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Cyber-physical security of an electric microgrid

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CYBER-PHYSICAL SECURITY OF AN ELECTRIC MICROGRID

by

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ABSTRACT

Cyber-physical systems (CPSs) are physical systems that are controlled or monitored by computer-based systems. CPSs are a combination of computation, networking, and physical processes. As CPSs are a combination of various diverse components, they are vulnerable to several security threats. Moreover, there are many different security domains (not just high/low, nor necessarily hierarchical). This paper utilizes previously developed multiple security domain nondeducibility (MSDND) to uncover potential integrity vulnerabilities in an electric microgrid. Invariants are manually generated using the insights obtained through MSDND analysis and use linear regression to automate the generation of invariants. The vulnerabilities are then mitigated, to the extent possible, by adding executable invariants on system operation. Implementation on the Electric Power and Intelligent Control (EPIC) testbed at the Singapore University of Technology and Design is reported. Limitations of the design and successes/shortcomings of attack mitigation are reported.

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NOMENCLATURE

Greek

$\oplus$	Exclusive OR (xor)
ϵ	random error or residual in linear regression
ϕ	A boolean statement that can be evaluated

Subscripts

W	The set of all possible worlds of the system
SD^i	Represents the security domain with respect to i
w	A world of interest
s_x	A boolean state variable, x is true or false
$B_i\ \phi$	Modal BELIEF operator
$I_{i,j}\ \phi$	Modal INFORMATION TRANSFER operator
$T_{i,j}\ \phi$	Modal TRUST operator
RPM	revolutions per minute of AC motor
RR	Relay readings
CD	Batteries charging/discharging percentage
CBS	Circuit breaker status
CBC	Circuit breaker command

V	Voltage reading from Relay
i	Current reading from Relay
f	Frequency reading from smart meter
fR	Frequency reading from Relay
P	Power reading from Relay
V_x^y	valuation function of boolean x in domain y

1. INTRODUCTION

Cyber-physical systems (CPS) are smart systems that include engineered interacting networks of physical and computational components. One of the significant requirements of a CPS is to be resilient (NIS, 2017). The next generation CPS must be resilient to correlated threats (threats in which more than one attacker acts on an entity) where simple perimeter protections are not sufficient. As such, CPSs need to be looked at in a different light, one in which multiple components exist and sometimes overlap containing entities that interact with each other. Figure 1.1 shows the basic architecture of an electric smart grid with multiple interacting components (FitzPatrick and Wollman, 2010).

In such architectures, transmission must interact with distribution, markets, service providers, operations, and, increasingly, customers through information exchange and computation in addition to the transfer of the commodity - power.

Classical models do not capture this well; within the context of an electric power system, a subset of domains can be categorized into two primary types of entities, control centers and business networks activities. Within the control centers, energy management and Supervisory control and data acquisition (SCADA) systems control/read from remote terminal units (RTUs) which, in turn, control/read from sensors and actuators. The control center must also interact with peer control centers, potentially not in the same organization. The classical hierarchical model of Biba (Bishop, 2003) forces the arrangement of security partitions into just the two (McMillin and Roth, 2017) seen in a modern electric utility, essentially that the business enterprise of a utility cannot write up into the control system, by placing the control system at a higher security level; this prevents a potential virus that has compromised the business enterprise from impacting with the control system as

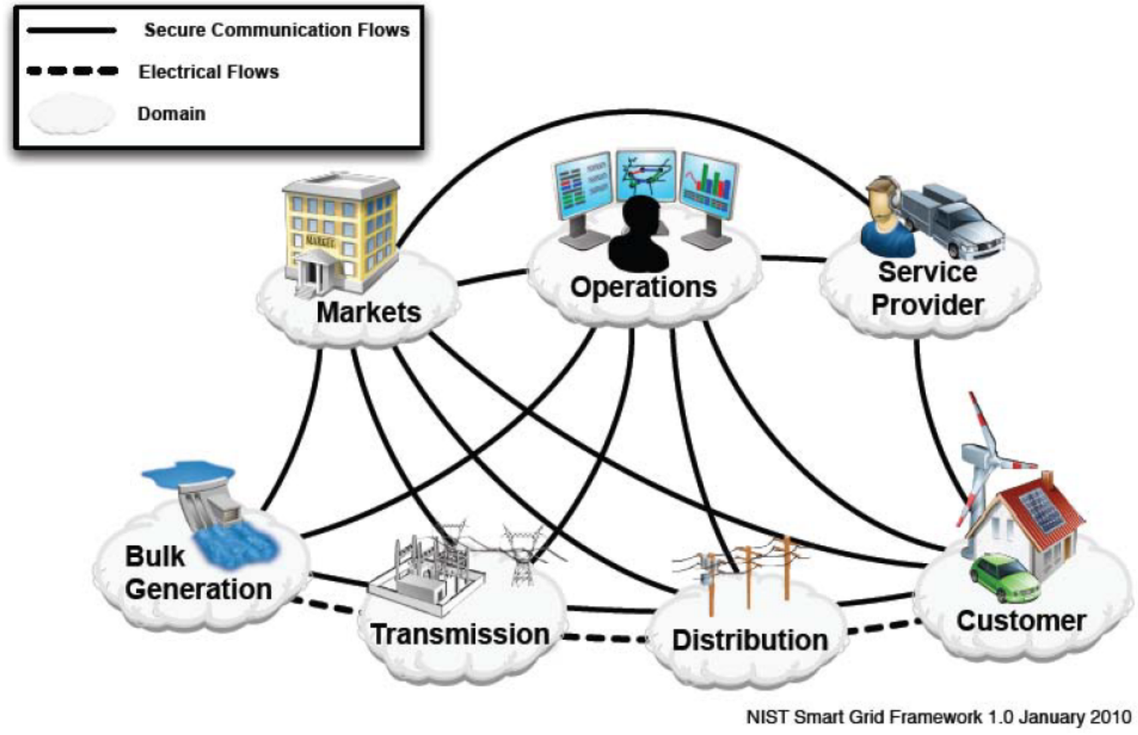


Figure 1.1. Electric Distribution System Architecture (FitzPatrick and Wollman, 2010)

shown in Figure 1.2. Unfortunately, it does not prevent attacks coming from cyber or physical components within the security domain and perimeter defenses cannot secure these components as it would disrupt the normal information flow within the power grid.

In this document, we examine the general security concerns of an electric grid through a testbed instantiation using Design-centric approach (DeC) and Data-centric approach (DaC). The DeC approach uses Multiple Security Domains Nondeducibility (MSDND) (Howser and McMillin, 2014) (Howser and McMillin, 2013) models and Belief, Information transfer and Trust (BIT) logic (Liau, 2003) (Liau, 2005) to address the issues of vulnerabilities within this multi-domain environment by making use of manually designed invariants. The DaC approach makes use of the machine learning algorithm- Linear regression (Lin, 1997) to automate invariant generation. The invariants generated from two methods are then evaluated for their efficiency in identifying faults/attacks in the system.

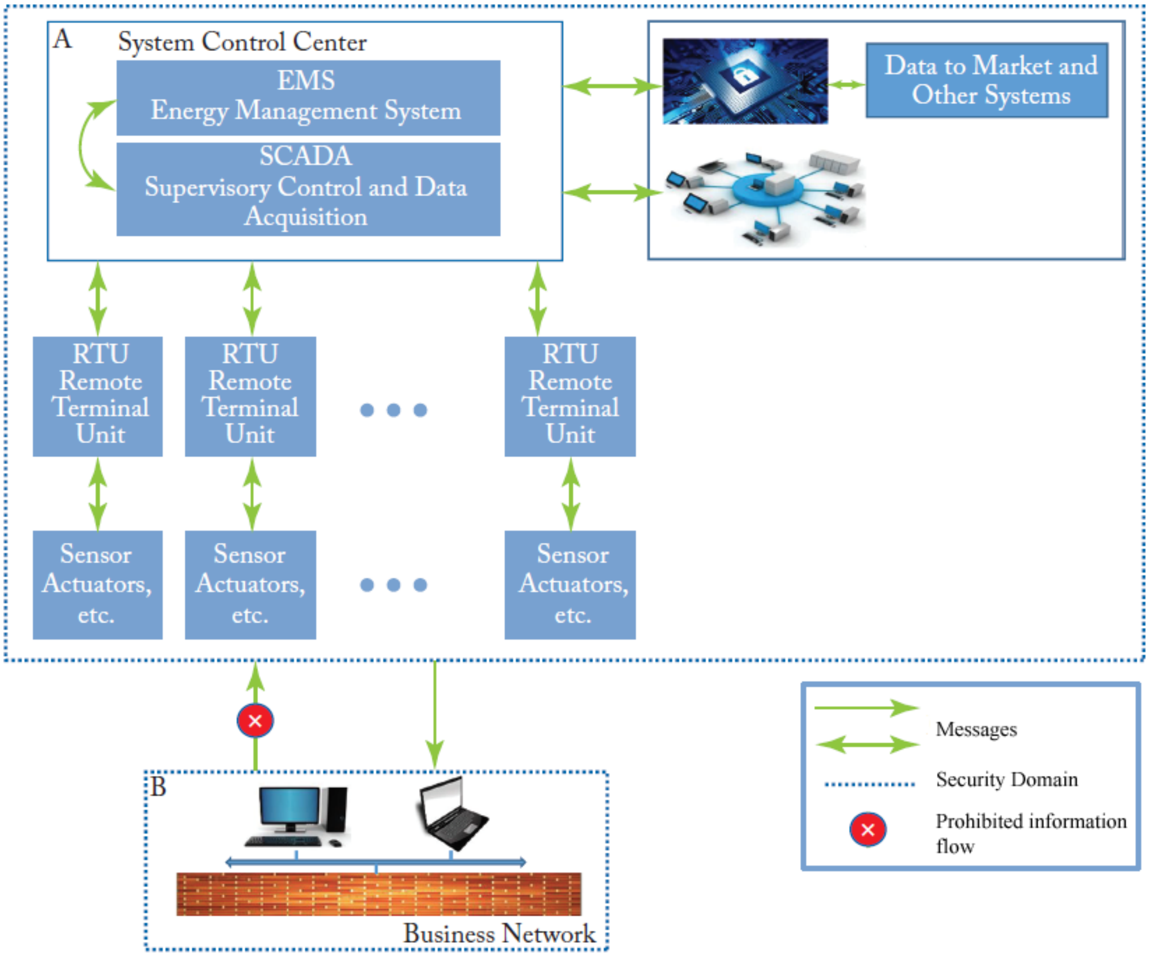


Figure 1.2. Biba Model of an Electric Power System (McMillin and Roth, 2017)

Thesis outline. This thesis is organized as follows, Section 2 explains the different approaches, models that are used for vulnerability analysis and invariant generation, and the model of a microgrid. Section 3 explains the problem statement, Section 4 describes the work that has been done related to this problem, Section 5 analyses the vulnerabilities. Section 6 describes mathematical methods for security analysis, mitigations to the potential threats and those threats that cannot be mitigated due to design restrictions, and invariant generation. Section 7 explains the results, Section 8 presents concluding remarks and Section 9 outlines future work.

2. BACKGROUND

2.1. APPROACHES

2.1.1. Design-centric Approach (DeC). In DeC, the CPS are analyzed for vulnerabilities and attack detection methods are generated manually based on the physics of the system.

2.1.1.1. Nondeducibility (ND) (Sutherland, 1986). Nondeducibility approach models the information flow between the different partitions in a system. Partitions are usually created within the system based on functionality. The system partitions are normally termed as high and low and are separated from each other. If the information in one partition is not deductible at the other, then they are nondeducibilty secure with each other. The partitions in ND model are absolute and simple. If the partitions overlap as in the case of critical infrastructure like industrial control systems, then the ND model does not have the required features to model the information flow. To address this MSDND model was developed which has better control over the information being transferred.

2.1.1.2. Valuation function. $V_x^y(\phi)$ represents the valuation function the domain y has about the state x. The valuation function assigns a Boolean value to the question ϕ based on the status of x with respect to the security domain y.

2.1.1.3. Security domain (SD^i) (Howser and McMillin, 2013). The system is split into several security domains SD^i as observed by each entity i in the system by the event system. The domains might overlap or be disjoint with respect to each other. An entity i in a system is a component that can perform action or observation on its own.

2.1.1.4. Multiple security domain nondeducibility .

MSDND does not partition the system into just high and low, but instead, it partitions into domains which can be overlapping, disjoint or wholly contained in other domains. From one security domain if we do not have valuation function to determine the state of the other domain, then these two domains are said to be MSDND secure with each other.

Formally the MSDND model can be defined as, 'There exists some world with a pair of states where one must be true and the other false (exclusive OR), but an entity i has no valuation function for those states. In security domain SD^i, i simply cannot know which state is true and which is false' (Howser and McMillin, 2013).

MSDND(ES): $\exists \mathrm{w} \in \mathrm{W} \vdash [\,(s_x \vee s_y)\,] \wedge \sim(s_x \wedge s_y) \wedge [\,\mathrm{w} \models (\nexists V_x^i(\mathrm{w}) \wedge \nexists V_y^i(\mathrm{w}))\,]$

An equivalent formula is,

MSDND(ES): $\exists\ \mathrm{w} \in \mathrm{W} \vdash [\,(s_x \oplus s_y)\,] \wedge [\,\mathrm{w} \models (\nexists V_x^i(\mathrm{w}) \wedge \nexists V_y^i(\mathrm{w}))\,]$

In the confidentiality aspect, MSDND secure information path is good for the system and in the integrity aspect, an MSDND secure information path is bad for the system (Dunaka and McMillin, 2017). For example, when a burglar enters a house, the owner should know about the intrusion (integrity). On the other hand, a burglar outside the house should not know whether the owner is present in the house or not (confidentiality).

MSDND analysis helps in identifying information paths that are vulnerable to integrity attacks and provides insights for creating invariants, which can help in enhancing the resiliency of a CPS.

2.1.1.5. BIT logic.

BIT logic is an approach to formally define the belief, information transfer and trust of cyber systems. Initially it was used for handling trust in software systems (Liau, 2003) (Liau, 2005). If there are human interactions involved, then BIT logic is effective to use in CPS as well. Spoofing in the system can be well explained using formal proofs that utilizes BIT logic. The belief and trust that an entity i has in information from an entity j can be reasoned using BIT logic. BIT Logic makes use of three new modal operators to describe what entities believe, trust, and communicate with each other, they are:

- $T_{i,j}\ \phi$ - trust that domain i has on report from domain j, when j tells that ϕ is true
- $B_i\ \phi$ - belief that domain i has on information ϕ; regardless of ϕ's value, i always believes ϕ to be true
- $I_{i,j}\ \phi$ - transfer of information from domain j to i that the value ϕ is true

2.1.2. Data-centric Approach (DaC).

In DaC, the system is operated for a considerable period of time in different use cases and data is collected from them. The collected data is used to train a suitable machine learning algorithm and rules (invariants) which always hold true throughout the system operation are extracted from it. These invariants when implemented in the system would notify the operator when there is something abnormal with the system.

Linear regression. With an assumption of a linear relationship between dependent variable (Y) and independent variable (X), linear regression represents the relationship with a best fitting linear model calculated with observed data. A population linear regression model can be interpreted as,

$$Y = aX + b + \epsilon$$

Where, a is the population slope, also called regression coefficient; b is the population y-intersection, and ϵ is the random error or residual (Lin, 1997). With linear regression, significant independent predictors can be identified, and outliers can be detected with a specific threshold.

2.2. APPLICATION: ELECTRIC SMART GRID

Electric Power and Intelligent Control (EPIC) is one of the four testbeds at iTrust (iTrust, 2016), which is a center for research in cybersecurity that strengthens the infrastructure available to researchers in cybersecurity, and is located at the Singapore University of Technology and Design (SUTD). EPIC is a power testbed, and it comprises four stages: Generation, Transmission, Micro-grid, and Smart Home.

The Generation stage consists of a power source from SUTD's grid and three generators. The three generators are rated at 10 kW each and provide a total of 30 kW of maximum power. At the transmission stage, an autotransformer is used to step up or step down the voltage to the smart home or micro-grid. The smart home consists of two load banks with programmable variable resistive, inductive, and capacitive loads. The micro-grid consists of 110 photovoltaic cells (PV) and two sets of batteries. One battery is a backup for the PV in case of cloud cover, and the other battery is 5 kW and is used to supply power to SCADA in case of a complete blackout to carryout load shedding. PV cells along with the first set of batteries produce a total power of 34 kW. Power management between the PV cells and the battery, and the battery charging/discharging percentage is controlled by a SMA cluster controller. Figure 2.1 shows the EPIC testbed with electric components.

Smart meters with advanced metering infrastructure (AMI) obtain readings of voltages, current, power factor, and power consumption and are installed at several locations throughout the EPIC grid. Readings from individual meters can be viewed via a web-based workstation, and the readings from the SCADA are recorded through Historian, which is a database software application that logs time-based process data. Historian, AMI, and SCADA run on different machines as shown in Figure 2.2. SCADA and Historian are in the same network, but AMI is in a different network.

Examples of critical information:

- Revolutions per minute (RPM): The RPM of the motor plays a key role in the power grid system. It determines the voltage and frequency of the generated electricity. The RPM value is regulated by the device called the variable speed drive (VSD). VSD also provides the RPM values to the SCADA.
- Relay reading (RR): The RR from the IED/Relay contains the readings of voltage, current, frequency, and power of the line in which the relay is present:

  $$RR = (V, i, fR, P); \tag{2.1}$$

  where V-voltage, i-current, fR-frequency, and P-power.

  For normal operation of EPIC, frequency should be 50 Hz and flow voltage should be 415 V, with an allowed deviation of ±6%. If the frequency or voltage is above or below the threshold, then the relay would send commands to trip the circuit breaker.
- Battery charging/discharging rule (CD) in percentage: The battery level percentage at which the battery should only undergo charging and the percentage at which it can discharge are set at the cluster controller. CD plays an important role in maintaining health of the battery and having backup power in times of need.
- Circuit breaker status (CBS): The status of the circuit breaker determines whether or not there will be flow of electricity further down the system. CBS is sent from the relay to the control system.
- Circuit breaker command (CBC): The instruction for opening or closing the circuit breaker sent from the control system to the circuit breaker. Before passing the CBC from the control system, the relay modifies or simply transfers the CBC to the circuit breaker based on the flow voltage.

Each of the critical information pieces have an information path associated with them.

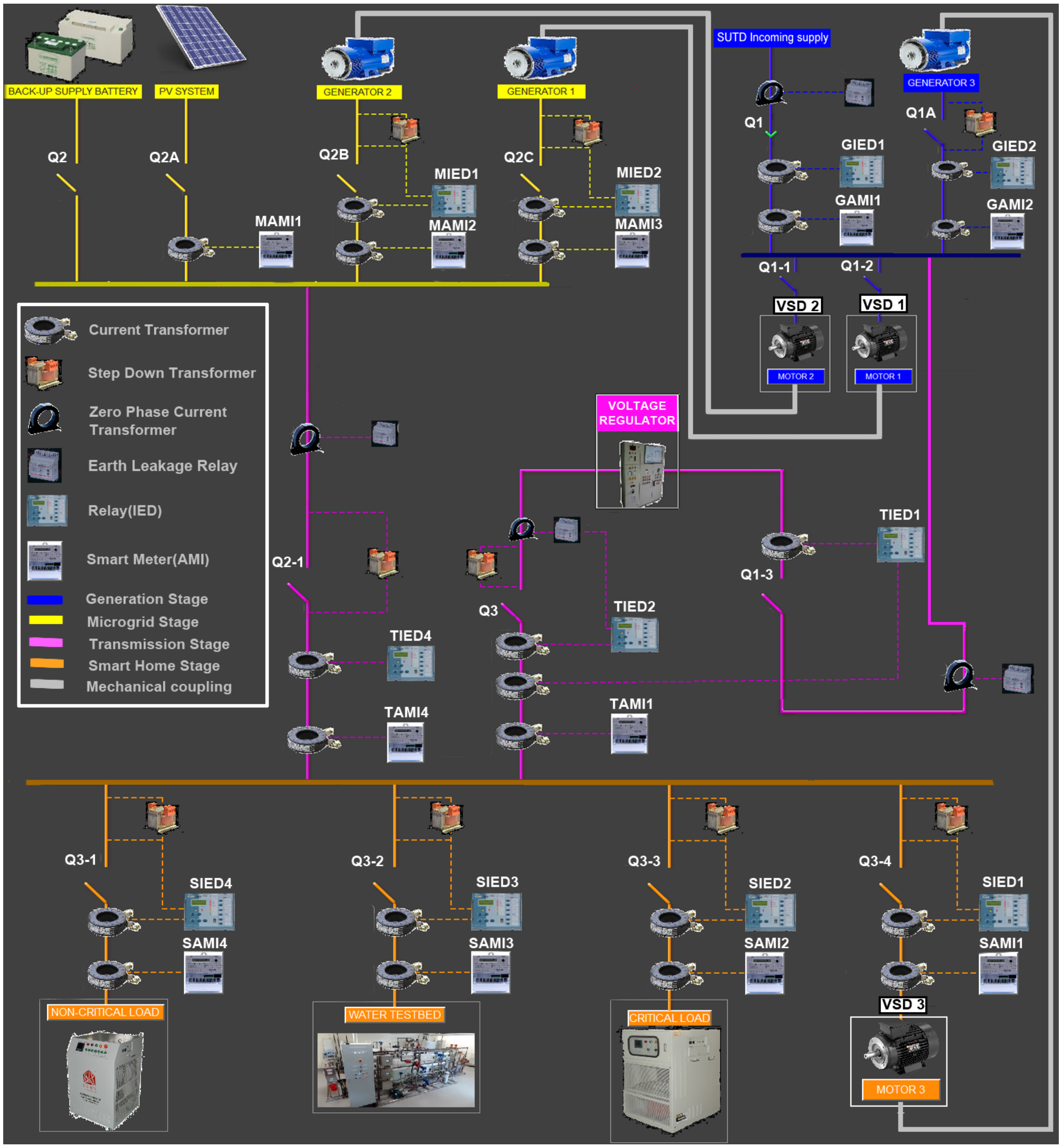


Figure 2.1. EPIC- Single Line Diagram

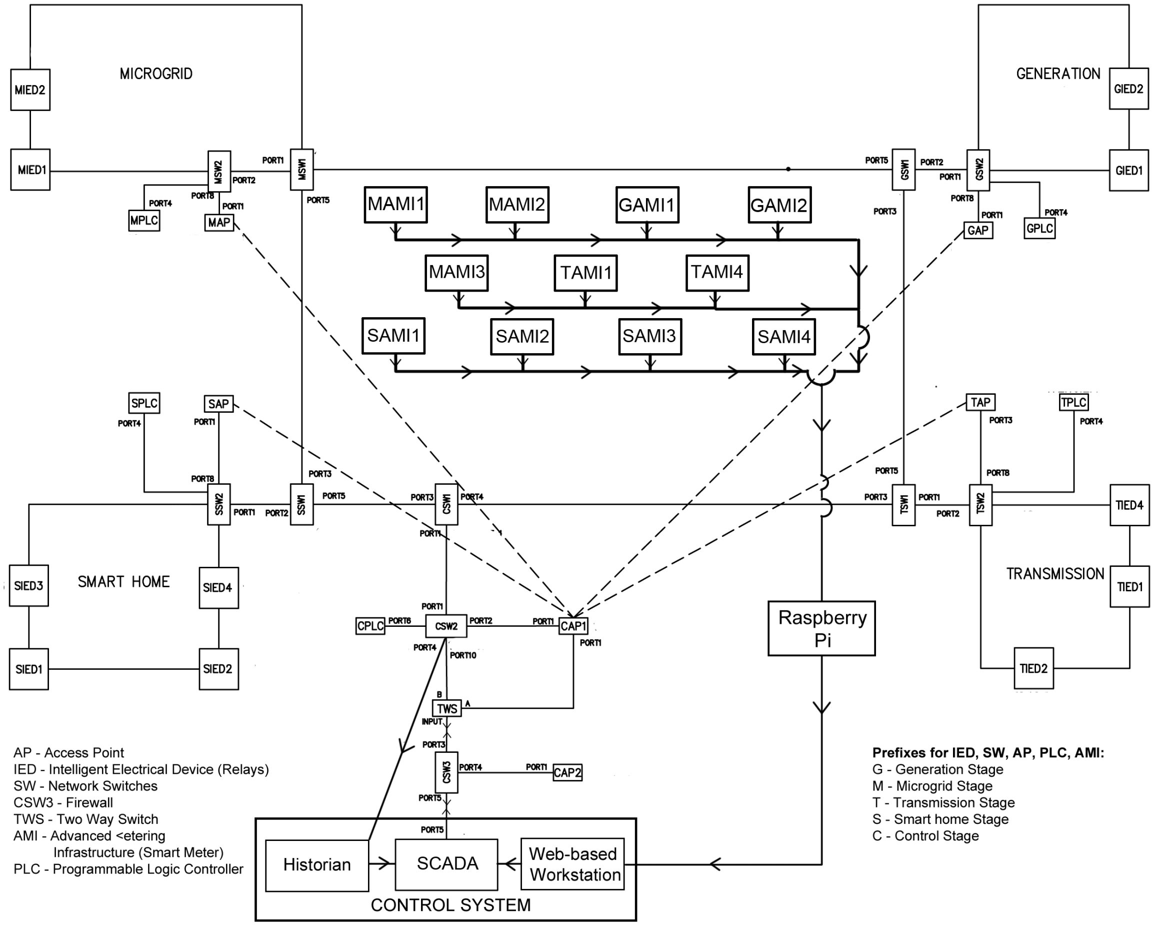


Figure 2.2. EPIC- Network Diagram (iTrust, 2016). Examples for interpreting the devices from diagram: i) MAMI2 - Microgrid stage Smart meter, device 2, ii) TIED4 - Transmission stage Relay, device 4.

3. PROBLEM STATEMENT

Power grids are the most critical infrastructure of all countries. Power grids nowadays are largely smart and have many devices installed throughout the system to enable easy operation and monitoring, which makes them more prone to cyber attacks. Cyber attacks on such a critical CPS can cause a major disaster to a nation and have a serious impact on its economy. In most of these attacks, the attacker has a good understanding of the various devices in the CPS and designs malware for them. This malware carries out a man-in-the-middle attack that fakes process control sensor signals so an infected system does not shut down due to detected abnormal behavior. The malware also modifies the data sent to the control system to make it look normal. So, there is no way for the operator to know that the CPS is under attack. An attack of this kind happened in Iran (Falliere *et al.*, 2011). In this case, the Stuxnet was executed from the Siemens PLC and varied the centrifuge's rotor speed between high and low continuously in an attempt to damage the centrifuge. The Stuxnet also sent recorded false positive reports that indicated normal rotor speeds back to human operators. Because of this, the attack was undetected and many centrifuges were damaged. In 2016, a malware caused a power outage for about an hour in Ukraine that affected more than tens of thousands of households. The malware was found to be capable of launching automated assaults against industrial control systems managing the electric grid.

In this thesis, a model-based approach is carried out to find the vulnerable information paths in the system. Invariants were generated through DeC and DaC methods and implemented in the control system to identify Stuxnet-like attacks and abnormalities in a smart grid.

4. VULNERABILITY ANALYSIS

In this thesis, a Stuxnet-like attack model is assumed in an electric microgrid. The goal of these attacks is to disrupt system operation by confusing the system through deception.

4.1. ATTACK MODEL

Stuxnet-like worms are malicious codes that can be injected into a system through USB flash drives, shared networks, etc. Once Stuxnet is injected, it replicates to spread and hides by faking a healthy working condition of the system. To do this, the worm targets SCADA systems. In specific, it gets access to the programmable logic controller (PLC), infects it with harmful operational commands and returns previously recorded normal feedbacks to devices (sym, 2010). The undetectable mechanism of a Stuxnet-like worm makes use of the security vulnerability of a system along with rootkits to make the attack hard to be identified (Mueller and Yadegari, 2012). If an observer does not have valuation function to ascertain whether the state of the system is true or false, then the system is secure with respect to integrity. The operator cannot deduce if there is any fault or attack in the system. Thus, secure paths within a system are bad.

4.2. INVARIANTS

An invariant is a logical predicate on system state and its truth value must not change if it is satisfied by system execution. It is a property, function or quantity that stays unchanged whilst a stated transformation is applied. Invariants were initially created for cyber systems (Owicki and Gries, 1976). Lately, invariants have also been extended for CPSs like power systems (Gamage *et al.*, 2015) (Paul *et al.*, 2014) and water treatment systems (Adepu and Mathur, 2016). Defining invariants for CPSs are much harder than in cyber processes because it requires a thorough understanding of the working of physical and cyber components in the system.

The invariant equations in the EPIC testbed are executed at the control system. Coupling MSDND and the invariant equations, the bounds on parameters measured in a power grid can be minimized and the corrupt information path can be identified with a better precision.

5. RELATED WORK

An attestation framework that makes use of physical process constraints as invariants was proposed (Roth and McMillin, 2016) to validate behaviors and identify attacks in cyber-physical systems, in particular, a smart power grid. In the paper, false injection attacks are concentrated as a typical attack method that commonly used against a smart grid. There exist malicious cyber injection attacks that are proven to be hidden from pure software detection. In such cases, physical verification plays an important role in exhibiting faulty behaviors in the system.

The authors introduced a signature-based invariant protocol, 7-node attestation, which is based on a manually summarized violation pattern on the law of the conservation of energy. It examines neighboring household power migrations and setup invariants calculated with actual power flow parameters, such as voltages and phase angles. Both current measurements and saved conservations of such parameters are involved in the computation of the invariant between a set of smart nodes. Under the proclaimed framework, a fake supply attack where a malicious supplier pretends to increase the generation power to meet the demand but actually violates the protocol can be deduced. Although the framework introduced the physical layer attestation, due to the limitation of the invariant, a malicious participant can be located only over specific topologies. It will also not work in network partitions, which have limited communication between nodes.

MSDND approach helps in identifying integrity attacks within a system and has been used in modeling security for several other cyber physical infrastructures like air traffic control systems (Thudimilla and McMillin, 2017), chemical plants (Dunaka and McMillin, 2017) and vehicle platoon systems (Kanteti, 2017).

6. SECURITY ANALYSIS AND INVARIANT GENERATION

6.1. DESIGN-CENTRIC APPROACH

MSDND Analysis. In MSDND analysis, the information flow paths of different critical information pieces in the system are analyzed in the proofs using BIT logic. Mathematical analysis of each piece of information is performed from the source to the destination (control system) through different security domains in which the information gets passed. The point at which the information can get corrupted is identified, and invariants are generated to create a valuation function that helps detect the attack.

There are five different types of critical information in the testbed, as seen in Section 2.2. Each type of critical information has an information path associated with it. The security domains for each of the information paths is shown in Figures 6.1, 6.2, 6.3 and 6.4. In the following proofs, invariants are used to break the MSDND security of an integrity attack.

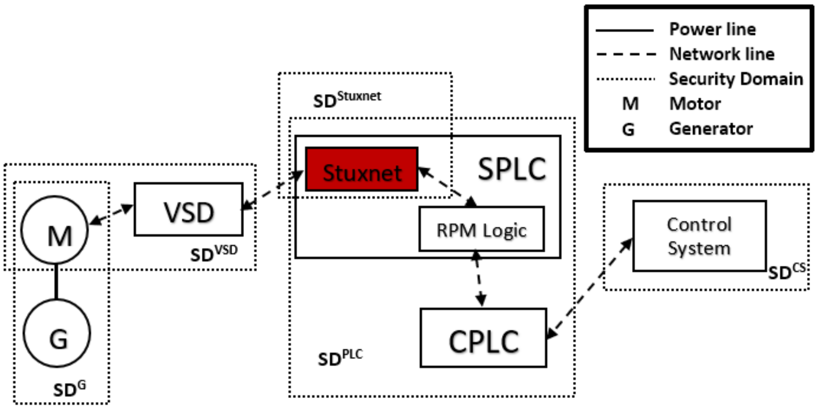


Figure 6.1. Security domains of ‘RPM’ information path

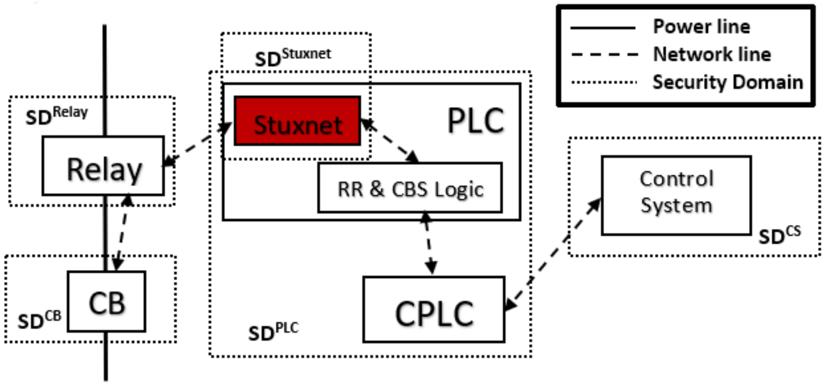


Figure 6.2. Security domains of ‘RR and CBS’ information path

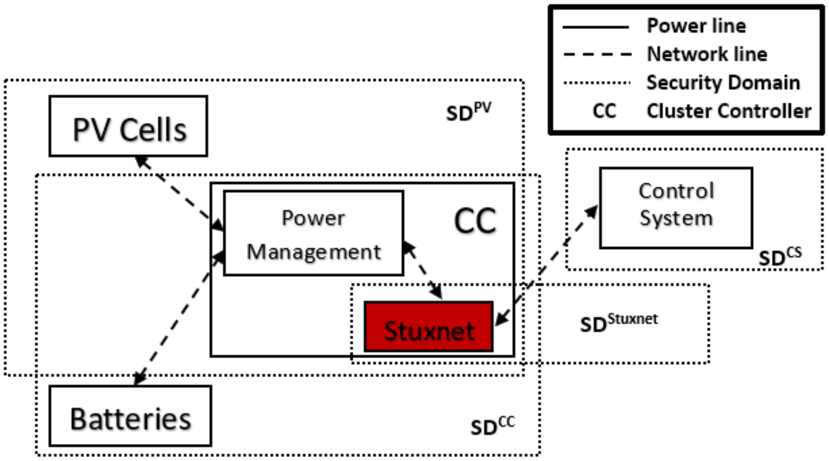


Figure 6.3. Security domains of ‘CD’ information path

Assumption. *RR* contains various values as mentioned in Equation 2.1. For a successful attack, the attacker needs to change all the values in *RR* proportionately. This assumption has been used in the DeC approach for generating invariants. Only the frequency values are considered in generating the invariant. If the frequency of *RR* fails the invariant equation, then the other values will also fail.

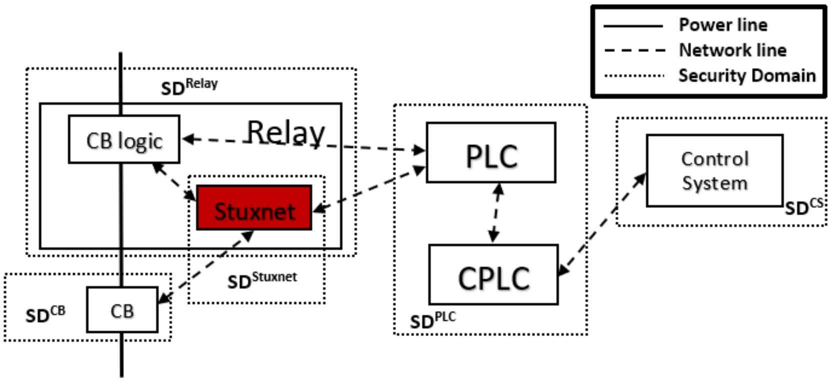


Figure 6.4. Security domains of ‘CBC’ information path

Macros. The following macro is used in the theorems defined below.,

$IBT_{1,2}$Val = $I_{1,2}Val$; /*2 reported to 1 that Val is true*/

$B_1 I_{1,2} Val$; /*1 believes that Val is true*/

$T_{1,2} Val$; /*The trust that 1 has on 2 about the information Val*/

$B_1 I_{1,2}\ Val \wedge T_{1,2}\ Val \rightarrow B_1\ Val$; /*1 believes that Val is correct*/

- **Single-point attacks**

Analysis of vulnerability in RPM information path.

Theorem 1. *The RPM reading RPM from VSD is MSDND secure at the Control System (CS) when RPM is not normal but the reading is normal.*

Proof. Here the RPM reading from VSD is modified by the Stuxnet and sent to the CS.

1. $\sim RPM$ = true; The RPM is not normal

2. w $\models V^{VSD}_{\sim RPM}$ (w) = true; RPM reading is not normal at the VSD

3. $IBT_{Stuxnet,VSD}\ \sim RPM$; Stuxnet intercepts the abnormal RPM sent by VSD to PLC

4. w $\models V^{Stuxnet}_{\sim RPM}$ (w) = true; Stuxnet observes that RPM is abnormal

5. $IBT_{PLC,Stuxnet}\ RPM$; Stuxnet modifies RPM to make it look normal and sends it to PLC and PLC believes it

6. w $\models V^{PLC}_{RPM}$ (w) = true; RPM appears normal in PLC world

7. $IBT_{CS,PLC}\ RPM$; PLC tells CS that RPM is normal and CS believes it

8. w $\models V^{CS}_{RPM}$ (w) = true; CS believes that RPM is normal, it does not have valuation function to verify it

9. MSDND(ES): $\exists\, \mathrm{w} \in \mathrm{W} \vdash [\, (\, S_{RPM} \oplus S_{\sim RPM}\,)\,] \wedge [\, \mathrm{w} \models (\, \nexists V^{CS}_{\sim RPM}(\mathrm{w}) \wedge \nexists V^{CS}_{RPM}(\mathrm{w})\,)\,]$

The CS believes the false positive RPM reading reported by the Stuxnet and believes that everything is normal. Therefore RPM information is MSDND secure from the CS. There are three such MSDND secure paths in the system as shown in Table 6.1. □

Theorem 2. *The RPM reading RPM from VSD is not MSDND secure when RPM is not normal but the reading is normal and an invariant on the frequency f and RPM are considered.*

Proof. Let us assume the frequency reading f from the AMI is correct. Let the invariant $iRPM$: $RPM = 30f$ be in the control system. The invariant is derived from the equation, $RPM = \dfrac{(120 \times f)}{P}$, where P is the number of poles in the motor, here $P = 4$.

1. $\sim RPM$ = true; The RPM is not normal

2. w $\models V^{VSD}_{\sim RPM}$ (w) = true; RPM reading is not normal at the VSD

3. $IBT_{Stuxnet,VSD} \sim RPM$; Stuxnet intercepts the abnormal RPM sent by VSD to PLC

4. w $\models V^{Stuxnet}_{\sim RPM}$ (w) = true; Stuxnet observes that RPM is abnormal

5. $IBT_{PLC,Stuxnet}\ RPM$; Stuxnet modifies RPM to make it look normal and sends it to PLC and PLC believes it

Table 6.1. Summary of MSDND analysis for RPM information path

S.No.	MSDND Secure Paths	Invariant Available
1	VSD1→SPLC→CPLC→CS	Yes
2	VSD2→SPLC→CPLC→CS	Yes
3	VSD3→SPLC→CPLC→CS	Yes

6. w $\models V^{PLC}_{RPM}$ (w) = true; RPM appears normal in PLC world

7. $IBT_{CS,PLC}\ RPM$; PLC tells CS that RPM is normal and CS believes it

8. $\sim RPM \implies \sim f$; when RPM is not normal it affects the RR

9. $IBT_{CS,AMI}\ \sim f$; CS obtains the f reading from smart meter and believes it

10. $\sim iRPM \implies \sim RPM$; from our assumption that the frequency reading f from the AMI is correct and the invariant $iRPM$, the CS deduces that RPM is not normal

11. $(S_{iRPM}, S_{RPM}) = S''$; System is working normally if and only if S'' is true

12. w $\models V^{CS}_{\sim RPM}$ (w) = true; CS now has deduced that RPM is abnormal

13. ~MSDND(ES): $\exists\, w \in W \vdash [\,(S'' \oplus S_{\sim RPM})\,] \wedge [\,w \models (\exists\, V^{CS}_{\sim RPM}(w) \wedge \nexists\, V^{CS}_{RPM}(w))\,]$

The system is not MSDND secure as we have valuation function for normal working of the system as shown in Figure 6.5, and fault/threat can be detected. This can be used to break three MSDND secure paths in the system. □

Analysis of vulnerability in CD information path.

Theorem 3. *The battery charging/discharging percentage CD set at the cluster controller (CC) is MSDND secure at the control system (CS)*

Proof. 1. $\sim CD$ = true; charging/discharging percentage set is not normal

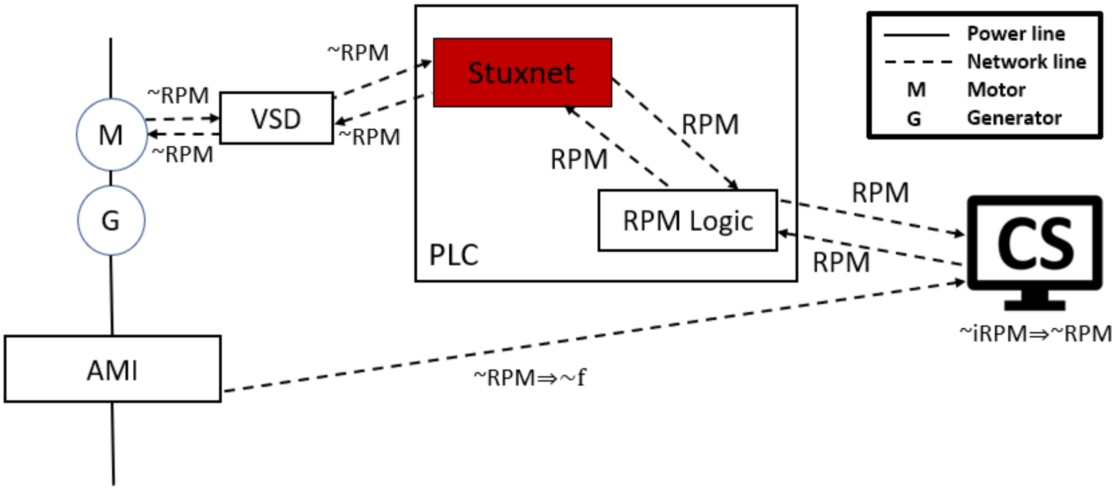


Figure 6.5. Information flow when RPM is abnormal and invariant is used. Attack model for this is explained in Theorem 1 and attack detection is explained in Theorem 2.

2. w $\models V^{CC}_{\sim CD}$ (w) = true; CD is not normal in CC world

3. $IBT_{Stuxnet,CC}$ $\sim CD$; Stuxnet intercepts the abnormal CD sent by Cluster controller to CS

4. w $\models V^{Stuxnet}_{\sim CD}$ (w) = true; Stuxnet observes that CD is abnormal

5. $IBT_{CS,Stuxnet} CD$; Stuxnet reports that the CD is normal to CS and CS believes it

6. w $\models V^{CS}_{CD}$(w) = true; CS believes CD to be normal

7. MSDND(ES): $\exists$ w $\in$ W $\vdash$ [($S_t \oplus S_{\sim t}$)] $\wedge$ [w $\models$ ($\nexists\, V^{CS}_{\sim CD}$(w) $\wedge \nexists\, V^{CS}_{CD}$(w))]

The control system believes that battery charging/discharging level set in the cluster controller is in desired range. The CD cannot be evaluated at the CS and hence it is MSDND secure. Moreover, there are no alternate information paths to define invariant for this path as seen in Figure 6.6. □

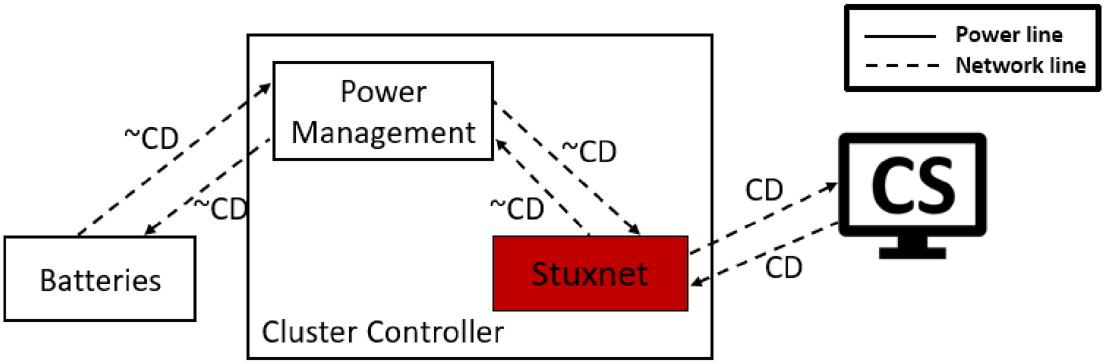


Figure 6.6. Information flow when CD is abnormal. Attack model for this is explained in Theorem 3.

Analysis of vulnerability in RR information path.

Theorem 4. *RR (within threshold or not) information is MSDND secure when the flow voltage is normal but the circuit breaker trips*

Proof. Here, the voltage that flows through the relay is within threshold but still the circuit breaker is tripped, i.e., CBS = open.

1. fV = true; The flow voltage is within threshold
2. w $\models V_{fV}^{Relay}$ (w) = true; The relay observes that the voltage is normal
3. $fV \implies CBS$; When the flow voltage is normal, the relay sends the CB the same command that SCADA sends to CB, so here it directs CB to remain closed
4. CBS = true; CBS is normal
5. w $\models V_{CBS}^{Relay}$ (w) = true; CBS is normal in relay world
6. $IBT_{Stuxnet,Relay}$ CBS; Stuxnet intercepts the normal CBS sent by Relay to CB
7. w $\models V_{CBS}^{Stuxnet}$ (w) = true; Stuxnet observes that CBS is normal

8. $IBT_{CB,Stuxnet}$ $\sim CBS$; The Stuxnet instructs the CB to open even though the flow voltage is normal

9. CBS=open $\Longrightarrow$ RR = 0; When CB is open the relay reading is zero

10. $\sim RR$ = true; RR is now not normal

11. w $\models V^{Relay}_{\sim RR}$ (w) = true; Relay observes that RR is not normal

12. $IBT_{PLC,Relay}$ $\sim RR$; Relay tells PLC that RR is not normal and PLC believes it

13. w $\models V^{PLC}_{\sim RR}$ (w) = true; RR is not normal in PLC world

14. $IBT_{CS,PLC}$ $\sim RR$; PLC tells CS that RR is not normal and CS believes it

15. w $\models V^{CS}_{\sim RR}$ (w) = true; RR is abnormal in CS, CS believes it is because of abnormal flow voltage

16. MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[\,(\,S_{RR} \oplus S_{\sim RR}\,)\,] \;\wedge\; [\,\text{w} \models (\,\nexists\, V^{CS}_{\sim RR}(\text{w}) \;\wedge\; \nexists\, V^{CS}_{RR}(\text{w})\,)\,]$

The RR reading received at the CS are all zero hence it is not possible to deduce at the CS whether the CB trip was because of voltage beyond threshold or because of fault/attack. Hence, the system is MSDND secure. There are eleven such MSDND secure paths in the system as listed in the Table 6.3. □

Theorem 5. *RR (within threshold or not) information is not MSDND secure if the invariant is used when the flow voltage is normal but the circuit breaker trips*

Proof. Here the CBS = open and hence RR=0. To check whether the trip was because of fault/attack we take the readings pRR from the Relays that are present immediately before the relay that got tripped. Table 6.2 lists the relay readings that need to be used for each of the relays that has zero reading because of tripping. If two relays are listed then any one of them that does not have zero reading can be used. $Proj_{pFR}(pRR) = pfR$. Let us assume

Table 6.2. Relay association with previous closest relays

Relay with zero reading	Relay reading to use
GIED1	Not available
GIED2	SIED1
TIED1	GIED1/GIED2
TIED2	TIED1
TIED4	MIED1/MIED2
MIED1	GIED1/GIED2
MIED2	GIED1/GIED2
SIED1	TIED2/TIED4
SIED2	TIED2/TIED4
SIED3	TIED2/TIED4
SIED4	TIED2/TIED4

the frequency reading pFR from the closest previous relay is accurate. Let the invariant $iFThresh : 47 < pFR < 53$ be in the control system. The normal operating frequency of the EPIC system is 50 Hz with an allowed deviation of ± 6%.

1. fV = true; The flow voltage is within threshold
2. w $\models V_{fV}^{Relay}$ (w) = true; The relay observes that the voltage is normal
3. $fV \implies CBS$; When the flow voltage is normal, the relay sends the CB the same command that SCADA sends to CB, so here it directs CB to remain closed
4. CBS = true; CBS is normal
5. w $\models V_{CBS}^{Relay}$ (w) = true; CBS is normal in relay world
6. $IBT_{Stuxnet,Relay}$ CBS; Stuxnet intercepts the normal CBS sent by Relay to CB
7. w $\models V_{CBS}^{Stuxnet}$ (w) = true; Stuxnet observes that CBS is normal
8. $IBT_{CB,Stuxnet}$ $\sim CBS$; The Stuxnet instructs the CB to open even though the flow voltage is normal

9. CBS=open $\implies$ RR=0; When CB is open RR is zero

10. $\sim RR$ = true; RR is now not normal

11. w $\models V^{Relay}_{\sim RR}$ (w) = true; Relay observes that RR is not normal

12. $IBT_{PLC,Relay}$ $\sim RR$; Relay tells PLC that RR is not normal and PLC believes it

13. w $\models V^{PLC}_{\sim RR}$ (w) = true; RR is not normal in PLC world

14. $IBT_{CS,PLC}$ $\sim RR$; PLC tells CS that RR is not normal and CS believes it

15. w $\models V^{CS}_{\sim RR}$ (w) = true; RR is abnormal in the CS world, CS believes it is because of abnormal flow voltage

16. $IBT_{PLC,Relay}$ pRR; pRR is extracted from previous closest relay to the relay in which zero reading was shown

17. w $\models V^{PLC}_{pRR}$ (w) = true; pRR is normal in PLC world

18. $IBT_{CS,PLC}$ pRR; PLC tells CS that pRR is normal and CS believes it

19. $iFThresh \implies pFR \implies RR$ ($\because Proj_{pFR}(pRR) = pFR$); From our assumption that the frequency reading pFR from the closest previous relay is accurate and the invariant $iFThresh$, the CS deduces that RR is normal

20. S'' = ($S_{iFThresh}$, S_{RR}) ; System is working normally if and if only S'' is true

21. w $\models V^{CS}_{RR}$ (w) = true; RR is normal in the CS world

22. ~MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[\,(S'' \oplus S_{\sim RR})\,] \wedge [\,\mathrm{w} \models (\exists\, V^{CS}_{\sim RR}(\mathrm{w}) \wedge \nexists\, V^{CS}_{RR}(\mathrm{w}))\,]$

When the RR reading received at the CS are all zero but pRR readings are all within threshold during this period, then we can deduce that the trip in the CB was not because of abnormal flow voltage, but because of fault/attack. Hence, the system is no longer MSDND

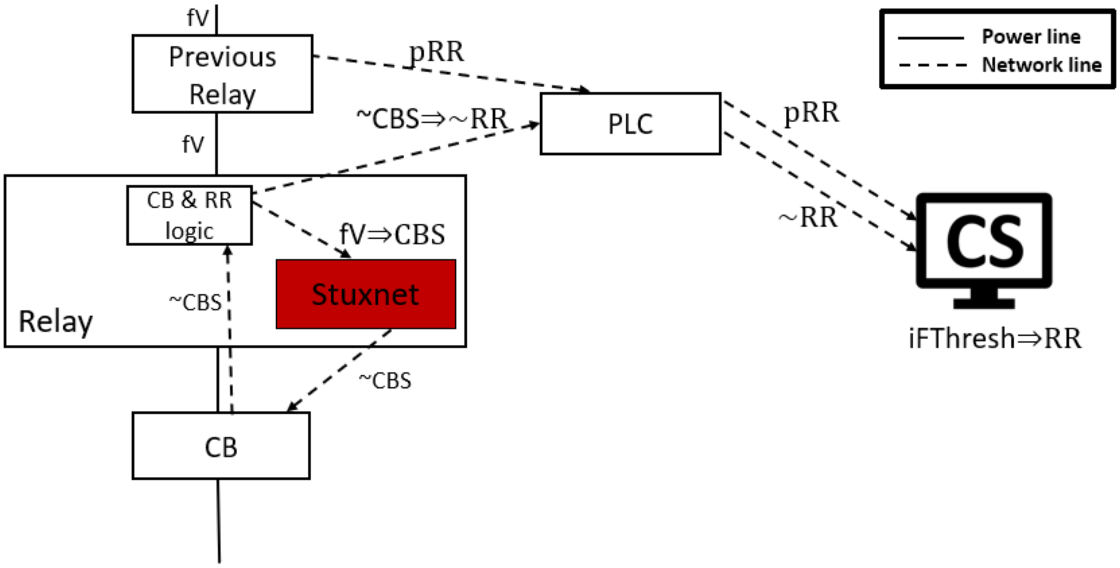


Figure 6.7. Information flow when *RR* is normal but the CB trips, and invariant is considered. Attack model for this is explained in Theorem 4 and attack detection is explained in Theorem 5.

secure as seen in Figure 6.7. This theorem can be used to break ten MSDND secure paths out of the eleven. The MSDND secure path when GIED1 *RR* shows zero can not be broken, because there are no relays present before it. This is a design flaw in the system. □

Theorem 6. *RR (within threshold or not) information is MSDND secure when the flow voltage is abnormal but the circuit breaker does not trip*

Proof. Here the voltage that flows through the relay is not within threshold, but the circuit breaker does not trip, i.e., CBS = closed. The Stuxnet changes the circuit breaker command sent from the relay to the CB (i.e., open to closed) and masks the *RR* sent from the relay to the CS.

1. $\sim fV$ = true; The flow voltage is not within threshold

2. w $\models V^{Relay}_{\sim fV}$ (w) = true; The relay observes that the voltage is not within threshold

3. $\sim fV \implies \sim CBS$; When the flow voltage is not normal, the relay ignores the SCADA command to CB and directs it to open

4. $\sim CBS$ = true; CBS at relay is different from CBS at SCADA

5. w $\models V^{Relay}_{\sim CBS}$ (w) = true; CBS is not normal at the relay

6. $IBT_{Stuxnet,Relay}$ $\sim CBS$; Stuxnet intercepts the abnormal CBS sent by relay to CB

7. w $\models V^{Stuxnet}_{\sim CBS}$ (w) = true; Stuxnet knows that the CBS is not normal

8. $IBT_{CB,Stuxnet}$ CBS; Stuxnet modifies the CBS and instructs the CB that it is normal, CB believes it

9. $\sim fV \implies \sim RR$; The flow voltage is not normal so that reflects RR

10. $\sim RR$ = true; RR is not normal

11. w $\models V^{Relay}_{\sim RR}$ (w) = true; RR is abnormal in relay world

12. $IBT_{Stuxnet,Relay}$ $\sim RR$; Stuxnet intercepts the abnormal RR sent by relay to CB

13. w $\models V^{Stuxnet}_{\sim RR}$ (w) = true; Stuxnet observes that RR is abnormal

14. $IBT_{PLC,Stuxnet}$ RR; Stuxnet modifies RR to make it look normal and transmits it to PLC and PLC believes it

15. w $\models V^{PLC}_{RR}$ (w) = true; RR looks normal in PLC world

16. $IBT_{CS,PLC}$ RR; PLC tells CS that RR is normal and CS believes it

17. w $\models V^{CS}_{RR}$ (w) = true; CS believes that RR is normal and system is normally working

18. MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[\,(S_{RR} \oplus S_{\sim RR})\,] \wedge [\,$w $\models (\nexists\, V^{CS}_{\sim RR}(\mathrm{w}) \wedge \nexists\, V^{CS}_{RR}(\mathrm{w}))\,]$

The RR readings received at the CS are all normal as the Stuxnet had sent false positives. Hence, it is not possible to deduce at the CS whether the RR is within threshold or not. Thus, the system is MSDND secure. There are eleven such MSDND secure paths in the system as listed in Table 6.3. □

Theorem 7. *The Relay reading RR (within threshold or not) information is not MSDND secure when the flow voltage is abnormal but the circuit breaker does not trip if the invariants are considered.*

Proof. Let us assume the frequency reading f from the AMI is correct. Let fR be the frequency reading from the relay. Let the invariant $iFreq : f == fR$ and $47 < f < 53$ be in the CS.

1. $\sim fV$ = true; The flow voltage is not within threshold
2. w $\models V^{Relay}_{\sim fV}$ (w) = true; The relay observes that the voltage is not within threshold
3. $\sim fV \implies \sim CBS$; When the flow voltage is not normal, the relay ignores the SCADA command to CB and directs it to open
4. $\sim CBS$ = true; CBS at relay is different from CBS at SCADA
5. w $\models V^{Relay}_{\sim CBS}$ (w) = true; CBS is not normal at the relay
6. $IBT_{Stuxnet,Relay} \sim CBS$; Stuxnet intercepts the abnormal CBS sent by relay to CB
7. w $\models V^{Stuxnet}_{\sim CBS}$ (w) = true; Stuxnet knows that the CBS is not normal
8. $IBT_{CB,Stuxnet}\ CBS$; Stuxnet modifies the CBS and instructs the CB that it is normal, CB believes it
9. $\sim fV \implies \sim RR$; The flow voltage is not normal so that reflects RR
10. $\sim RR$ = true; RR is not normal

11. w $\models V_{\sim RR}^{Relay}$ (w) = true; RR is abnormal in relay world

12. $IBT_{Stuxnet,Relay}$ $\sim RR$; Stuxnet intercepts the abnormal RR sent by relay to CB

13. w $\models V_{\sim RR}^{Stuxnet}$ (w) = true; Stuxnet observes that RR is abnormal

14. $IBT_{PLC,Stuxnet}$ RR; Stuxnet modifies RR to make it look normal and transmits it to PLC and PLC believes it

15. w $\models V_{RR}^{PLC}$ (w) = true; RR looks normal in PLC world

16. $IBT_{CS,PLC}$ RR; PLC tells CS that RR is normal and CS believes it

17. $\sim fV \implies \sim f$; When fV is abnormal, even the AMI readings are abnormal

18. $IBT_{CS,AMI}$ $\sim f$; CS obtains the f reading from AMI and believes it

19. $\sim iFreq \implies \sim fR \implies \sim RR$ ($\because$ $\text{Proj}_{fR}(RR) = fR$); From our assumption that the frequency reading f from the AMI is correct and the invariant $iFreq$, the CS deduces that RR is abnormal

20. $S^{''}$ = ($S_{invariant}$, S_{RR}) ; System is working normally if and if only $S^{''}$ is true

21. w $\models V_{\sim RR}^{CS}$ (w) = true; CS with help of invariant knows that RR is not normal

22. ~MSDND(ES): $\exists$ w $\in$ W $\vdash$ [($S^{''} \oplus S_{\sim RR}$)] $\wedge$ [w $\models$ ($\exists\, V_{\sim RR}^{CS}$(w) $\wedge \nexists\, V_{RR}^{CS}$(w))]

When the frequency reading from the AMI and relay does not match, and when the frequency reading from the AMI is not within threshold, then we can deduce at the CS that the RR was not within threshold, but still the relay did not trip. This is demonstrated in Figure 6.8. Thus, the system is not MSDND secure. Using this invariant, all the eleven such MSDND secure paths in the system listed in Table 6.3 can be broken, including the path involving GIED1. □

Table 6.3. Summary of MSDND analysis for RR information path

S.No.	MSDND Secure Paths	Invariant Available
1	GIED1→GPLC→CPLC→CS	No
2	GIED2→GPLC→CPLC→CS	Yes
3	MIED1→MPLC→CPLC→CS	Yes
4	MIED2→MPLC→CPLC→CS	Yes
5	TIED1→TPLC→CPLC→CS	Yes
6	TIED2→TPLC→CPLC→CS	Yes
7	TIED4→TPLC→CPLC→CS	Yes
8	SIED1→SPLC→CPLC→CS	Yes
9	SIED2→SPLC→CPLC→CS	Yes
10	SIED3→SPLC→CPLC→CS	Yes
11	SIED4→SPLC→CPLC→CS	Yes

Analysis of vulnerability in CBS information path.

Theorem 8. *The Circuit breaker status CBS is MSDND secure at the CS when the CB is open but SCADA shows it as closed and also when the CB is closed but SCADA shows it as open.*

Proof. Here the Stuxnet changes the true value of the CBS. It changes it from true to false or from false to true.

1. CBS = true; CBS is normal

2. w $\models V^{CB}_{CBS}$ (w) = true; CBS is normal in CB world

3. $IBT_{Relay,CB}$ CBS; CB tells relay that CBS is normal and Relay believes it

4. w $\models V^{Relay}_{CBS}$ (w) = true; CBS is normal in relay world

5. $IBT_{PLC,Relay}$ CBS; relay tells PLC that CBS is normal and PLC believes it

6. w $\models V^{PLC}_{CBS}$ (w) = true; CBS is normal in PLC world

7. $IBT_{Stuxnet,PLC}$ CBS; Stuxnet intercepts the normal CBS sent by PLC to CS

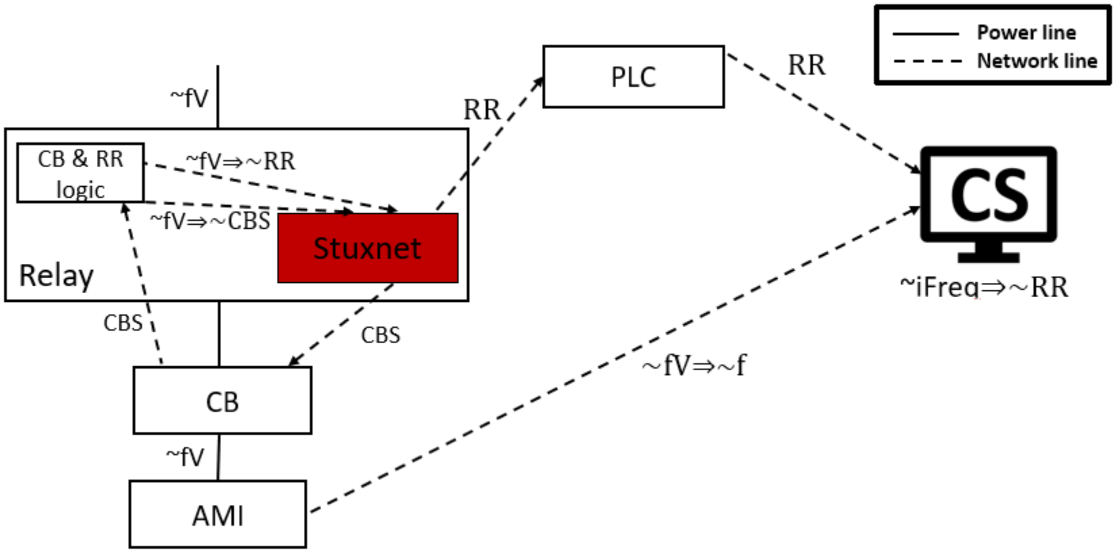


Figure 6.8. Information flow when *RR* is abnormal but CB does not trip, and invariant is considered. Attack model for this is explained in Theorem 6 and attack detection is explained in Theorem 7.

8. $\sim CBS$ = true; The Stuxnet reverses the CBS from the original status

9. w $\models V^{Stuxnet}_{\sim CBS}$ (w) = true; The Stuxnet knows that it has altered the CBS from its original status

10. $IBT_{CS,Stuxnet}$ CBS; Stuxnet reports the CS that the CBS is normal and CS believes it

11. w $\models V^{CS}_{\sim CBS}$ (w) = false; CS does not know that CBS is not normal

12. MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[\,(\, S_{CBS} \oplus S_{\sim CBS}\,)\,] \wedge [\,\mathrm{w} \models (\, \nexists\, V^{CS}_{\sim CBS}(\mathrm{w}) \wedge \nexists\, V^{CS}_{CBS}(\mathrm{w})\,)\,]$

The Stuxnet modifies the actual CBS received from the PLC and sends a false value to the CS and the CS believes it to be the true state of the CB. Hence, it is not possible to deduce at the CS whether the CBS is correct or not. Thus, the system is MSDND secure. There are thirty such MSDND secure paths in the system, fifteen when the CB is open and the SCADA shows it as closed, and fifteen when the CB is closed and the SCADA shows it as open. There are two possible cases for each of the listed paths in Table 6.4. □

Theorem 9. *CBS is not MSDND secure at the CS when the CB is open but SCADA shows it as closed if the invariant is taken into consideration.*

Proof. Let us assume that the relay reading RR is correct. Let fR be the frequency reading from the relay. Let the invariant $iCBClosedCheck : CBS == closed\ and\ fR \neq 0$ be in the CS

1. CBS = true; CBS is normal and its value is open
2. w $\models V_{CBS}^{CB}$ (w) = true; CBS is normal in CB world
3. $IBT_{Relay,CB}$ CBS; CB tells relay that CBS is normal and relay believes it
4. w $\models V_{CBS}^{Relay}$ (w) = true; CBS is normal in relay world
5. $IBT_{PLC,Relay}$ CBS; relay tells PLC that CBS is normal and PLC believes it
6. w $\models V_{CBS}^{PLC}$ (w) = true; CBS is normal in PLC world
7. $IBT_{Stuxnet,PLC}$ CBS; Stuxnet intercepts the normal CBS sent by PLC to CS
8. $\sim CBS$ = true; The Stuxnet changes the CBS status as closed from open
9. w $\models V_{\sim CBS}^{Stuxnet}$ (w) = true; The Stuxnet knows that it has altered the CBS from its original status
10. $IBT_{CS,Stuxnet}$ CBS; The Stuxnet reports the CS that the CBS is open and it is normal
11. w $\models V_{\sim CBS}^{CS}$ (w) = false; CS does not know that CBS is not normal
12. RR = true; RR is normal
13. w $\models V_{RR}^{Relay}$ (w) = true; RR is normal in relay world
14. $IBT_{PLC,Relay}RR$; relay tells PLC that RR is normal and PLC believes it
15. w $\models V_{RR}^{PLC}$ (w) = true; RR is normal in PLC world

16. $IBT_{CS,PLC}RR$; PLC tells CS that RR is normal and CS believes it

17. w $\models V_{RR}^{CS}$ (w) = true; RR is normal in CS world

18. $Proj_{fR}(RR) = fR, \sim iCBClosedCheck \implies \sim CBS$; when the invariant $iCBClosedCheck$ fails, CS deduces that CBS is not normal

19. w $\models V_{\sim CBS}^{CS}$ (w) = true; CS world now has deduced that CBS is abnormal

20. $S^{"}$ = $(S_{iCBClosedCheck}, S_{CBS})$; System is working normally if and only if $S^{"}$ is true

21. ~MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[\,(S^{"} \oplus S_{\sim CBS})\,] \wedge [\,\mathrm{w} \models (\exists\, V_{\sim CBS}^{CBS}(\mathrm{w}) \wedge \nexists\, V_{CBS}^{CS}(\mathrm{w}))\,]$

When the CB is closed, the fR should not be zero, if fR is zero then that indicates that the CBS at the CS is not correct. Hence, the system is no longer MSDND secure. This is demonstrated in Figure 6.9. This theorem can be used to break twelve MSDND secure paths in the system out of the fifteen as shown in Table 6.4. The three CB Q1-1, Q1-2 and Q2 does not have a relay or a smart meter next to them to validate their state through this invariant.

Note: For the circuit breaker Q2A there are no relays next to it, we make use of the frequency reading from the AMI in the invariant $iCBClosedCheck$ instead of fR. □

Theorem 10. *The Circuit breaker state CBS is not MSDND secure at the CS when the CB is closed but SCADA shows it as open if the invariant is taken into consideration.*

Proof. Let us assume that the relay reading RR is correct. Let fR be the frequency reading from the relay. Let the invariant $iCBOpenCheck : CBS == open\ and\ fR = 0$ be in the CS

1. CBS = true; CBS is normal and its value is closed

2. w $\models V_{CBS}^{CB}$ (w) = true; CBS is normal in CB world

Table 6.4. Summary of MSDND analysis for CBS information path

S.No.	MSDND Secure Paths	Invariant Available
1	Q1→GIED1→GPLC→CPLC→CS	Yes
2	Q1A→GIED2→GPLC→CPLC→CS	Yes
3	Q1-1→GPLC→CPLC→CS	No
4	Q1-2→GPLC→CPLC→CS	No
5	Q2→MPLC→CPLC→CS	No
6	Q2A→MPLC→CPLC→CS	Yes
7	Q2B→MIED1→MPLC→CPLC→CS	Yes
8	Q2C→MIED2→MPLC→CPLC→CS	Yes
9	Q1-3→TIED1→TPLC→CPLC→CS	Yes
10	Q3→TIED2→TPLC→CPLC→CS	Yes
11	Q2-1→TIED4→TPLC→CPLC→CS	Yes
12	Q3-4→SIED1→SPLC→CPLC→CS	Yes
13	Q3-3→SIED2→SPLC→CPLC→CS	Yes
14	Q3-2→SIED3→SPLC→CPLC→CS	Yes
15	Q3-1→SIED4→SPLC→CPLC→CS	Yes

3. $IBT_{Relay,CB}$ CBS; CB tells relay that CBS is normal and relay believes it

4. w $\models$ V_{CBS}^{Relay} (w) = true; CBS is normal in relay world

5. $IBT_{PLC,Relay}$ CBS; relay tells PLC that CBS is normal and PLC believes it

6. w $\models$ V_{CBS}^{PLC} (w) = true; CBS is normal in PLC world

7. $IBT_{Stuxnet,PLC}$ CBS; Stuxnet intercepts the normal CBS sent by PLC to CS

8. $\sim CBS$ = true; The Stuxnet changes the CBS status as open from closed

9. w $\models$ $V_{\sim CBS}^{Stuxnet}$ (w) = true; The Stuxnet knows that it has altered the CBS from its original status

10. $IBT_{CS,Stuxnet}$ CBS; The Stuxnet reports the CS that the CBS is closed and CBS is normal

11. w $\models V^{CS}_{\sim CBS}$ (w) = false; CS does not know that CBS is not normal

12. RR = true; RR is normal

13. w $\models V^{Relay}_{RR}$ (w) = true; RR is normal in relay world

14. $IBT_{PLC,Relay}RR$; relay tells PLC that RR is normal and PLC believes it

15. w $\models V^{PLC}_{RR}$ (w) = true; RR is normal in PLC world

16. $IBT_{CS,PLC}RR$; PLC tells CS that RR is normal and CS believes it

17. w $\models V^{CS}_{RR}$ (w) = true; RR is normal in CS world

18. $Proj_{fR}(RR) = fR, \sim iCBOpenCheck \implies \sim CBS$; when the invariant $iCBOpenCheck$ fails, CS deduces that CBS is not normal

19. w $\models V^{CS}_{\sim CBS}$ (w) = true; CS world now has deduced that CBS is abnormal

20. S'' = $(S_{invariant}, S_{CBS})$; System is working normally if and only if S'' is true

21. ~MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[\,(\,S'' \oplus S_{\sim CBS}\,)\,] \;\wedge\; [\,\mathrm{w} \models (\,\exists\, V^{CBS}_{\sim CBS}(\mathrm{w}) \;\wedge\; \nexists\, V^{CS}_{CBS}(\mathrm{w})\,)\,]$

When the CB is open, the fR should be zero; if fR is not zero, then that indicates that the CBS at the CS is not correct and it is actually closed. Hence the system is no longer MSDND secure. This is demonstrated in Figure 6.9. This theorem can be used to break twelve MSDND secure paths in the system out of the fifteen as shown in Table 6.4. The three CB Q1-1, Q1-2 and Q2 does not have a relay or a smart meter next to them to validate their state through this invariant.

Note: For the circuit breaker Q2A there are no relays next to it, we make use of the frequency reading from the AMI in the invariant $iCBOpenCheck$ instead of fR. □

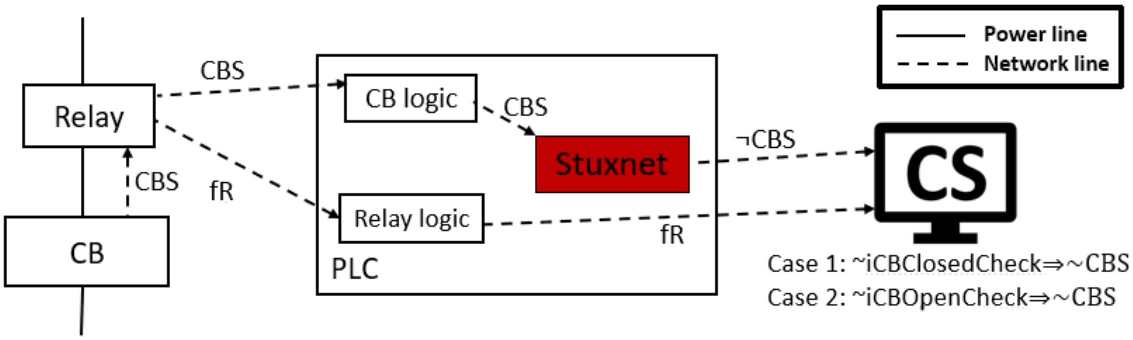


Figure 6.9. Information flow when CBS is abnormal but SCADA shows the inverse of it, and invariant is considered. Attack model for this is explained in Theorem 8, attack detection when CB is originally open is explained in Theorem 9, and attack detection when CB is originally closed is explained in Theorem 10.

Analysis of vulnerability in CBS and RR information path.

Theorem 11. *The Circuit breaker status CBS and the relay reading RR are MSDND secure at the CS when the CS commands the CB to open but CB is closed and also when the CS commands the CB to close but CB is open.*

Proof. Let CBC represent the command sent by the CS to the CB.

1. CBC = true; CBC is normal

2. w $\models V^{CS}_{CBC}$ (w) = true; CBC is normal in CS world

3. $IBT_{PLC,CS}$ CBC; CS sends CBC to PLC and PLC believes it

4. w $\models V^{PLC}_{CBC}$ (w) = true; CBC is true in PLC world

5. $IBT_{Stuxnet,PLC}$ CBC; Stuxnet intercepts the normal CBC sent by PLC to relay

6. $\sim CBC$ = true; The Stuxnet reverses the CBC

7. w $\models V^{Stuxnet}_{\sim CBC}$ (w) = true; The Stuxnet knows that the CBC is not correct

8. $IBT_{Relay,Stuxnet}$ CBC; The Stuxnet reports the Relay that CBC is normal and Relay believes it

9. w $\models V^{Relay}_{\sim CBC}$ (w) = false; relay does not know that CBC is abnormal

10. $IBT_{CB,Relay}$ CBC; relay sends CBC to CB and CB believes it to be normal

11. w $\models V^{CB}_{\sim CBC}$ (w) = false; CB does not know that CBC is abnormal

12. $\sim CBC \implies \sim CBS, \sim RR$; When the CBC is not normal then even the CBS and RR will not be normal

13. $\sim CBS, \sim RR$ = true; CBS and RR are not normal

14. w $\models V^{Relay}_{\sim CBS, \sim RR}$ (w) = true; CBS and RR are not normal in relay world

15. $IBT_{Stuxnet,Relay}$ $\sim CBS, \sim RR$; Stuxnet intercepts the abnormal CBS and RR sent by relay to PLC

16. w $\models V^{Stuxnet}_{\sim CBS, \sim RR}$ (w) = true; Stuxnet knows that CBS and RR are abnormal

17. $IBT_{PLC,Stuxnet}$ CBS, RR; The Stuxnet changes the CBS and RR values and tells the PLC that it is normal

18. w $\models V^{PLC}_{\sim CBS, \sim RR}$ (w) = false; CBS and RR are abnormal but in PLC world it appears normal

19. $IBT_{CS,PLC}$ CBS, RR; PLC tells CS that CBS and RR are normal and CS believes that

20. w $\models V^{CS}_{CBS,RR}$ (w) = true; In the CS world CBS and RR are true

21. MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[\,(S_{CBS,RR} \oplus S_{\sim CBS,RR})\,] \wedge [\,\mathrm{w} \models (\nexists\, V^{CS}_{\sim CBS,RR}(\mathrm{w}) \wedge \nexists\, V^{CS}_{CBS,RR}(\mathrm{w}))\,]$

The Stuxnet reverses the actual CB command CBC sent from the CS and then sends false positive RR and CBS to the CS. it is not possible to deduce at the CS whether the CBS and RR are correct or not. Thus, the system is MSDND secure. There are thirty such MSDND secure paths in the system, fifteen when the CS instructs open but CB is closed, and fifteen when the CS instructs closed but CB is open. There are two possible cases for each of the listed paths in Table 6.4. □

Theorem 12. *The Circuit breaker status CBS and the relay reading RR are not MSDND secure at the CS when the CS commands the CB to open but CB is closed if the invariants are considered.*

Proof. Let us assume that the frequency reading f from the AMI is correct. Let fR be the frequency reading in RR and let the invariant $iCBRROpen : CBS == open\ and\ f == 0\ and\ f == fR$ be the invariant in the CS.

1. CBC = true; CBC is normal
2. w $\models V^{CS}_{CBC}$ (w) = true; CBC is normal in CS world
3. $IBT_{PLC,CS}$ CBC; CS sends CBC to PLC and PLC believes it
4. w $\models V^{PLC}_{CBC}$ (w) = true; CBC is true in PLC world
5. $IBT_{Stuxnet,PLC}$ CBC; Stuxnet intercepts the normal CBC sent by PLC to relay
6. $\sim CBC$ = true; The Stuxnet reverses the CBC
7. w $\models V^{Stuxnet}_{\sim CBC}$ (w) = true; The Stuxnet knows that the CBC is not correct
8. $IBT_{Relay,Stuxnet}$ CBC; The Stuxnet reports the Relay that CBC is normal and Relay believes it
9. w $\models V^{Relay}_{\sim CBC}$ (w) = false; relay does not know that CBC is abnormal

10. $IBT_{CB,Relay}$ CBC; relay sends CBC to CB and CB believes it to be normal, here CBC=open

11. w $\models V^{CB}_{\sim CBC}$ (w) = false; CB does not know that CBC is abnormal

12. $\sim CBC \implies \sim CBS, \sim RR$; When the CBC is not normal then even the CBS and RR will not be normal

13. $\sim CBS, \sim RR$ = true; CBS and RR are not normal

14. w $\models V^{Relay}_{\sim CBS,\sim RR}$ (w) = true; CBS and RR are not normal in relay world

15. $IBT_{Stuxnet,Relay}$ $\sim CBS, \sim RR$; Stuxnet intercepts the abnormal CBS and RR sent by relay to PLC

16. w $\models V^{Stuxnet}_{\sim CBS,\sim RR}$ (w) = true; Stuxnet knows that CBS and RR are abnormal

17. $IBT_{PLC,Stuxnet}$ CBS, RR; The Stuxnet changes the CBS and RR values and tells the PLC that it is normal

18. w $\models V^{PLC}_{\sim CBS,\sim RR}$ (w) = false; CBS and RR are abnormal but in PLC world it appears normal

19. $IBT_{CS,PLC}$ CBS, RR; PLC tells CS that CBS and RR are normal and CS believes that

20. w $\models V^{CS}_{CBS,RR}$ (w) = true; In the CS world CBS and RR are true

21. $\sim CBS \implies \sim f$; as CBS is not normal, the AMI readings are also not normal

22. $IBT_{CS,AMI}$ $\sim f$; We obtain the frequency reading from the AMI at the CS

23. w $\models V^{CS}_{\sim f}$ (w) = true; f is not normal in CS world

24. $Proj_{fR}$(RR)=fR;

25. $\sim iCBRROpen \implies \sim CBS, \sim RR$; when the invariant $iCBRROpen$ fails, CS deduces that CBS and RR are not normal

26. w $\models V^{CS}_{\sim CBS,\sim RR}$ (w) = true; CS world now has deduced that CBS and RR are not normal

27. $S^{''}$ = ($S_{iCBRROpen}$, $S_{CBS,RR}$) ; System is working normally if and only if $S^{''}$ is true

28. ~MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[(S^{''} \oplus S_{\sim CBS,RR})] \wedge [$w $\models (\exists V^{CS}_{\sim CBS,RR}(\text{w}) \wedge \nexists V^{CS}_{CBS,RR}(\text{w}))]$

If the CB is open, then f should be zero; if the RR is true, then it should match with the corresponding AMI reading. When this is not true, we can deduce that the RR and the CBS at the CS are incorrect as shown in Figure 6.10. This invariant can be used to break eleven out of the fifteen MSDND secure paths. The four circuit breakers Q1-1, Q1-2, Q2 and Q2A does not have a relay next to them to validate their state through the invariant $iCBRROpen$. The paths that are broken in Table 6.4 holds, but the line item 6 involving Q2A does not have an invariant. □

Theorem 13. *The Circuit breaker status CBS and the relay reading RR are not MSDND secure at the CS when the CS commands the CB to close but CB is open if the invariants are considered.*

Proof. Let us assume that the frequency reading f from the AMI is correct. Let fR be the frequency reading in RR and let the invariant $iCBRRClose : CBS == closed\ and\ f \neq 0\ and\ f == fR$ be the invariant in the CS.

1. CBC = true; CBC is normal

2. w $\models V^{CS}_{CBC}$ (w) = true; CBC is normal in CS world

3. $IBT_{PLC,CS}$ CBC; CS sends CBC to PLC and PLC believes it

4. w $\models V^{PLC}_{CBC}$ (w) = true; CBC is true in PLC world

5. $IBT_{Stuxnet,PLC}$ CBC; Stuxnet intercepts the normal CBC sent by PLC to relay

6. $\sim CBC$ = true; The Stuxnet reverses the CBC

7. w $\models V^{Stuxnet}_{\sim CBC}$ (w) = true; The Stuxnet knows that the CBC is not correct

8. $IBT_{Relay,Stuxnet}$ CBC; The Stuxnet reports the Relay that CBC is normal and Relay believes it

9. w $\models V^{Relay}_{\sim CBC}$ (w) = false; relay does not know that CBC is abnormal

10. $IBT_{CB,Relay}$ CBC; relay sends CBC to CB and CB believes it to be normal, here CBC=open

11. w $\models V^{CB}_{\sim CBC}$ (w) = false; CB does not know that CBC is abnormal

12. $\sim CBC \implies \sim CBS, \sim RR$; When the CBC is not normal then even the CBS and RR will not be normal

13. $\sim CBS, \sim RR$ = true; CBS and RR are not normal

14. w $\models V^{Relay}_{\sim CBS,\sim RR}$ (w) = true; CBS and RR are not normal in relay world

15. $IBT_{Stuxnet,Relay}$ $\sim CBS, \sim RR$; Stuxnet intercepts the abnormal CBS and RR sent by relay to PLC

16. w $\models V^{Stuxnet}_{\sim CBS,\sim RR}$ (w) = true; Stuxnet knows that CBS and RR are abnormal

17. $IBT_{PLC,Stuxnet}$ CBS, RR; The Stuxnet changes the CBS and RR values and tells the PLC that it is normal

18. w $\models V^{PLC}_{\sim CBS,\sim RR}$ (w) = false; CBS and RR are abnormal but in PLC world it appears normal

19. $IBT_{CS,PLC}$ CBS, RR; PLC tells CS that CBS and RR are normal and CS believes that

20. w $\models V^{CS}_{CBS,RR}$ (w) = true; In the CS world CBS and RR are true

21. $\sim CBS \Longrightarrow \sim f$; as CBS is not normal, the AMI readings are also not normal

22. $IBT_{CS,AMI} \sim f$; We obtain the frequency reading from the AMI at the CS

23. w $\models V^{CS}_{\sim f}$ (w) = true; f is not normal in CS world

24. $Proj_{fR}$(RR)=fR;

25. $\sim iCBRRClose \Longrightarrow \sim CBS$, $\sim RR$; when the invariant $iCBRRClose$ fails, CS deduces that CBS and RR are not normal

26. w $\models V^{CS}_{\sim CBS,RR}$ (w) = true; CS world now has deduced that CBS and RR are abnormal

27. $S^{''}$ = ($S_{iCBRRClose}$, $S_{CBS,RR}$) ; System is working normally if and only if $S^{''}$ is true

28. ~MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[(S^{''} \oplus S_{\sim CBS,RR})]$ $\wedge$ $[$w $\models$ $(\exists\, V^{CS}_{\sim CBS,RR}(w)$ $\wedge$ $\nexists$ $V^{CS}_{CBS,RR}($w$))]$

If the CB is closed, then f should not be zero; if the RR is true, then it should match with the corresponding AMI reading. When this is not true, we can deduce that the RR and the CBS at the CS are incorrect as shown in Figure 6.10. This invariant can be used to break eleven out of the fifteen MSDND secure paths. The four circuit breakers Q1-1, Q1-2, Q2 and Q2A does not have a relay next to them to validate their state through the invariant $iCBRRClose$. The paths that are broken in Table 6.4 holds, but the line item 6 involving Q2A does not have an invariant. □

- **Multi-point attacks**

Analysis of vulnerability in RPM and RR information path.

Theorem 14. *The RPM reading RPM from VSD and the relay readings RR from the relay are MSDND secure at the Control System (CS) when RPM and RR are not normal but the readings are normal.*

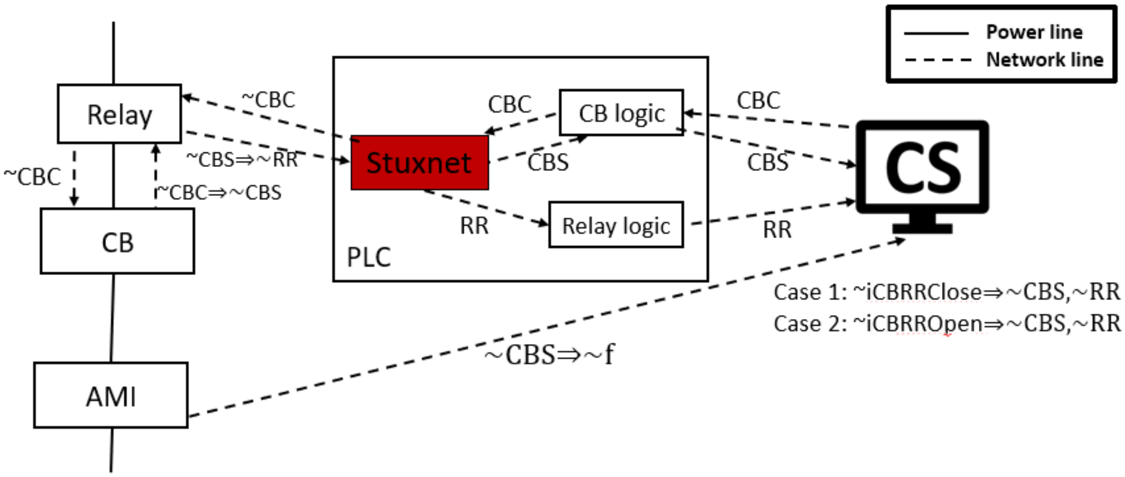


Figure 6.10. Information flow when CBS and RR are abnormal, and invariant is considered. Attack model for this is explained in Theorem 11, attack detection when CB is originally closed is explained in Theorem 12, and attack detection when CB is originally open is explained in Theorem 13.

Proof. Here the RPM reading from VSD and the relay readings (current, voltage, frequency) RR from the relay are incorrect at the CS. This is a multi-point attack and there are two Stuxnets involved. One executes at the MPLC and corrupts the RR sent to the CS, the other executes at the SPLC and corrupts the RPM reading sent to the CS.

1. $\sim RPM$ = true; The RPM is not normal
2. w $\models V^{VSD}_{\sim RPM}$ (w) = true; RPM is not normal in VSD world
3. $IBT_{Stuxnet,VSD}\ \sim RPM$; Stuxnet intercepts the abnormal RPM sent by VSD to SPLC
4. w $\models V^{Stuxnet}_{\sim RPM}$ (w) = true; Stuxnet observes that RPM is abnormal
5. $IBT_{SPLC,Stuxnet}\ RPM$; Stuxnet modifies RPM to make it look normal and transmits it to SPLC and SPLC believes it
6. w $\models V^{SPLC}_{RPM}$ (w) = true; RPM looks normal in SPLC world
7. $IBT_{CPLC,SPLC}\ RPM$; SPLC tells CPLC that RPM is normal and CPLC believes it

8. w $\models V_{RPM}^{CPLC}$ (w) = true; RPM looks normal in CPLC world

9. $IBT_{CS,CPLC}$ RPM; CPLC tells CS that RPM is normal and CS believes it

10. w $\models V_{RPM}^{CS}$ (w) = true; CS believes that RPM is normal

11. $\sim RR$ = true; RPM is not normal so the RR is also not normal

12. w $\models V_{\sim RR}^{Relay}$ (w) = true; RR is not normal in relay world

13. $IBT_{Stuxnet,Relay}$ $\sim RR$; Stuxnet intercepts the abnormal RR sent by relay to MPLC

14. w $\models V_{\sim RR}^{Stuxnet}$ (w) = true; Stuxnet observes that RR is abnormal

15. $IBT_{MPLC,Stuxnet}$ RR; Stuxnet modifies RR to make it look normal and transmits it to MPLC and MPLC believes it

16. w $\models V_{RR}^{MPLC}$ (w) = true; RR appears normal in MPLC world

17. $IBT_{CPLC,MPLC}$ RR; MPLC tells CPLC that RR is normal and CPLC believes it

18. w $\models V_{RR}^{CPLC}$ (w) = true; RR is normal in $CPLC$ world

19. $IBT_{CS,CPLC}$ RR; CPLC tells CS that RR is normal and CS believes it

20. w $\models V_{RR}^{CS}$ (w) = true; CS observes RR to be normal

21. $S = (S_{RPM}, S_{RR})$; S is a world where RR and RPM are normal

22. $S'' = (S_{\sim RPM}, S_{\sim RR})$; S'' is a world where RR and RPM are abnormal

23. MSDND(ES): $\exists$ w $\in$ W $\vdash [(S \oplus S'')] \wedge [\mathrm{w} \models (\nexists V_{\sim RPM}^{CS}(\mathrm{w}) \wedge \nexists V_{RPM}^{CS}(\mathrm{w}) \wedge \nexists V_{\sim RR}^{CS}(\mathrm{w}) \wedge \nexists V_{RR}^{CS}(\mathrm{w}))]$

The CS believes the false RPM reading reported by the Stuxnet and the false positive RR reading reported by the other Stuxnet. Therefore, RPM information and RR are MSDND secure at the CS. There are three such MSDND secure paths in the system as shown in Table 6.5. □

Table 6.5. Summary of MSDND analysis for RPM and RR information path

S.No.	MSDND Secure Paths	Invariant Available
1	VSD1→SPLC→CPLC→CS and MIED2→MPLC→CPLC→CS	Yes
2	VSD2→SPLC→CPLC→CS and MIED1→MPLC→CPLC→CS	Yes
3	VSD3→SPLC→CPLC→CS and GIED2→GPLC→CPLC→CS	Yes

Theorem 15. *The RPM reading RPM from VSD and the Relay Reading RR from the relay are not MSDND secure at the Control System (CS) when RPM and RR are not normal but the readings at CS are normal when the invariants are considered.*

Proof. Let us assume the frequency reading f from the AMI is correct. Let fR be the frequency reading from the relay. Let the invariant $iRPM$: $RPM = 30f$ and iF: $f == fR$ be in the control system.

1. $\sim RPM$ = true; The RPM is not normal

2. w $\models V^{VSD}_{\sim RPM}$ (w) = true; RPM is not normal in VSD world

3. $IBT_{Stuxnet,VSD}$ $\sim RPM$; Stuxnet intercepts the abnormal RPM sent by VSD to SPLC

4. w $\models V^{Stuxnet}_{\sim RPM}$ (w) = true; Stuxnet observes that RPM is abnormal

5. $IBT_{SPLC,Stuxnet}$ RPM; Stuxnet modifies RPM to make it look normal and transmits it to SPLC and SPLC believes it

6. w $\models V^{SPLC}_{RPM}$ (w) = true; RPM looks normal in SPLC world

7. $IBT_{CPLC,SPLC}$ RPM; SPLC tells CPLC that RPM is normal and CPLC believes it

8. w $\models V^{CPLC}_{RPM}$ (w) = true; RPM looks normal in CPLC world

9. $IBT_{CS,CPLC}$ RPM; CPLC tells CS that RPM is normal and CS believes it

10. w $\models V^{CS}_{RPM}$ (w) = true; CS believes that RPM is normal

11. $\sim RR$ = true; As RPM is not normal in the VSD world, it affects the RR in the link below it and hence RR is not normal

12. w $\models V^{Relay}_{\sim RR}$ (w) = true; RR is not normal in relay world

13. $IBT_{Stuxnet,Relay}$ $\sim RR$; Stuxnet intercepts the abnormal RR sent by relay to MPLC

14. w $\models V^{Stuxnet}_{\sim RR}$ (w) = true; Stuxnet observes that RR is abnormal

15. $IBT_{MPLC,Stuxnet}$ RR; Stuxnet modifies RR to make it look normal and transmits it to MPLC and MPLC believes it

16. w $\models V^{MPLC}_{RR}$ (w) = true; RR appears normal in MPLC world

17. $IBT_{CPLC,MPLC}$ RR; MPLC tells CPLC that RR is normal and CPLC believes it

18. w $\models V^{CPLC}_{RR}$ (w) = true; RR is normal in $CPLC$ world

19. $IBT_{CS,CPLC}$ RR; CPLC tells CS that RR is normal and CS believes it

20. w $\models V^{CS}_{RR}$ (w) = true; CS observes RR to be normal

21. $S = (S_{RPM}, S_{RR})$; S is a world where RR and RPM are normal

22. $S^{"} = (S_{\sim RPM}, S_{\sim RR})$; $S^{"}$ is a world where RR and RPM are abnormal

23. $\sim RPM \implies \sim f$; as RPM is not normal, the AMI readings are also not normal

24. $IBT_{CS,AMI} \sim f$; CS obtains the f reading from smart meter and believes it

25. $\sim iRPM \implies \sim RPM$; from the assumption that the frequency reading f from the AMI is correct and the invariant $iRPM$, the CS deduces that RPM is not normal

26. w $\models V^{CS}_{\sim RPM}$ (w) = true; CS now has deduced that RPM is abnormal

27. From (2.1), $Proj_{fR}(RR) = fR$, $\sim iF \implies \sim RR$; from the assumption that the frequency reading f from the AMI is correct and the invariant iF, the CS finds that RR is abnormal

28. w $\models V^{CS}_{\sim RR}$ (w) = true; CS now has valuation function to know that RR is not normal

29. $S_{invariant}$ = (S_{iRPM}, S_{iF}); Defining a world with invariants

30. S^1 = ($S_{invariant}$, S) ; System is working normally if and if only S^1 is true

31. ~MSDND(ES): $\exists$ w $\in$ W $\vdash$ $[\,(S^1 \oplus S^{"})\,] \wedge [\,\mathrm{w} \models (\exists\, V^{CS}_{\sim RPM}(\mathrm{w}) \wedge \nexists\, V^{CS}_{RPM}(\mathrm{w}) \wedge \exists\, V^{CS}_{\sim RR}(\mathrm{w}) \wedge \nexists\, V^{CS}_{RR}(\mathrm{w})\,)\,]$

The system is not MSDND secure as we have a valuation function for abnormal working of the system and hence fault/threat can be detected as shown in Figure 6.11. This proof can be applied to break all the three MSDND secure paths listed in Table 6.5. □

6.2. DATA-CENTRIC APPROACH

6.2.1. Data. The data collected from the EPIC testbed over a period of two weeks is used to carry out the analyses. Data is extracted from a SCADA system using the Historian. The SCADA system contains the readings from eleven relays that have voltage, current, frequency and power readings as shown in Figure 6.12. Other readings, for example, the circuit breaker statuses and status about the three motors like the flags set, rotation per minute, and statuses, are also included in the SCADA system. In total, there are around two hundred and ninety different variables from the SCADA system, and the sampling rate for collecting the data is ten seconds.

There are two different types of data in the EPIC dataset:

1. Numeric data- frequency, voltage, current, power, rpm

2. Binary data- circuit breaker on/off status, trip status, relay on/off state

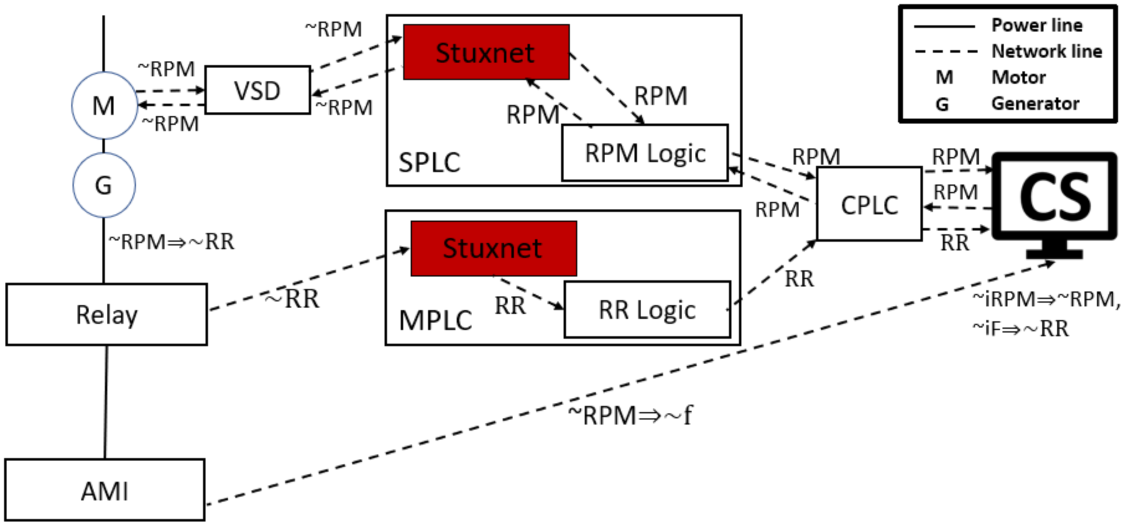
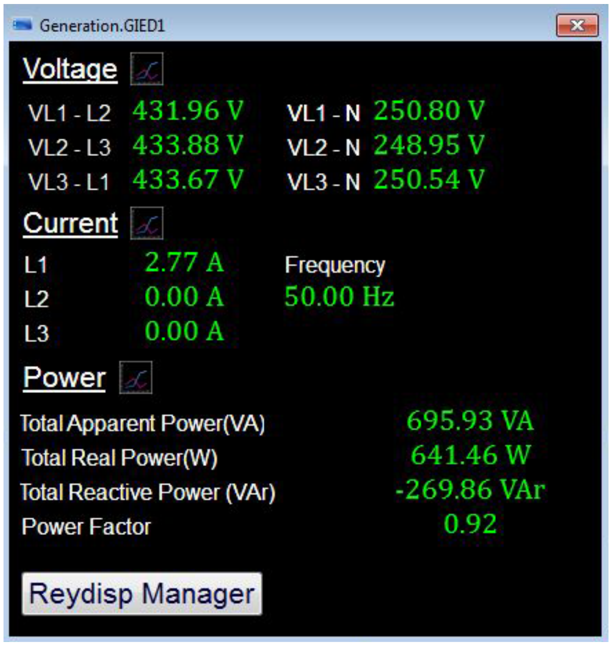


Figure 6.11. Information flow when RPM and RR are actually abnormal and invariant is considered. Attack model for this is explained in Theorem 14. Attack detection is explained in Theorem 15.

6.2.2. Invariant Generation using Linear Regression. Figure 6.13 shows the variation of the fourteen variables of the relay GIED1 over a six-hour period. From this figure, it is understood that certain variables vary relative to one and another and there exists a strong linear relationship between certain variables. Throughout a power grid, several variables are linearly related to each other, which is why linear regression would be a suitable approach for generating invariants.

The binary data and the smart meter readings from the AMI were removed from the processed dataset, because binary data like the breaker status would not make a valid field for the linear regression algorithm. Linear regression was applied to the remaining one hundred and fifty-two numeric data values of EPIC to derive mathematical relations between them. The very high coefficient of determination (R^2) of the prediction was set for deriving invariants using linear regression for a higher accuracy. An R^2 score of .99 out of



Voltage

VL1 - L2 431.96 V VL1 - N 250.80 V
VL2 - L3 433.88 V VL2 - N 248.95 V
VL3 - L1 433.67 V VL3 - N 250.54 V

Current

L1 2.77 A Frequency
L2 0.00 A 50.00 Hz
L3 0.00 A

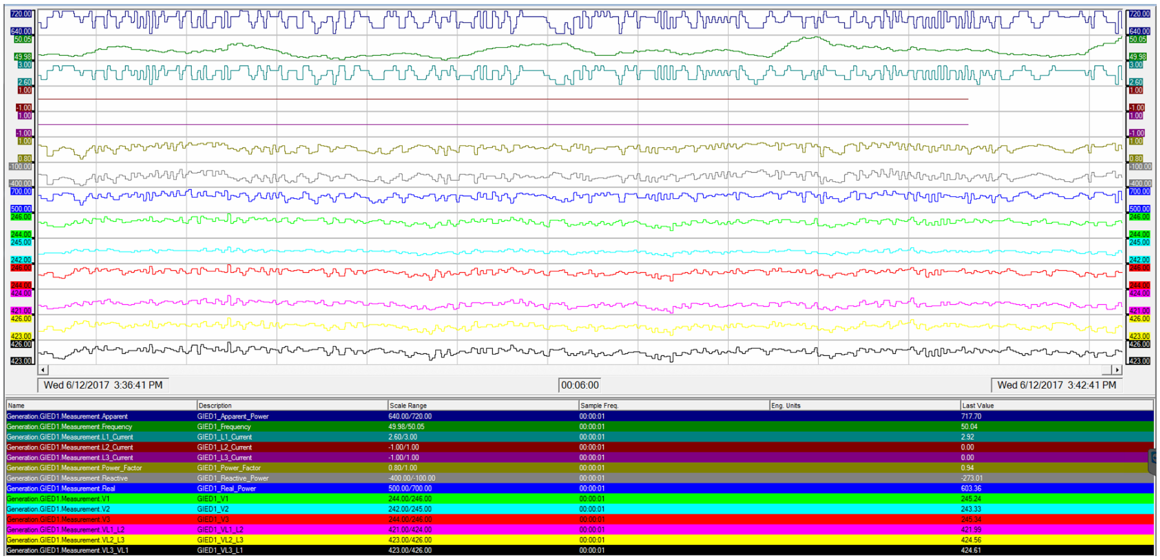
Power

Total Apparent Power(VA)	695.93 VA
Total Real Power(W)	641.46 W
Total Reactive Power (VAr)	-269.86 VAr
Power Factor	0.92

Figure 6.12. Reading from the Relay GIED1

1 was set for deriving invariants. The algorithm would then run through each column and determine the mathematical relation of the form $A = x \times B$, where A and B are column names and x is a constant.

Care was taken to avoid duplicate invariants by considering only the upper triangular matrix of the data frame while generating invariants. The fields A and B were rearranged in such a way while generating invariants that x was greater than 1. This was done to avoid generating the invariant $\frac{A1}{B1} = 2$ and $\frac{B1}{A1} = 0.5$ differently, which would make the grouping of invariants tedious. Filtering was done to remove the invariant relation between different devices like frequency of relay1 with voltage of relay2 because one of them can be closed and the other can be in open state and that time the relation might still hold just because one of them is zero, which would not actually make sense. For an R^2 score of .99, a total of 215 invariants were generated and 199 of them were categorized into nine types based on electrical equations that obey the law of physics. The nine types of invariants are as follows:



Name	Description	Scale Range	Sample Freq.	Eng. Units	Last Value
Generation.GIED1.Measurement.Apparent	GIED1_Apparent_Power	640.00/720.00	00:00:01		717.70
Generation.GIED1.Measurement.Frequency	GIED1_Frequency	49.98/50.05	00:00:01		50.04
Generation.GIED1.Measurement.L1_Current	GIED1_L1_Current	2.60/3.00	00:00:01		2.92
Generation.GIED1.Measurement.L2_Current	GIED1_L2_Current	-1.00/1.00	00:00:01		0.00
Generation.GIED1.Measurement.L3_Current	GIED1_L3_Current	-1.00/1.00	00:00:01		0.00
Generation.GIED1.Measurement.Power_Factor	GIED1_Power_Factor	0.80/1.00	00:00:01		0.94
Generation.GIED1.Measurement.Reactive	GIED1_Reactive_Power	-400.00/-100.00	00:00:01		-273.01
Generation.GIED1.Measurement.Real	GIED1_Real_Power	500.00/700.00	00:00:01		603.36
Generation.GIED1.Measurement.V1	GIED1_V1	244.00/246.00	00:00:01		245.24
Generation.GIED1.Measurement.V2	GIED1_V2	242.00/245.00	00:00:01		243.33
Generation.GIED1.Measurement.V3	GIED1_V3	244.00/246.00	00:00:01		245.34
Generation.GIED1.Measurement.VL1_L2	GIED1_VL1_L2	421.00/424.00	00:00:01		421.99
Generation.GIED1.Measurement.VL2_L3	GIED1_VL2_L3	423.00/426.00	00:00:01		424.56
Generation.GIED1.Measurement.VL3_VL1	GIED1_VL3_L1	423.00/426.00	00:00:01		424.61

Figure 6.13. Variation of the Relay GIED1 Variables over Six Hours

Type 1. The Type 1 invariant is based on the power triangle shown in Figure 6.14. Nine invariants were generated, and they were of the following format:

$$x = Sec\theta = A/B = \frac{Apparentpower}{Realpower}$$

From these nine invariants, it was found that the impedance angle θ of the EPIC system was around $-12°$. A sample invariant from this type is of the form:

$$\frac{SIED2.Measurement.Apparent}{SIED2.Measurement.Active} = 1.000016576$$

Type 2. The Type 2 invariant is based on the electrical relation between line to line voltage (V_{LL}) and line to neutral voltage (V_{LN}) in a three-phase AC circuit, which is given by the equation:

$$V_{LL} = \sqrt{3} \times V_{LN}$$

There is a total of eighty-one invariants of this form, and a sample invariant from this stage is of the form:

$$TIED2.Measurement.VL3\_VL1 = 1.732599711 \times TIED2.Measurement.V1$$

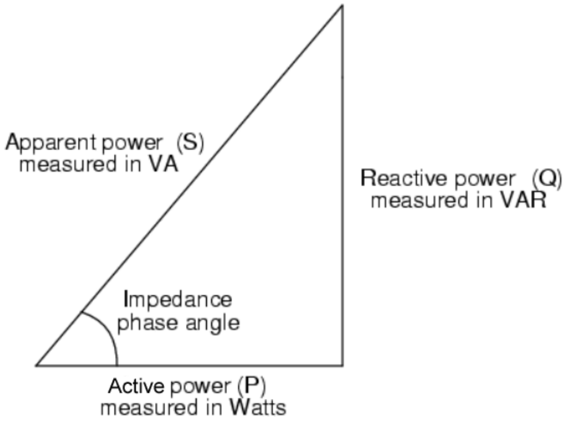


Figure 6.14. The Power Triangle Relating Apparent Power to Active (Real) Power and Reactive Power

Type 3. The Type 3 invariant is based on the relation between the RPM and the line to line voltage (V_{LL}). There is no generic equation in physics available for this relation, but for EPIC it is defined by the equation:

$$RPM = k \times V_{LL}$$

where k is a constant and is different for different circuits. Nine invariants were generated in this type, and here is a sample invariant:

$$VSD1.ActualSpeed = 3.545424313 \times MIED2.Measurement.VL2\_L3$$

Type 4. The Type 4 invariant defines a relation between the frequency and the line to neutral voltage. There is no formally defined equation available for this relation, but a large number of invariants (twenty-four) were generated for the EPIC system with a more or less same constant, which validates this invariant with respect to this system. The average constant was found to be 4.85. The invariant in this type would appear as follows:

$$TIED2.Measurement.V1 = 4.76740974 \times TIED2.Measurement.Frequency$$

Type 5. The Type 5 invariant is similar to the Type 3 invariant and is a relation between the RPM and the line to neutral voltage (V_{LN}). It also satisfies the equation specified in the Type 2 invariant. The k value in this relation is $\sqrt{3}$ times the k value in Type 3. Just like Type 3, nine invariants are generated for this type. Below is a sample invariant:

$$VSD2.ActualSpeed = 6.182578696 \times MIED1.Measurement.V2$$

Type 6. The Type 6 invariant is similar to the Type 4 invariant and is a relation between the frequency and the line to line voltage (V_{LN}). This obeys the Type 2 relation; the k value in this relation is $\sqrt{3}$ times the k value in Type 4, and the average k value is 8.401. There are twenty-four invariants generated in this type and an invariant of this type would appear as follows:

$$TIED4.Measurement.VL2\_L3 = 8.464169799 \times TIED4.Measurement.Frequency$$

Type 7. The Type 7 invariant is based on a defined electrical relation between the RPM and the frequency. As per law of physics, the RPM of the system is given by:

$$RPM = \tfrac{120 \times F}{P}$$

Here F is the frequency and P is the number of poles in the motor. The motor used in the EPIC system has 4 poles, so this makes the above equation as follows:

$$RPM = 30 \times F$$

Three invariants were generated, one for each motor, and they were found to accurately match the above equation. Below is a sample invariant of this type:

$$VSD3.ActualSpeed = 30 \times GIED2.Measurement.Frequency$$

Type 8 and Type 9. The Type 8 and 9 invariants are based on the similarity between the impedance and the resistance in the EPIC system. The Active power is given by:

$$ActivePower = I^2 \times R$$

Here I is the current and R is the resistance. The apparent power is given by:

$$ApparentPower = I^2 \times Z$$

Here Z is the magnitude of the impedance of the system. There are forty invariants generated for Type 8 and 9.

The sample invariants of Type 8 and 9 are of the form:

$$\frac{SIED2.Measurement.Real}{SIED2.Measurement.L3\_Current} = 722.1180407$$

$$\frac{SIED2.Measurement.Apparent}{SIED2.Measurement.L3\_Current} = 722.1486546$$

7. RESULTS

7.1. DESIGN-CENTRIC APPROACH

More than one hundred information paths were analyzed in the EPIC testbed, and eighty-nine information paths were found to be MSDND secure. Whenever an information path is MSDND secure it is bad for the system because the operator will not have any valuation function to identify that the system is in a corrupt state. The fewer the MSDND secure paths, the better it is for the system. Invariants were used to break as many as seventy-three MSDND secure paths in the system. Out of these, twenty-four invariants described in Theorem 11 and 12 were implemented in the system. Man-in-the-middle attacks were simulated in the corresponding information paths by corrupting the values in the PLC being sent to SCADA. Invariants involving smart meter readings were not implemented because at present the smart meters in the EPIC are daisy chained to a single Raspberry Pi and hence the readings are not accurate. The results of the study is summarized in the Table 7.1.

The circuit breaker status flows from the circuit breaker to the Historian in the path as shown in Figure 7.1. The invariants from Theorem 11 and 12 were tested against the EPIC data collected through the Historian software. On analysis, it was found that the status of circuit breaker going to the OPC server was actually correct, but it gets corrupted in the OPC server to the Historian path. This was because when invariants were implemented directly on the OPC server, the CBS was satisfying the invariants, but when it was implemented on data collected through Historian, CBS did not satisfy the invariants.

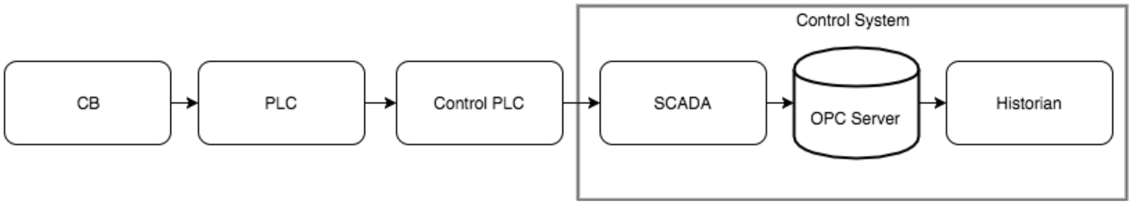


Figure 7.1. CBS flow from the circuit breaker to Historian

Table 7.1. Result summary of MSDND analysis

Summary	**Count**
Information paths analyzed	100+
MSDND secure paths found	89
MSDND secure paths broken using invariants (total invariants generated)	73
Invariants implemented in the system	24

7.2. DATA-CENTRIC APPROACH

With the training dataset from the EPIC system, we get candidate invariants between system variables by applying linear regression. A code to automate the generation of a Python script to implement the invariant logic is created using the generated linear regression invariants as inputs. Given a set of invariants, the success of these results is evaluated by testing their performance on the EPIC system. The testing dataset is the set of execution logs of the system gathered across multiple months. Thanks to the large sampling size, the data can accommodate bias caused by different insolations. To ensure a high representativeness, only data during maximum operation of the EPIC system is considered.

To gain a better understanding of the large set of invariants, each invariant is classified into a type using a mathematical relation. It ends up with nine distinct types over a total of one hundred and ninety-nine valid invariants. After classification, each type of invariant is evaluated by sampling and finding the mean.

In real-time systems, the power variables will not strictly follow the invariant equations: there will be slight deviation from the actual relation. If the deviation value is less, then the invariant is better. If an invariant with a higher deviation percentage is implemented in the system, then it will raise false alarms. Consider an invariant relation involving two variables P and Q given by the relation:

$$P = k \times Q$$

where k is a constant. Then, the relation involving deviation percentage and invariant is given by the following equation:

$$\left(\frac{100-deviation\,percentage}{100} \times P\right) \;\leq\; (k \times Q) \;\leq\; \left(\frac{100+deviation\,percentage}{100} \times P\right)$$

The success rate of each invariant type is calculated for deviation percentages ±1% to ±6%. The success rate of an invariant for a particular deviation percentage is given by the following relation:

$$Success\ rate = \frac{Number\ of\ true\ alarms\ raised\ in\ an\ interval}{Total\ number\ of\ alarms\ raised\ in\ an\ interval} \times 100\,\%$$

From Figures 7.2 and 7.3, all nine types of invariants experience monotonic increases on the success percentage as the deviation goes up. In another words, when releasing the restriction on the percentage of deviation, more linear regression generated invariants tend to be accepted by the power grid system. Type 1 to 8 all achieve a success rate high than 98.5%. However, the success rate given by Type 9 is among the 30s.

7.3. COMPARISON BETWEEN DeC AND DaC GENERATED INVARIANTS

The DeC invariants are generated by making use of SCADA and AMI variables, but the DaC invariants are generated only using the SCADA variables, because of the issue mentioned in Section 7.1. In the nine Stuxnet attacks that were modeled, the DeC invariants can identify eight of them, as seen in the proofs. The DaC invariants generated without AMI variables cannot identify any of the attacks, but if AMI variables are considered, then

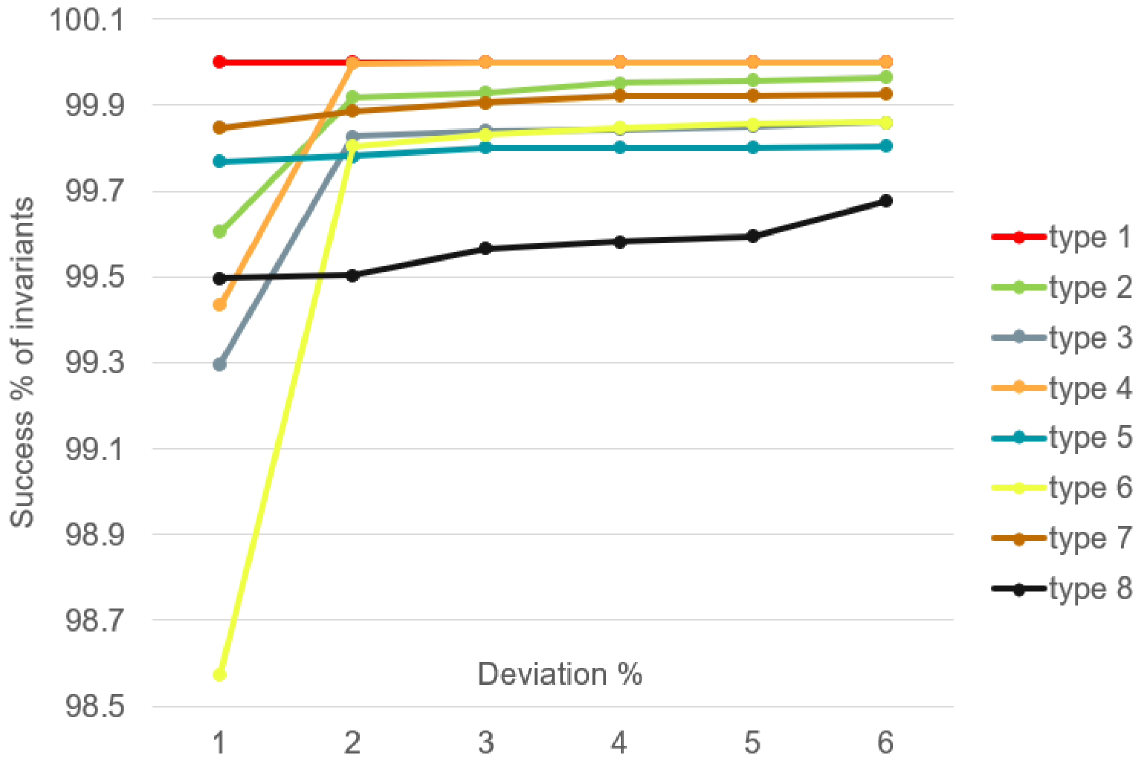


Figure 7.2. Success rates of the invariants of type 1 to 8

it can identify one attack among the nine. This is because in DeC, there is a conjunction present between two conditions, and we also consider Boolean states in this approach, which makes it easier to identify the information path in which the fault/attack occurred. However, because of the variety of system properties that were captured in DaC, these invariants are much better in identifying faults that occur in the SCADA system when it is working normally, and also in identifying uncorrelated attacks. For example, if an attacker changes the line to line voltage of a particular relay, but did not change the line to neutral voltage, the Type 2 DaC invariant would raise an alarm. A DeC invariant that uses both binary (status) and numeric data is much better at identifying correlated attacks where the attacker manages to corrupt all related variables with respect to a particular device. The comparison between DeC and DaC generated invariants are summarized in the Table 7.2.

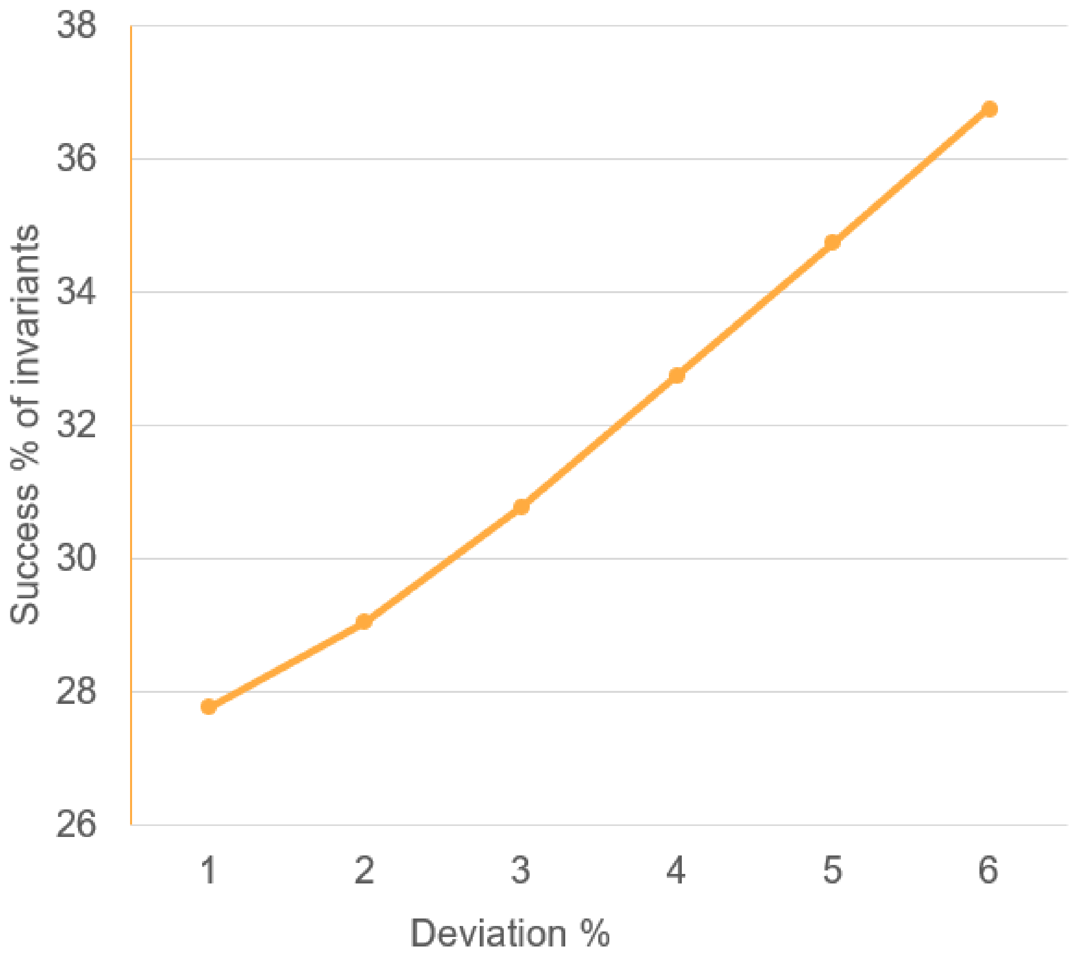


Figure 7.3. Success rate of the type 9 invariant

Table 7.2. Summary of DeC and DaC generated invariants

Summary	**Count**
Stuxnet attacks modeled	9
DeC invariants generated	73
DaC invariants generated (without AMI variables)	199
Attacks DeC invariants identify	8
Attacks DaC invariants (without AMI variables) identify	0
Attacks DaC invariants could identify (with AMI variables)	1

8. CONCLUSION

Vulnerable information paths were found in the EPIC testbed by MSDND analysis. Over seventy-three invariants were created manually using the physics of the system. Some of these invariants were implemented on the live system. Man-in-the-middle attacks were launched, and on all instances they identified the attack and broke the MSDND secure path, which is good for the system. Some invariants were also run on the data collected from EPIC, which helped identify the problem in the logger of the EPIC system.

Over one hundred and fifty-two numeric variables in the SCADA system of the EPIC testbed were analyzed using linear regression, and one hundred and ninety-nine invariants were generated. Scripts were created to automate the generation of scripts to implement the created invariants. The invariants were then categorized into nine types based on the defined electrical equations and the efficiency of each type was analyzed for various deviation percentages ranging from ±1% to ±6%, which is the allowed deviation in the EPIC system.

The invariants generated through DeC and DaC approaches were compared for their efficiency in identifying fault/attack, and it was found that the DeC invariants are better in identifying correlated attacks and DaC invariants work better in identifying faults and uncorrelated attacks in the system. DeC invariant generation heavily relies on the knowledge of the system, and generating invariants for a large smart grid could be time-consuming. To build a highly secure system, DeC would be the best approach to generate invariants although it consumes more time. To identify faults arising in the system due to day-to-day operation, DaC would be the best approach to generate invariants.

9. FUTURE WORK

The circuit breaker status was incorrect in the EPIC data that was collected by Historian. To resolve this, a logger software can be created that directly retrieves live values of the circuit breaker data from the OPC server and logs it into a CSV file. This would eliminate the faulty status being recorded in the OPC server to Historian path. Using the newly collected data, invariants can be generated using the association rule mining as done by (Umer *et al.*, 2017). Another direction would be to look into the possibility of merging the linear regression and association rule mining generated invariants of the system on the basis of a device.

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