Cyber-Physical System Security of the Power Grid

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Power and Energy Center (PEC)

- Founded by A. Phadke in 1986
- **Original members:** A. Phadke; L. Mili; R. Broadwater; S. Rahman; K. Tam; Y. Liu; and J. DeLaRee

- 1988: First Phasor Measurement Unit (PMU)
- 2002: Frequency Monitoring Network (FNET)
- 2008: A. Phadke and J. Thorp awarded Benjamin Franklin Medal in EE
- 2013: PMU-only three-phase state estimator in Dominion Virginia Power

PEC Core Faculty

Chen-Ching Liu
Director & AEP Professor
- Distribution systems, cyber security of the grid
- Industry software for system restoration: EPRI (Trans.), PNNL (Distr.)

Jaime De La Ree
Associate Professor &
Assistant Dept. Head

Lamine M. Mili
Professor (NVC)
- Static and dynamic state estimation
- Robust power system parameter and dynamic state estimation w/ PMUs

Mona Ghassemi
Assistant Professor
- High voltage and high field engineering
- High voltage tests and high field phenomena modeling: GE, Eversource, Hydro-Quebec, SaskPower, Manitoba Hydro

Robert Broadwater
Professor
- Distribution systems

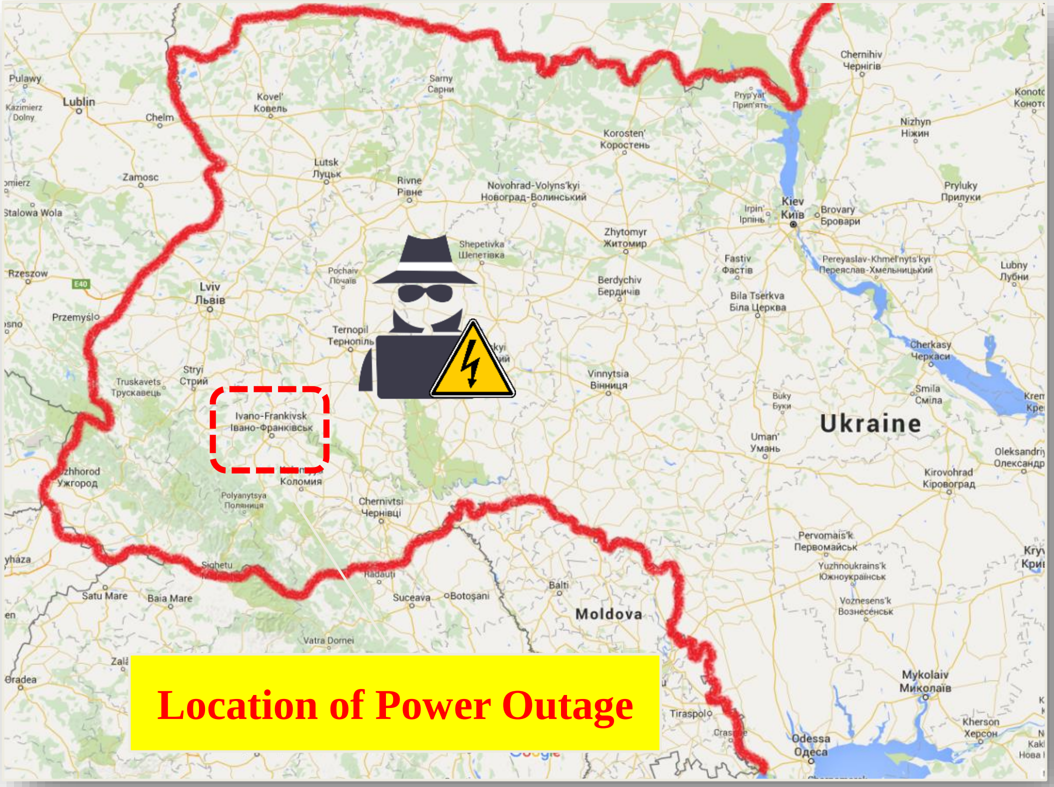
Saifur Rahman
Joseph Loring Professor (VT-ARC)
- Energy efficiency and sensor integration
- DoE BEMOSS Platform; President of IEEE PES

Vassilis Kekatos
Assistant Professor
- *Optimization and learning of smart grids*

Virgilio A. Centeno
Associate Professor
- PMU
- Instrumentation

Cyber Attack in Ukraine’s Power System

- **Attack on Ukraine’s power grid**
  - ❑ December 23, 2015.
  - ❑ Malware installation.
  - ❑ Falsify SCADA data injection.
  - ❑ Flood attack on telephone system.
  - ❑ Trip circuit breakers in multiple substations.
- **Results**
  - ❑ Over 225,000 customers experienced power outage.



Source: Google map

Supervisory Control And Data Acquisition (SCADA)

	Electric Power	Natural Gas Pipelines, Process Control Systems	Transportation
Sectors	Transmission, Distribution, Substation Network Monitoring) Wind Farms	Gas Pipeline, Chemical, Oil and Gas, Power Plants	Roadway, Rail System, Space and Air Traffic
Example Protocols	ICCP / DNP3i / Modbus over TCP/IP / IEC870-5-101/104 / IEC 61850	Fieldbus or Profibus	Cellular Digital Packet Data Network and Global Positioning System
Framework	Data Polling Acquisition & Control / Automation Are Configured for Interlocking and Protection Scheme	Automation by Programmable Logic Controller (PLC)	Ensuring Associated Tasks with Given Function, Satisfying System Performance in Centre
Input Variables	Voltage, Current, Frequency, Time, Active Power, Reactive Power, Apparent Power	Temperature, Pressure, Time, etc.	Traffic and Roadway Sensors, Visual Closed Circuit Television Sensors, Voice Communication, Probe Vehicle and Database Services, Global Positioning System
Control Variables	Switching Devices	Valve, Pump	Controls of Roadway Access and Intersection Devices
Application	Energy Management System () / Distribution Management System (DMS) / Substation Automation System (SAS)	Generation Management System (GMS), Resource Planning System (ERP)	Adaptive Traffic Control System, Incident Detection and Location System, and Predictive Traffic Modelling System

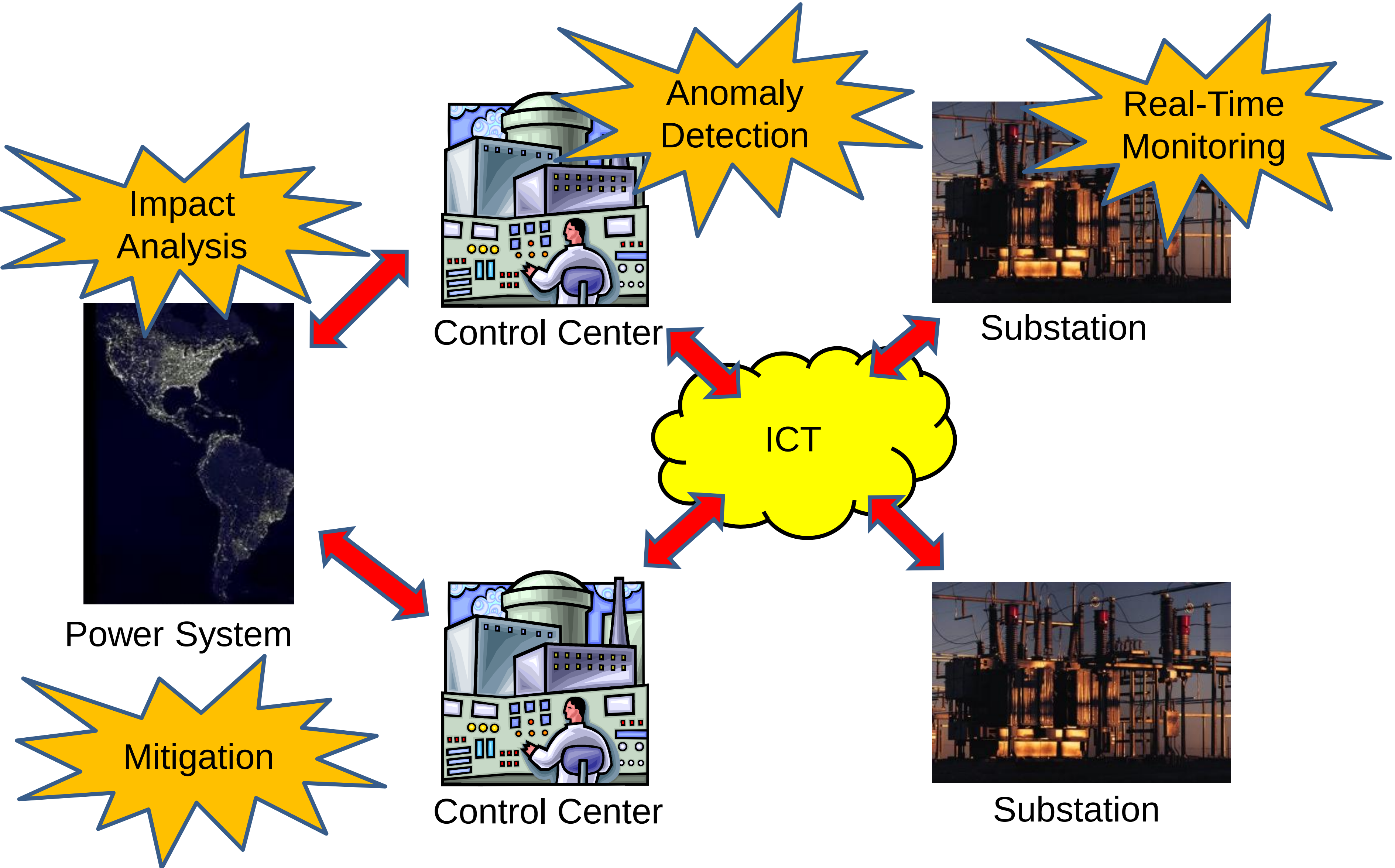
Escalating Cyber Security Factors

- Adoption of standardized technologies with known vulnerabilities
- Connectivity of control systems to other networks
- Constraints on use of existing security technologies and practices
- Insecure remote connections
- Widespread availability of technical information about control systems

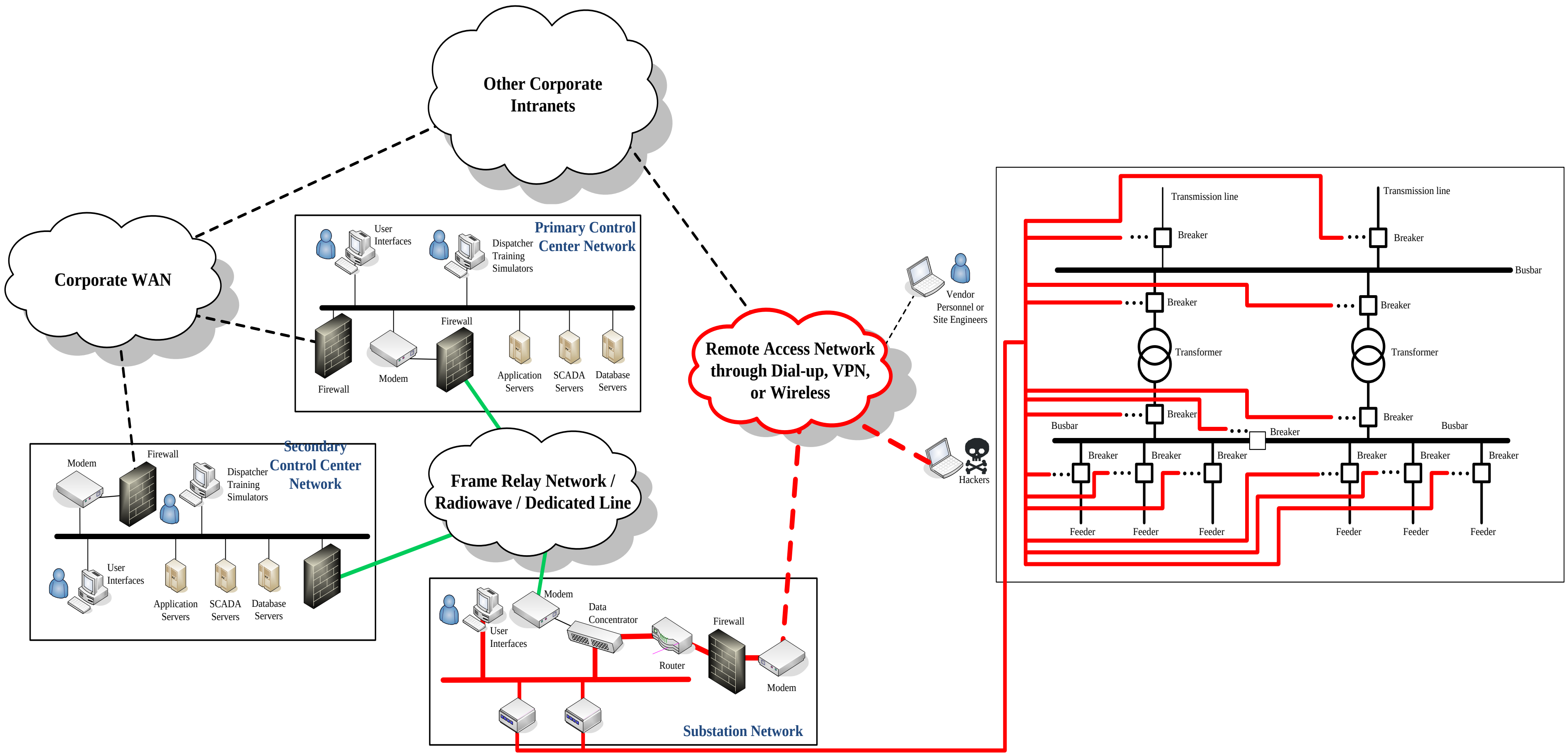
Cyber Security Standards NERC CIP 002-009

- Critical asset identification (e.g. RTU, which support the reliable operation of a power system.)
- Security management controls (e.g. How to manage the authentication, card or password, or both.)
- Personnel training (e.g. Contrators and vendor must be authorized to gain access (cyber and physical), and training staff on security awareness.)
- Electronic security perimeter (e.g. Periphery to protect all the cyber asset within.)
- Physical security of critical cyber assets (e.g. Control policies on people who are authorized to have access to the critical cyber assets.)
- System security management (e.g. Monitoring system events)
- Incident reporting and response planning (e.g. Report to related authorities if necessary)
- Recovery plans for critical cyber assets (e.g. When threat is over, recover the system and enhance the control policies)

Cyber Security Monitoring



Cyber Systems in Power Infrastructure



System Vulnerability

- A system is defined as the wide area interconnected, IP-based computer communication networks linking the control center and substations-level networks
- System vulnerability is the maximum vulnerability level over a set of scenarios represented by I

$$V_S = \max\left(V(I)\right)$$

Scenario Vulnerability

- An intrusion scenario consists of the steps taken by an attempted attack from a substation-level network

- Substation-level networks in a power system
  - substation automation systems
  - power plant control systems
  - distribution operating centers

- Scenario vulnerability is defined by

$$V(I) = \{V(i_1), V(i_2), \ldots, V(i_K)\}$$

where K is the number of intrusion scenarios to be evaluated

Access Point Vulnerability

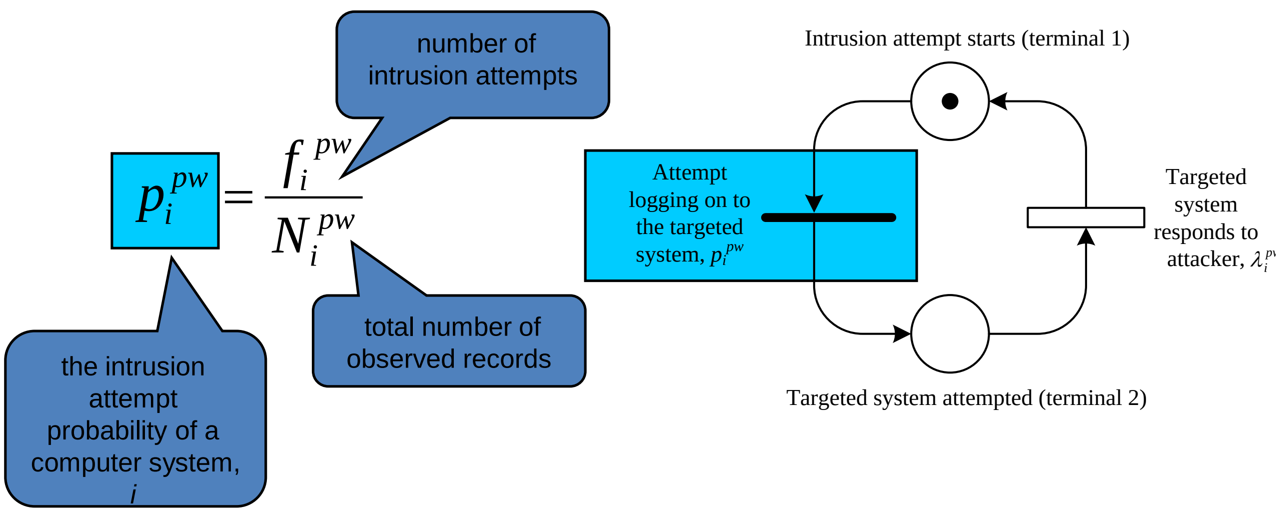
- Access point provides the port services to establish a connection for an intruder to penetrate SCADA computer systems
- Vulnerability of a scenario i, V(i), through an access point is evaluated to determine its potential damage
- Scenario vulnerability - weighted sum of the potential damages over the set S.

$$V(i) = \sum_{j \in S} \pi_j \times \gamma_j$$

where π_j is the steady state probability that a SCADA system is attacked through a specific access point *j*, which is linked to the SCADA system. The damage factor, γ_j , represents the level of damage on a power system when a substation is removed

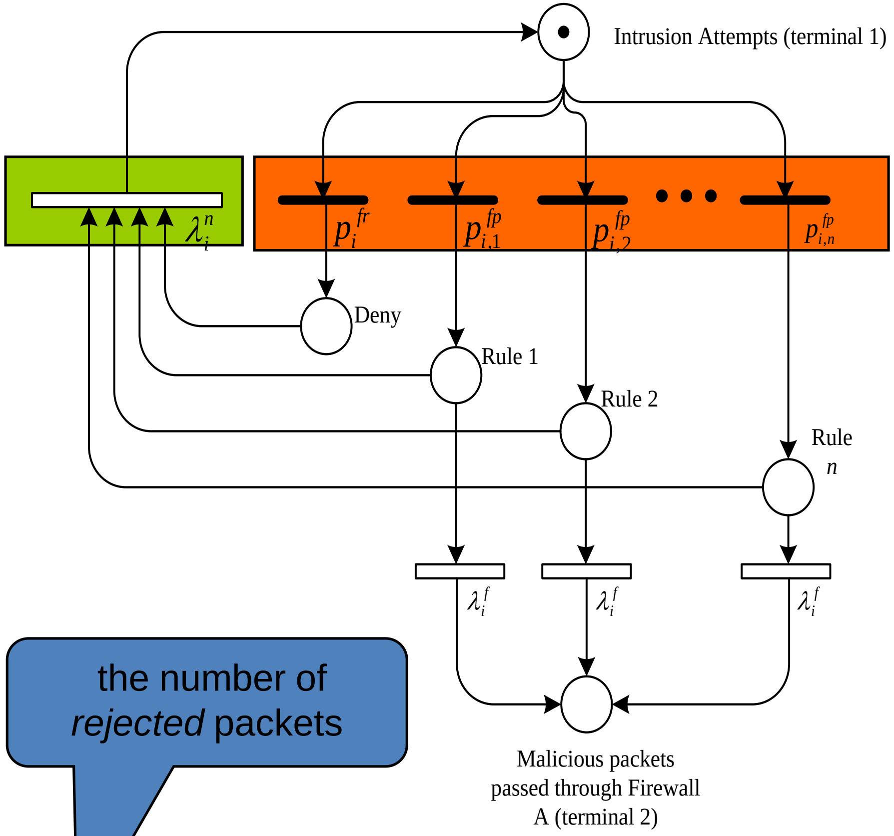
Password Model

- Intrusion attempt to a machine
  - A solid bar - transition probability
  - An empty bar - processing execution rate that responds to the attacker
- Account lockout feature, with a limited number of attempts, can be simulated by initiating the N tokens (password policy threshold).



Firewall Model

- Firewall model
  - Denial or access of each rule
  - Malicious packets traveling through policy rule j on each firewall i is taken into account.



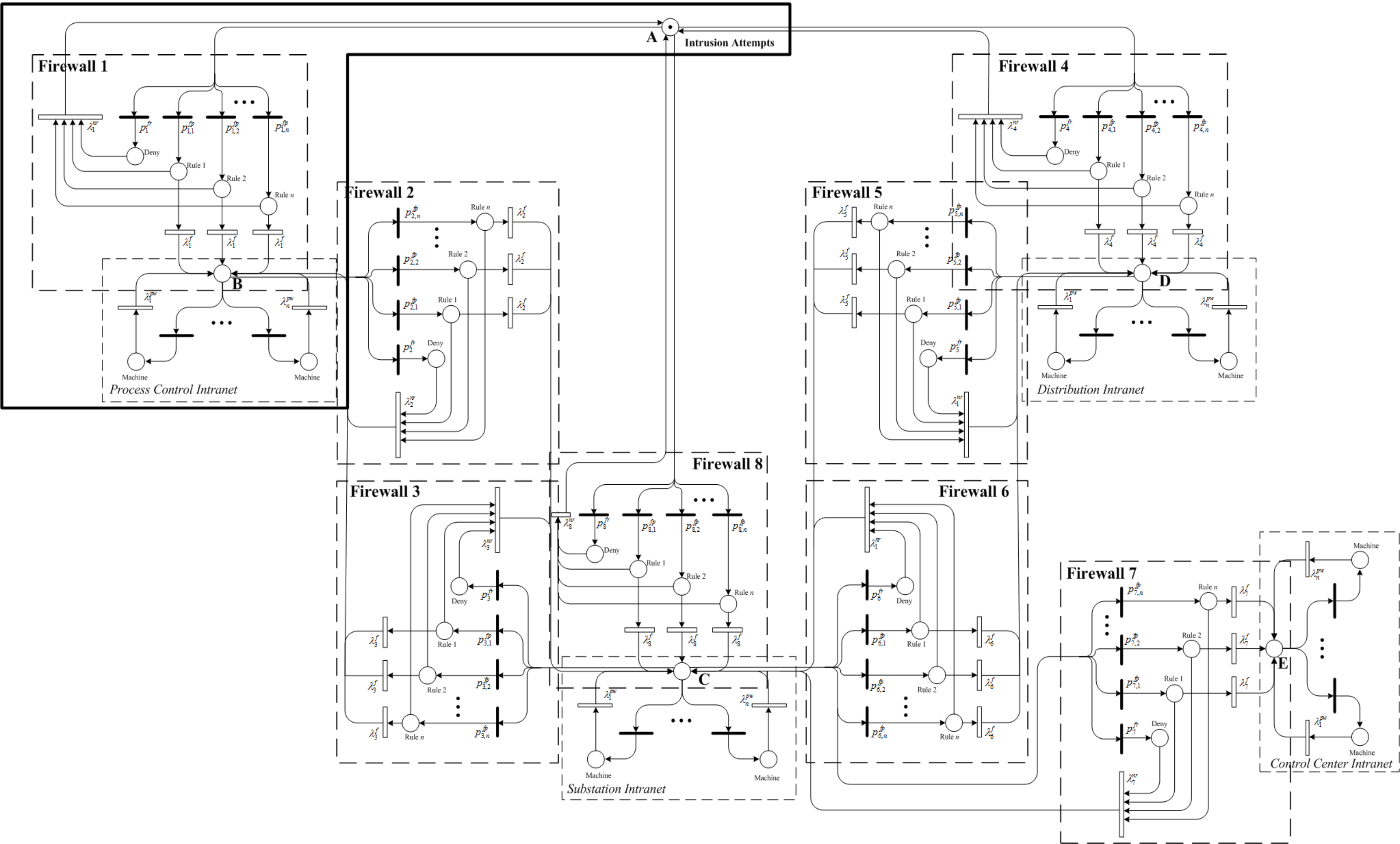
$$p_{i,j}^{fp} = \frac{f_{i,j}^{fp}}{N_{i,j}^{fp}}$$

- $p_{i,j}^{fp}$: probability of malicious packets traveling through a firewall rule
- $f_{i,j}^{fp}$: denotes the frequency of malicious packets through the firewall rule
- $N_{i,j}^{fp}$: total record of firewall rule *j*.

$$p_i^{fr} = \frac{f_i^{fr}}{N_i^{fr}}$$

- p_i^{fr}: probability of the packets being *rejected*
- f_i^{fr}: the number of *rejected* packets
- N_i^{fr}: denotes the total number of packets in the firewall logs

Construction of Cyber-Net Based on Substation with Load and Generator



Impact Factor Evaluation

- Impact factor for the attack upon a SCADA system is

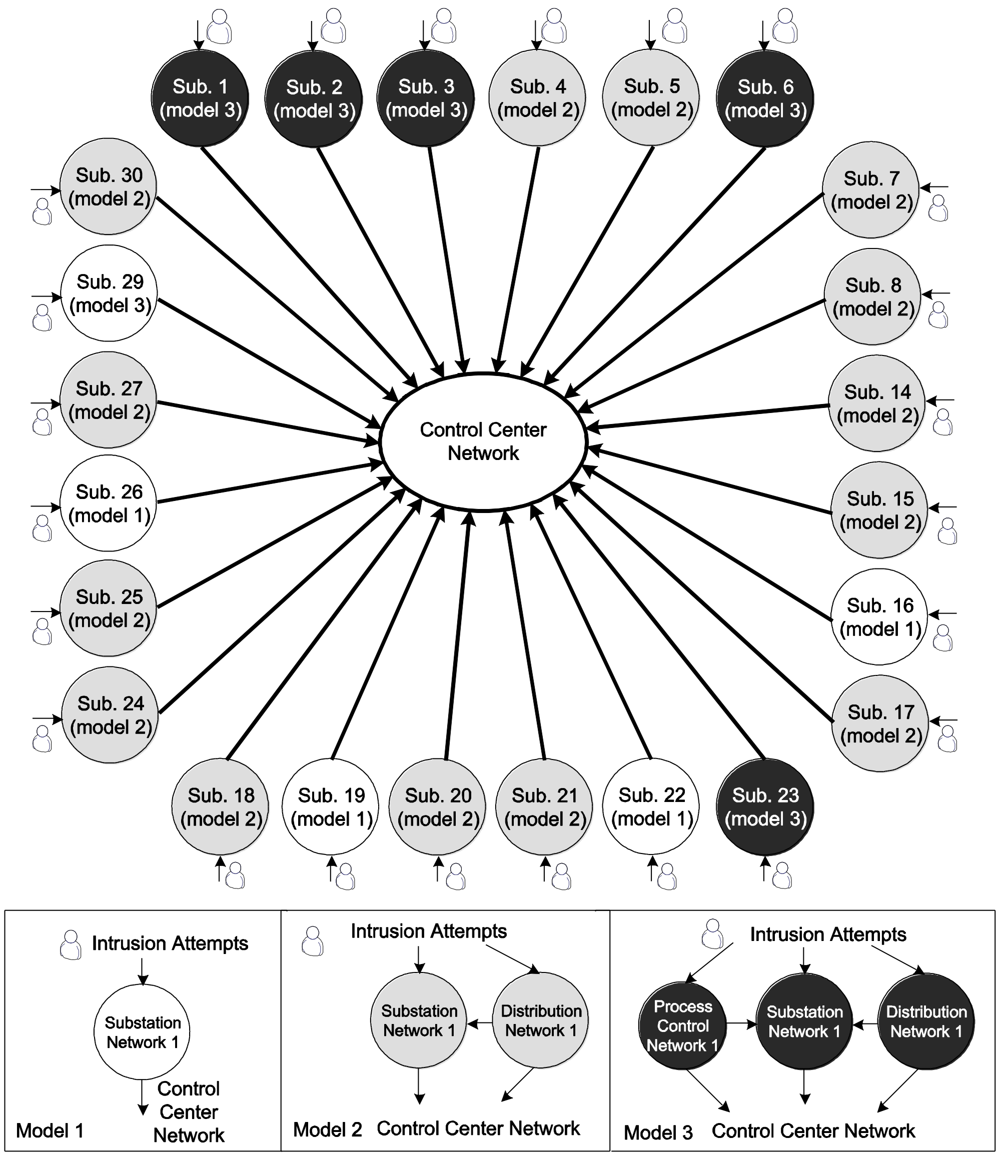
$$\gamma = \left(\frac{P_{LOL}}{P_{Total}} \right)^{L-1}$$

- Loss of load (LOL) is quantified for a disconnected substation
- To determine the value of L, one starts with the value of L=1 at the substation and gradually increases the loading level of the entire system without the substation that has been attacked.
- Stop when power flow fails to converge (System is considered unstable)

Impact Factor Evaluation for IEEE 30-Bus System

Impact Factor for Each Substation

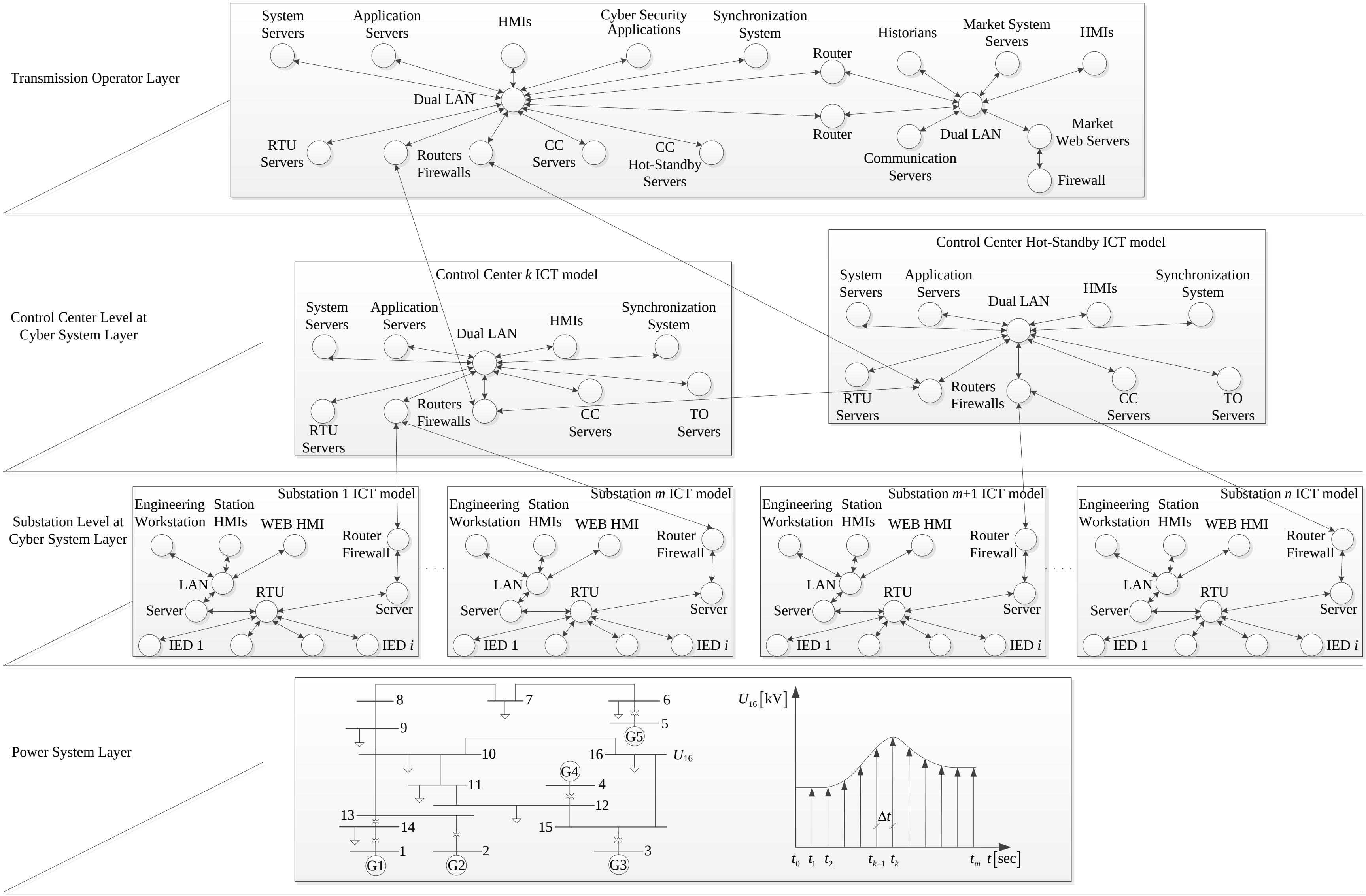
Sub.	Associated Buses	LOL(MW)	L	γ
1	1	.3	2.5	.0016
2	2	21.7	1.8	.1769
3	3	2.4	2.5	.0014
4	4, 12, 13	18.8	1.4	.3971
5	5	0	2.5	0
6	6, 9, 10, 11	5.8	1	1
7	7	22.8	2.8	.0222
8	8	30	3.6	.0083
9	14	6.2	2.9	.0015
10	15	8.2	3	.0019
11	16	3.5	2.6	.0017
12	17	9	2.9	.0031
13	18	3.2	3.1	.0002
14	19	9.5	2.9	.0034
15	20	2.2	2.9	.0002
16	21	17.5	2.6	.0222
17	22	0	2.2	0
18	23	3.2	2.7	.0010
19	24	8.7	2.9	.0029
20	25	0	2.8	0
21	26	3.5	2.8	.0008
22	27, 28	0	1	1
23	29	2.4	2.8	.0004
24	30	10.6	2.8	.0056



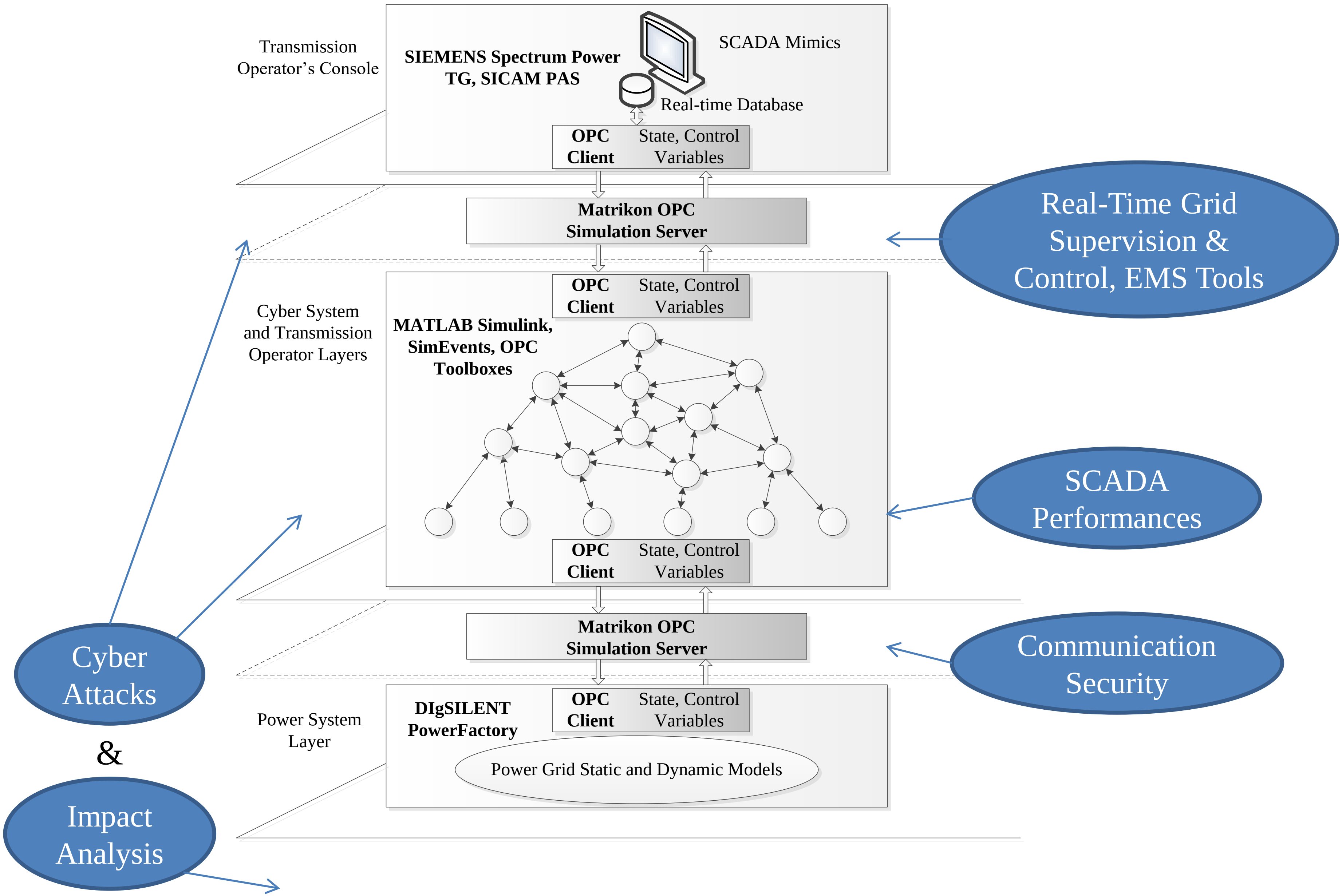
Modeling Integrated Cyber-Power System

- **Methodology for CPS modeling of power systems**
  - Develop the ICT model of SCADA system
  - Integrate power grid model with ICT model for SCADA and grid control hierarchy
  - Dynamics of a power grid and its data infrastructure are combined
- **CPS tool used for assessment of SCADA communication performance**
  - Plan SCADA and ICT systems for power grids
- **CPS tool used for cyber security assessment in co-simulation environment**
  - Model cyber attacks and assess CPS security
    - Simulate cyber attacks at the cyber system layer
    - Perform impact analysis at the power system layer
    - Compute impact indices and attack efficiencies to disrupt power grid operation

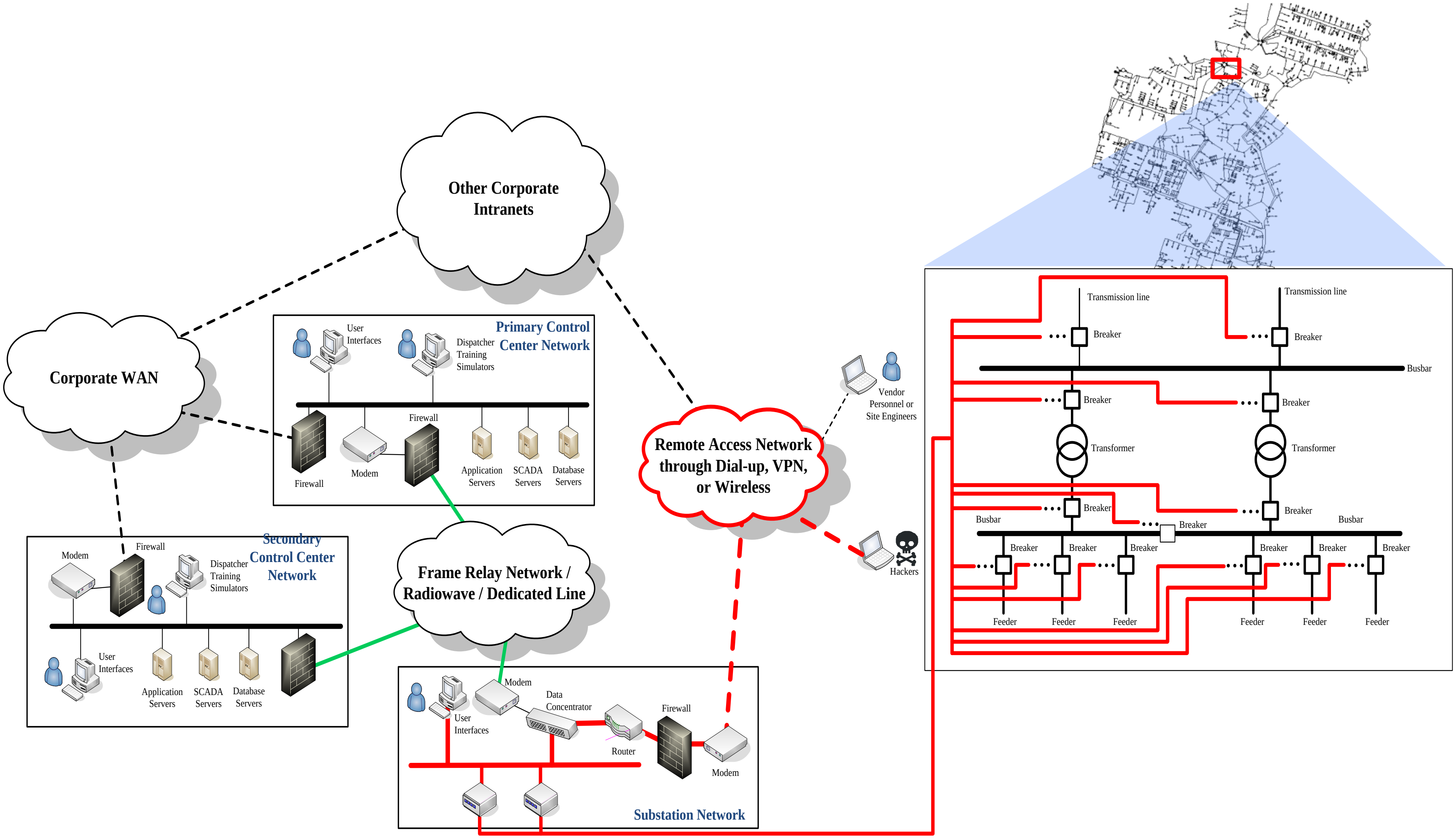
Cyber-Physical System Model



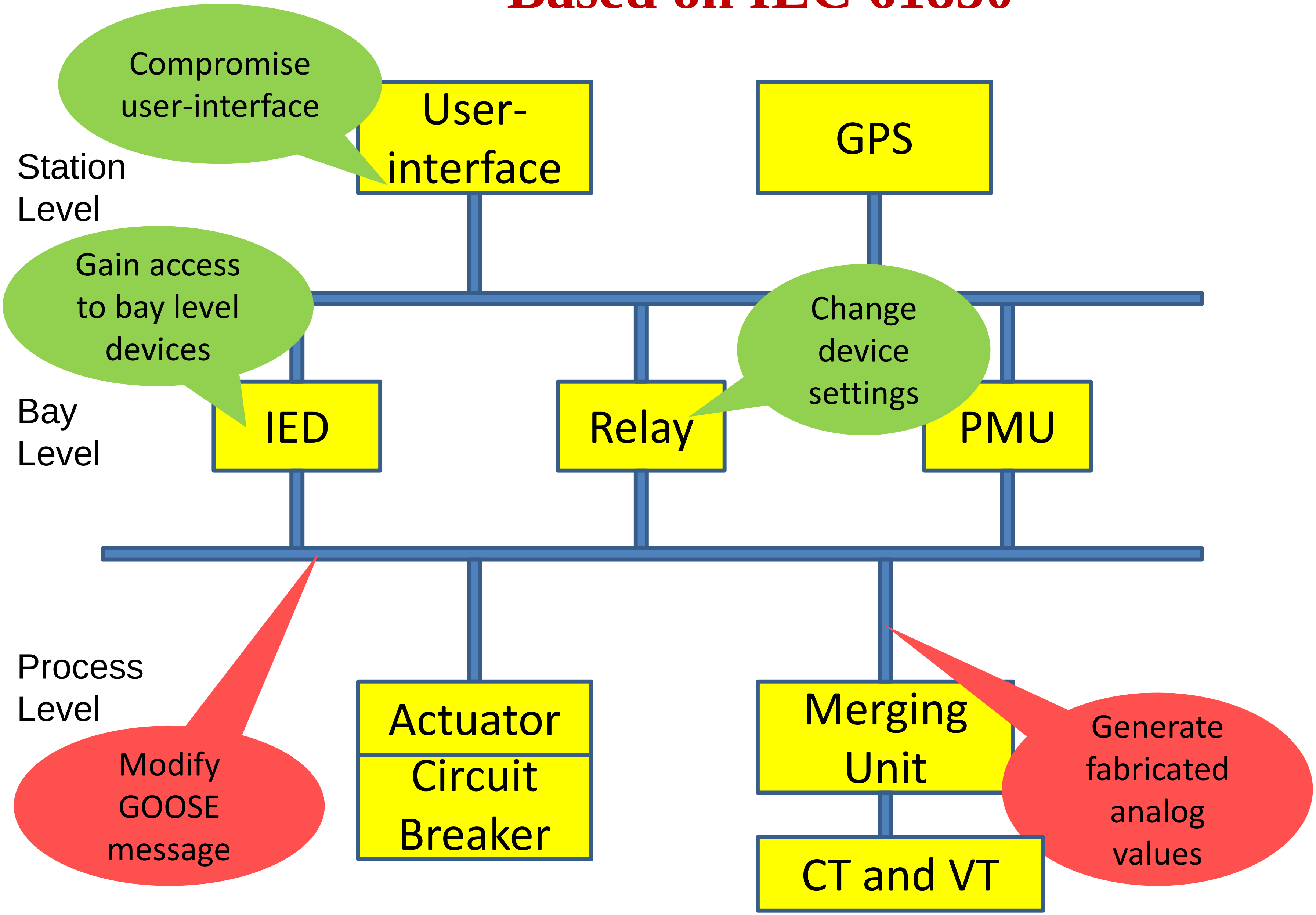
Cyber-Physical System Tool



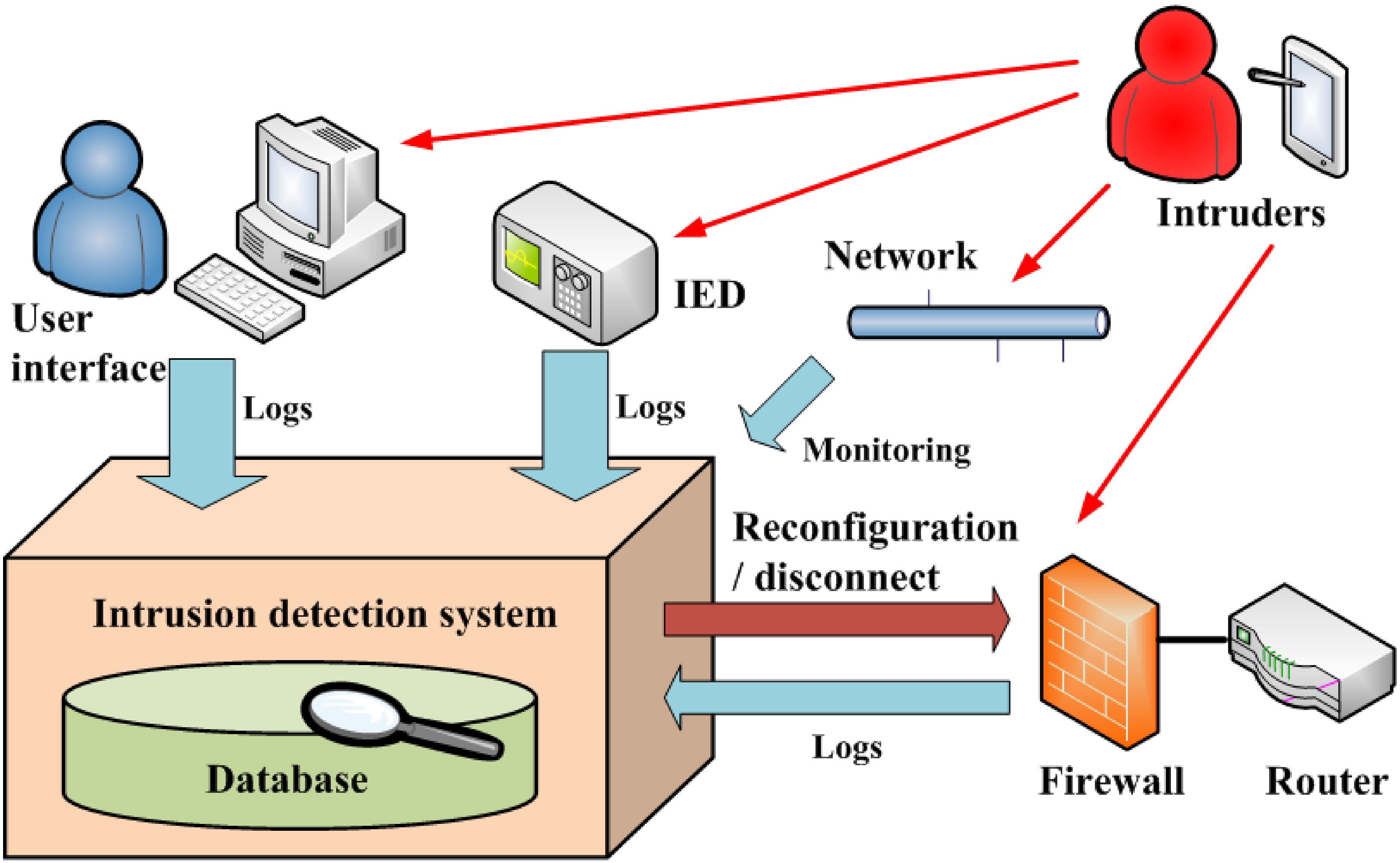
Intrusion into a Substation Network



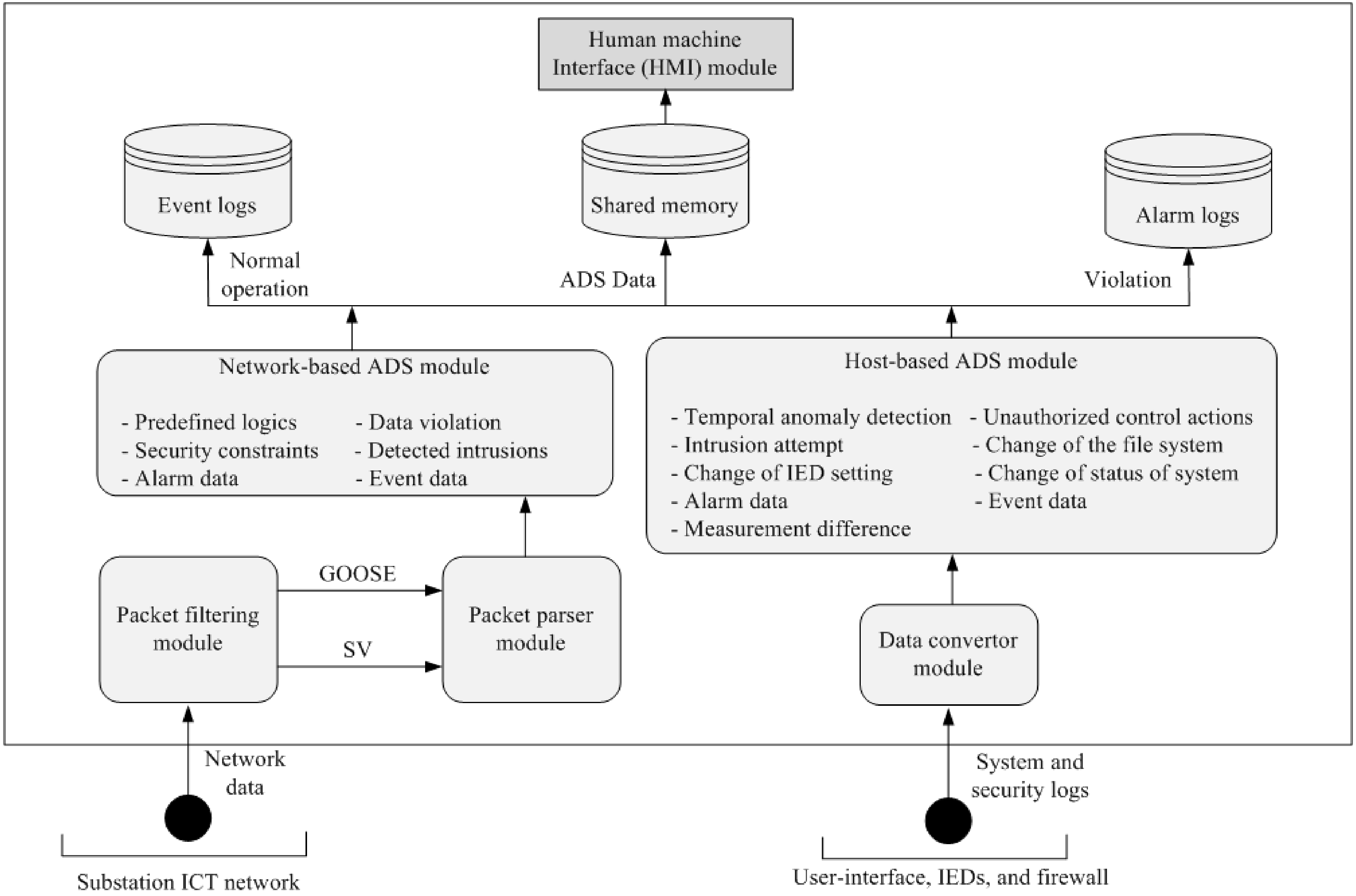
Potential Threats in a Substation Based on IEC 61850



Anomaly Detection at Substations



Integrated Anomaly Detection System



Host-Based Anomaly Detection

- Detection of temporal anomalies is performed by comparing consecutive row vectors representing a sequence of time instants

$$V_{h(i)}^{\boldsymbol{\Omega}} = \frac{\sum_{j=1}^{n} \left| \boldsymbol{\Omega}_{(i,j)} - \boldsymbol{\Omega}_{(i+1,j)} \right|}{n}, \; i=1,\ldots,6,$$

- If a discrepancy exists between two different periods (rows, 10 seconds), the anomaly index is a number between 0 and 1

- A value of 0 implies no discrepancy whereas 1 indicates the maximal discrepancy

Host-based anomaly indicators

- ψ^a (intrusion attempt on user interface or IED)
- ψ^cf (change of the file system)
- ψ^cs (change of IED critical settings)
- ψ^o (change of status of breakers or transformer taps)
- ψ^m (measurement difference)

Substation A

$$\boldsymbol{\Omega} = \begin{matrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \\ t_7 \end{matrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

Host-Based Anomaly Detection

Substation A				
o.	**Date**	**Time**	**Contents**	**Issue**
45	15.09.2013	10:28:33,560	IED 1	Wrong password attempt
46	15.09.2013	10:35:43,159	User-interface	Unauthorized file change
47	15.09.2013	11:02:04,368	IED 2	Unauthorized setting change
48	15.09.2013	11:03:14,270	Transformer 1	Unauthorized tap change

Substation A

$$\Omega = \begin{matrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \\ t_7 \end{matrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

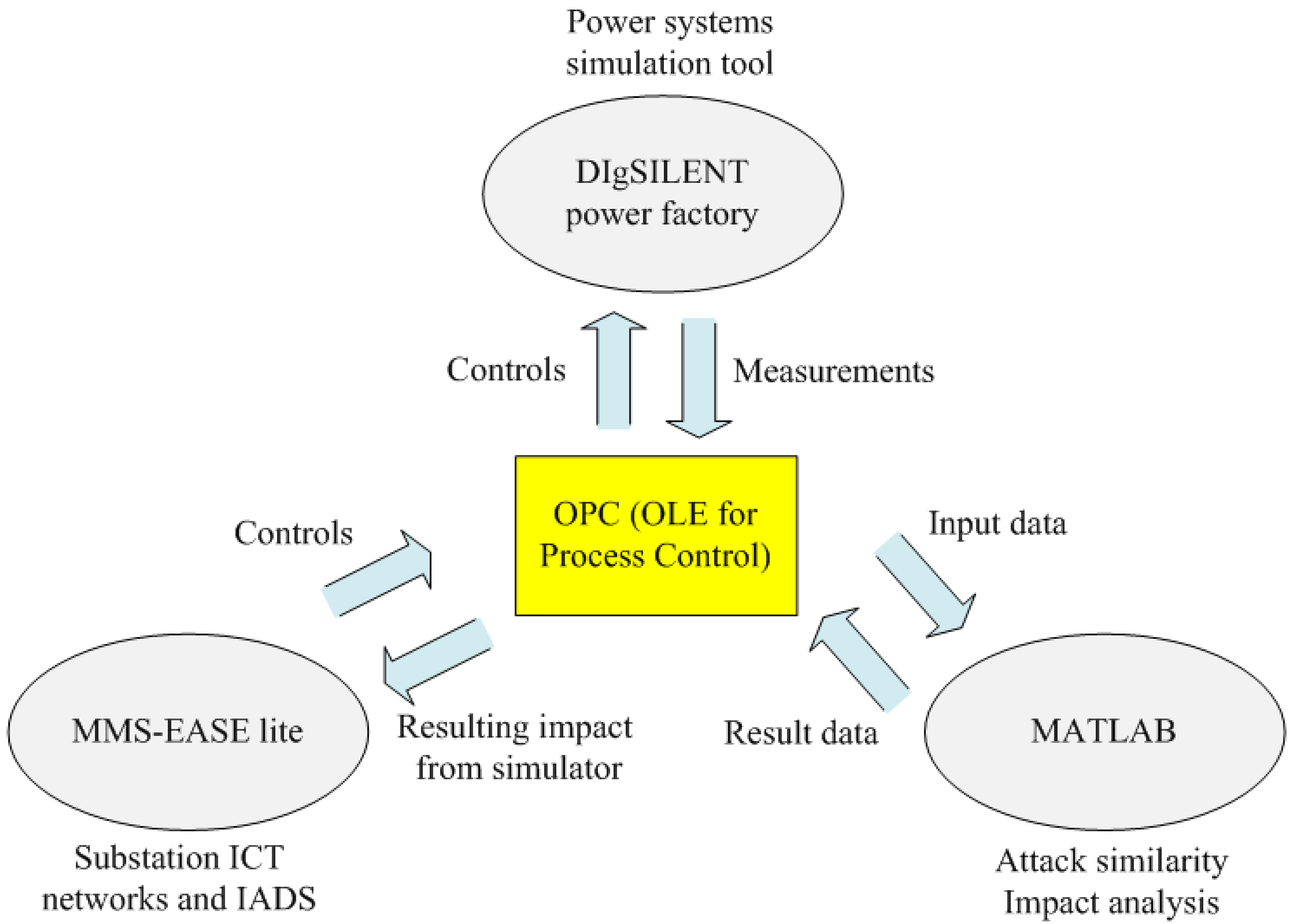
- At 10:20:000, there is no anomaly so t_1 is [0 0 0 0 0].
- At 10:30:000, ADS detects a wrong password attempt to IED 1 so t_2 is [1 0 0 0 0].
- At 10:40:000, ADS detects an unauthorized file change to the user-interface so t_3 is [1 1 0 0 0].
- At 10:50:000, there is no change so t_4 is [1 1 0 0 0].
- At 11:00:000, there is no change so t_5 is [1 1 0 0 0].
- At 11:10:000, ADS detects two anomalies, unauthorized setting change to IED 2 and unauthorized tap change to transformer 1 so t_6 is [1 1 1 1 0].
- At 11:20:000, there is no change so t_7 is [1 1 1 1 0].

Consequence of GOOSE Based Attack

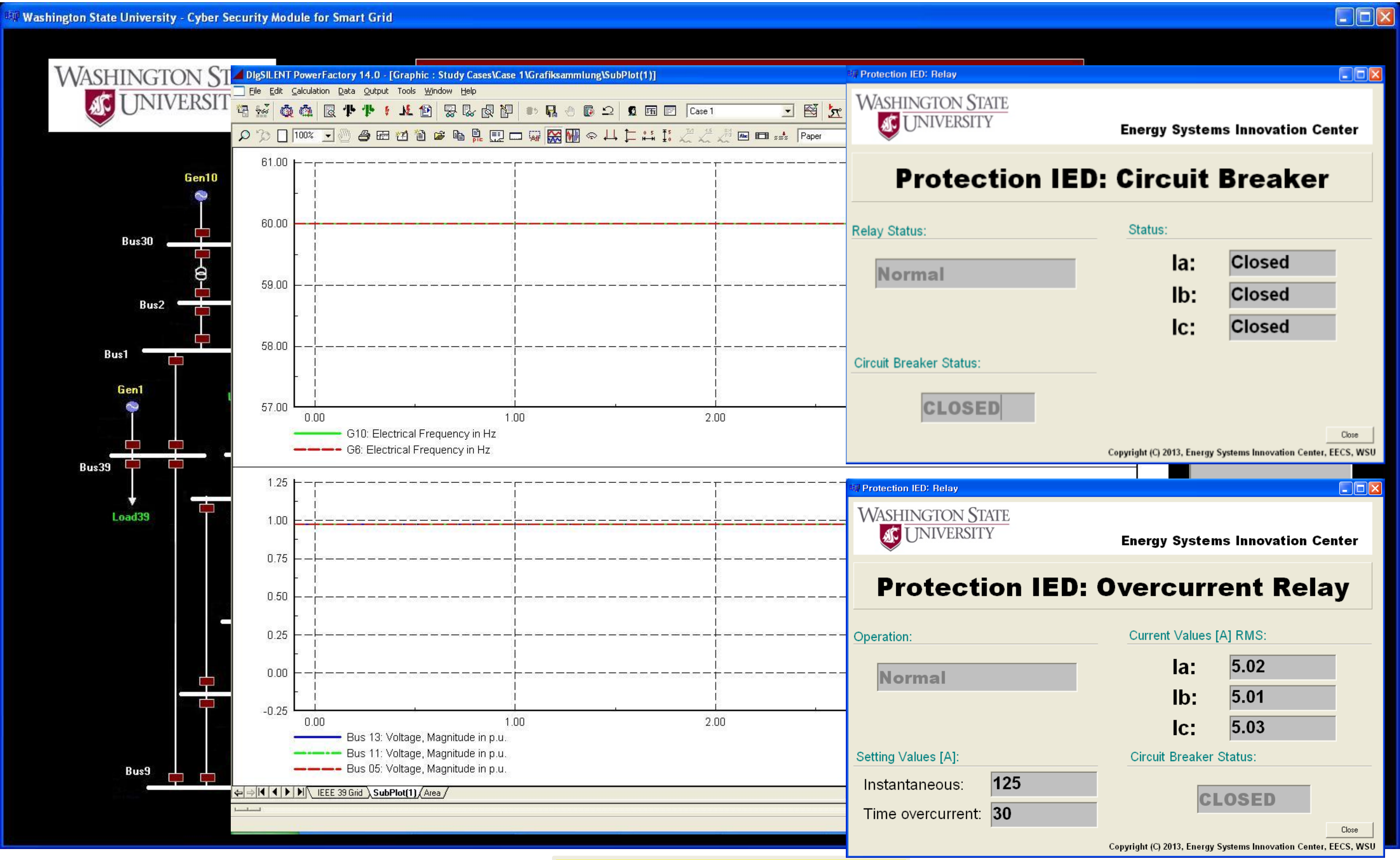
Action	Result
Disconnect Ethernet cable from IED	Lost availability of IED
Send normal control	Open CB
Replay attack	Open CB
Modify sequence & state number	Warning occurred at CB
Modify transferred time	Warning occurred at CB
Modify GOOSE control data	Open CB
Denial of Service attack	Lost availability of CB
Generate GOOSE control data	Open CB

WSU Smart City Testbed

System Integration

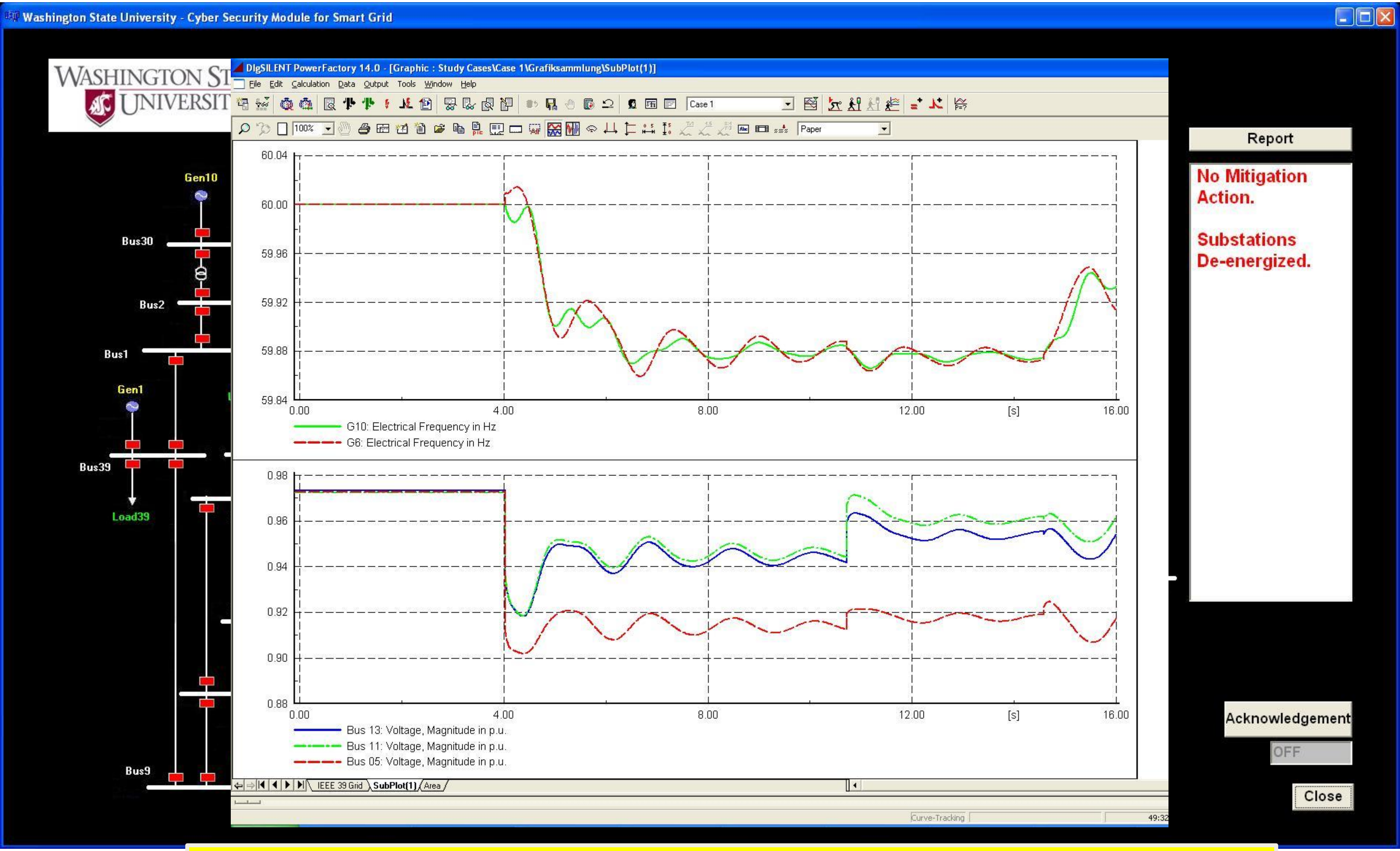


IEEE 39 Bus System

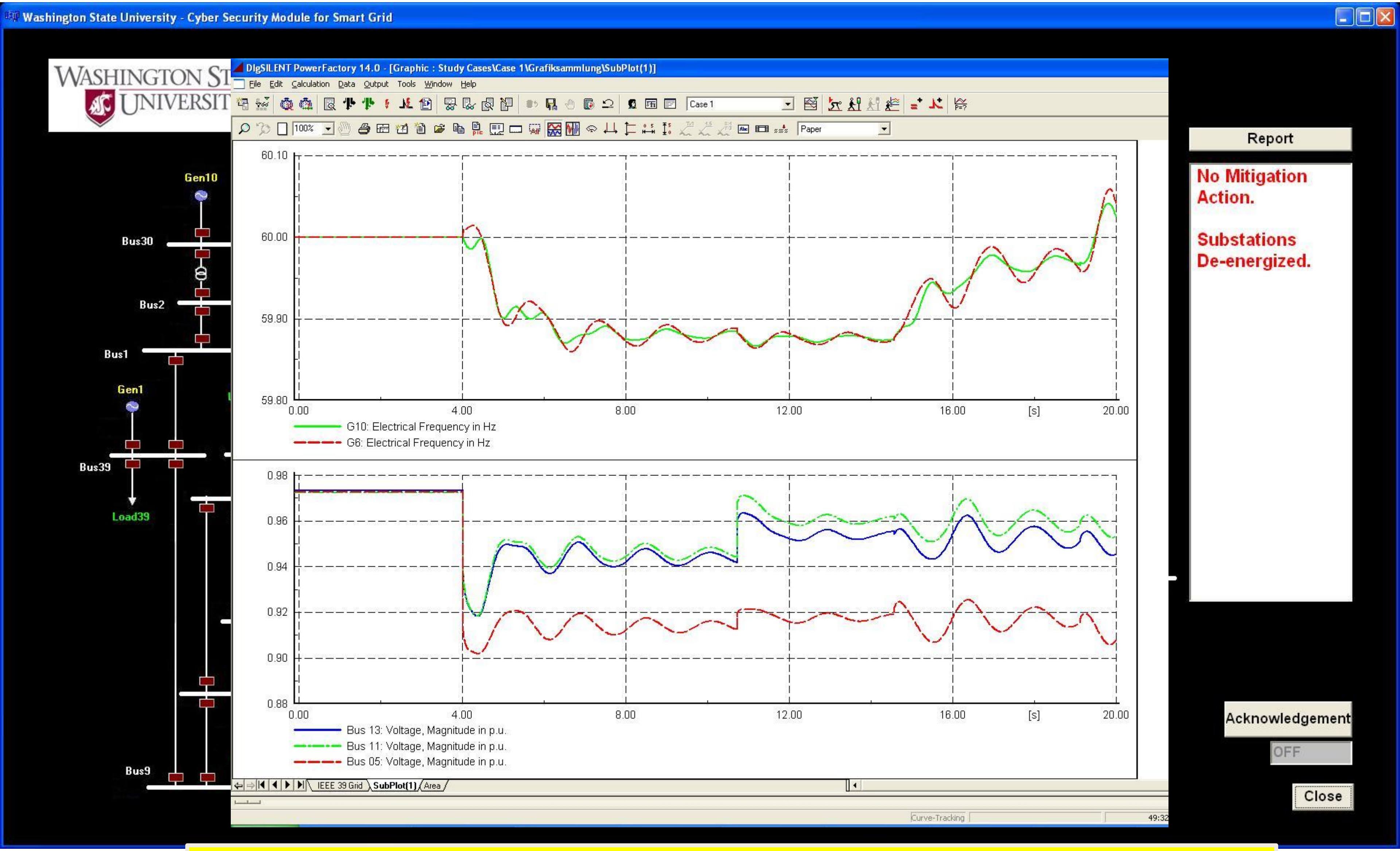


Normal status

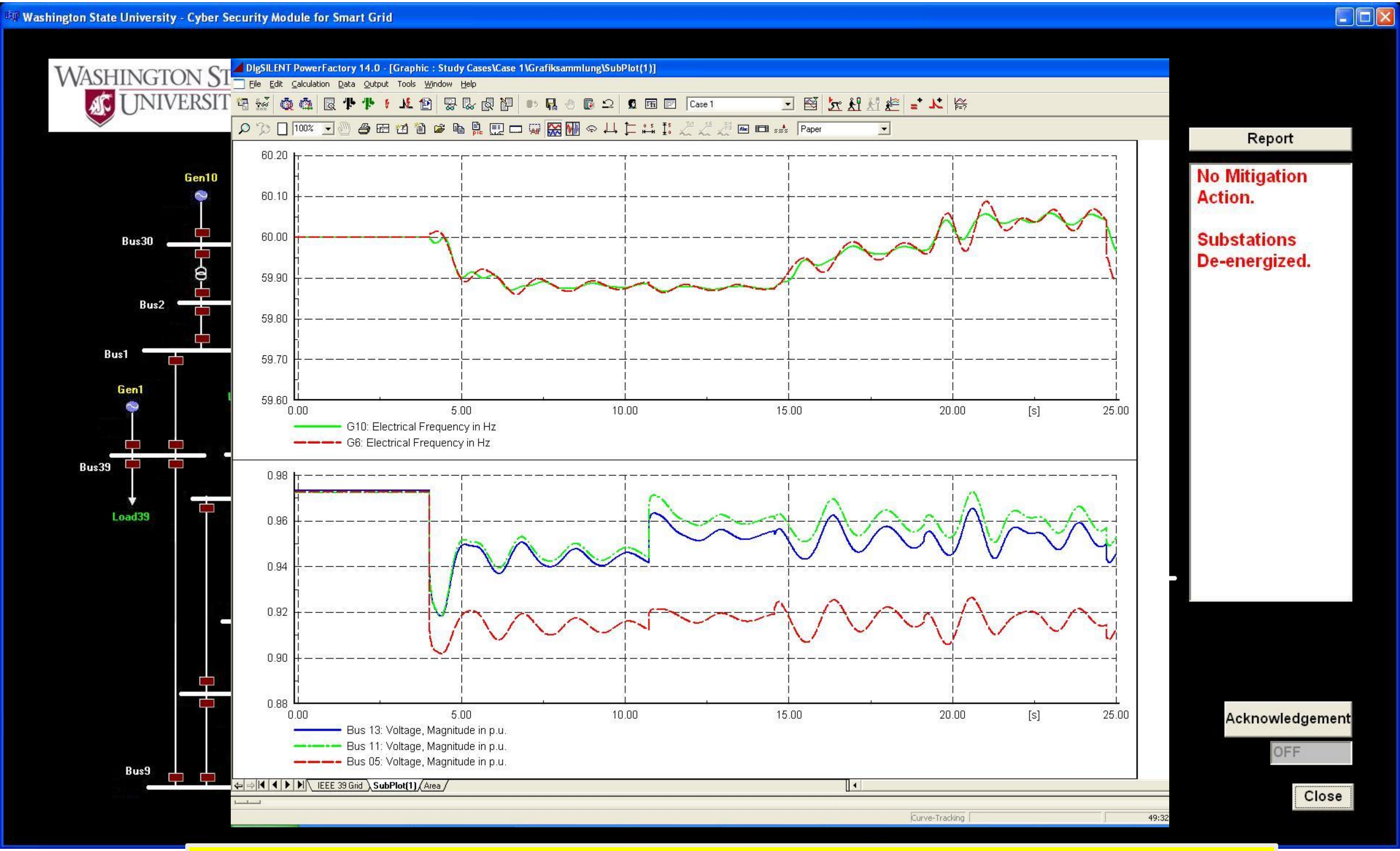
Sequential attacks – Sub # 6 → 12 → 15 → 28 → 36 → 33 → 34



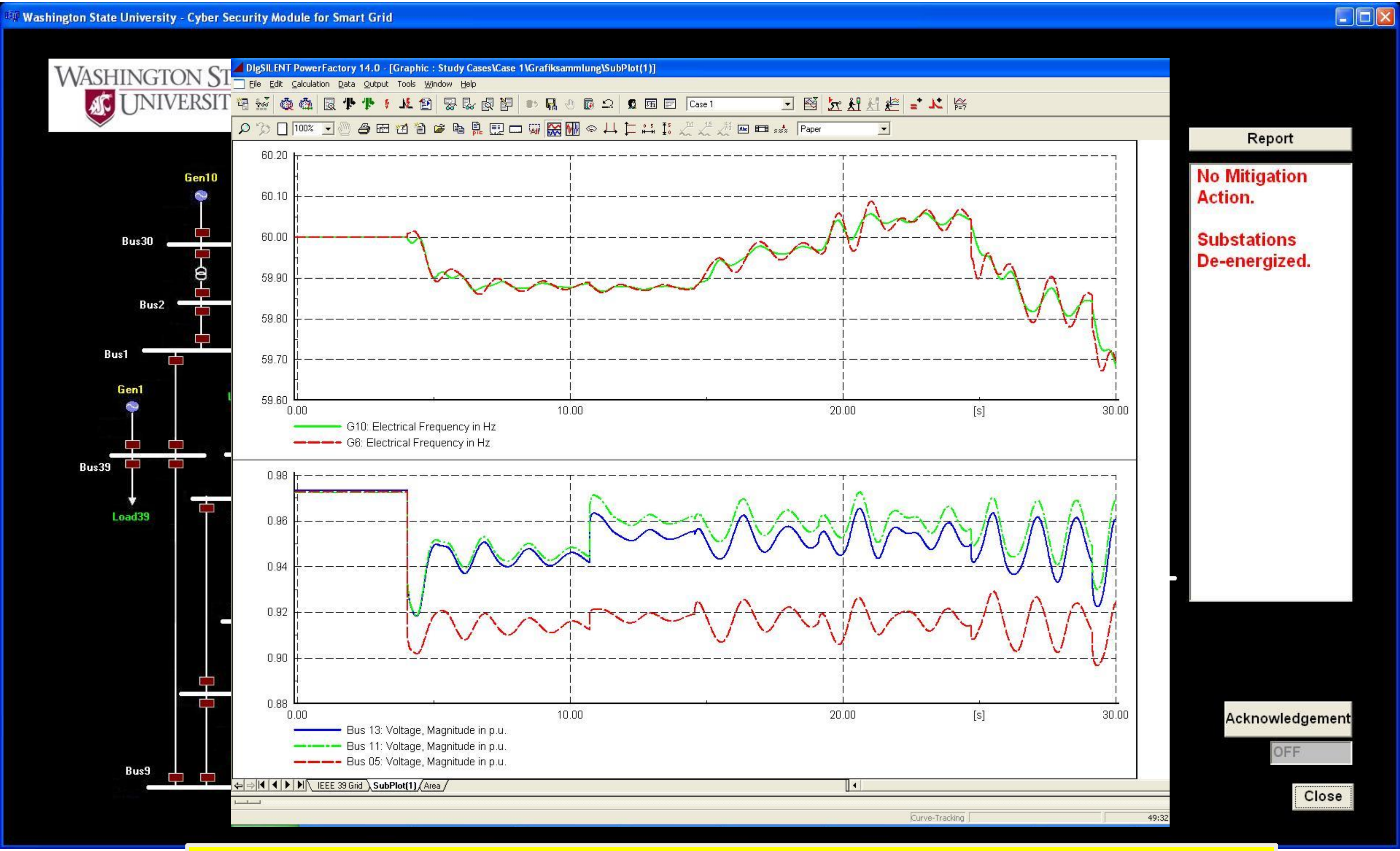
Sequential attacks – Sub # 6 → 12 → 15 → 28 → 36 → 33 → 34



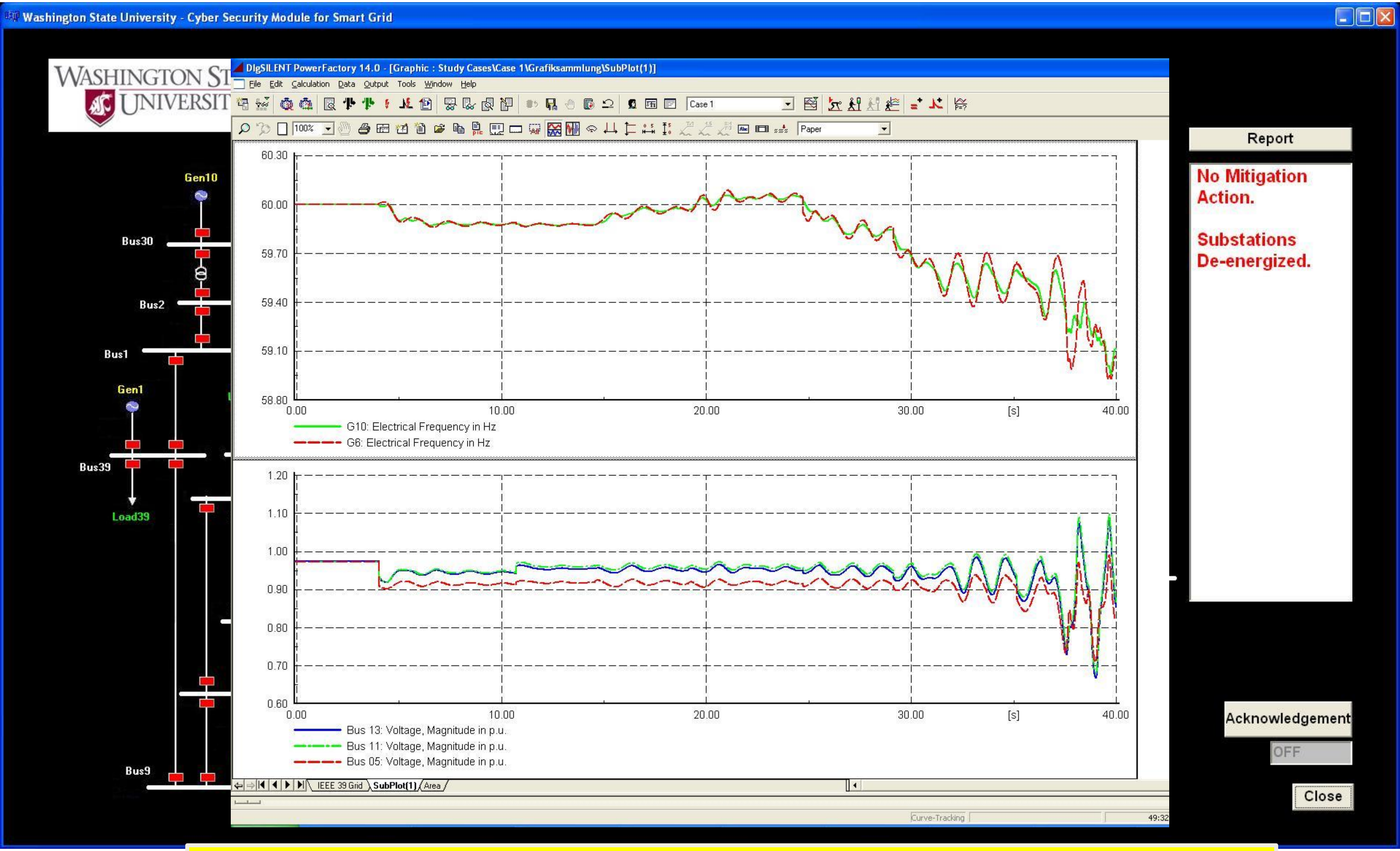
Sequential attacks – Sub # 6 → 12 → 15 → 28 → 36 → 33 → 34



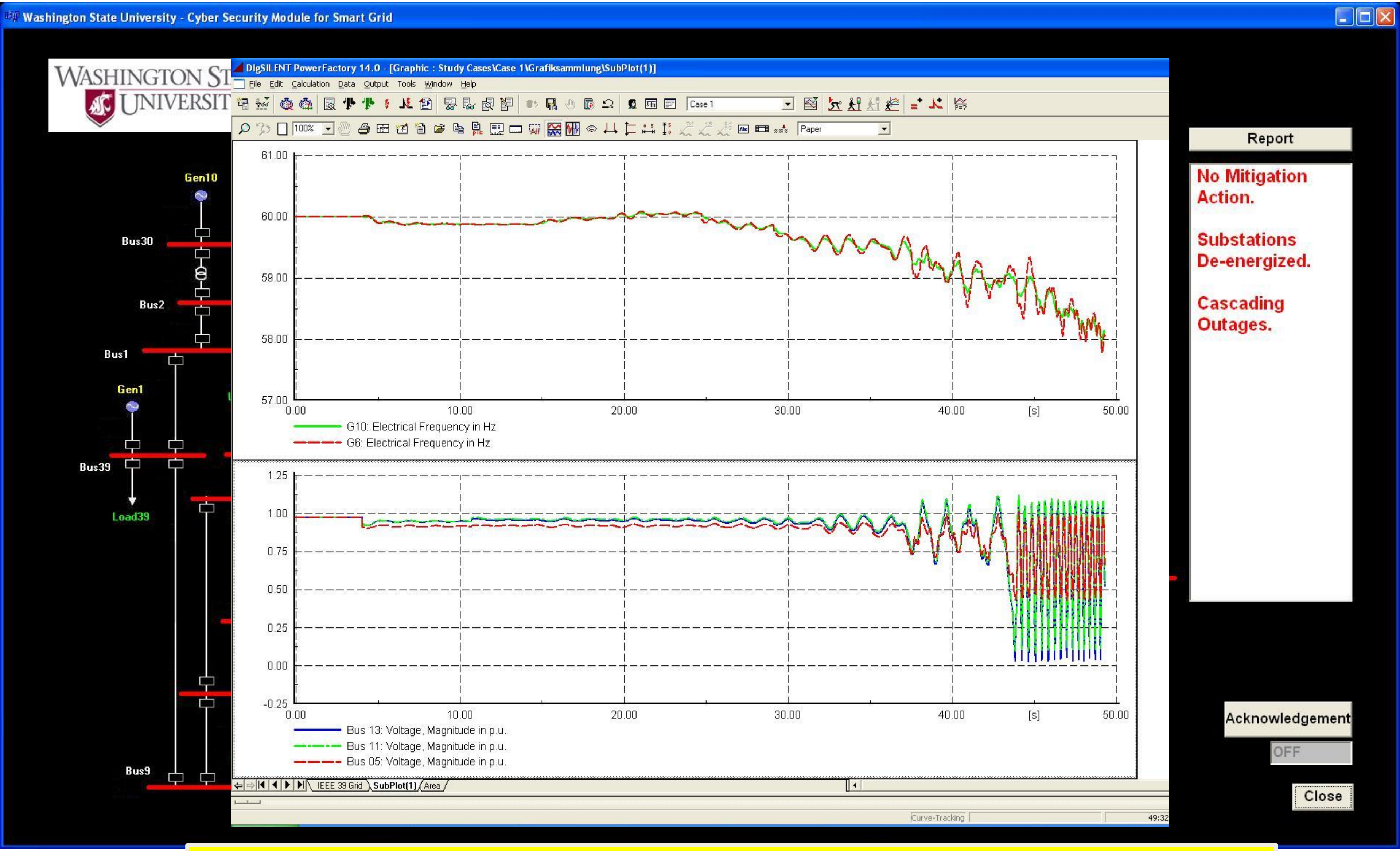
Sequential attacks – Sub # 6 → 12 → 15 → 28 → 36 → 33 → 34



Sequential attacks – Sub # 6 → 12 → 15 → 28 → 36 → 33 → 34

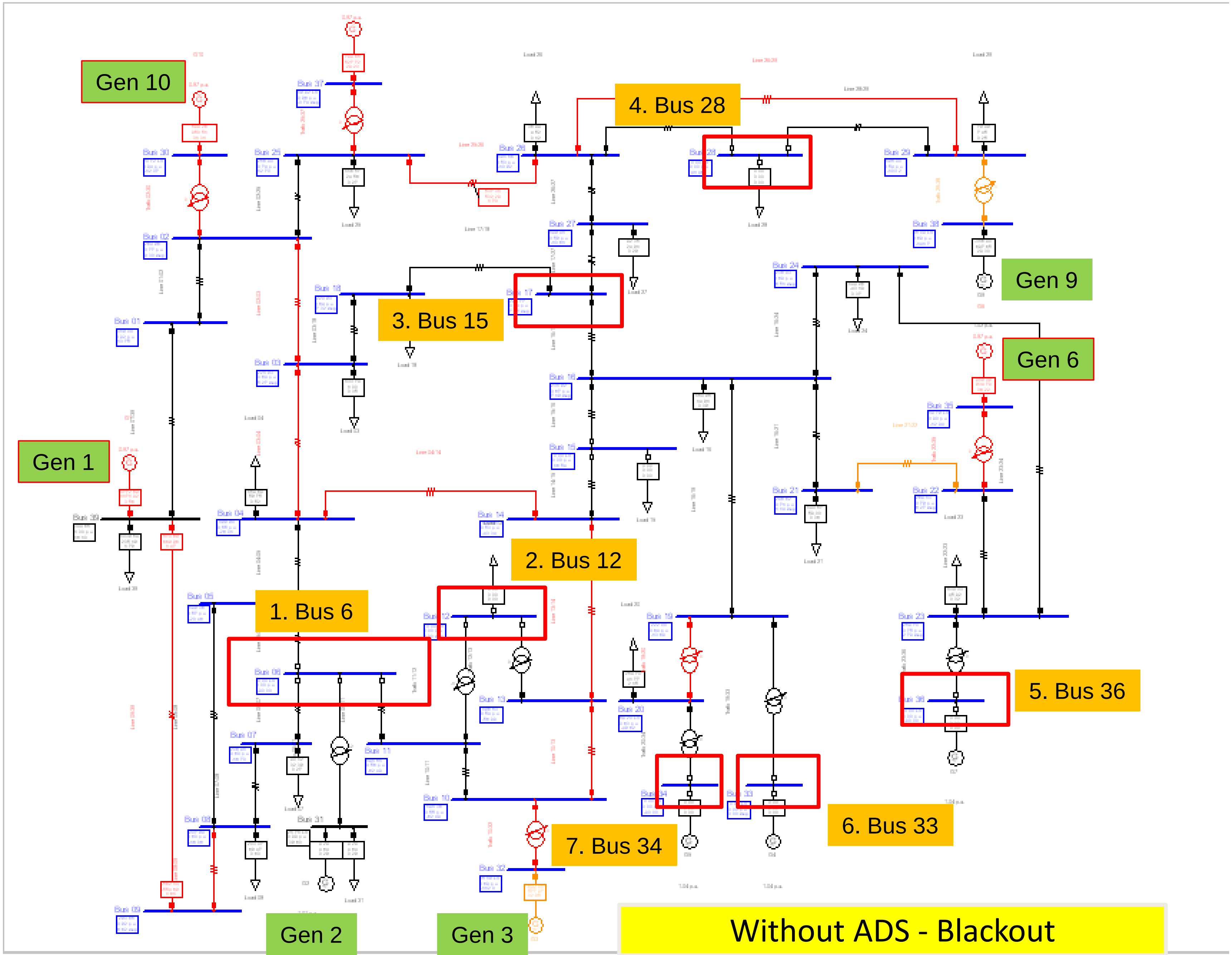


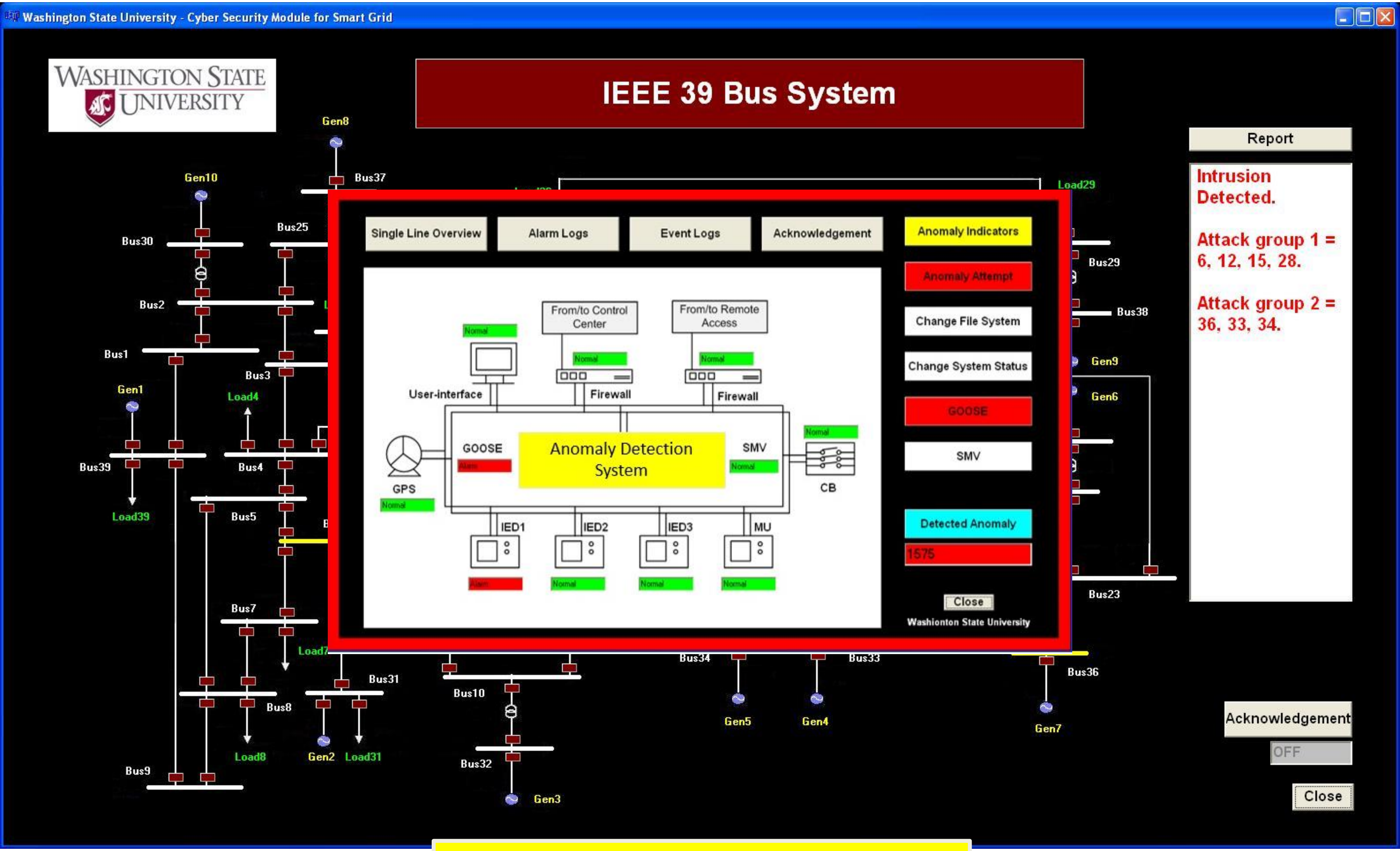
Sequential attacks – Sub # 6 → 12 → 15 → 28 → 36 → **33** → 34



Sequential attacks – Sub # 6 → 12 → 15 → 28 → 36 → 33 → **34**

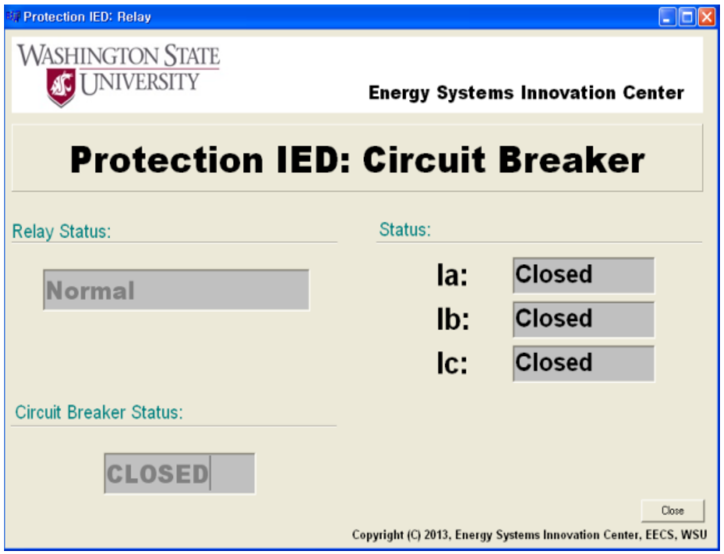
IEEE 39 Bus System (DIgSILENT)

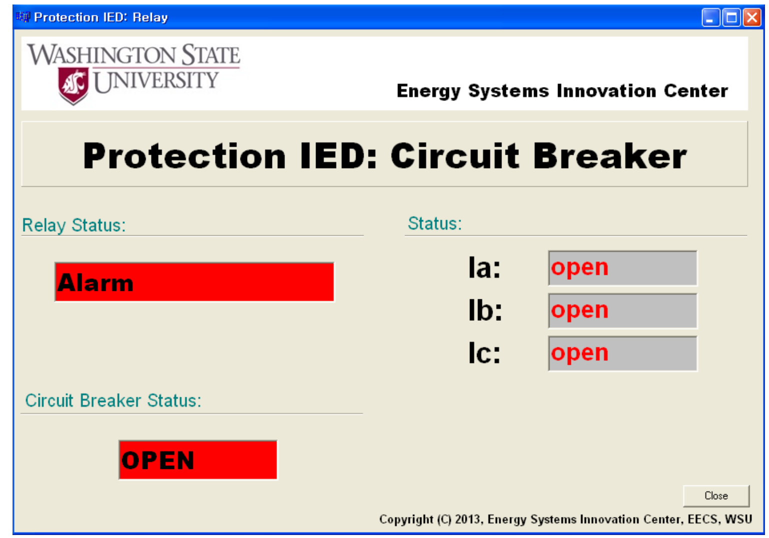


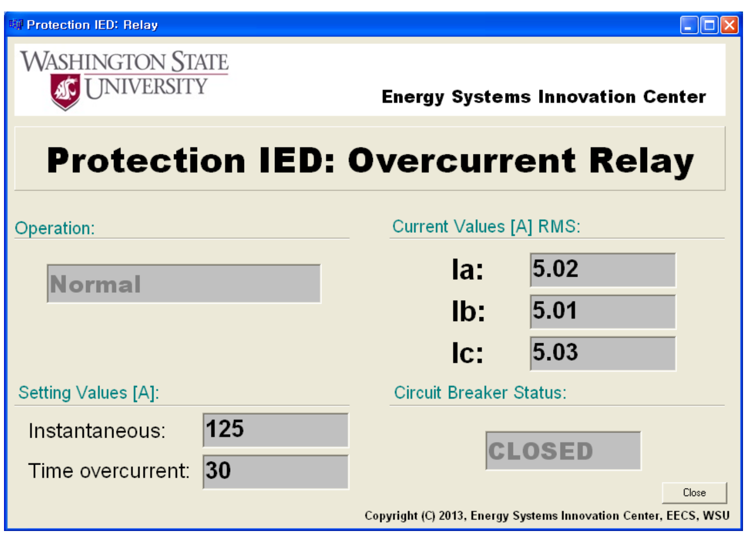


Sequential attacks with ADS

HMI


Protection IED: Relay
Washington State University
Energy Systems Innovation Center
Protection IED: Circuit Breaker
Relay Status:
Normal
Status:
Ia: Closed
Ib: Closed
Ic: Closed
Circuit Breaker Status:
CLOSED
Close
Copyright (C) 2013, Energy Systems Innovation Center, EECS, WSU


Protection IED: Relay
Washington State University
Energy Systems Innovation Center
Protection IED: Circuit Breaker
Relay Status:
Alarm
Status:
Ia: open
Ib: open
Ic: open
Circuit Breaker Status:
OPEN
Close
Copyright (C) 2013, Energy Systems Innovation Center, EECS, WSU


Protection IED: Relay
Washington State University
Energy Systems Innovation Center
Protection IED: Overcurrent Relay
Operation:
Normal
Current Values [A] RMS:
Ia: 5.02
Ib: 5.01
Ic: 5.03
Setting Values [A]:
Instantaneous: 125
Time overcurrent: 30
Circuit Breaker Status:
CLOSED
Close
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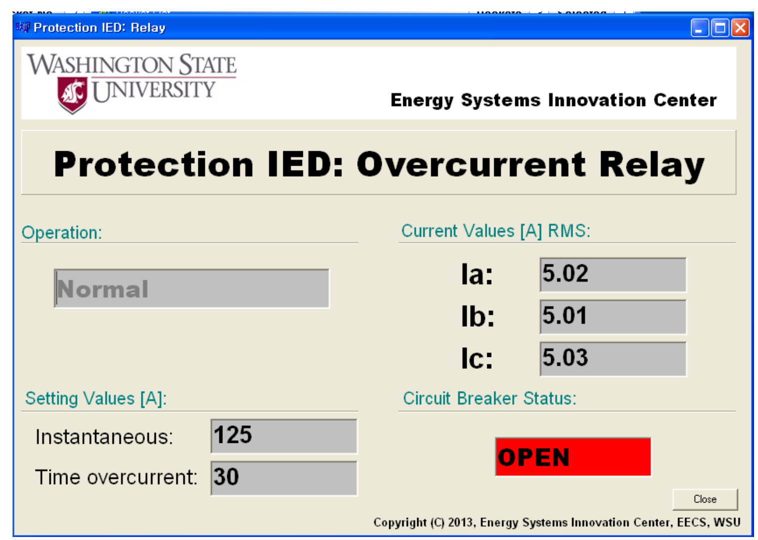
Protection IED: Relay
Washington State University
Energy Systems Innovation Center
Protection IED: Overcurrent Relay
Operation:
Normal
Current Values [A] RMS:
Ia: 5.02
Ib: 5.01
Ic: 5.03
Setting Values [A]:
Instantaneous: 125
Time overcurrent: 30
Circuit Breaker Status:
OPEN
Close
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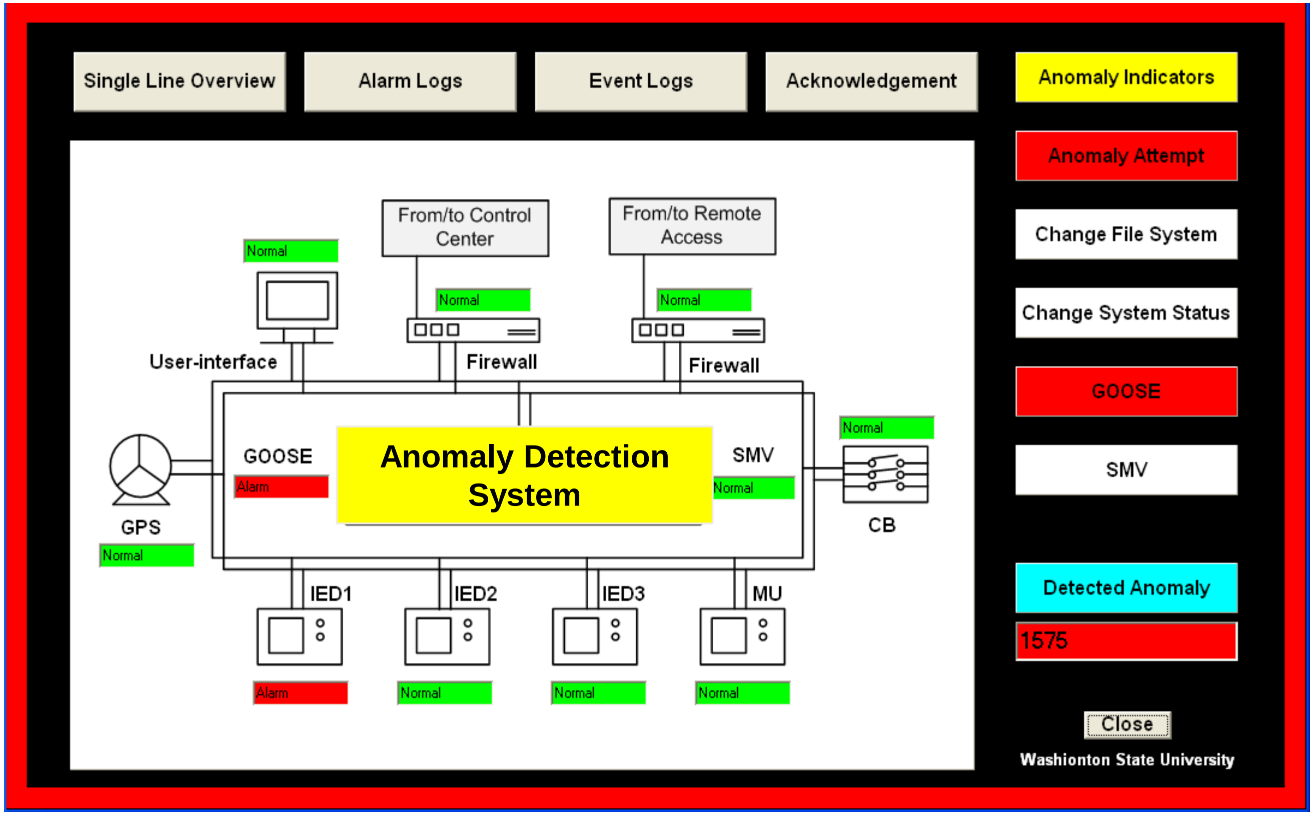
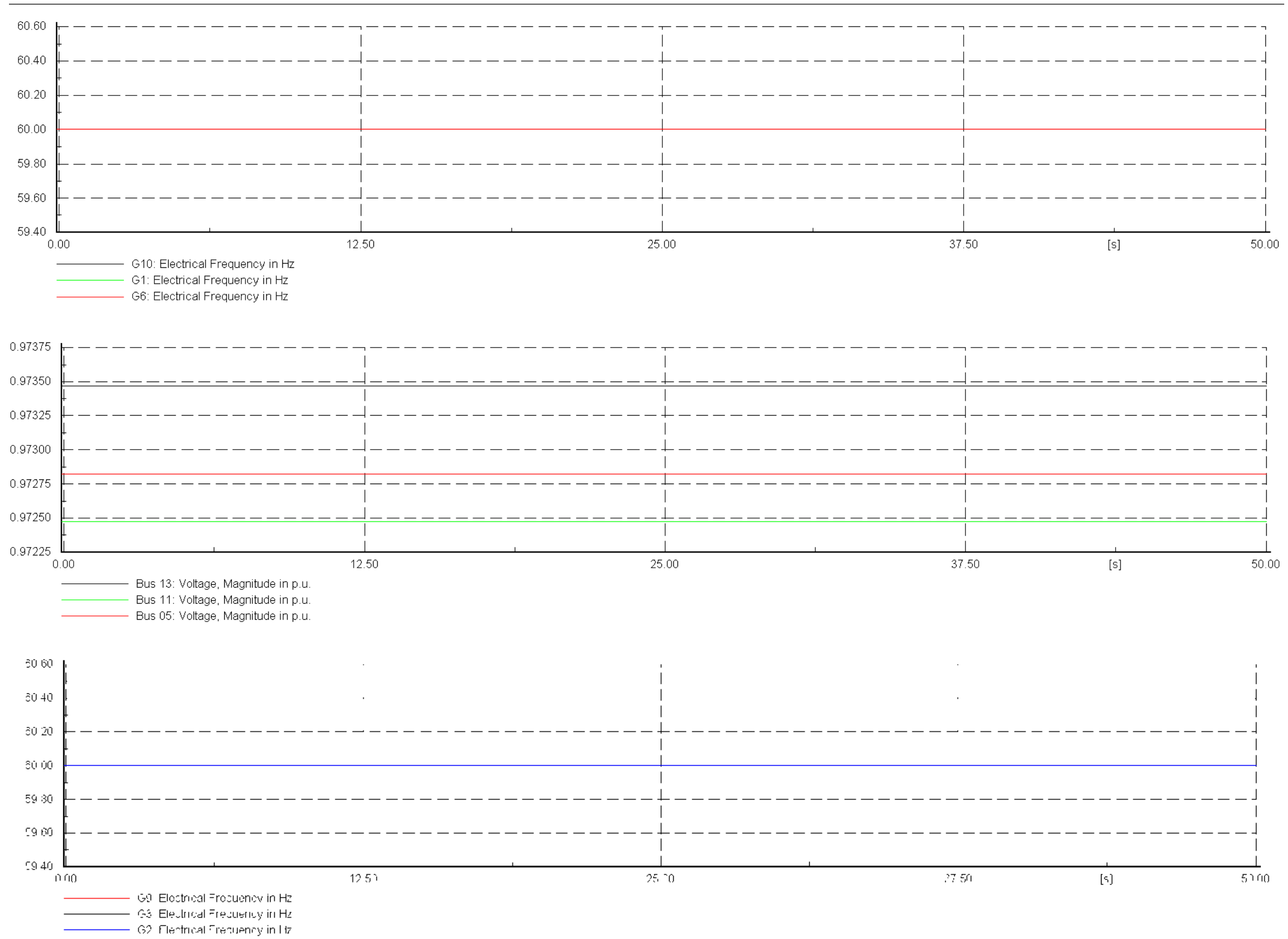
HMI

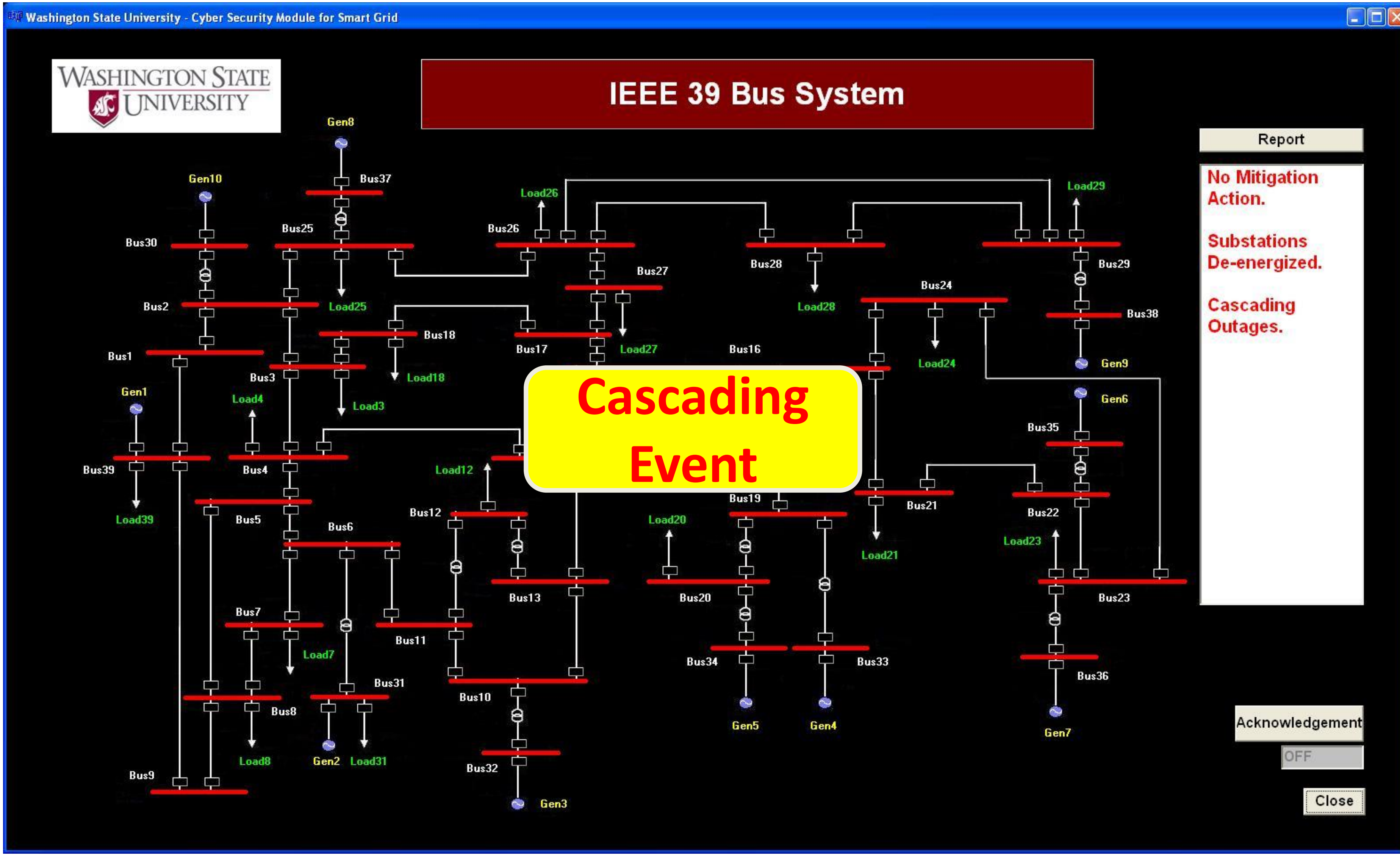

Single Line Overview
Alarm Logs
Event Logs
Acknowledgement
Anomaly Indicators
Anomaly Attempt
Change File System
Change System Status
GOOSE
SMV
Detected Anomaly
1575
Close
Washionton State University
From/to Control Center
From/to Remote Access
Normal
Normal
Normal
User-interface
Firewall
Firewall
GOOSE
Alarm
Anomaly Detection System
SMV
Normal
Normal
CB
GPS
Normal
IED1
IED2
IED3
MU
Alarm
Normal
Normal
Normal

IEEE 39 Bus System (DIgSILENT)

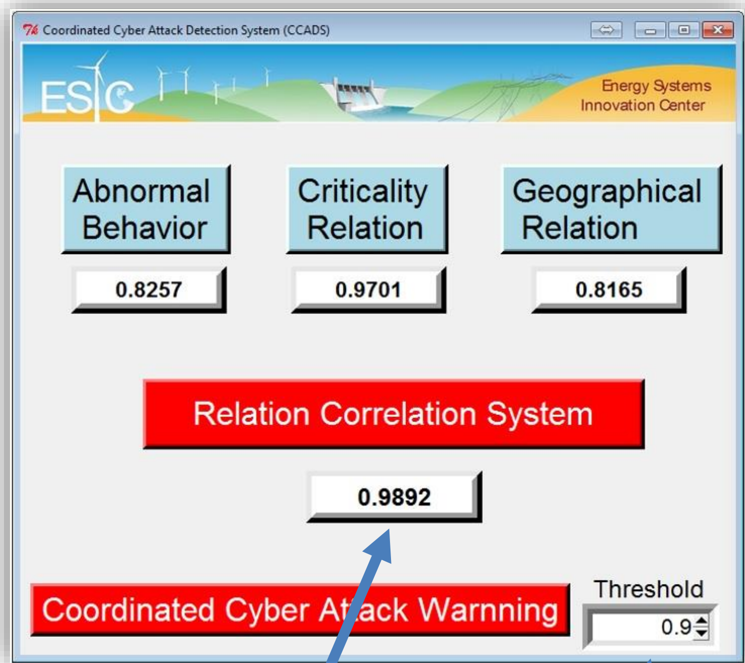


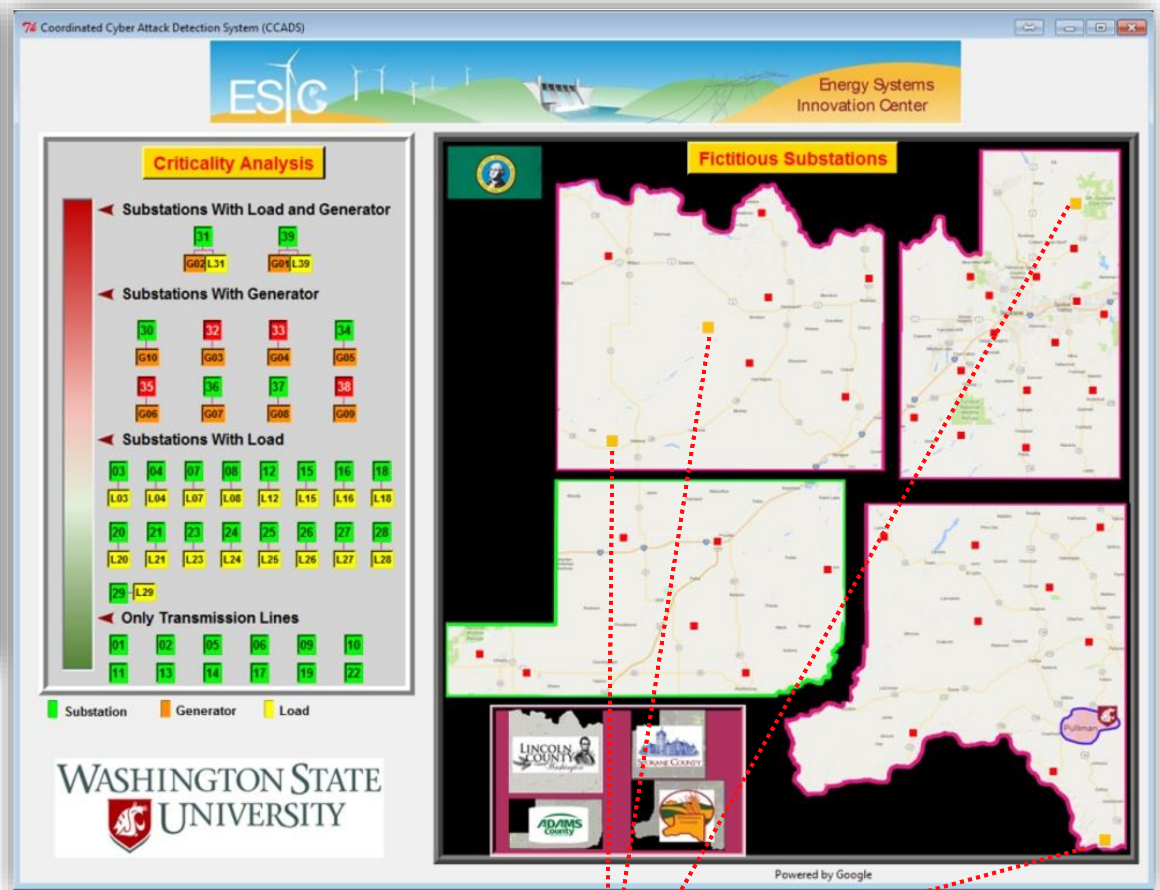
With ADS - Normal

Coordinated Cyber Attack



GUI of CCADS



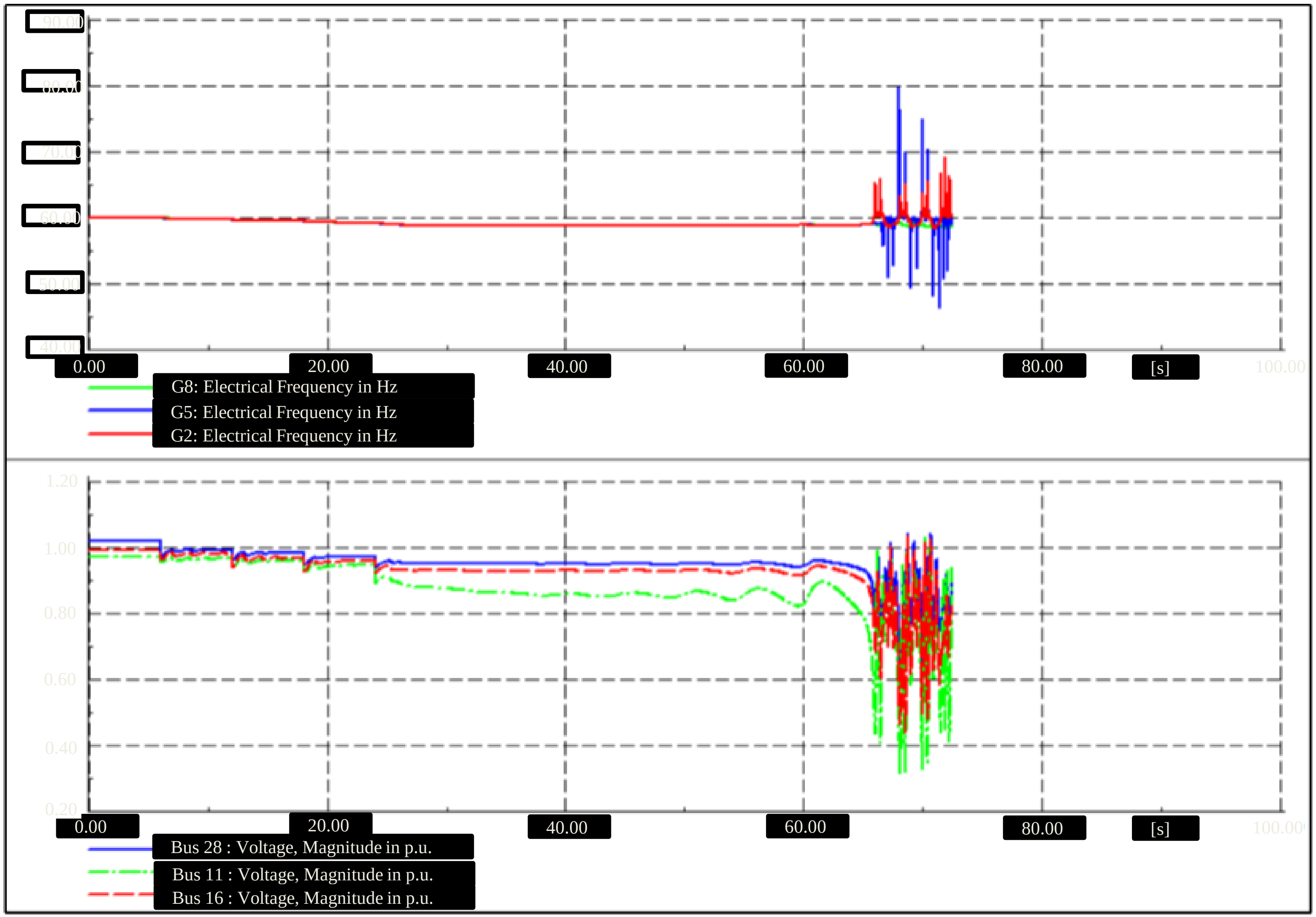


Similarity index

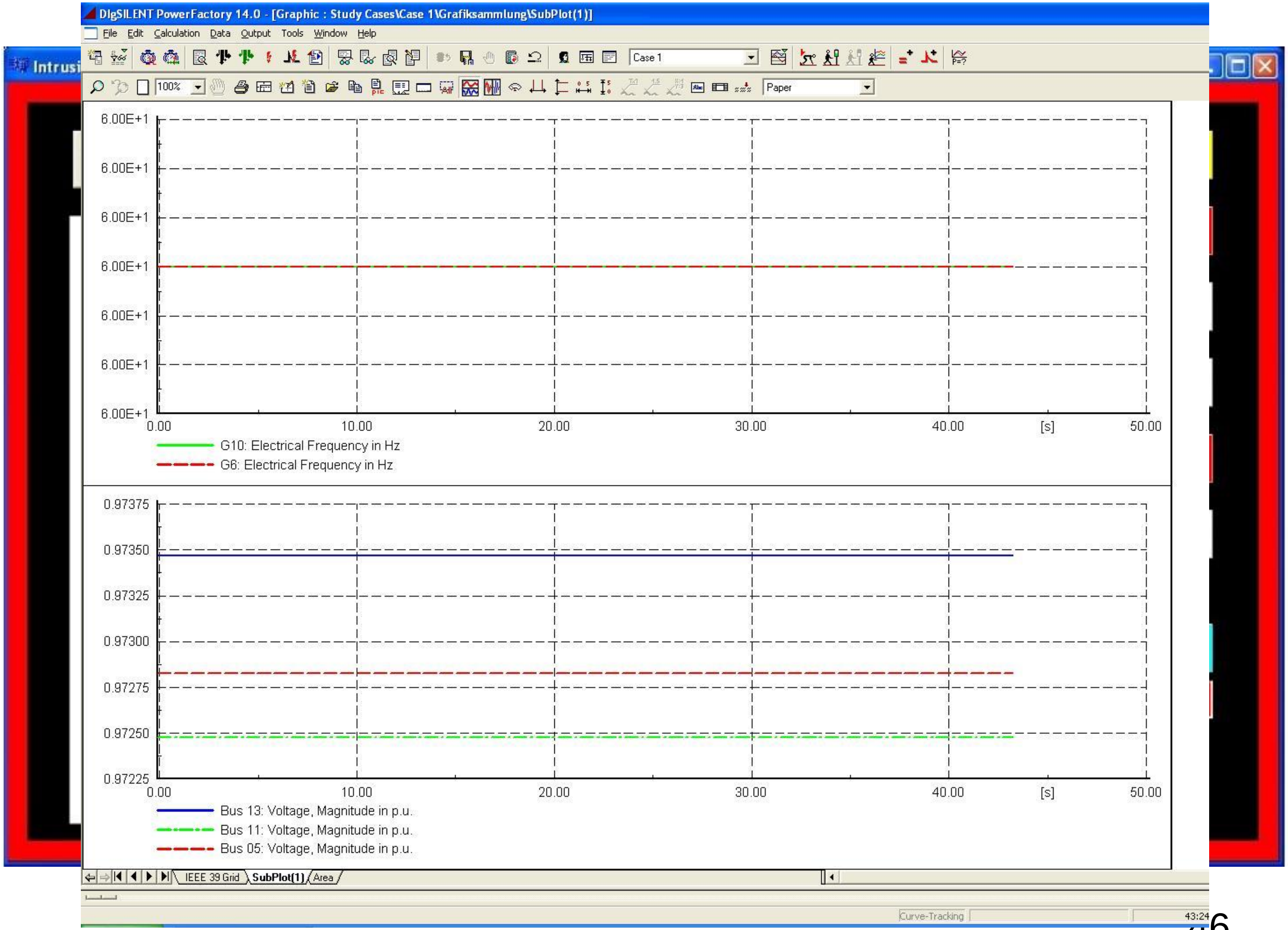
User defined threshold value

Compromised substations

Simulation of Power System



Intrusion Detection System



Further Information

[1] C. W. Ten, C. C. Liu, and M. Govindarasu, “Vulnerability Assessment of Cybersecurity for SCADA Systems,” *IEEE Trans. Power Systems*, Nov. 2008, pp. 1836-1846. [4] C. W. Ten, J. Hong, and C. C. Liu, “Anomaly Detection for Cybersecurity of the Substations,” *IEEE Trans. Smart Grid*, Dec 2011, pp. 865-873.

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