

# Vulnerability Assessment of Cybersecurity for SCADA Systems Using Attack Trees

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**Abstract**— By penetrating the SCADA system, an intruder may remotely operate a power system using supervisory control privileges. Hence, cybersecurity has been recognized as a major threat due to the potential intrusion to the online system. This paper proposes a methodology to evaluate the cybersecurity vulnerability using attack trees. The attack tree formulation based on power system control networks is used to evaluate the system, scenario, and leaf vulnerabilities. The measure of vulnerabilities in the power system control framework is determined based on existing cybersecurity conditions before the vulnerability indices are evaluated. After the indices are evaluated, an upper bound is imposed on each scenario vulnerability in order to determine the pivotal attack leaves that require countermeasure improvements. The proposed framework can be extended to security investment analysis.

**Index Terms**-- Attack Tree, Cybersecurity, Defense Systems, Power System Control, Security Vulnerability.

## I. INTRODUCTION

SINCE the September 11, 2001 terrorist attack, the level of vigilance has been raised to prevent attacks on power grids. Conventional design of power systems does not provide a power system with the protection against cyber attacks. The threats include sending control commands via the supervisory control system. Effects of a cyber attack include loss of production, degradation of the online control performance, and inability to take preventive and corrective actions in time. Damages caused by cyber attacks can be catastrophic.

The widespread interconnectivity of the power system control network poses significant risks to the nation's critical operations. Without proper control of these computer systems, individuals or organizations may disrupt the operations from remote locations for malicious purposes [1]. Recent findings include plans of terrorism to disrupt the U.S. power grid [2]. Recent NERC directives make it mandatory to undertake cybersecurity vulnerability assessment at the operator locations and to take corrective measures [3]. The NERC security document and ISO/IEC17799 Standard specify guidelines for cybersecurity in power systems [3-5]. In addition, computer crime and security survey conducted by the Computer Security Institute (CSI) indicated inadequate investment to security awareness training in utilities [6]. The lack of security awareness is increasingly problematic as the cyber attacks become more sophisticated. There have been novel contributions to identify vulnerability of cybersecurity for a power grid. A testbed has been set up in [7] with

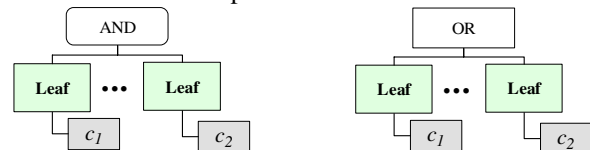
possible intrusion scenarios to recognize and mitigate the effect of attacks. In [8], a new threat is assumed in generation control that hackers could access to tamper with the generator control loop parameters. This may lead to destabilization and tripping of critical units on the power grid.

The contribution of this paper is an analytical method to measure the vulnerabilities of a control center and its related computer systems. An attack tree model is used as a framework to derive the quantitative vulnerability measures. Potential intrusion scenarios can be determined with different combinations of security breaches in order to penetrate the system. The penetration may allow an intruder to use SCADA control capabilities to take undesirable actions, causing serious damages. This paper provides a systematic procedure to evaluate vulnerability indices.

The remaining of this paper is organized as follows. Section II provides an overview of attack tree modeling and control center networks. The attack tree modeling and methodology is described in Section III. Section IV analyzes intrusion scenarios in case studies and provides examples of a quantitative vulnerability analysis. Pivotal attack leaves are determined by imposing an upper bound on the scenario vulnerability. Section VII is the conclusion and future research.

## II. ATTACK TREE MODELING

An attack tree is a graph that connects more than one attack leaf from each node [9-10]. An attack tree may consist of a multi-level hierarchy in a predecessor-successor structure that captures the possible ways to achieve sub-goals. The top node of an attack tree is the ultimate goal with combinations of sub-goals. Each attack leaf may include one or more defense nodes that are direct successors of the attack leaf. Defense nodes provide countermeasures. In Fig. 1(a), the box labeled  $c_1$  is a countermeasure for attack leaf on the left side. An attack leaf can be an element of different intrusion scenarios, depending on the node connectivity associated with it. The predecessors of each attack leaf are nodes that are attributed with logic operators "AND" or "OR." Each predecessor node is specific for the given leaf node. Fig. 1 shows attack trees with "AND" and "OR" configurations. All leaves lead to an AND box will have to be penetrated in order to move up the attack tree, i.e., a subsystem has been penetrated. On the other hand, in Figure 1(b), if one of the attack leaves is penetrated, it is sufficient to move up the attack tree.



(a) An attack leaf with logic operator "AND" (b) An attack leaf with logic operator "OR"  
Fig. 1. Attack Leaves with "AND" or "OR"

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### A. Control center communication networks

Fig. 2 shows the communication paths within power system control networks. Entities in the control center, substation automation system, distribution management system, Independent System Operator (ISO), and power plant process control system are interlinked. The interdependency of the communication and power system infrastructures plays an essential role to wide area monitoring and control. The communication link is an optical fiber network or a microwave system. Backup control centers provide coverage for disaster scenarios that may disable the primary control center, e.g., loss of data communication, critical monitoring and control facilities. In addition, Web-Based SCADA is the Internet-Based SCADA and application services to utility industry that provides convenient and low cost maintenance by out-sourcing the maintenance services. This is implemented using a client-server architecture though Internet.

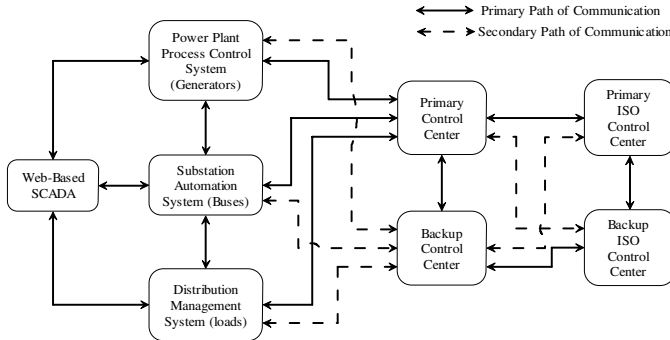


Fig. 2. Real-Time Communication within Power System Control Networks

The overall communication and computer infrastructure is complex. Deficiencies of security guidelines and policy enforcements may result in penetration to the networks. Vulnerability assessment for each entity is to identify the access points to the network as well as cyber assets. This includes comprehensive password policy enforcement and constant auditing of unused default ports available.

### B. Introduction to the methodology

A cybersecurity vulnerability index is a measure of the likelihood that an attack tree or attack leaf will be compromised by hackers [11]. Each attack leaf may have weaknesses that are prone to attack. The vulnerability index ranges from 0 to 1, from the most invulnerable (0 value) to the most vulnerable (1 value). There are separate vulnerability indices for each attack leaf and each intrusion scenario. There is also an overall system vulnerability index. All indices range from 0 to 1.

A vulnerability index is determined based on: (1) *evidence of attempted intrusions*; (2) *existing countermeasures and improved countermeasures* [12]; and (3) *password policy enforcement* [13]. The vulnerability index is evaluated with the hypothesis listed in Table I [14]. Three conditions are defined in Table I. Condition 1 states that there is no evidence to suggest that there are intrusion attempts for the system. Condition 1 is not met when there are credible evidences of malicious attempts based on electronic data. Condition 2 is

met when there are one or more countermeasures implemented for an attack leaf. Any technology that is applied to defend the attack leaf would satisfy condition 2. An example is a web server installed with a firewall that monitors the access to prevent malicious intrusions through online traffic. Password implementation for each attack leaf is considered for assessment. Poor password practices result in unauthorized access. A system can face the risks of unauthorized access, even though it may be password protected. Condition 2 and condition 3 may influence condition 1. For instance, implementation of the new technological countermeasures can reduce the likelihood of intrusions. Applying boundary protection in a firewall with a set of rules can also reduce access from anonymous users. This would reduce attempted intrusions and enhance system security. The other example is that condition 3, with stronger password policies, would also protect the system from being compromised. However, this does not change the number of attempts.

TABLE I  
RULES FOR CONDITIONS 1,2, AND 3

Conditions	Rules
Condition 1	The system is free of intrusion attempt that is concluded from the electronic evidences in the system.
Condition 2	At least one or more countermeasures are implemented to protect an attack leaf.
Condition 3	At least one or more password policies are enforced corresponding to each attack leaf.

### III. VULNERABILITY ASSESSMENT OF CYBERSECURITY

The procedure to evaluate vulnerability indices is depicted in Fig. 3. As shown in the figure, the procedure starts with an analysis of the attack objectives. Then the attack tree and countermeasures are established. The *system* vulnerability index is obtained by evaluating the *scenario* vulnerability and the *leaf* vulnerability for selected scenarios and the corresponding attack leaves.

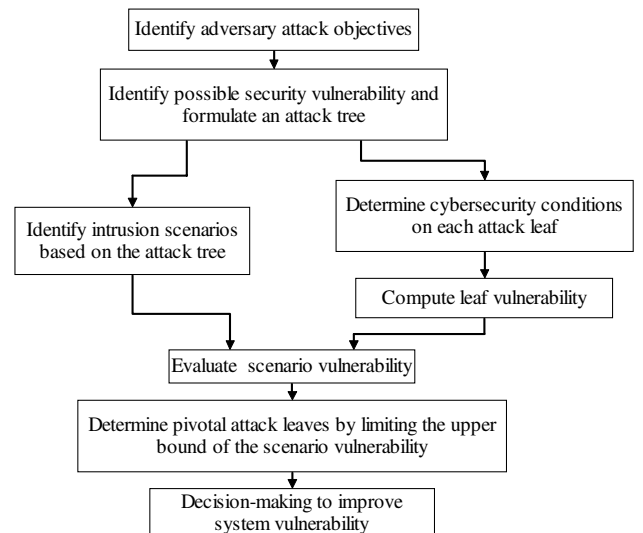


Fig. 3. Procedure to Evaluate Vulnerability Indices

This section describes the procedure to evaluate the vulnerability indices: (a) cybersecurity conditions, and (b) evaluation of vulnerability indices.

#### A. Cybersecurity conditions

This section evaluates the cybersecurity conditions,  $\omega$ , that is a preliminary evaluation before the specific vulnerability indices related to leaves and scenarios are calculated. The cybersecurity condition assessment is based on technological countermeasures and enforcement of the password policy.

The cybersecurity condition is measured by a number  $\omega$ , that assumes the values of 0, 0.5, or 1. The value 0 indicates that the system condition is invulnerable while value 1 indicates the system is vulnerable.

1)  $\omega=0.00$ :

If [(Condition 1) AND (Condition 2) AND (Condition 3)], then  $\omega=0.00$

→ All conditions in Table I are satisfied. Advanced countermeasures are deployed and comprehensive password policies are enforced. There is no evidence that the system is subject to malicious attempts.

2)  $\omega=0.50$ :

If <[(Condition 1) AND (Condition 2)] OR [(Condition 1) AND (Condition 3)] OR [(Condition 2) AND (Condition 3)]>, then  $\omega=0.50$

→ Any two of the conditions in Table I are satisfied.

3)  $\omega=1.00$ :

If [(Condition 1) OR (Condition 2) OR (Condition 3)] OR (None of the condition)], then  $\omega=1.00$

→ Only one of the conditions is met or,

→ None of the conditions are satisfied.

#### B. Evaluation of vulnerability indices

This section is concerned with the cybersecurity vulnerability of an attack tree. There are four steps to assess the security vulnerability: (1) Identifying the intrusion scenarios, (2) Evaluating vulnerability indices for the system, intrusion scenarios, and attack leaves, (3) Evaluating security improvements, and (4) Identifying the pivotal leaves.

##### 1) Identifying the intrusion scenarios from the attack tree:

First, the intrusion scenarios from the attack tree are identified. Then, the possible intrusion scenarios are enumerated. Each of the intrusion scenarios is the combination of attack leaves that are formed with “AND” or “OR” attributes configured in the attack tree. The leaf vulnerability index  $v(G_k)$  of each attack leaf is evaluated once all the intrusion scenarios are determined. The scenario vulnerability is the product of the corresponding attack leaf vulnerabilities.

##### 2) Evaluating vulnerability indices:

There are three security vulnerability indices: (i) system vulnerability, (ii) scenario vulnerability, and (iii) leaf

vulnerability. The system vulnerability,  $V_s$ , is the vulnerability of an attack tree determined from the scenario vulnerability, as shown in (1).  $K$  is the total number of intrusion scenarios. A vector of scenario vulnerabilities is given in (2) where  $I = \{i_1, i_2, \dots, i_k\}$  is a set of intrusion scenarios. The  $V_s$  is determined from the maximum value of the scenario vulnerability set. Each intrusion scenario is a possibility that leads to successful penetration of the system. The vulnerability of a scenario is the product of leaf vulnerabilities where each scenario vulnerability is formed with a different subset of  $S$ . Scenario vulnerability indices are given in (3) where  $s_1, s_2, \dots, s_k \in S$  and  $S = \{1, 2, \dots, n\}$ . The symbol  $s$  represents an index subset of  $S$  that is the universal index set of attack leaves and  $n$  is the total number of attack leaves.

$$V_s = \max\{V(i_1), V(i_2), \dots, V(i_k)\} = \max(\mathbf{V}(I)) \quad (1)$$

$$\mathbf{V}(I) = [V(i_1) \ V(i_2) \ \dots \ V(i_k)]^T \quad (2)$$

$$\mathbf{V}(I) = \begin{bmatrix} V(i_1) = \prod_{j \in s_1} v(G_j) \\ V(i_2) = \prod_{j \in s_2} v(G_j) \\ \vdots \\ V(i_k) = \prod_{j \in s_k} v(G_j) \end{bmatrix} \quad (3)$$

A leaf vulnerability is evaluated by (4). The cybersecurity condition number  $\omega$  must be identified first. The basis for evaluation is to pre-determine the leaf vulnerability condition with respect to the evidence of attempted intrusions, technological countermeasures, and password policy enforcement, which was discussed in Section III(A). To evaluate the strength of technological countermeasures, the total number of countermeasure types is determined, which is denoted by a constant 5 in (4). Then, the ratio between the countermeasures implemented at the specific attack leaf to the total number of countermeasure types is determined, where  $n_{c,T}$  is the number of countermeasures types implemented at an attack leaf [12]. The strength of the ratio is deducted from 1 to convert it to the vulnerability ratio.

$$v(G_k) = \begin{cases} \max\{ \omega \cdot (1 - (n_{c,T}/5)), \omega \cdot \max\{\Theta(C^p)\} \} & , \omega > 0 \\ \max\{ (1 - (n_{c,T}/5)), \max\{\Theta(C^p)\} \} / 3 & , \omega = 0 \end{cases} \quad (4)$$

Second, the weighting factor of the password policy enforcement is evaluated. Each password policy should be assigned with a value  $\Theta(C^p)$  based on Table II. The weight assignment of the password policy enforcement indicates the level of difficulty to crack the password. In Table II, an increment of (approximately) 0.33 point starting from the strong password policies of 0 value for  $\Theta(C^p)$  is used. The strongest password policies deter or prolong the cracking process. Neither brute-force trials nor social engineering techniques can break through in a short period of time.

The highest weight assignment of the password policy enforcement is taken as the measure that would be the most vulnerable of the set. The notation  $C^P$  represents the set of four levels of password policies as shown in Table II. If the password policy enforcement has a password length of more than 8 characters long, then  $\Theta(c^P) = 0.00$ . If the factory default password is not removed, then  $\Theta(c^P) = 0.67$ . The overall value of  $\Theta(c^P)$  is the maximum among the password policy levels that are applicable for the specific attack leaf, i.e.,  $\max\{\Theta(C^P)\} = 0.67$ .

In (4), for  $\varpi > 0$ , the final evaluation of leaf vulnerability is based on the more vulnerable of the two measures, which is the higher value among the two sets,  $C^P, C^T \in C$  where  $C^P \not\subset C^T$ , and  $C^T \not\subset C^P$ . On the other hand, for  $\varpi = 0$ , the more vulnerable of two countermeasures is divided to reflect the fact that 3 measures are used for cybersecurity conditions, i.e., evidence of malicious attempts, technology countermeasures, and password policy enforcement.

### 3) Evaluating security improvements

Security improvement can be achieved by a replacement or additional countermeasures. The improvements for an attack leaf and intrusion scenario can be measured with the implementation of the defense nodes denoted as  $v'(G)$  and  $v'(i)$  respectively, for the leaf and scenario vulnerability after an improvement is implemented. The degree of improvement for a leaf vulnerability is given by  $\left| \frac{v'(G) - v(G)}{v(G)} \times 100\% \right|$  and similarly for scenario improvement.

### 4) Determine the pivotal leaves

The system vulnerability is evaluated based on (2). Improvements of the leaf vulnerability can lead to higher system vulnerability. To identify the pivotal leaves for system vulnerability enhancement, an optimization problem is proposed:

$$\min V_s \quad (5)$$

s.t.

$$\mathbf{V}(I) \leq \bar{\mathbf{V}}(I) \quad (6)$$

$$\mathbf{v}(G) \leq \bar{\mathbf{v}}(G) \quad (7)$$

$$\text{where } 0 \leq \mathbf{v}(G), \mathbf{V}(I) \leq 1$$

The combination of scenario vulnerability is subject to the configuration of an attack tree because system vulnerability is expressed as a function of scenario vulnerability. The objective of this formulation is to minimize system vulnerability by lowering the upper bound of the scenario vulnerability,  $\bar{\mathbf{V}}(I)$ . By doing so, the pivotal leaf combination for system improvement is determined. The

improvement is observed through changes in  $\bar{\mathbf{V}}(I)$ . A uniform upper bound for all leaf nodes can be enforced, such as 0.5 for all leaves. The vector of upper bounds  $\bar{\mathbf{v}}(G)$  is then a vector with all elements equal to 0.5. This is to ensure the least secured leaf nodes are properly enforced. The pivotal leaves are the leaf nodes in  $\mathbf{v}(G)$  with a reduced value compared to the corresponding values before the upper bounds are reduced.

TABLE II  
WEIGHT ASSIGNMENT FOR PASSWORD POLICY ENFORCEMENT

Descriptions	$\Theta(c^P)$
<u>Absence of password policies</u>	1.00
<ul style="list-style-type: none"> <li>▪ No password exists for a user account</li> <li>▪ Existence of a guest account that is known to many, e.g., the password is the same as username</li> </ul>	
<u>Poor password policies</u>	0.67
<ul style="list-style-type: none"> <li>▪ With factory default password</li> <li>▪ Set with combination of username, company name, date of birth, that is possible to crack using social engineering</li> </ul>	
<u>Good password policies</u>	0.33
<ul style="list-style-type: none"> <li>▪ Password length with 7 characters long</li> <li>▪ Implement maximum password age</li> </ul>	
<u>Comprehensive password policies</u>	0.00
<ul style="list-style-type: none"> <li>▪ The old passwords are not allowed for new password change</li> <li>▪ 4-character categories of combination (A-Z, a-z, 0-9, !@# (non-alphabetic characters))</li> <li>▪ Password length with 8 characters or longer</li> <li>▪ Enforce a password age to less than 3 months</li> </ul>	

## IV. CASE STUDIES

The methodology proposed in the previous section is applied to study cases here. The purpose is to identify the access points of power system control networks and evaluate the network vulnerability. The objective of the proposed attack tree is focused on penetration of the control center intranet from others, e.g., substation intranet with Virtual Private Network (VPN) connection. An attack tree based on Fig. 2 is constructed; the case studies are subject to specific business practices. The model incorporates the existence of factory default password and insufficient security improvement [16]. The attack leaves include countermeasures to improve the system vulnerability.

An attack tree illustrated in Fig. 4 consists of disruptions through a power plant, substation, or web-based SCADA. The disruptions include sabotage on computer systems and power systems. These combinations may result in an intrusion into the control center. To derive the scenario combination, groups of attack leaves are arranged as follows:

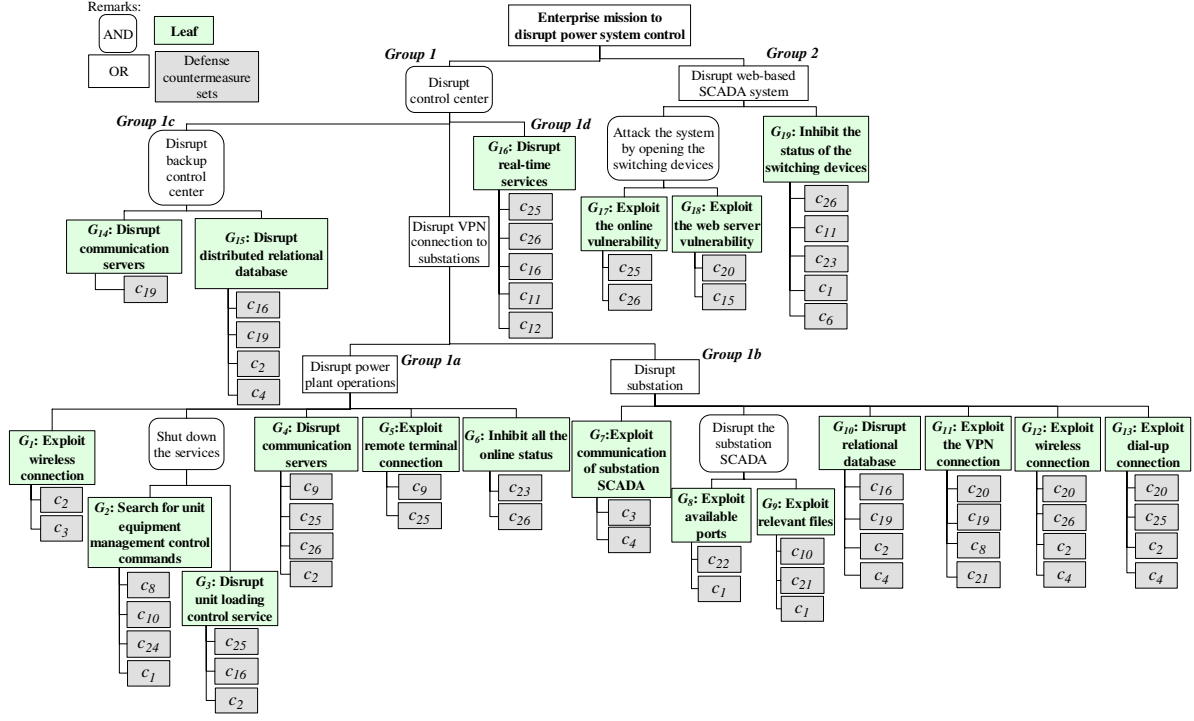


Fig. 4. Attack Tree of Power System Control Framework

$$\begin{aligned}
 & \text{Group 1a: } \begin{bmatrix} G_1 \\ G_2 \times G_3 \\ G_4 \\ G_5 \\ G_6 \end{bmatrix}; \text{ Group 1b: } \begin{bmatrix} G_7 \\ G_8 \times G_9 \\ G_{10} \\ G_{11} \\ G_{12} \\ G_{13} \end{bmatrix}; \\
 & \text{Group 1c: } [G_{14} \times G_{15}]; \text{ Group 1d: } [G_{16}]; \\
 & \text{Group 2: } \begin{bmatrix} G_{17} \times G_{18} \\ G_{19} \end{bmatrix}
 \end{aligned}$$

$$\begin{aligned}
 & \prod_{i=1,14,15,16} G_i \rightarrow i_1 \quad \prod_{i=2,3,14,15,16} G_i \rightarrow i_2 \quad \prod_{i=4,14,15,16} G_i \rightarrow i_3 \\
 & \prod_{i=5,14,15,16} G_i \rightarrow i_4 \quad \prod_{i=6,14,15,16} G_i \rightarrow i_5 \quad \prod_{i=7,14,15,16} G_i \rightarrow i_6 \\
 & \prod_{i=8,9,14,15,16} G_i \rightarrow i_7 \quad \prod_{i=10,14,15,16} G_i \rightarrow i_8 \quad \prod_{i=11,14,15,16} G_i \rightarrow i_9 \\
 & \prod_{i=12,14,15,16} G_i \rightarrow i_{10} \quad \prod_{i=13,14,15,16} G_i \rightarrow i_{11} \quad \prod_{i=17,18} G_i \rightarrow i_{12} \\
 & \prod_{i=19} G_i \rightarrow i_{13}
 \end{aligned} \tag{8}$$

where  $i_1, i_2, \dots, i_{13} \in I$

Each group represents the security flaw of a sub-network from power plant, substation networks, and web-based SCADA system. Groups 1a and 1b represent a disruption of power plant operations and substation automation. Security breaches in these groups may also result in penetration to the control center. Groups 1c and 1d represent a disruption of the backup control center and real-time services in the primary control center. The importance of a backup control center is to take over functions of the primary control center under extreme circumstances. Communication, relational database, and real-time application services in control centers are critical elements. Group 2 represents the disruption of Web Based SCADA system where security breaches in a web server may be exploited by intruders.

Each intrusion scenario is derived from attack leaves, where  $G_1, G_2, \dots, G_{19}$  are attack leaves. Intrusion scenarios are expressed as follows:

These attack leaves include countermeasures that can be technological countermeasures or password policy enforcements. The description of each countermeasure is listed in the Appendix. The sets  $C^P = \{c_1, c_2, \dots, c_7\}$  and  $C^T = \{c_8, c_9, \dots, c_{26}\}$  are countermeasure sets for password and technological countermeasure, while  $C = \{c_1, c_2, \dots, c_{26}\}$  is the universal countermeasure set.

$\mathbf{v}(G)$  and  $\mathbf{v}'(G)$  are computed in accordance with the configuration of the attack tree; the results are given in the Appendix. The leaf vulnerability and its improvement are depicted in Figs. 5(a) and (b). The vulnerability improvement for each attack leaf is depicted in Fig. 5(b). By eliminating the factory default password and enhancing security countermeasures, the leaf vulnerability has been improved. According to (4), the number of countermeasures types implemented at an attack leaf is essential because it influences the vulnerability of a leaf. Attack leaves 5 and 17 do not

improve if the same technological countermeasure is implemented on that attack leaf. (The improvement is based on the same countermeasure technology, i.e., access control.) Attack leaf 3 has the greatest improvement. This is due to the combination of technological countermeasure types and elimination of the guest account. Eliminating the factory default password and guest account improved the leaf vulnerability.

In the next step,  $\mathbf{V}(I)$  and  $\mathbf{V}'(I)$  are evaluated using (3). Each intrusion scenario is the product of attack leaves in (8). The scenario vulnerability is plotted in Fig. 6. Note that the logarithmic scale is used in Fig. 6(a) to highlight the difference between  $\mathbf{V}(I)$  and  $\mathbf{V}'(I)$ . As shown in Fig. 6(a), the first 11 intrusion scenarios have a greater improvement. However, intrusion scenarios 12 and 13 do not show much improvement. Fig. 6(b) shows vulnerability improvement for each intrusion scenario. Finally, the system vulnerability indices before and after the improved countermeasures are implemented,  $V_s$  and  $V'_s$ , respectively, are determined from  $\mathbf{V}(I)$  and  $\mathbf{V}'(I)$ . The system vulnerability indices,  $V_s$  and  $V'_s$ , are 0.33 and 0.13, respectively.

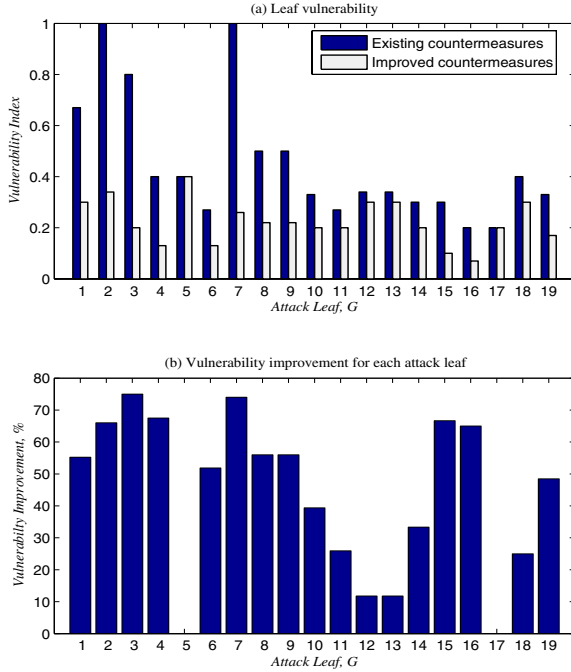


Fig. 5. Leaf Vulnerability with Existing and Improved Countermeasures

It is desirable to identify critical attack leaves that are influential for the improvement of system vulnerability. Table III shows the numerical results based on (5)-(7). The upper bound of the  $\bar{\mathbf{v}}(G)$  is set to 0.5 which represents an intermediate level of vulnerability. Table III shows the required changes for each attack leaf with a different upper bound of scenario vulnerability shown in each column. The highlights are changes from the output of optimization. By

limiting  $\bar{\mathbf{v}}(I)$  from 1 to 0.000001, it is seen that attack leaves 7, 15, 16, 17, 18, 19 are the pivotal leaves to improve the security measure in order to satisfy  $\bar{\mathbf{v}}(I)$ .

## V. CONCLUSION AND FUTURE WORK

The proposed methodology can be used to systematically evaluate the vulnerability and improvements based on cybersecurity conditions, technological countermeasures, and password policy enforcement. Security improvement of an attack tree depends on the total number of countermeasure types and password policy enforcement on each attack leaf. Case studies of the power system control networks have been performed to determine the vulnerability indices. To avoid manual, exhaustive search on each attack leaf, an optimization problem is formulated that can be solved to determine pivotal leaves for security improvements.

The formulation of attack trees does not capture the sequence in which attack leaves are penetrated in a scenario, however, an attack tree can be used as the foundation to emulate penetration testing, confirm the hypothesis, and study security flaws. Besides, attack trees can include budgetary constraints to evaluate system vulnerability that determines the optimal security investment based on this framework.

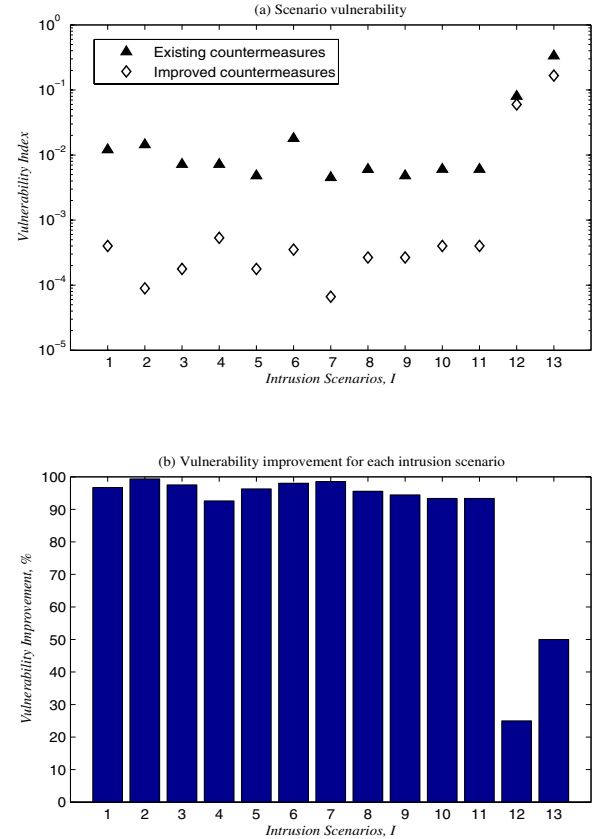


Fig. 6. Scenario Vulnerability with Existing and Improved Countermeasures

$\bar{\mathbf{v}}(I)$	1	0.01	0.0001	0.000001
$v(G_I)$	0.3611	0.3611	0.4355	0.4407
$v'(G_I)$	0.2000	0.2000	0.1995	0.1980

$v(G_2)$	0.0000	0.2890	0.2744	0.2733
$v'(G_2)$	0.2200	0.2200	0.2200	0.2196
$v(G_3)$	0.2600	0.2600	0.2573	0.2561
$v'(G_3)$	0.2000	0.2000	0.2000	0.1996
$v(G_4)$	0.2600	0.2600	0.2529	0.2508
$v'(G_4)$	0.1300	0.1300	0.1300	0.1280
$v(G_5)$	0.2600	0.2600	0.2529	0.2508
$v'(G_5)$	0.2600	0.2412	0.2486	0.2580
$v(G_6)$	0.2700	0.2700	0.2629	0.2608
$v'(G_6)$	0.1300	0.1300	0.1300	0.1280
$v(G_7)$	0.3300	0.2700	0.0961	0.0940
$v'(G_7)$	0.3877	0.0000	0.0000	0.0000
$v(G_8)$	0.3300	0.3300	0.3276	0.3270
$v'(G_8)$	0.2200	0.2200	0.2200	0.2196
$v(G_9)$	0.3300	0.3300	0.3276	0.3270
$v'(G_9)$	0.2200	0.2200	0.2200	0.2196
$v(G_{10})$	0.3300	0.3300	0.3229	0.3208
$v'(G_{10})$	0.2000	0.2000	0.1995	0.1980
$v(G_{11})$	0.2700	0.2700	0.2629	0.2608
$v'(G_{11})$	0.2000	0.2000	0.1995	0.1980
$v(G_{12})$	0.2200	0.2200	0.2129	0.2108
$v'(G_{12})$	0.2000	0.2000	0.1995	0.1980
$v(G_{13})$	0.2200	0.2200	0.2129	0.2108
$v'(G_{13})$	0.2000	0.2000	0.1995	0.1980
$v(G_{14})$	0.0000	0.0000	0.0000	0.0000
$v'(G_{14})$	0.0923	0.0923	0.0996	0.1007
$v(G_{15})$	0.0000	0.0000	0.0000	0.0000
$v'(G_{15})$	0.0000	0.0000	0.0048	0.0000
$v(G_{16})$	0.0000	0.0000	0.0000	0.0000
$v'(G_{16})$	0.0000	0.0000	0.0048	0.0000
$v(G_{17})$	0.0000	0.0000	0.0000	0.0000
$v'(G_{17})$	0.0000	0.0000	0.0000	0.0000
$v(G_{18})$	0.1062	0.1363	0.1238	0.1238
$v'(G_{18})$	0.0000	0.0000	0.0000	0.0000
$v(G_{19})$	0.0000	0.0000	0.0000	0.0000
$v'(G_{19})$	0.0000	0.0000	0.0000	0.0000

## VI. Appendix

$C$	Descriptions
$c_1$	Eliminate guest account
$c_2$	Eliminate factory default password
$c_3$	Implement password age
$c_4$	4-character categories of combination password policy is enforced
$c_5$	Enforce a password age less than 3 months
$c_6$	Implement password length at least 8 characters
$c_7$	Increase password change frequency
$c_8$	Install computer forensic tools
$c_9$	Implement biometric for authentications
$c_{10}$	Install integrity checkers to monitor alternations to system files
$c_{11}$	Implement patch management system to update security patches available
$c_{12}$	Install antivirus software
$c_{13}$	Install content management to monitor web and messaging applications
$c_{14}$	Set the rule of the IP address that is allowed

$c_{15}$	Implement digital certificates
$c_{16}$	Monitor the security event logs to determine malicious operations
$c_{17}$	Configure different port of the services
$c_{18}$	Document and audit the use of each static IP addresses
$c_{19}$	Install intrusion detection system to monitor the traffic within the network
$c_{20}$	Enhance with the policy of firewall in substation LAN
$c_{21}$	Eliminate administrative right to limited users like vendors who can change the configuration
$c_{22}$	Install network analyzer to monitor malicious traffic
$c_{23}$	Install a redundant system in case of urgent need to switch
$c_{24}$	Install a scanner to identify malicious traffic of the network
$c_{25}$	Install smart tokens to establish strong authentication
$c_{26}$	Audit the user rights that contain privileges accessing critical commands

### Improved Countermeasures Set Used for Each Attack Leaf and Descriptions

Attack Leaf	Evidence of Attempted Intrusion	Technological Countermeasures	Password Policy Enforcement
1	Malicious attempt detected	Firewall	Factory default password remains
		Antivirus	
2	Absence of malicious attempt	Authentication	Guest account
3	Malicious attempt detected	Firewall	Factory default password remains
4	Absence of malicious attempt	User rights and privileges are set	Factory default password remains
		Personal firewall	
		Antivirus	
5	Malicious attempt detected	User rights and privileges are set	Implemented password age
			Password length with at least 8 characters
6	Absence of malicious attempt	Firewall	Implemented password age
		User rights and privileges are set	Password length with at least 8 characters
7	Malicious attempt detected	User rights and privileges are set	No password
8	Absence of malicious attempt	Firewall	Guest account
9	Absence of malicious attempt	Firewall	Guest account
10	Absence of malicious attempt	User rights and privileges are set	Factory default password remains
		Firewall	Password length with at least 8 characters
11	Absence of malicious attempt	Firewall	Implemented password age
12	Malicious attempt detected in the logs of substation LAN	Firewall	Factory default password remains
		Anti-virus	Password length with at least 8 characters
13	Malicious attempt detected	User rights and privileges are set	Factory default password remains
		Intrusion detection system	Password length with at least 8 characters
14	Malicious attempt detected	User rights and privileges are set	Password length with at least 8 characters
		Digital certificates	4-character categories of

			combination
15	Malicious attempt detected	User rights and privileges are set	Factory default password remains
		File integrity checkers	Password length with at least 8 characters
16	Absence of malicious attempt	User rights and privileges are set	Factory default password remains
		Antivirus	4-character categories of combination
		Firewall	Old passwords are not allowed to replace as new
17	Absence of malicious attempt	Firewall	4-character categories of combination
		Antivirus	Password length with at least 8 characters
18	Attempted logon with more than 3 time	User rights and privileges are set	4-character categories of combination
		Firewall	Password length with at least 8 characters
19	Malicious attempt detected	Authentication	Password length with at least 8 characters
		User rights and privileges are set	Guest account
		Digital certificates	4-character categories of combination

Implemented Countermeasures for Each Attack Leaf

## VII. ACKNOWLEDGMENT

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