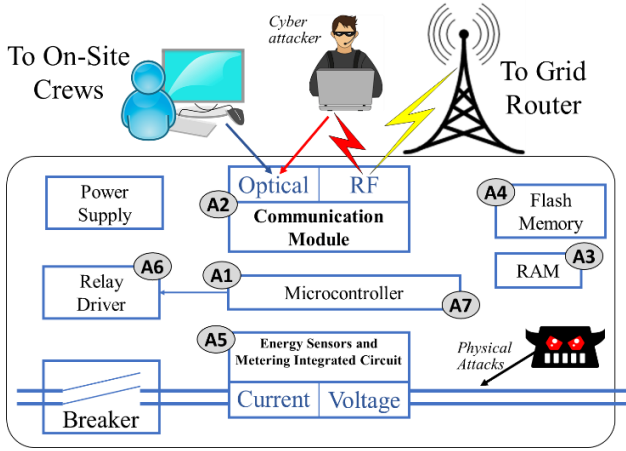


Figure 13. Hardware components inside a smart meter with potential attack targets

A commonly used graphical model, Time Failure Propagation Graph (TFPG), is used to represent the cause-effect relations between failure modes, behavioral system discrepancies, and failure propagations. A TFPD along with a pattern recognition algorithm is used as an intrusion detection instrument. Arbitrarily reported anomaly events cannot be conclusive as evidence to identify an attack because system failures (e.g., communication delay, low battery, and poor data sampling) may also cause a false positive. Too many false intrusion alarms may affect the regular operation of a distribution system. Therefore, an anomaly-based detection mechanism is developed to perform an in-depth inspection. An attack model should be able to help intrusion detection systems successfully identify malicious attacks. A TFPD is a model-based diagnosis technique for a dynamic system. TFPD was used to capture causal and temporal relationships between failures and consequences in a system. This feature is used to model temporal relationships between anomaly events (causes) and attack types (effects). Figure 14 shows a TFPD model that describes the cause-effects of cyber-attacks in a smart meter.

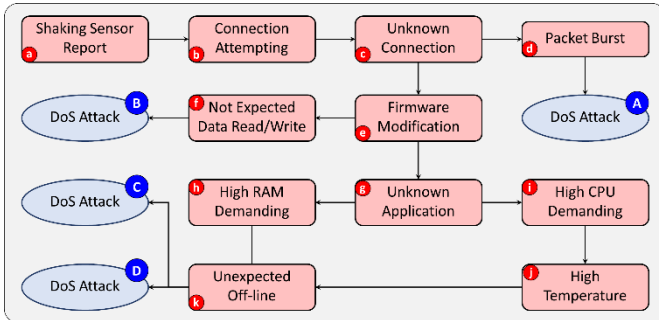


Figure 14. Intrusion processes based on the TFPD model for smart inverters. Anomaly event in red and attack type in blue.

In the attack model, anomaly event nodes and arrows illustrate different attack routes. A series of anomaly events will be considered an intrusion behavior only if the events are detected in a sequence that is matched with the attack model. Otherwise, the anomaly events are regarded as a system failure. The description of anomaly types is given in Table IV.

TABLE IV. Anomaly types for smart meters in TFPD model

Anomaly Type	Defects
--------------	---------

a	Shaking Sensor Report	Smart meters have an onboard sensor to detect suspicious vibration events.
b	Connection Attempting	Too many incorrect password attempts are likely from an unauthorized user.
c	Unknown Connection	Smart meters have fixed communication parent/children nodes. Any exceptions are regarded as an anomaly.
d	Packet Burst	Smart meters are configured to send beacon and measurement data every fixed time cycle. The incoming command from a control center is not a typical case.
e	Firmware Modification	The firmware should be kept at the latest version.
f	Not Expected Data R/W	The measurement data is written and sent to an MDMS every fixed time cycle.
g	Unknown Application	Smart meters are not allowed to install any third-party software by customers.
h	High RAM Demanding	The routine tasks of smart meters are not designed to over consume the RAM.
i	High CPU Demanding	The routine tasks of smart meters are not designed to over consume the CPU.
j	High Temperature	The electronic components can only work within a certain range of temperature.
k	Unexpected Off-line	Smart meters are designed to operate 24 hours a day.

TABLE V. Attack route set that generated from attack model

Attack Path	Attack Type	Dictionary
P_1	DoS Attack (A)	abcd
P_2	False Data Injection (B)	abcef
P_3	Filling Buffer (C)	abceghk
P_4	Overloading (D)	abcegiijk

In the proposed IDS, two assumptions are made: (i) intruders' actions follow the sequence in the attack model, and (ii) anomaly detection systems may have a false negative problem that fails to capture one or more anomaly events. Each anomaly event is assigned an English letter from the alphabet as shown in Figure 14. Each path, $P \in \{P_1, P_2, P_3, P_4\}$, from the first anomaly event node (i.e., node a) to an attack type node (i.e., nodes A, B, C, and D) is considered a correct sequence based on the dictionary as shown in Table V.

IX. CYBER-PHYSICAL SYSTEM MODEL

The importance of co-simulation of the physical power system and corresponding cyber system has been recognized with the increasing penetration of smart devices, distributed generations (e.g., photovoltaics and wind generators), energy storage, and flexible loads on the distribution side. Monitoring and control of the field components is facilitated by the information and communications technology. Real-time control schemes for power system stability, sensing, and data acquisition are motivations for the integrated model. The comprehensive framework of the cyber-distribution system forms an extensive network for data transfer between the different nodes and the remote-control capabilities. In this smart grid environment, cyber threats can cause a disruption of power system monitoring and operation. The impact of a cyberattack ranges from minor service disruptions to wide area cascading events.

This section provides simulation cases of cyberattacks and the mitigation actions to demonstrate critical concepts of cyber-physical system security of distribution systems. Three cyberattack types described in Section V, i.e., FDI, DoS, and

Replay, are used to demonstrate the impact of cyber attacks on the physical system and their mitigation actions. The CPS model is based on the communication infrastructure in the distribution system with Feeder Remote Terminal Units (FRTUs) connected to a distribution operating center. The FRTUs are pole mounted devices, which communicate with DMS using IEC 101 or 104 communication protocols via machine-to-machine over public broadband. The focus is on the CPS communication model and the cyber security aspects associated with the communication network. The impact of various cyberattacks on the power system is evaluated with an integrated CPS model. The ICT model for the distribution system follows the discrete event system based on the queueing model [103]. For demonstration, the CPS model has a power system layer (using static and dynamic power system models) simulated in DiGSILENT PowerFactory and a cyber layer simulated in MATLAB Simulink. These are time-synchronized by the OPC server for data exchange.

Data flow of the integrated CPS model is shown in Figure 15. The simulated distribution ICT model (cyber layer) has two levels i.e., a distribution system level with the field measurements (values from FRTUs) and a control center level which receives the measurements from FRTU level and sends control commands to be executed in the physical system. Measurements from the FRTUs go through the communication channel via the queueing system (which is a computer queue model of the cyber system). It is received by the control center. By the control decision-making process, the control command is sent back through the transmitter of the control center and is received by the receiver at FRTUs. The communication channel may be a physical fiber optical cable or wireless networks based on 4G and 5G technology or a combination of various communication technologies. The bi-directional data flow requires a reliable and secure communication system.

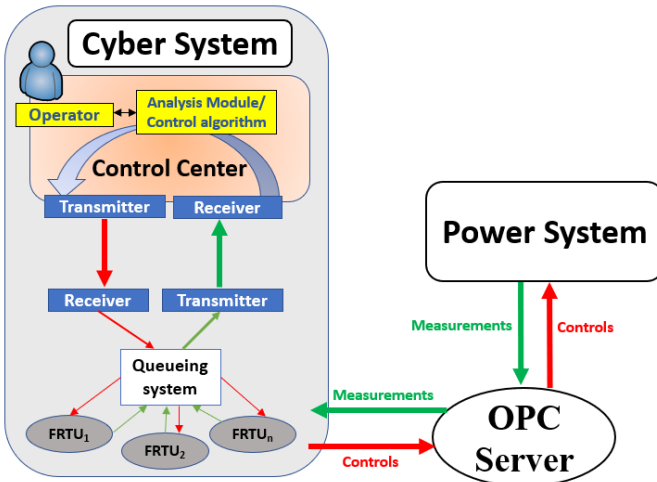


Figure 15. CPS simulation setup.

Figure 16 shows the ICT simulation arrangement for an FRTU based on the D/D/m/K queueing system, where packet service time and inter-arrival time are deterministic (D) in nature. Also, m is the number of servers-system with a finite K queueing capacity. This model is used for the ICT devices in the system. Inputs (power, current, voltage, and switch status) from different FRTUs are combined using a round-robin algorithm

and sent to the first in first out (FIFO) queue which is further sent to the control center through the processor. The SCADA system at CC receives real-time data from different FRTUs and based on the system state, the operator takes the required control action. The control command data packet is sent from the CC through a queueing system to the output switch of corresponding FRTUs. The deterministic bi-directional communication system is the basic structure for continuous data exchange in the system along with security considerations for possible cyber threats.

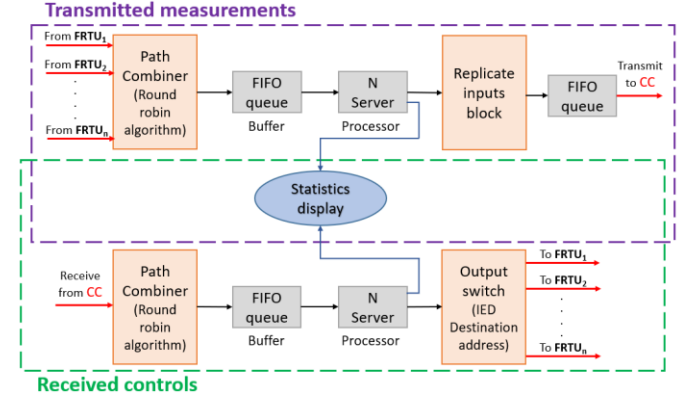


Figure 16. Queueing model [103].

The measurement data and control signals are sent in the form of data packets which are encrypted to ensure data confidentiality and integrity. The data packet consists of the measurement, timestamp, and an authentication code. A less computationally intensive and effective symmetric key encryption method, 256-bit Advanced Encryption Standard (AES) is implemented here [101].

A. Test system

The demonstration here is based on the IEEE 13-node distribution system with a diesel generator, a wind generator, a solar PV, and a battery storage. Different types of cyberattacks are simulated in the cyber layer of the distribution system. During normal operation, the distribution system is connected to the utility system. Each node represents a FRTU in the cyber system to maintain observability of the system for control and operation by the distribution operating center. It is assumed that the distribution feeder serves as a microgrid with the capability to operate in a grid-connected mode or an islanded mode when the utility system is not available. In an islanded mode, the diesel generator provides the control capabilities to maintain system stability and regulate the voltage and frequency of the microgrid.

1) False data injection (FDI) attack

The simulated scenario is as follows: The system goes from grid-connected to islanded mode at $t=2$ sec. The attacker gains access by remote connection to the energy storage device and disconnects ($\text{Storage}_{\text{switching}} = 0$) it at $t=3$ sec. Meanwhile, the attacker is sending false data ($\text{Storage}_{\text{switching}} = 1$) to the CC from $t=3$ sec showing that the storage device is connected. This attack is simulated by capturing the data packet with the switching device from the storage device at the OPC server. It is then modified and inserted back to the OPC server from which the falsified measurement packets are encrypted at the

cyber layer. The control center in the absence of a detection mechanism in the cyber layer is unable to detect or mitigate the FDI attack. As a result, the system undergoes major frequency and voltage perturbations.

The FDI attack should be detected and mitigated in the cyber layer to avoid any impact on the microgrid as shown in Figure 17. To detect the FDI attack, an IDS with authentication functionalities is used. The authentication code hashing algorithm [104] returns a value generated by performing the algorithm on the measurement. This code is verified at the CC to detect data tampering. On detecting the FDI attack, CC triggers an alarm and executes a mitigation process based on the network visibility and OPF algorithm. In this simulated event, CC sends the command to connect storage at $t=5$ sec to maintain a stable operating condition of the power system.

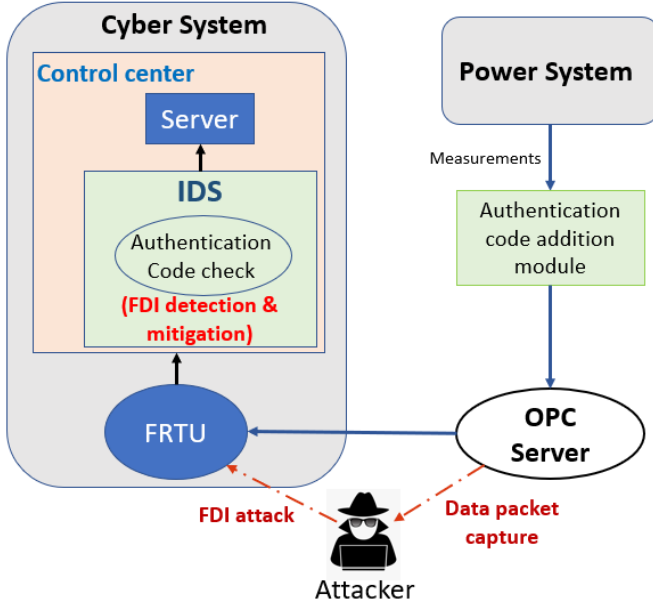


Figure 17. Simulated FDI attack and detection setup.

Figure 18 shows the system response to the simulated FDI attack. The system frequency returns to 60 Hz as the attack is mitigated. In the absence of detection, there is an undervoltage condition, but, on successful detection, the voltage is maintained within its operable limits. As the storage device is disconnected, the machine's power output goes up and after $t=5$ sec the generator speed comes back to its normal operative condition.

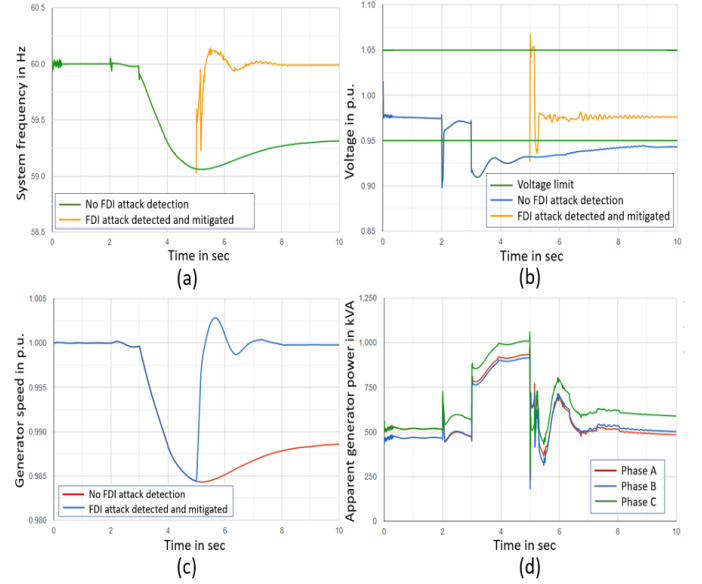


Figure 18. System responses to FDI attack. a) Electrical Frequency measured (Hz). b) Voltage at the affected node in the simulated event (p.u.). c) Speed of the diesel generator (p.u.). d) Apparent power of the diesel generator when FDI attack is detected and mitigated (kVA).

2) Replay attack

In this scenario, at $t=2$ sec the microgrid transitions from a grid-connected to an islanded mode. Initially, the capacitor present in the remote load node is in the OFF state. During normal operation, the voltage at the remote node starts decreasing due to an increase in load demand, causing an under-voltage condition. As these voltage measurements are communicated to the CC, based on the control algorithm, CC sends the command to switch the capacitor ON to inject reactive power to restore the voltage profile.

The attacker gains access to the lower level of the cyber system i.e., the FRTU level. The replay attack is initiated with malicious intent by intercepting the valid data packet and re-transmitting it at a later instance as shown in Figure 19. The data packet consisting of the actual data and an authentication code is incapable of detecting a replay attack as there is no modification to the data packet. In this simulation, a timestamp-based replay attack detection method is used. The timestamp of the measurement is appended in the data packet along with the authentication code. When the attacker captures the packet and replays it at a later stage, the difference between the sent and received timestamp of the data packet will exceed a tolerance communication delay value. On detecting the replay attack, an alarm is triggered by the CC, and another secure communication channel is established after blocking the attacker's connection.

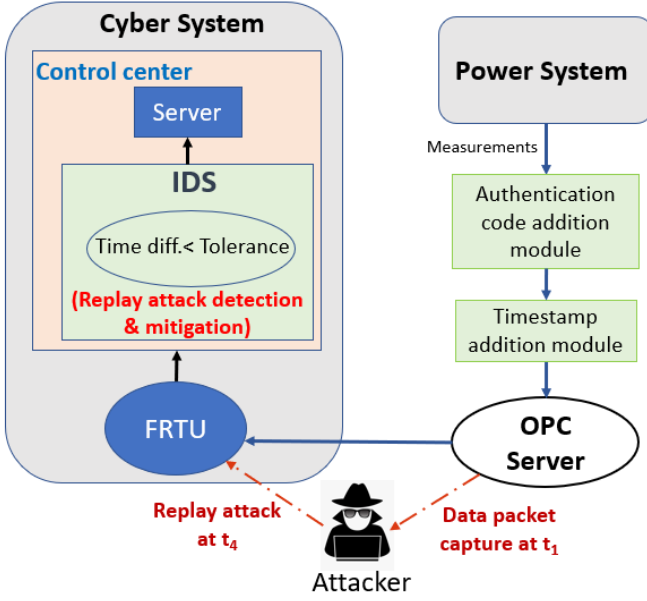


Figure 19. Simulated replay attack and detection setup.

The loading level of a remote load ramps up from 3 sec to 8 sec, as shown in Figure 20(a). In the absence of a detection process for the cyberattack, the capacitor is in the OFF state and the voltage falls below the acceptable threshold of 0.95 p.u. As the replay attack is mitigated and CC sends a control action to switch the capacitor ON, illustrated in Figure 20(b). A replay attack is initiated at $t=4$ sec and the CC receives the re-transmitted data packet as seen in Figure 20(c). As a result of the mitigation, the voltage comes within its normal operating limits at $t=6.8$ sec.

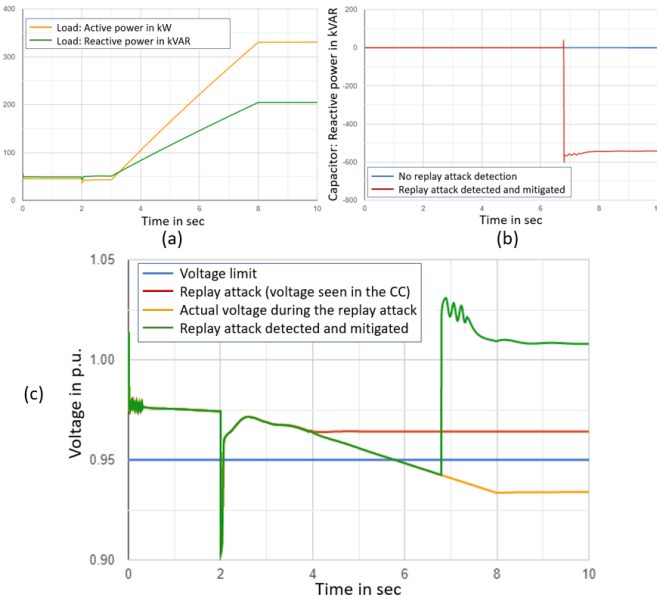


Figure 20. a) Ramp increase in a remote load in the test case. b) Capacitor reactive power injection at the remote node (kVAR). c) Voltage at the affected node in the simulated event (p.u.).

3) Denial-of-Service (DoS) attack

The attacker attempts to overload the cyber system by sending connection requests or data packets (in case of established connection) to prevent legitimate packets to reach the control center. The cyber system from the FRTUs to the

control center is shown in Figure 21(a). Figure 21(b) shows that the server's average utilization during normal system operation is 0.4285 but it increases to 0.8978 under the DoS attack scenario. During the attack, the utilization escalates as the server is flooded with data packets coming from both the legitimate senders and the attacker. This leads to a situation where the server is unable to process valid data traffic.

In the CPS model, it is assumed that there is complete network visibility with knowledge of the data traffic rate, so a preventive approach to DoS attack is preferred. The setup, illustrated in Figure 21(a), includes a firewall along with a data traffic rate-limiting router in the CC to detect and prevent DoS attacks. The firewall filters the data packets based on its sender's address, so any attempt to flood the CC by sending connection requests from an external source will be denied. However, the firewall fails to detect the case where a legitimate sender (or FRTU) initiates a DoS attack. As the data rate from each FRTU is a known parameter, the router has the rate-limiting capability to check for a maximum number of data packets departed for every time instance. This approach screens for DoS attacks and prevents burdening the server in the CC. In this simulated DoS attack, the attacker or compromised FRTU tries to flood the router in the control center with data packets, but the rate-limiting capability of the router curbs the illegitimate incoming traffic.

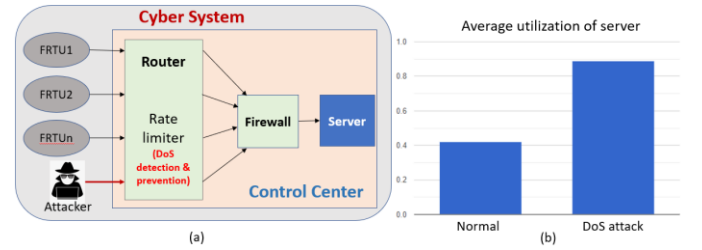


Figure 21. a) Simulated DoS attack and detection setup. b) Average utilization of the server during a normal operation and during a DoS attack in the absence of preventive measures.

X. CONCLUSION

This paper provides a survey of cyber-physical system security concepts, attack models, and defense measures for the distribution systems. To illustrate the interactions between the communication system and physical system, simulation cases are used to demonstrate the cyberattack types and mitigation actions. While transmission systems rely on the SCADA system for communication between the control center and substations, distribution systems are more fragmented in their communication and control. Indeed, as shown in this paper, distribution SCADA, renewable and storage facilities, smart remote-controlled devices, and smart meters tend to be developed as independent systems without a holistic structure. In the future, cyber-physical system security of distribution systems will require a holistic solution to prevent gaps in security measures between subsystems with diverse communications and protocols.

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