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RESEARCH ARTICLE

Distributed Dynamic Security Assessment for Modern Power System Operational Situational Awareness

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ABSTRACT The complexity of the power system has increased due to recent grid modernization and active distribution systems. As a result, monitoring and controlling modern power systems have become challenging. Dynamic security assessment (DSA) in power systems is a critical operational situational awareness (OpSA) tool for the energy control center (ECC). State-of-the-art (SOTA) DSA has been based on traditional state estimation utilizing the supervisory control and data acquisition (SCADA) / phasor measurement units (PMU) and transmission network topology processing (TNTP) based on SCADA monitoring of relay signals (TNTP-SMRS). Due to the slow data rates of SCADA, these applications cannot efficiently support an online DSA tool. Furthermore, an inaccurate network model based on TNTP-SMRS can lead to erroneous DSA. In this paper, a distributed dynamic security assessment (D-DSA) based on multi-level distributed linear state estimation (D-LSE) and efficient and reliable hierarchical transmission network topology processing utilizing synchrophasor network (H-TNTP-PMU) has been proposed. The tool can be used in real-time operation at the ECC of modern power systems. D-DSA architecture comprises three levels, namely Level 1 - component level security assessment (substations and transmission lines), Level 2 - area level security assessment, and Level 3 - network level security assessment. D-DSA concurrently evaluates all available substations' security in the substation security assessment (SSA) and all available transmission lines' security in the transmission line security assessment (TSA). Under the area security assessment (ASA), all SSA and TSA in each area are separately integrated to assess the area SSI (ASI-SSI) and TSI (ASI-TSI). Subsequently, each area's area-level security index (ASI) is calculated by fusing ASI-SSI and ASI-TSI. At the network level security assessment, network SSI (NSI-SSI) and TSI (NSI-TSI) are estimated by fusing all ASI-SSIs and ASI-TSI, respectively. Network level security index (NSI) is estimated by fusing the NSI-SSI and NSI-TSI in network security assessment (NSA). Typical results of D-DSA are presented for two test systems, the modified two-area four-machine power system model and the IEEE 68 bus power system model. Results indicate that the proposed D-DSA can complete the assessment accurately at the PMU data frame rate, enabling online security assessment regardless of the network size.

INDEX TERMS Distributed linear state estimation, dynamic security assessment, hierarchical transmission network topology processing, synchrophasor.

NOMENCLATURE

AAR	Ambient adjusted rating.
ASA	Area security assessment.

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DSA	Dynamic security assessment.
D-DSA	Distributed dynamic security assessment.
D-LSE	Distributed linear state estimation.
ECC	Energy control center.
EMS	Energy management system.
FIS	Fuzzy inference system.
GPS	Global position system.
H-TNTP-PMU	Hierarchical transmission network topology processing utilizing synchrophasor network.
NETS	New England test system.
NSA	Network security assessment.
NYPS	New York power system.
OpSA	operational situational awareness.
PMU	Phasor measurement unit.
RMSE	Root mean square error.
RTDS	Real-Time digital simulator.
SCADA	Supervisory control and data acquisition.
SMRS	Supervisory control and data acquisition system monitoring of relay signals.
SOTA	State-of-the-art.
SA	Security assessment.
SE	State estimation.
SSA	Substation security assessment.
SSE	Static state estimation.
T-S	Tagaki-Sugeno.
TNTP	Transmission network topology processing.
TNTP-SMRS	Supervisory control and data acquisition system monitoring of relay signal based transmission network topology processing.
TSA	Transmission line security assessment.
λ_{Max}	Maximum load factor.
$\mu(i, j)$	Degree of the membership of input i for j^{th} rule.
ASI_i	Area security index of area i.
$ASI - TSI_i$	Transmission line security index of area i.
$ASI - SSI_i$	Substation security index of area i.
F	Number of FISs.
I_{AAR}	Ambient adjusted rating current.
I_{AL}	Normalized current limit for the alert state.
I_{FEI}	Fully emergency state initial normalized current point.
I_{FNL}	Fully normal state normalized current limit.
$I_{Measured}$	Measured transmission line current.
I_N	Normalized current.
I_{NL}	Normalized current limit for the normal state.
I_{Rated}	Default transmission line current rating.
k	Number of areas.
m_q	Number of transmission lines in area q.
M	Total number of transmission lines in the network.
n_q	Number of substations in area q.
N	Total number of substations in the network.
NSI	Network security index.
$NSI - TSI$	Transmission line security index for the network.
$NSI - SSI$	Substation security index for the network.
NSI_X	NSI for the X approach.
p_i	Number of reduced rules for a i^{th} FIS.
p'_i	Number of rules of the largest FIS in the i^{th} level of the D-DSA.
P	Total number of reduced rules of each FIS fusion level for the longest vertical path in the complete D-DSA architecture.
Q	Number of rules fired for given input for the FIS.
r	Number of inputs for the FIS.
S	Number of samples considered for the RMSE analysis.
SSI_{AL}	SSI limit for alert state.
SSI_{EL}	SSI limit for emergency state.
$SSI_{i,j}$	Substation security index of substation j in area i.
$SSI_{i,k}$	Transmission line security index of transmission line k of area i.
TSI_{AL}	TSI limit for alert state.
TSI_{EL}	TSI limit for emergency state.
V_{ALL}	Lower voltage limits for alert state.
V_{ALU}	Upper voltage limits for alert state.
V_{FEIL}	Lower fully emergency state initial voltage point.
V_{FEIU}	Upper fully emergency state initial voltage point.
V_{NLL}	Lower voltage limits for normal state.
V_{NLU}	Upper voltage limits for normal state.
W_j	Activation level of the j^{th} rule.
z_j	Output of the j^{th} rule.

I. INTRODUCTION

Modernizing the electric bulk power system has more dependency on renewable resources, and the demand has been growing rapidly and becoming more dynamic [1] with electrified transportation, active distribution sources and swift establishment of spot loads such as data centers. Furthermore, the electricity market has become more competitive, requiring the system to operate more economically, where transmission reconfiguration is becoming a regularly utilized tool [2], [3]. These changes in the power system result in a more dynamic power system operation where control has to be modernized.

One of the foundational applications used in the security assessment of the power system is state estimation (SE), which is used to derive the system state variables from imperfect measurements. The traditional power system was limited to static state estimation (SSE) majorly due to

the higher sampling rates of the measurements from the supervisory control and data acquisition (SCADA) system, where typical measurements are received at the energy control center (ECC) every 2 s to 5 s [4], which makes the traditional SE inefficient. Furthermore, the network connectivity derived from the traditional SCADA system monitoring of relay signals (SMRS) based transmission network topology processing (TNTP-SMRS) is used in the SSE as the network model. The traditional TNTP has limitations [5]. Thus, the security assessment based on these traditional foundational applications is insufficient for modern power systems. However, the extensive deployment of the phasor measurement unit (PMU) opens up the possibility of improving the energy management system (EMS) application development, including TNTP, SE, and security assessment (SA). The typical PMU data frequency is 30Hz, and the measurements are synchronized (with reference to the global position system (GPS) time) [4]. A PMU-based reliable and efficient hierarchical transmission network topology processing approach has been proposed in [5], which can derive TNTP in every PMU data frame. Furthermore, an improved multilevel distributed linear state estimation (D-LSE) approach has been proposed in [6], where the robustness, resiliency and accuracy of the estimation are ensured by the architecture. These enhanced foundational applications of the EMS can be used to develop a more efficient dynamic security assessment (DSA) at every PMU frame, which opens up the capability for assessing the security of the power system online.

The primary methods used for DSA are time-domain simulations, which are highly accurate but computationally expensive; direct methods, which are less detailed but provide a faster assessment; and artificial intelligence – particularly neural networks and classification tools, where a thorough training process is required and is highly system-dependent. The primary challenges associated with these methods are the inefficiency, dependence on unreliable foundational applications such as TNTP-SMRS, difficulty to adopt for the high dynamicity and the intermittency introduced by the rapid development of renewable sources. The potential solution is the development of more efficient, multi-level and distributed algorithms. The aim is to achieve true real-time dynamic security assessment under uncertainties associated with the changing power system. A distributed processing architecture for contingency analysis [7], where the computation efficiency enables an online DSA assessment. Although distributed processing is helpful, the foundational application for DSA has to be efficiently designed. Several works of literature have investigated intelligent approaches for DSA. A machine-learning-based probabilistic approach is proposed in [8], where an offline training model under different operating conditions is used. Decision tree-based DSA techniques have been proposed in [9], [10], [11], and [12]. An extreme learning machine with ensemble learning-based hard limiter borderline classification is used to develop a reliable and accurate DSA in [13]. A user-oriented expert rule constraint-based DSA is proposed in [14]. An integrated DSA tool integrating real-time snapshots from the EMS with both bus/branch and node/breaker models is proposed in [15]. Usage of the traditional network model derived from SMRS is a limitation of this approach. A collaborative DSA architecture for a multi-area power system with multiple transmission system operators is proposed in [15]. A complete hierarchical architecture that integrates components to the network level is preferred over collaborative architecture established based on the traditional DSA. It is clearly identified that an efficient, reliable and distributed DSA architecture is preferred for the modern power system. Although, a complete solution is lacking in the literature. Furthermore, the dependency of literature on traditional EMS tools, such as SE and TNTP-SMRS, drastically limits the capabilities of proposed DSA techniques in the literature.

A secured power system must ensure the voltages between secure limits and power flows of the transmission lines do not violate the capacity of the transmission line. The assessment of these conditions is a security assessment. Assessing the power system security and determining the state (Normal, Alert or Emergency) is a security assessment. This paper focuses on establishing distributed dynamic security assessment (D-DSA), which comprises three levels, to assess system security efficiently. The three levels of the D-DSA are Level 1: Component level (substation security assessment (SSA) and transmission line security assessment (TSA)), Level 2: area level (area security assessment (ASA)) and Level 3: network level (network level security assessment (NSA)). The organization of the D-DSA levels is shown in Fig. 1. The state variables considered in the D-DSA are the substation voltage and transmission line current. The substation voltages are estimated from the D-LSE [6], ensuring efficiency, resiliency, and robustness. The transmission line currents feed directly from the synchrophasor units. Furthermore, the network model is derived using the H-TNTP-PMU [5] for improved efficiency and reliability of the network model. A summarized D-DSA feature that addressed shortcomings of the state-of-the-art (SOTA) identified in the literature survey is shown in Table 1. The three approaches of DSA considered in this study for comparison purposes are presented in Fig. 2.

The main contributions of this paper are:

- A multi-level distributed dynamic security assessment (D-DSA) tool is proposed to enhance operational situational awareness (OpSA) at the energy control center. The D-DSA comprises three levels. D-DSA provides quantitative and qualitative visualization at each level so that ECC operators can easily understand the power system's security state. The H-TNTP-PMU provides the substation and transmission line connection statuses to all three levels.
  - Level 3: Network Level, where NSA is conducted. First, the network level substation security index (NSI-SSI) is estimated by fusing all area level substation security indexes (ASI-SSIs), and the

TABLE 1. Summary of the D-DSA features that addressed the shortcomings of the current techniques.

Feature	Current Level	Shortcoming	D-DSA Feature
SE	LSE	Scalability challenges to large power networks	• Utilizes D-LSE. • Distributed multi-level architecture. • Suitable for any size power network.
TNTP	TNTP-SMRS	Inefficient and less reliable	• Utilizes H-TNTP-PMU. • Efficient. • Reliable.
Flexibility	Moderate	System overall upgrade is required.	• Any power network change can be easily integrated into the existing D-DSA system.
Architecture	Non-hierarchical	Difficult to scale-up.	• Hierarchical architecture (D-DSA, D-LSE, and H-TNTP-PMU). • Improved scalability.
Processing	Centralized	Capability to complete within PMU data rate.	• Capable of distributed processing. • Improved computational efficiency.

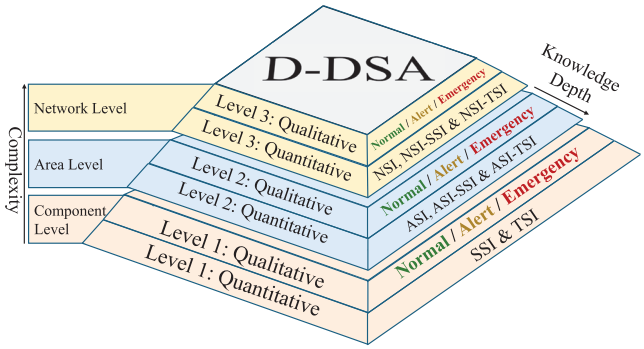

FIGURE 1. Multi-Level hierarchical organization of the D-DSA illustrating the complexity and knowledge depth.

network level transmission line security index (NSI-SSI) is estimated by fusing all area level transmission line security indexes (ASI-TSIs). Next, the network security index (SSI) is derived from the NSI-SSI and NSI-TSI. Based on the index value, the state of the network is defined as either Normal, Alert or Emergency.

  - Level 2: Area Level, where ASA is conducted. ASI-SSI is estimated by fusing all substation security indexes (SSIs) in the area, and the ASI-TSI is estimated by fusing all transmission line security indexes (TSIs) in the area. Next, the area security index (SSI) is derived from the ASI-SSI and ASI-TSI. Based on the index value, the state of each area is defined as either Normal, Alert or Emergency.
  - Level 1: Component Level, where SSA and TSA are conducted, SSI and TSI are derived from the D-LSE and direct PMU measurements, respectively. Based on the index value, the state of each substation and transmission line is defined as either Normal, Alert or Emergency.

- The D-DSA has been illustrated on two benchmark test power systems. The two power systems, a two-area four-machine power system (small network) and the IEEE 68 bus system (medium size network, inter-connected New England test system (NETS) and New York power system (NYPS) reduced equivalent model), have been implemented on a real-time power system simulator with phasor measurement units. The typical results were obtained with the D-DSA with D-LSE and H-TNTP-PMU under multiple disturbances.
- Proposed D-DSA is scalable and computationally efficient due to the distributed architecture and the efficient rule arrangement of the Tagaki-Sugeno (T-S) [16] fuzzy inference system (FIS) model in each level fusions.

The rest of the paper is organized as follows: Section II presents the proposed D-DSA methodology. Typical results for D-DSA for two power system models and the discussion are presented in Section IV. Section V provides the conclusion and future directions.

II. METHODOLOGY

The power system can be classified into two main security state categories, namely secure and insecure, which are sub-categorized into Normal (secure), Alert (insecure), and Emergency (insecure). These three states were proposed in [17], which was inspired from [18]. The normal state can be described as the total load of the system supplied by the power system (equality constraint), and all the variables are within the normal limits (inequality constraints). The system changes to an alert level subsequent to system dynamics and when certain variables violate an alert threshold, although it is an acceptable system operating state considering equality and inequality constraints. The system can reach the emergency state due to a considerable dynamic impact. In the emergency state, inequality constraints are violated due to system state variables exceeding their acceptable thresholds, although the equality constraints are satisfied by generation supplying the required demand. At this level, the operator has to take timely control actions to avoid the system reaching the in-extremis state, where the equality constraint is violated. The primary task of the ECC operators is to take the best course of action efficiently and take the system back to its normal state. If the system reaches the in-extremis state, to avoid power systems leading to a blackout, the power supply must

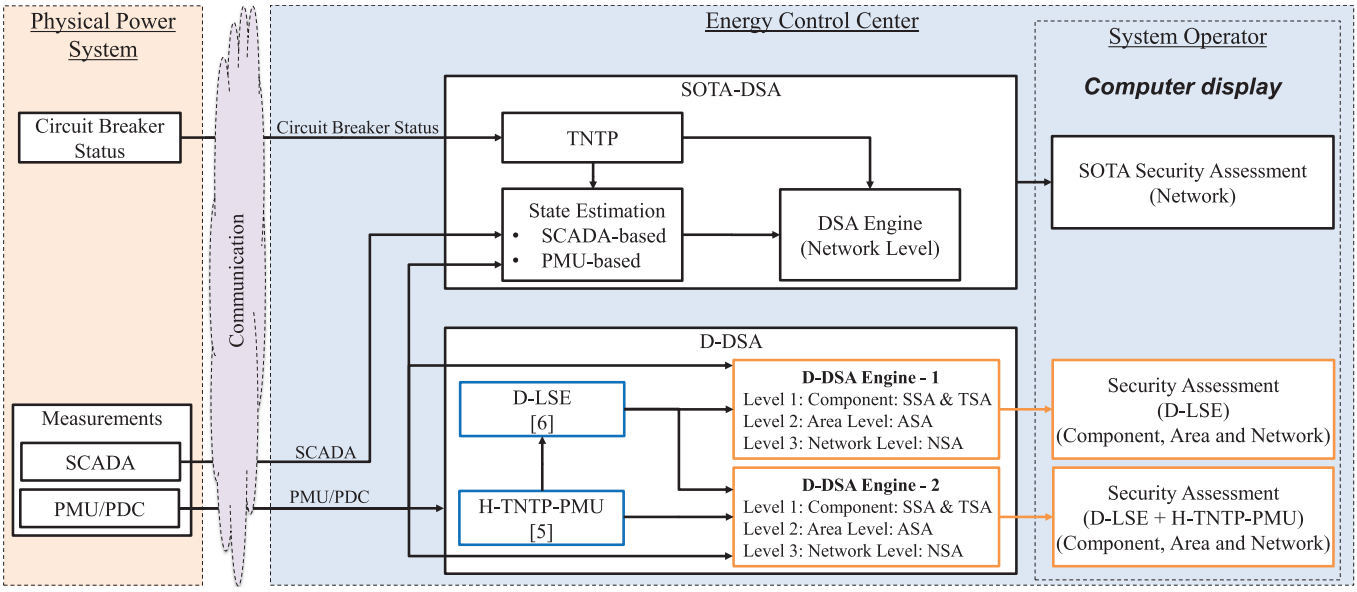

FIGURE 2. Advancement and the applications of dynamic security assessment (DSA). The 'orange-line' blocks present the contribution of this work. The 'blue-line' blocks present the foundational work of this paper from the authors.

be disrupted for a certain number of consumers. Furthermore, a comprehensive restorative plan has to be deployed, and the loads must be connected to the system accordingly by balancing the supply and demand. This state is referred to as the restorative state.

Thus, improving OpSA at the ECC is paramount, where operators can continuously monitor the system security efficiently. The proposed D-DSA architecture is shown in Fig. 3. The SSI pre-processing is to calibrate each SSA characteristic. The TSI pre-processing is for conducting the ambient adjusted rating (AAR) [19], [20] calculation considering the ambient conditions. An efficient and reliable OpSA is paramount for the secure operation of the modern power system, where operators can take effective control action quickly and avoid inaccurate, missed or delayed control actions, which can lead the system to a cascade failure.

A. LEVEL 1: SUBSTATION SECURITY ASSESSMENT (SSA)

Each substation in the transmission network contributes and is critical to the overall power system operation, where the protection schemes and control devices are established. All the control actions taken by the operators at the ECC are employed on the Substations. SSA is based on the substation voltage. In D-DSA Level 1, each substation's security is based on individual characteristics, as shown in Fig. 4. The characteristics function parameters of the low voltage portion are based on the P-V curve [21] as shown in Fig. 5. Each load substation P-V curve is unique. The voltage limits are set considering the maximum load factor (λ_{Max}). This can be customized according to user preference. The P-V curve describes the relationship between the active power and the voltage at the load substations. P-V curves are vital in identifying the limits of the active power of a power system for voltage stability. A substation security index (SSI) index for the substation security assessment is derived from the characteristics of each substation by following the individually calibrated substation SSA characteristic.

V_{FEIL} refers to the lower fully Emergency state initial voltage point (the substation is considered under fully emergency beyond this level), where the index is at its lowest, "0". V_{ALL} and V_{NLL} refer to the lower voltage limits for alert and normal, respectively. All these lower voltage limit values are customized according to the P-V curve of the load substations. The load substations' high voltage limits are based on the mirrored values over the "1" pu unit of the lower values identified from the P-V curve. Where V_{FEIU} refers to the upper fully emergency state initial voltage point (the substation is considered under fully emergency beyond this level), where the index is at its lowest, "0". V_{ALU} and V_{NLU} refer to the upper voltage limits for alert and normal, respectively. Furthermore, the SSI limits for the alert state (SSI_{AL}) and emergency state (SSI_{EL}) are selected based on the system user preference. The rest of the substation characteristics are calibrated according to the nearest load substation characteristics parameters. All the SSA characteristics function parameters for the two-area four-machine power system model are presented in Table 8.

Each Substation voltage is estimated accurately and efficiently by the D-LSE [6], where bad, noisy or missing substation voltage measurements can occur. Thus, the D-LSE voltage values are the most accurate state values available at the ECC. The substation's connectivity to the network derived from the H-TNTP-PMU is considered, and if the substation is not connected to the network, the substation is omitted from the aggregation.

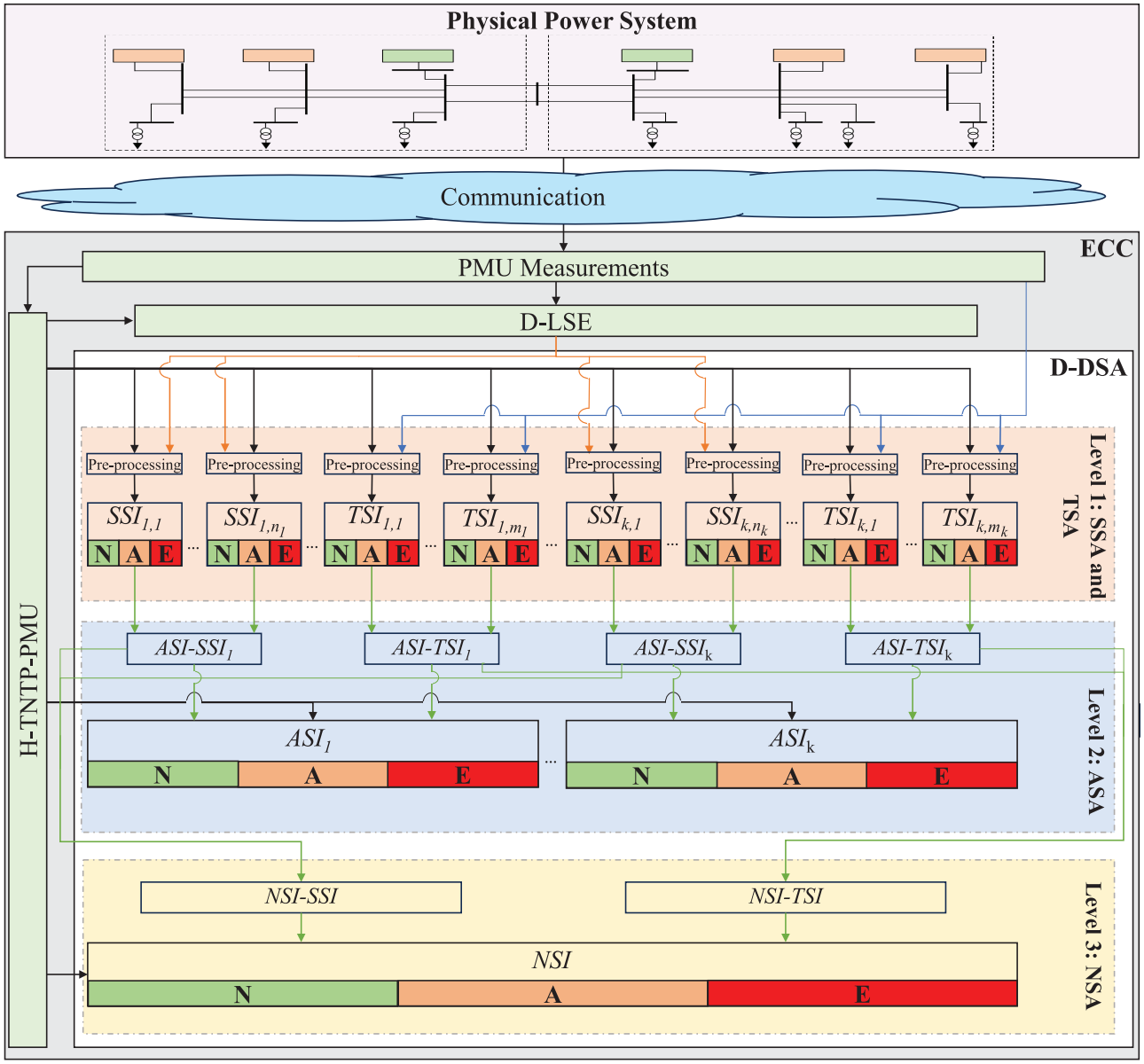

FIGURE 3. The proposed D-DSA based on the D-LSE [6] and H-TNTP-PMU [5] architecture. "N" represents the Normal State, "A" represents the Alert State and "E" represents the Emergency State.

B. LEVEL 1: TRANSMISSION LINE SECURITY ASSESSMENT (TSA)

The transmission lines in the network are the critical power-carrying bridges from the generation to load centers. Substations are the two ends of the transmission line where the protection and controls are established. Each transmission line current is measured. The critical security factor of the transmission lines is the current carrying capacity of the conductor. The current carrying capacity of the conductor defines the amount of power that can be transmitted through at the rated voltage. The characteristic based on the normalized current (I_N) with respect to the AAR current of the particular transmission line is used to infer the transmission line security index (TSI) as shown in Fig. 6. I_{FNL} refers to the fully normal state normalized current limit where the normalized transmission line current is ensured complete normal state, where the index is at its highest, "1". I_{NL} and I_{AL} refer to the limit for the normal and alert state limits, respectively. I_{FEI} is the fully emergency state initial normalized current point (the transmission line is considered fully emergency beyond this level), where the index is at its lowest, "0".

The transmission line's connectivity to the network is identified from the H-TNTP-PMU. The transmission line ratings are susceptible to weather factors, including ambient temperature and wind speed [19]. The AAR current (I_{AAR}) can be estimated by multiplying the default transmission line current rating (I_{Rated}) that is defined by the manufacturer

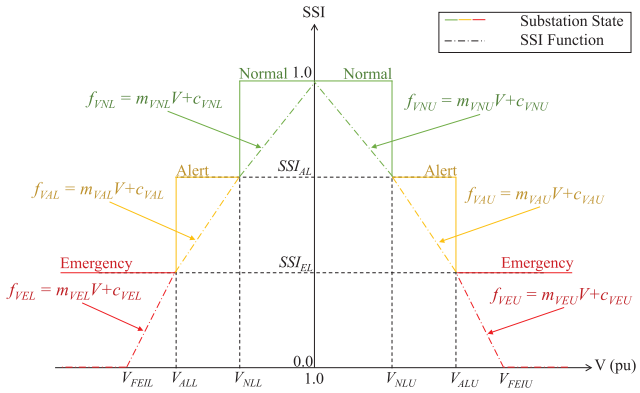

FIGURE 4. Substation security assessment (SSA) characteristic at Level 1 of the D-DSA. The functions are calibrated for each substation.

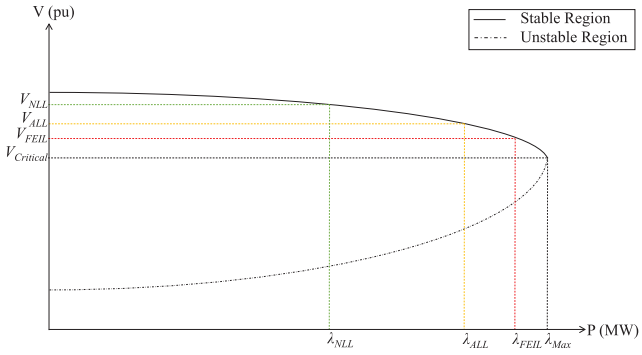

FIGURE 5. Substation security assessment (SSA) at Level 1 of the D-DSA for load substations based on the P-V curve [21].

under given testing conditions with the factor calculated using the ambient weather parameters as shown in (1). Further detail of calculating the line rating under AAR is explained in [20]. The I_N can be estimated by taking the ratio between the measured transmission line current ($I_{Measured}$) and the AAR current estimated with (1) as shown in (2). All the TSA characteristics function parameters for the two-area four-machine power system model are presented in Table 11.

$$I_{AAR} = f(Temperature, Wind\ Speed) \times I_{Rated} \tag{1}$$

$$I_N = \frac{I_{Measured}}{I_{AAR}} \tag{2}$$

C. LEVEL 2: AREA SECURITY ASSESSMENT (ASA)

The ASA is derived utilizing both SSA and TSA information. The FIS based on the T-S modeling approach [16] is considered for the fusion of the individual SSIs to establish an ASI-SSI and the fusion of individual TSIs to establish an ASI-TSI. The T-S FIS is a fuzzy logic system designed to model complex systems with high accuracy, which is particularly useful in decision-making processes due to its ability to handle nonlinearities and uncertainties effectively, similar to the security assessment addressed in this paper. Unlike the traditional Mamdani-type FIS, the T-S FIS uses fuzzy rules with fuzzy sets. In the defuzzification, the consequent is calculated using the mathematical function shown in (3),

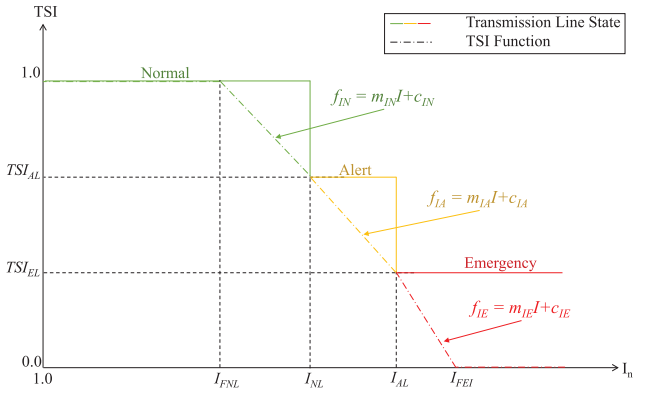

FIGURE 6. Transmission line security assessment (TSA) characteristic at Level 1 of the D-DSA.

where W_j is the activation level of the j^{th} rule and Z_j is the output of the j^{th} rule. Q is the number of rules that are fired.

$$Fused\ Security\ Index = \frac{\sum_{j=1}^{Q} W_j \times Z_j}{\sum_{j=1}^{Q} W_j} \tag{3}$$

The estimation of the activation level of the j^{th} rule is based on (4), where $\mu(i, j)$ is the degree of the membership of input i. n is the number of inputs.

$$W_j = \prod_{i=1}^{n} \mu(i, j) \tag{4}$$

For example, in a system with two inputs. Input 1 is "Medium" with a degree of membership at 0.3 and "Normal" with a degree of membership at 0.7. Input 2 is "Low", with a degree of membership at 1. Under this circumstance, two rules will be fired. Rule 1 is "Input 1 is Medium, and Input 2 is Low" with an activation level of 0.3 (0.3×1). Rule 1 is "Input 1 is High, and Input 2 is Low" with an activation level of 0.7 (0.7×1)the relevant output values for Rule 1 and Rule 2 can be found in the Rule Table. The output values and the activation levels for all fired rules are used in (3) to calculate the fused security index value. The qualitative assessment for all the fusions is based on user-defined limits for Alert and Emergency, similar to the SSI and TSI qualitative assessment.

1) AREA LEVEL SUBSTATION SECURITY ASSESSMENT (ASI-SSI)

All substation SSIs are fused to derive ASI-SSI with the T-S FIS approach [16]. The size of the FIS significantly increases with the number of input SSIs (number of substations in the area). Thus, a simplification technique proposed in [22] is adopted.

The input levels through the membership functions are used to define the rules. Assuming there are r inputs and each input has three levels (Low, Medium and High, as shown in Fig. 7), 3^r number of rules can be defined, as shown in Table 2. Based on the fact that each input is given the same significance level, the logic to define the rules can be reduced

by combining similar combinations of memberships together as shown in Table 3, p is the number of the reduced rules from 3^r that preserves the same level of output information that is normalized to be an output value in between 0 and 1. p can be calculated for a three-level membership FIS using (5). The formulation of the reduced rule set will be different for different numbers of levels in the membership function.

$$p = 0.5r^2 + 1.5r + 1 \tag{5}$$

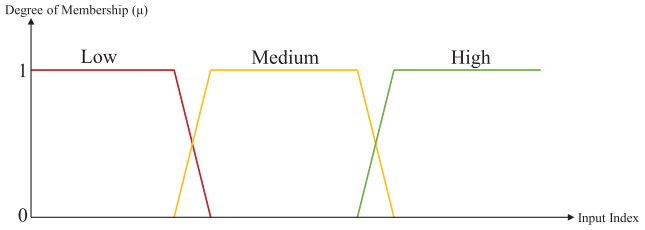

FIGURE 7. Input membership functions with three levels (Low, Medium and High) for the FIS fusion to derive ASI-SSI (from SSIs), ASI-TSI (from TSIs), ASI (from ASI-SSI and ASI-TSI), NSI-SSI (from ASI-TSIs), NSI-TSI (from ASI-TSIs) and NSI (from NSI-SSI and NSI-TSI).

TABLE 2. Example fuzzy Logic to define rules for SSI FIS fusion for an ASI-SSI with *m* substations and three membership levels. H: High, M: Medium and L: Low.

Rule Index	Inputs				Output
	1	2	...	r	
1	L	L	...	L	0
2	L	L	...	M	...
...	...	...	...	...	
$3^r - 1$	H	H	...	M	
3^r	H	H	...	H	1

TABLE 3. Example reduced fuzzy rules for SSI FIS fusion for an ASI-SSI with *m* substations and three membership levels. H: High, M: Medium and L: Low.

Rule Index	Count of "H"	Count of "M"	Count of "L"	Output
1	0	0	r	0
2	0	1	$r-1$	...
...	...	...	...	
$p-1$	$r-1$	1	0	
p	r	0	0	1

2) AREA LEVEL TRANSMISSION LINE SECURITY ASSESSMENT (ASI-TSI)

The area transmission line security index (ASI-TSI) follows the same methodology as the ASI-SSI and derives the ASI-TSI for the respective area, considering the transmission lines belong to each area. Finally, at Level 2, the ASI-SSI and ASI-TSI are fused together with the FIS to derive ASI for the area.

D. LEVEL 3: NETWORK SECURITY ASSESSMENT (NSA)

The power system NSA at Level 3 is based on all ASA at Level 2. All ASI-SSIs are integrated together with T-S FIS to estimate NSI-SSI, and all ASI-TSIs are integrated together using the T-S FIS to estimate NSI-TSI. Finally, a single NSI is calculated by the fusion of NSI-SSI and NSI-TSI. All the fusions are conducted utilizing the T-S FIS with reduced rules technique described in Section II-C1. The flow diagram shown in Fig. 8 illustrates the online implementation of D-DSA with the D-LSE and H-TNTP-PMU approach proposed by this paper.

III. IMPLEMENTATION OF D-DSA

This study considered two power system models, The modified two-area four-machine power system and the IEEE 68 bus power system, an equivalent reduced order model of the interconnected NETS and NYPS, for implementing the D-DSA. SSA, TSA, ASA and NSA are implemented. The IEEE 68 bus power system demonstrates the scalability of the proposed D-DSA.

A. SYSTEM 1: MODIFIED TWO-AREA FOUR-MACHINE POWER SYSTEM

The Kundur's two-area four-machine power system model [23] is a two-area symmetric system model used for transient stability analysis. Kundur's system (the modified two-area four-machine benchmark power system) has been modified in this study, consisting of ten generators in four power plants and two additional solar power plants as generations. Power Plant 1 at substation 5 in Area 1 consists of three identical generators. Power Plant 2 at Substation 6 in Area 1 consists of two identical generators. Apart from that, Area 1 has one solar plant connected to Substation 7. In Area 2, similar to Area 1, two conventional power plants and one solar plant are established. The system contains seven loads at Substations 5L, 6L, 7L, 9L,10L, and 11L. Two double-circuit tie-lines connect this multi-area power system. All conventional generators are configured with turbine governors, automatic voltage regulators, and power system stabilizers. The establishment of H-TNTP-PMU in the modified two-area four-machine system is elaborated in [5]. The D-LSE implementation and the analysis of the system are described in [6]. In the D-DSA, each substation voltage estimation from D-LSE is used for SSA and PMU current measurement from the transmission line is used for TSA. The H-TNTP-PMU provides an accurate topology of the network at every PMU data frame, which is used for fusion in D-DSA by only considering available transmission lines and substations in the network.

B. SYSTEM 2: IEEE 68 BUS POWER SYSTEM

The IEEE 68 bus power system model shown in Fig. 10 [24] consists of five interconnected areas, which is considered to illustrate the scalability of the D-DSA. Furthermore, the implementation of the D-LSE on the IEEE 68 bus system model is explained in [6]. Area 1 consists of generators G1 through G9. Area 2 consists of generators G10 through G13. Furthermore, Areas 3,4 and 5, respectively, consist of G14, G15 and G16. Area 1, 2, 3, 4 and 5 comprise 27, 22, 1, 1 and 1 substations, respectively, excluding generator substations.

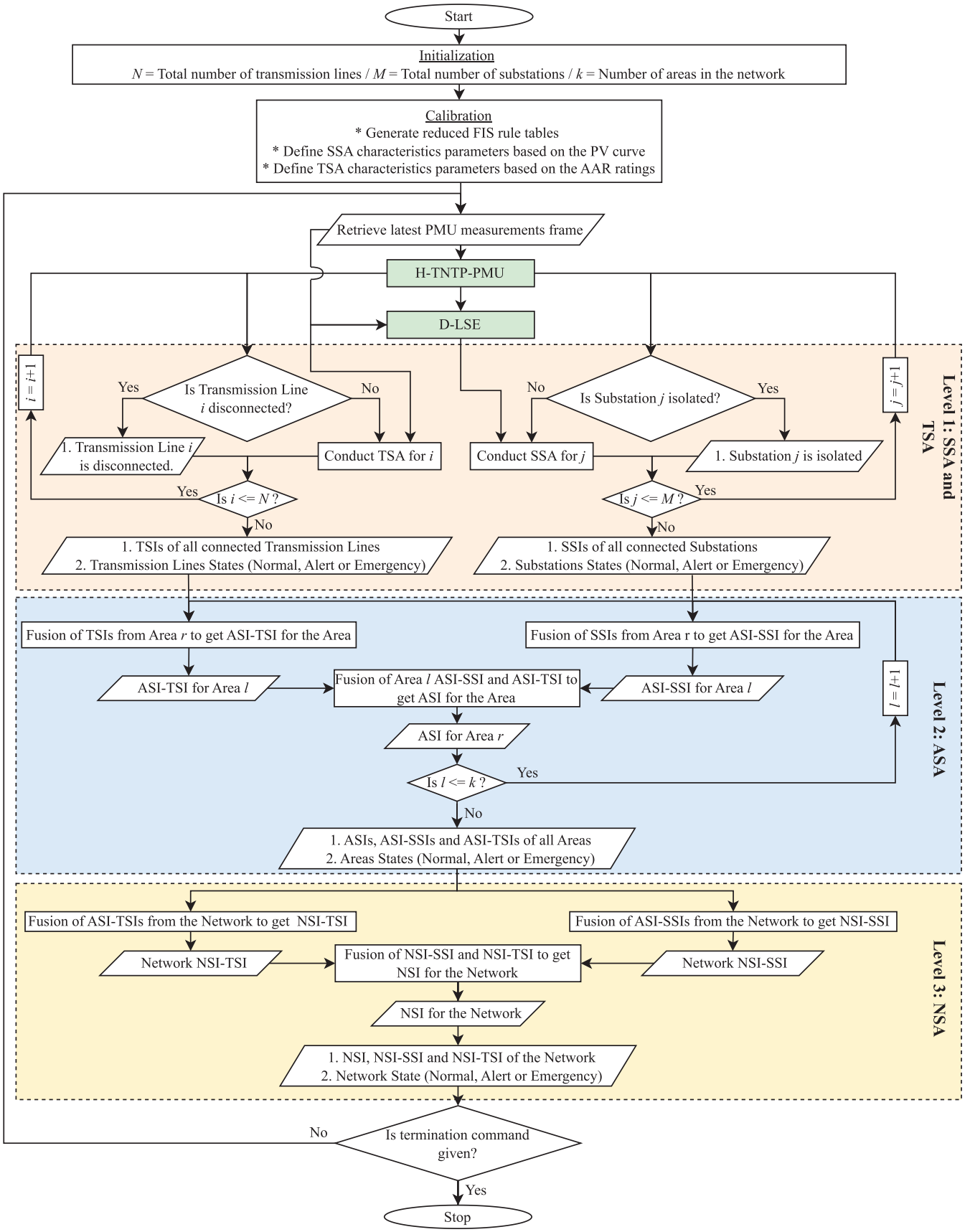

FIGURE 8. The flow diagram of the procedure of the online D-DSA based on the D-LSE [6] and H-TNTP-PMU [5] approaches.

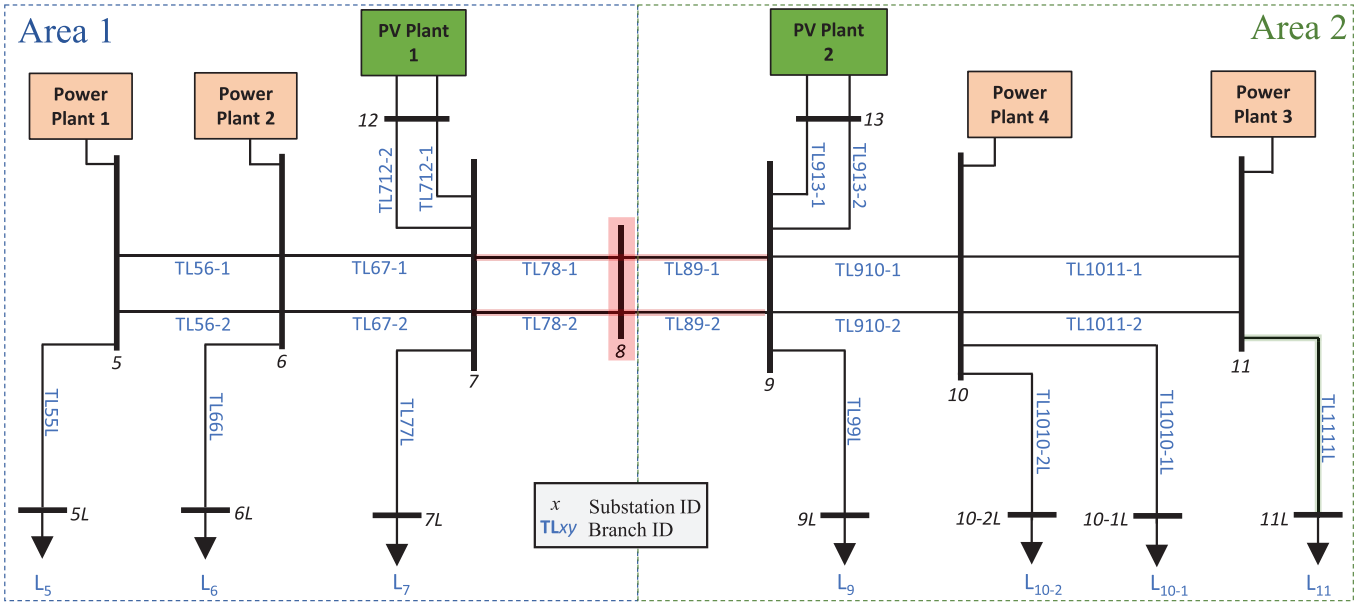

FIGURE 9. Modified two-area four-machine power system model illustrating the test cases, including area separation (Substation 8 isolation) and the transmission line TL1111L outage.

Areas 1, 2, 3, 4, and 5 have 17, 15, 1, 1, and 1 loads, respectively. The system operates at 345kV nominal voltage other than the generator substations. All conventional generators are configured with turbine governors and automatic voltage regulators. The simulation uses the RSCAD software on the Real-Time Digital Simulator (RTDS) [25]. RSCAD software PMUs are utilized for this study. The IEEE 68 bus power system model illustrates the scalability of the proposed approach.

A comparison of the D-DSA FIS structure size is shown in Table 4, where n_i is the number of substations in general system Area i, and the m_i is the number of transmission lines in Area i of the general system in Table 4. Furthermore, the advantage of using the reduced rules described in Section II-C1 is illustrated in the last three rows of Table 4 for three-level membership function FIS. The D-DSA is a hierarchical procedure where all previous-level computations must be completed to initiate the next level. Thus, each level is capable of parallel and distributed processing. In D-DSA at both Levels 2 and 3, multiple FIS fusions occur. ASI-SSI and ASI-TSI FISs are computationally expensive, considering the higher counts of substations and transmission lines in each area, translating into the number of inputs of the FISs. The complexity of the NSI-SSI and NSI-TSI FISs can be increased based on the number of areas. There are only two inputs for the ASI and NSI FISs. Thus, the bottleneck of D-DSA computation is typically at the ASI-SSI and ASI-TSI FISs. We consider the longest computation path considering the number of rules that need to be executed sequentially (the longest vertical path) as a metric for comparing power systems and architectures. P represents the number of rules that should be sequentially processed (the longest vertical path of the hierarchy) in the D-DSA four levels of fusions. For any FIS, the number of rules to consider in calculating the *Fused Security Index* is significantly reduced with the reduced fuzzy rule technique. For example, for System 1, considering non-hierarchical single network level FIS as the architecture, there are a total of 3^{39} (4.0525552×10^{18}) rules to be considered sequentially for FISs, and D-DSA architecture with the reduced rule set, it is decreased to only 109 rules in sequential at the four fusion levels (ASI-SSI or ASI-TSI = 91 rules, ASI Area 1 = 6 rules, NSI-SSI or NSI-TSI = 6 rules, and NSI = 6 rules). The order of magnitude for the System 1 is 16. The reduced rules techniques indeed help in power system online application building.

IV. RESULTS & DISCUSSION

The D-DSA results are presented for the modified two-area four-machine and the IEEE 68 bus power systems. For each system, SSA, TSA, ASA and NSA were conducted. SSI, ASI-SSI, TSI, ASI-TSI, ASI, NSI-SSI, NSI-TSI and NSI are evaluated under several typical power system disturbances. Under all test cases in the qualitative assessment based on the quantitative index (SSI limits for SSI_{AL} and SSI_{EL}, TSI limits for TSI_{AL} and TSI_{EL}, and Area and Network level FISs fusions) are selected at 0.667 and 0.333 for Alert and Emergency, respectively.

A. SYSTEM 1: MODIFIED TWO-AREA FOUR-MACHINE POWER SYSTEM

1) CASE 1A: CRITICAL TRANSMISSION LINE OUTAGE

The TL1111L transmission line serving a 300MW load is removed from the system. In D-DSA Engine - 1 (Network, Area and Component levels), D-LSE voltage estimated values and PMU measurements of the transmission line

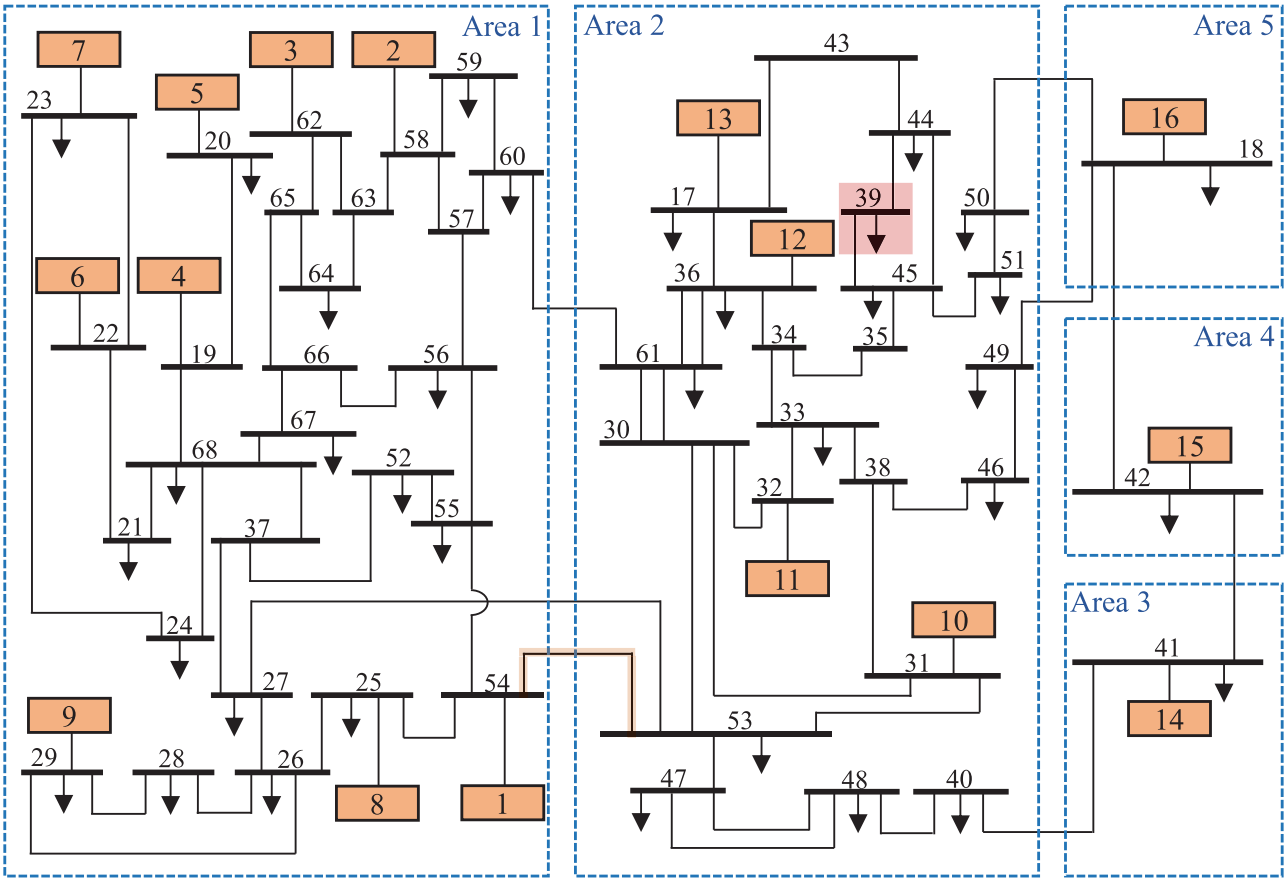

FIGURE 10. IEEE 68 bus Benchmark System [24] illustrating the test cases of Substation 39 isolation and the transmission line TL54-53 tie line outage.

TABLE 4. D-DSA configuration comparison for a general, two-area four-machine system, and IEEE 68 bus system. The general power system is referred from Fig. 3.

Level	Category	Index	Number of Inputs / Quantity							
			General	System 1		System 2				
3	Network	-	1	1		1				
	NSA	NSI	1	1		1				
		NSI-SSI	1	1		1				
		NSI-TSI	1	1		1				
2	Areas	-	k	2		5				
	ASA	ASI	k	2		5				
		ASI-SSI	k	2		5				
		ASI-TSI	k	2		5				
Area ID		-	-	**1**	**2**	**1**	**2**	**3**	**4**	**5**
1	Substations	-	$N = \sum_{i=1}^{k} n_i$	8	8	27	22	1	1	1
	SSA	SSI	N	8	8	27	22	1	1	1
	Transmission Lines	-	$M = \sum_{i=1}^{k} m_i$	11	12	36	35	3	2	2
	TSA	SSI	M	11	12	36	35	3	2	2
FIS	Total Fusions	-	$F = 3^{(k+1)}$	9		18				
Total number of rules in the longest vertical path of the architecture	A. DSA architecture as a network level single FIS	-	$3^{(N+M)}$	3^{39}		3^{130}				
	B. D-DSA architecture with reduced FIS rule tables	-	$P = \sum_{i=1}^{4} p_i'$	91+6+6+6 = 109		703+6+21+6 = 736				
	Order of Magnitude Reduction in number of rules from A to B	-	$\lfloor(\log_{10} 3^{(N+M)}\rfloor - \lfloor(\log_{10} P)\rfloor$	16		60				

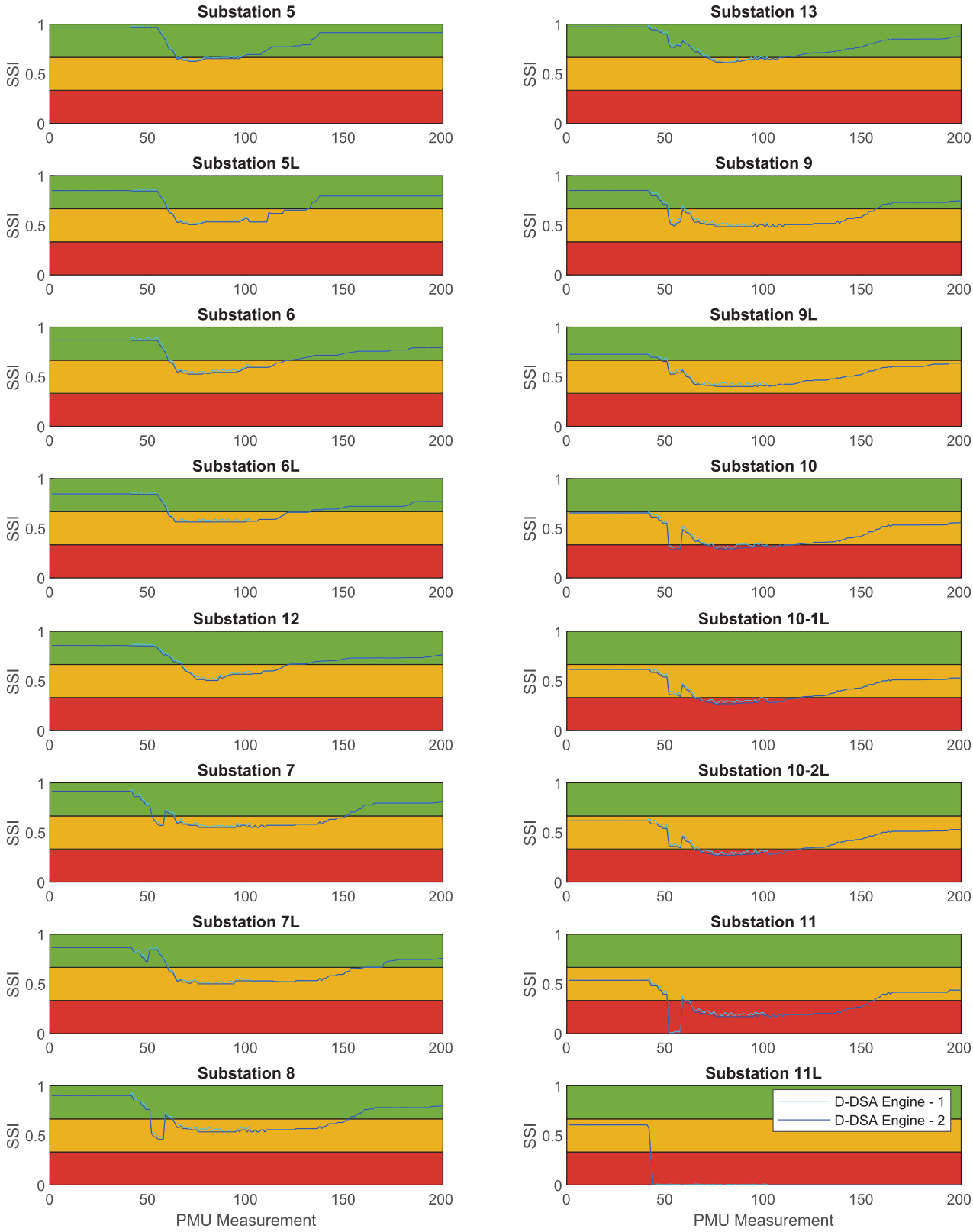

FIGURE 11. Substation security assessment index for TL1111L transmission line outage under D-DSA with D-LSE only and D-DSA with D-LSE and H-TNTP-PMU approaches. Area 1 Substations are shown on the left. Area 2 substations are shown on the Right.

are used with the TNTP-SMRS. In D-DSA Engine - 2 (Network, Area and Component levels), D-LSE voltage estimated values and PMU measurements of the transmission line are used with the H-TNTP-PMU. The test case removes

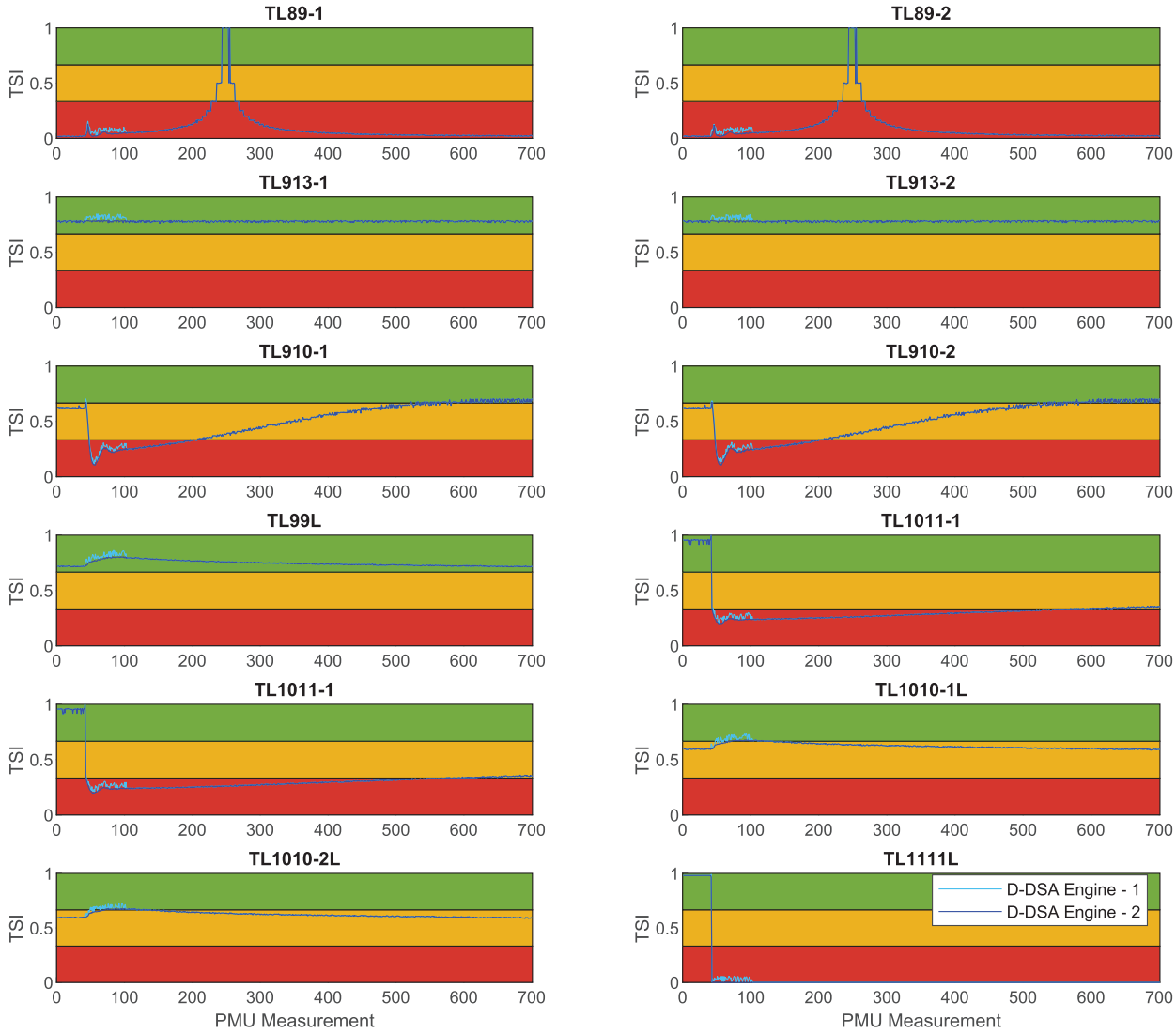

FIGURE 12. Transmission line security assessment index for TL1111L transmission line outage under D-DSA with D-LSE only and D-DSA with D-LSE and H-TNTP-PMU approaches. Area 2 Transmission Lines are presented.

TL1111L and isolates Substation 11L. The results for the SSA for all the substations of the two-area four-machine system under two D-DSA engines are shown in Fig. 11. The results for the TSA for all the transmission lines in Area 2 of the two-area four-machine system are shown in Fig. 12. The results for the ASA for both areas are shown in Fig. 13. A summarized security assessment results of the Network Level and case-relevant Area Level and Component Level for Actual (using ground truth measurements for substation voltages and transmission line currents with instantaneous topology update), SOTA (noisy measurements for substation voltages and transmission line currents with TNTP-SMRS), D-DSA Engine - 1, and D-DSA Engine - 2 approaches are shown in Fig. 14. Furthermore, the reduced rule set of the FIS for Area 1 of ASI-SSI is shown in Table 12.

Furthermore, root mean square error (RMSE) analysis using (6) is conducted for all test cases discussed above. S refers to the number of data samples in the considered window, and NSI_Actual_i is the NSI value for sample i for the Actual approach. NSI_X_i is the NSI value for the sample i of the X approach, where X referred to one approach out of the SOTA, D-DSA Engine - 1, and D-DSA Engine - 2.

$$RMSE = \sqrt{\frac{1}{S}\sum_{i=1}^{S}(NSI\_Actual_i - NSI\_X_i)^2} \qquad (6)$$

Based on the RMSE analysis for the data window shown in Fig. 14 ($S = 550$) shows the NSI of the D-DSA Engine - 2 is 7.51 times better than the SOTA approach (RMSE for D-DSA Engine - 2 is 0.0171 and RMSE for SOTA is 0.1284).

2) CASE 1B: CRITICAL SUBSTATION OUTAGE

Substation 8 connecting Area 1 and Area 2 is isolated by disconnecting TL78-1, TL78-2, TL89-1 and TL89-2.

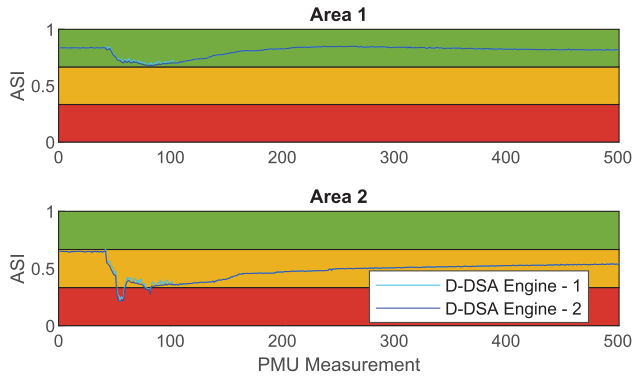

FIGURE 13. Area Security assessment index for TL1111L transmission line outage under D-DSA with D-LSE only and D-DSA with D-LSE and H-TNTP-PMU approaches.

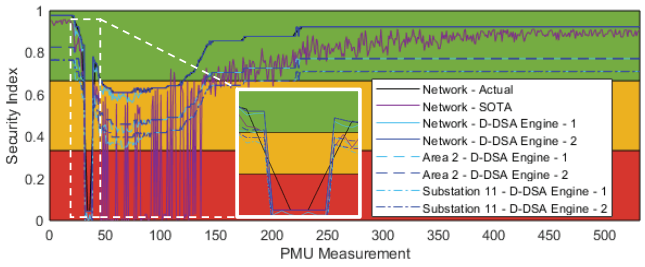

FIGURE 14. Security assessment index for TL1111L transmission line outage under Actual, SOTA, D-DSA Engine - 1 (Network, Area 2 and Substation 11) and D-DSA Engine - 2 (Network, Area 2 and Substation 11) approaches.

Area 1 and Area 2 automatic generation control [5], [26] is reconfigured for area standalone mode. A summarized security assessment results of the Network Level and case-relevant Area Level and Component Level for Actual (using ground truth measurements for substation voltages and transmission line currents), SOTA (noisy measurements for substation voltages and transmission line currents with TNTP-SMRS), D-DSA Engine - 1, and D-DSA Engine - 2 approaches are shown in Fig. 15. Based on the RMSE analysis for the data window shown in Fig. 15 ($S = 550$) shows the NSI of the D-DSA Engine - 2 is 7.98 times better than the SOTA approach (RMSE for D-DSA Engine - 2 is 0.0056 and RMSE for SOTA is 0.0447).

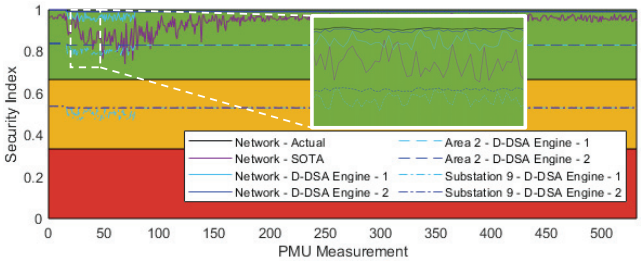

FIGURE 15. Security assessment index for Substation 8 isolation case under Actual, SOTA, D-DSA Engine - 1 (Network, Area 2 and Substation 9) and D-DSA Engine - 2 (Network, Area 2 and Substation 9) approaches.

3) CASE 1C: LOAD CHANGE

The load change scenario considered here is sequential load increment in Area 1 and Area 2. Load 7 has increased by 300 MW; next, Load 9 has increased by 300MW. Area 1 and 2 generations have increased to satisfy the load increment and tie-line flow. The generation in Area 2 has to increase rapidly to satisfy the 300MW load without Area 1 support. The topology update has not occurred in the scenario. A summarized security assessment results of the Network Level and case-relevant Area Level and Component Level for Actual (using ground truth measurements for substation voltages and transmission line currents), SOTA (noisy measurements for substation voltages and transmission line currents with TNTP-SMRS), D-DSA Engine - 1, and D-DSA Engine - 2 approaches are shown in Fig. 16. Based on the RMSE analysis for the data window shown in Fig. 16 ($S = 2500$) shows the NSI of the D-DSA Engine - 2 is 7.10 times better than the SOTA approach (RMSE for D-DSA Engine - 2 is 0.0058 and RMSE for SOTA is 0.0412).

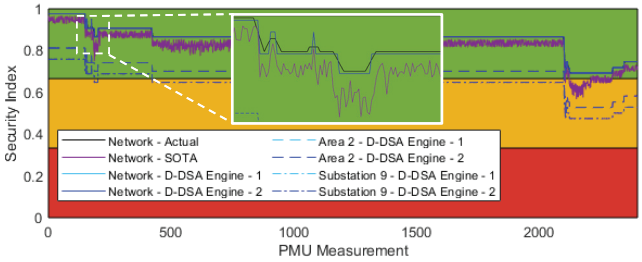

FIGURE 16. Security assessment index for load changes simulated by considering 300MW load increment in L7 and L9 sequentially under Actual, SOTA, D-DSA Engine - 1 (Network, Area 2 and Substation 9) and D-DSA Engine - 2 (Network, Area 2 and Substation 9) approaches.

4) CASE 1D: EXTREME OUTAGE CONDITION

The extreme condition is that TL1111L reconnects to Substation 11 while Substation 8 is isolated. The generation in Area 2 has to increase rapidly to satisfy the 300MW load without Area 1 support since the Area 1 tie-line supply to Area 2 is disconnected due to Substation 8 isolation. The topology is updated twice for the Substation 8 isolation and reconnecting TL1111L to the system. A summarized security assessment results of the Network Level and case-relevant Area Level and Component Level for Actual (using ground truth measurements for substation voltages and transmission line currents), SOTA (noisy measurements for substation voltages and transmission line currents with TNTP-SMRS), D-DSA Engine - 1, and D-DSA Engine - 2 approaches are shown in Fig. 17. Based on the RMSE analysis for the data window shown in Fig. 17 ($S = 2500$) shows the NSI of the D-DSA Engine - 2 is 10.72 times better than the SOTA approach (RMSE for D-DSA Engine - 2 is 0.0089 and RMSE for SOTA is 0.0954).

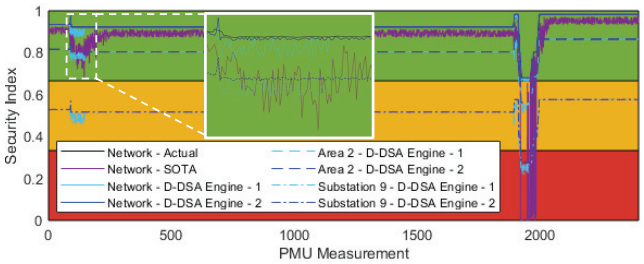

FIGURE 17. Security assessment index for extreme conditions simulated by considering both Substation 8 outage and TL1111L outage in sequence Actual, SOTA, D-DSA Engine - 1 (Network, Area 2 and Substation 9) and D-DSA Engine - 2 (Network, Area 2 and Substation 9) approaches.

B. SYSTEM 2: IEEE 68 BUS POWER SYSTEM

The IEEE 68 bus power system model simulation and D-DSA implementation are based on the system shown in Figure 10. The IEEE 68 bus system demonstrates the scalability of the D-DSA.

1) CASE 2A: CRITICAL TRANSMISSION LINE OUTAGE

The TL54-53 tie-line is removed from the system, introducing a disturbance to the power system. The topology is updated to reflect TL54-53 outage. A summarized security assessment results of the Network Level and case-relevant Area Level and Component Level for Actual (using ground truth measurements for substation voltages and transmission line currents), SOTA (noisy measurements for substation voltages and transmission line currents with TNTP-SMRS), D-DSA Engine - 1, and D-DSA Engine - 2 approaches are shown in Fig. 18. Based on the RMSE analysis for the data window shown in Fig. 18 ($S = 550$) shows the NSI of the D-DSA Engine - 2 is 6.63 times better than the SOTA approach (RMSE for D-DSA Engine - 2 is 0.0064 and RMSE for SOTA is 0.0424).

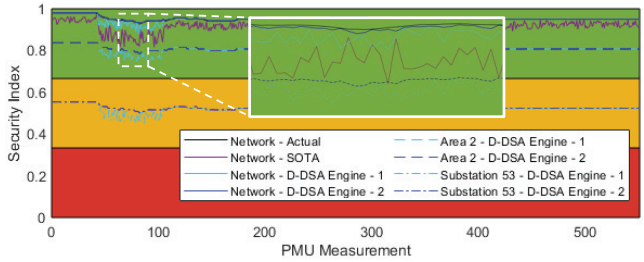

FIGURE 18. Security assessment index for TL54-53 transmission line outage under Actual, SOTA, D-DSA Engine - 1 (Network, Area 2 and Substation 53) and D-DSA Engine - 2 (Network, Area 2 and Substation 53) approaches.

2) CASE 2B: SUBSTATION OUTAGE

Substation 39 in Area 2 is isolated by disconnecting TL44-39 and TL45-39. The topology has been updated to reflect the outages of TL44-39, TL45-39, and Substation 39. A summarized security assessment results of the Network Level and case-relevant Area Level and Component Level for Actual (using ground truth measurements for substation voltages and transmission line currents), SOTA (noisy measurements for substation voltages and transmission line currents with TNTP-SMRS), D-DSA Engine - 1, and D-DSA Engine - 2 approaches are shown in Fig. 19. Based on the RMSE analysis for the data window shown in Fig. 19 ($S = 550$) shows the NSI of the D-DSA Engine - 2 is 6.56 times better than the SOTA approach (RMSE for D-DSA Engine - 2 is 0.0055 and RMSE for SOTA is 0.0361).

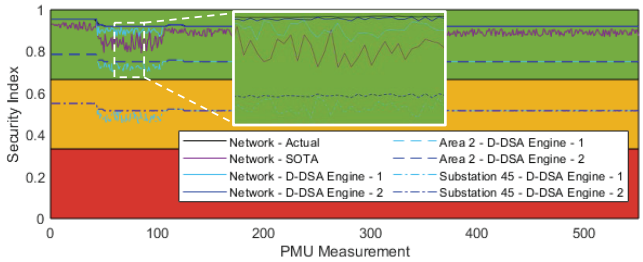

FIGURE 19. Security assessment index for Substation 39 isolation case Actual, SOTA, D-DSA Engine - 1 (Network, Area 2 and Substation 45) and D-DSA Engine - 2 (Network, Area 2 and Substation 45) approaches.

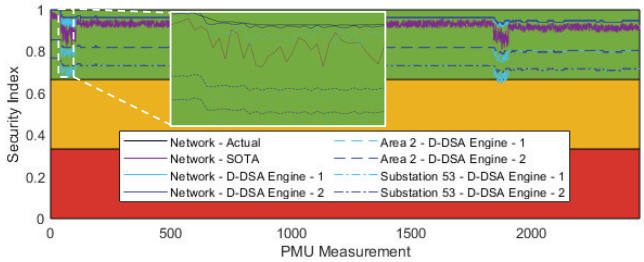

FIGURE 20. Security assessment index for extreme conditions simulated by considering both above outages in sequence under Actual, SOTA, D-DSA Engine - 1 (Network, Area 2 and Substation 53) and D-DSA Engine - 2 (Network, Area 2 and Substation 53) approaches.

3) CASE 2C: EXTREME OUTAGE CONDITION

The extreme condition is that Substation 39 is removed, and TL54-53 is disconnected sequentially. The topology is updated twice for the Substation 39 isolation and disconnection of the TL54-53 transmission line from the system. A summarized security assessment results of the Network Level and case-relevant Area Level and Component Level for Actual (using ground truth measurements for substation voltages and transmission line currents), SOTA (noisy measurements for substation voltages and transmission line currents with TNTP-SMRS), D-DSA Engine - 1, and D-DSA Engine - 2 approaches are shown in Fig. 20. Based on the RMSE analysis for the data window shown in Fig. 20 ($S = 2500$) shows the NSI of the D-DSA Engine - 2 is 7.14 times better than the SOTA approach (RMSE for D-DSA Engine - 2 is 0.0056 and RMSE for SOTA is 0.0400).

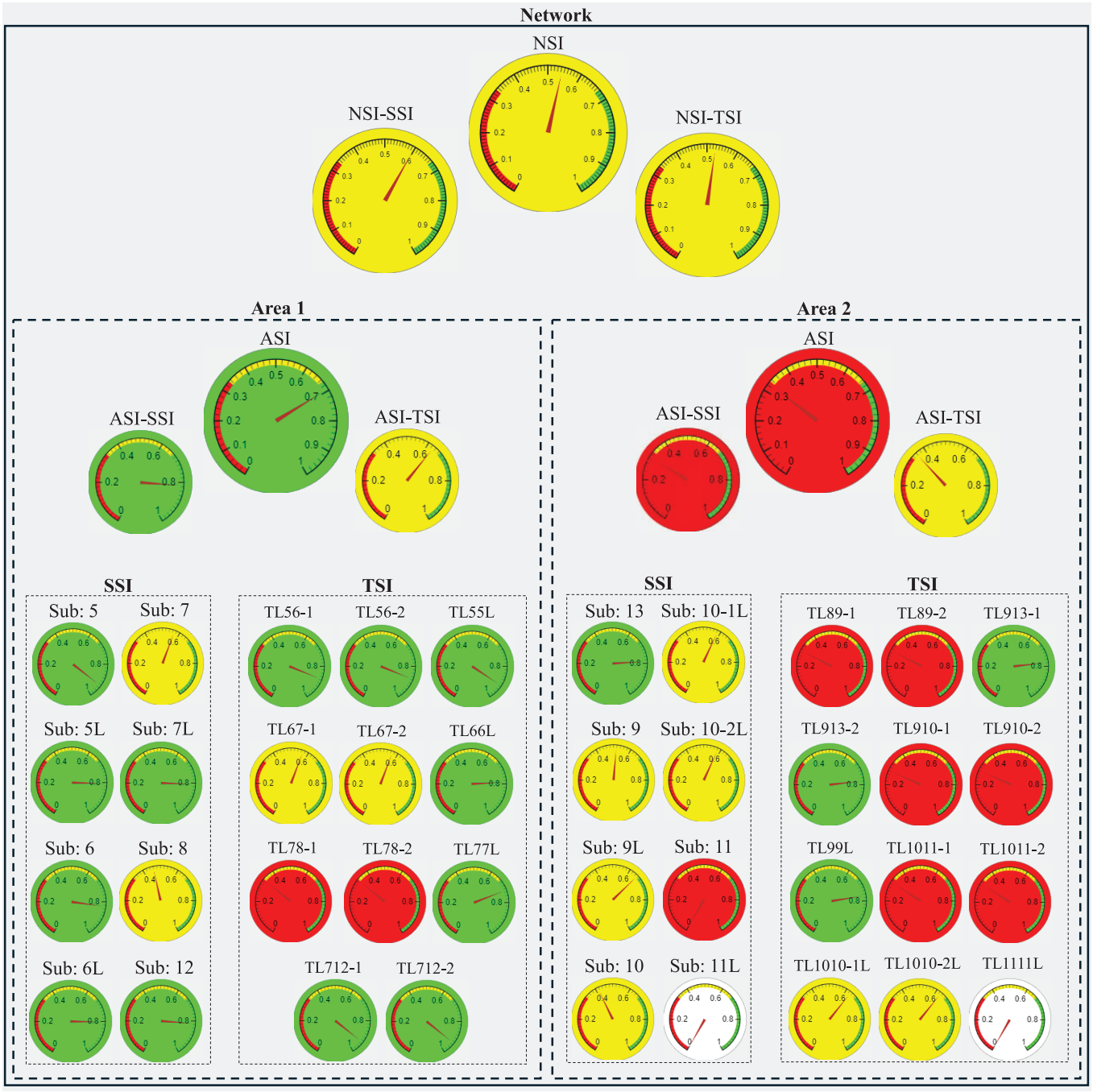

FIGURE 21. Substation Security assessment visualization for ECC operator with all the security indexes demonstrated for the two-area four-machine power system model under TL1111L transmission line outage (Case 1A: Critical Transmission Line Outage). The snapshot is at the 68th PMU frame.

C. VISUALIZATION

One of the main objectives of the DSA tools is to provide a simple but comprehensive understanding of the power system state to the ECC operators. The DSA visualization enables this goal. A suggested visualization for the ECC operator is shown in Fig. 21. The visualization snapshot has been taken for test case 1A at the 68^{th} PMU frame. The proposed online visualization utilizes the output from each level of the D-DSA to present a structured, easy-to-understand interpretation of the power system NSA with the capability of investigating ASA, SSA and TSA quickly. The index values (quantitative assessment) are shown from the dial. The security states (qualitative assessment) are shown in the dial's background color (Red - Emergency, Yellow - Alert, and Green - Normal). In the case of a substation isolation or a transmission line disconnection, the dial is set to "0" and the background color of the dial is set to white.

TABLE 5. Summary of proposed D-DSA properties overcoming SOTA DSA shortcomings.

SOTA Shortcomings	D-DSA Properties
Measurement quality	D-LSE delivers accurate estimations of substation voltages.
Model accuracy and reliability	H-TNTP-PMU derives accurate and reliable network topology.
Computational efficiency	D-DSA, D-LSE and H-TNTP-PMU are multi-level architectures that can be implemented using parallel and distributed processing.
Human-system interaction	D-DSA enables a simple hierarchical visualization with qualitative (Normal, Alert or Emergency) indicators and quantitative values. This visualization architecture facilitates rapid detection of power system security issues.
Vulnerability to cybersecurity threats	H-TNTP-PMU is immune to false SMRS. D-LSE is resilient to bad data (false data injection attacks) and robust to PMU unavailability (denial of service attacks).

The D-DSA can be conducted at every PMU frame for automatic systems. However, that update rate for ECC visualization is impractical for a human to understand. The authors suggest that the index values on the visualization can be held for 30-60 s. Thus, the ECC operators can understand the system state and take the best course of action. The visualization at the human-readable rate can bypassed to be updated instantaneously based on the least index values (if the system getting into a substandard system state). Thus, priority is given in the order: Emergency, Alert and Normal. Furthermore, the Alert and Emergency State can be registered as another additional alarm in the EMS alarm records. Due to the hierarchical architecture of the D-DSA, the visualization can be adapted easily at substations, area control centers or network control center. Furthermore, under insecure network conditions, tracking down the malfunctioning substation, transmission line, or area is simple and straightforward with a hierarchical visualization. This directly improves the efficiency of the control actions to mitigate the insecure state or, in the worst-case scenario, deploy field teams for maintenance.

D. DISCUSSION

A summarized list of mitigation for the SOTA shortcomings with the D-DSA is shown in Table 5. The measurement quality and availability are improved with the integration of the D-LSE. Furthermore, the network model accuracy and reliability are ensured by integrating H-TNTP-PMU. Both these foundational applications improve the accuracy of the D-DSA. RMSE analysis for each test case is summarized in Table 6. The RMSE for the D-DSA Engine 2 is lower compared to the SOTA and D-DSA Engine 1 for all test cases, which illustrates improved accuracy of the D-DSA architecture with the H-TNTP-PMU and D-LSE (D-DSA Engine - 2).

TABLE 6. Root mean square error (RMSE) estimated for SOTA, D-DSA Engine 1 and D-DSA Engine 2 with Actual for all the test cases of modified two-area four-machine power system model and IEEE 68 bus power system.

System	Case	S	RMSE with Actual calculated using NSI		
			SOTA	D-DSA Engine - 1	D-DSA Engine - 2
1	Case 1A	550	0.1284	0.0183	0.0171
	Case 1B	550	0.0447	0.0081	0.0056
	Case 1C	2500	0.0412	0.0058	0.0058
	Case 1D	2500	0.0954	0.0075	0.0089
2	Case 2A	550	0.0424	0.0086	0.0064
	Case 2B	550	0.0361	0.0082	0.0055
	Case 2C	2500	0.0400	0.0077	0.0056

The computational overhead estimated for 50 trials on an Intel Xeon(R) Gold 3.3 GHz system with 63.7 GB RAM for all test cases of System 1 under the three approaches at different levels is shown in Table 7. Table 7 demonstrates the improved efficiency of the proposed approach that used D-LSE and the H-TNTP-PMU. The fundamental objective is to develop an assessment tool that can be completed for every PMU data frame, which requires the foundational applications to be completed in the same time frame. The computational time details for D-LSE and H-TNTP-PMU can be found in [5] and [6], respectively. It is important to mention that the computational time is based on the computational platform utilized and the computational architecture. Utilizing parallel processing with SOTA good processing units can help to achieve better efficiency.

TABLE 7. Computational time in μs estimated for the three approaches for modified two-area four-machine power system model.

Approach	Level		
	Network	Area	Component
SOTA	$> 2 \times 10^6$	-	-
D-DSA Engine - 1	157 ± 8.255	26.976 ± 1.783	3.567 ± 0.162
D-DSA Engine - 2	187 ± 9.735	33.976 ± 2.863	8.567 ± 0.743

V. CONCLUSION

Modern power system security is critical due to the increased dynamicity introduced by renewable generations and active distribution systems. Traditional methods based on applications, such as transmission network topology processing based on supervisory control and data acquisition system monitoring of relay signal and linear state estimation, are inefficient and not scalable. The inefficiency of the foundational applications directly limits the performance of the dynamic security assessment tool. This paper proposed a distributed dynamic security assessment tool that leverages hierarchical efficient and reliable transmission network topology processing with an efficient, resilient, and robust multi-level distributed linear state estimation. The three-level D-DSA architecture delivers the qualitative and quantitative security assessment of each component, each area and the network. The experiments conducted on two distinct test systems illustrate the performance of D-DSA, thus enabling its usage for real-time operation. The proposed

TABLE 8. Substation Security Assessment Characteristic (Fig.4) Parameters for Modified Two-Area Four-Machine Power System Model.

Substation	m_{VEL}	m_{VAL}	m_{VNL}	m_{VNU}	m_{VAU}	m_{VEU}	c_{VEL}	c_{VAL}	c_{VNL}	c_{VNU}	c_{VAU}	c_{VEU}
5	16.5	11.0	6.8	-6.8	-11.0	-16.5	-14.9	-9.8	-5.8	7.8	12.2	18.2
5L	16.5	11.0	6.8	-6.8	-11.0	-16.5	-14.9	-9.8	-5.8	7.8	12.2	18.2
6	16.5	11.0	5.7	-5.7	-11.0	-16.5	-14.7	-9.7	-4.6	6.7	12.3	18.3
6L	16.5	11.0	5.7	-5.7	-11.0	-16.5	-14.7	-9.7	-4.6	6.7	12.3	18.3
12	16.5	11.0	5.7	-5.7	-11.0	-16.5	-14.7	-9.7	-4.6	6.7	12.3	18.3
7	16.5	11.0	11.3	-11.3	-11.0	-16.5	-15.2	-10.0	-10.3	12.3	12.0	17.8
7L	16.5	11.0	11.3	-11.3	-11.0	-16.5	-15.2	-10.0	-10.3	12.3	12.0	17.8
8	16.5	11.0	11.3	-11.3	-11.0	-16.5	-15.2	-10.0	-10.3	12.3	12.0	17.8
13	16.5	11.0	5.7	-5.7	-11.0	-16.5	-14.7	-9.7	-4.6	6.7	12.3	18.3
9	16.5	11.0	17.0	-17.0	-11.0	-16.5	-15.3	-10.1	-16.0	18.0	11.9	17.7
9L	16.5	11.0	17.0	-17.0	-11.0	-16.5	-15.3	-10.1	-16.0	18.0	11.9	17.7
10	16.5	11.0	6.8	-6.8	-11.0	-16.5	-14.9	-9.8	-5.8	7.8	12.2	18.2
10_1L	16.5	11.0	6.8	-6.8	-11.0	-16.5	-14.9	-9.8	-5.8	7.8	12.2	18.2
10_2L	16.5	11.0	6.8	-6.8	-11.0	-16.5	-14.9	-9.8	-5.8	7.8	12.2	18.2
11	16.5	11.0	6.8	-6.8	-11.0	-16.5	-14.9	-9.8	-5.8	7.8	12.2	18.2
11L	16.5	11.0	6.8	-6.8	-11.0	-16.5	-14.9	-9.8	-5.8	7.8	12.2	18.2

TABLE 9. Transmission line ratings define for modified two-area four-machine power system model.

ID	Rating (A)	ID	Rating (A)	ID	Rating (A)
TL55L	1250	TL78-1	150	TL910-2	100
TL56-1	150	TL78-2	150	TL99L	500
TL56-2	150	TL77L	1000	TL1011-1	100
TL66L	1000	TL89-1	150	TL1011-2	100
TL712-1	200	TL89-2	150	TL1010-1L	500
TL712-2	200	TL913-1	200	TL1010-1L	500
TL67-1	450	TL913-2	200	TL1111L	1250
TL67-2	450	TL910-1	100	-	-

TABLE 10. Transmission Line Ratings define for IEEE 68 bus power system model.

ID	Rating (A)	ID	Rating (A)	ID	Rating (A)
TL24-23	593	TL60-57	615	TL42-18	211
TL28-26	199	TL65-62	487	TL45-35	537
TL52-37	326	TL68-24	163	TL48-47-2	197
TL54-53	445	TL68-67	449	TL61-36-1	822
TL63-58	600	TL26-25	105	TL31-30	392
TL20-19	345	TL29-28	530	TL48-40	784
TL23-22	117	TL63-62	568	TL51-45	1237
TL27-26	364	TL67-66	116	TL61-36-2	822
TL55-52	89	TL29-26	278	TL41-40	876
TL59-58	765	TL54-25	427	TL51-50	1855
TL22-21	1035	TL66-56	322	TL53-30	440
TL37-27	144	TL66-65	440	TL61-30-1	591
TL56-55	150	TL33-32	1227	TL38-31	140
TL58-57	726	TL42-41	390	TL49-46	273
TL65-64	83	TL43-17	612	TL61-30-2	591
TL53-27	65	TL45-44	820	TL29-38	541
TL57-56	115	TL50-18	2095	TL36-34	645
TL59-60	385	TL53-31	270	TL44-43	612
TL64-63	59	TL36-17	4262	TL46-38	68
TL68-19	722	TL38-33	169	TL34-33	1190
TL55-54	347	TL45-39	621	TL44-39	195
TL61-60	664	TL48-47-1	197	TL53-47	85
TL68-21	589	TL49-18	564	-	-
TL68-37	479	TL32-30	369	-	-

TABLE 11. Transmission line security assessment characteristic (Fig.6) parameters.

m_{IN}	m_{IA}	m_{IE}	c_{IN}	c_{IA}	c_{IE}
-1.3	-1.3	2.2	1.6	1.6	2.5

TABLE 12. Fuzzy inference reduced rule table for area security assessment for modified two-area four-machine power system Area 1 contains 8 substations.

Rule Index	Count of "H"	Count of "M"	Count of "L"	Output
1	8	0	0	0
2	7	1	0	0.0625
3	7	0	1	0.125
4	6	2	0	0.125
5	6	1	1	0.1875
6	5	3	0	0.1875
7	6	0	2	0.25
8	5	2	1	0.25
9	4	4	0	0.25
10	5	1	2	0.3125
11	4	3	1	0.3125
12	3	5	0	0.3125
13	5	0	3	0.375
14	4	2	2	0.375
15	3	4	1	0.375
16	2	6	0	0.375
17	4	1	3	0.4375
18	3	3	2	0.4375
19	2	5	1	0.4375
20	1	7	0	0.4375
21	4	0	4	0.5
22	3	2	3	0.5
23	2	4	2	0.5
24	1	6	1	0.5
25	0	8	0	0.5
26	3	1	4	0.5625
27	2	3	3	0.5625
28	1	5	2	0.5625
29	0	7	1	0.5625
30	3	0	5	0.625
31	2	2	4	0.625
32	1	4	3	0.625
33	0	6	2	0.625
34	2	1	5	0.6875
35	1	3	4	0.6875
36	0	5	3	0.6875
37	2	0	6	0.75
38	1	2	5	0.75
39	0	4	4	0.75
40	1	1	6	0.8125
41	0	3	5	0.8125
42	1	0	7	0.875
43	0	2	6	0.875
44	0	1	7	0.9375
45	0	0	8	1

D-DSA demonstrates improved accuracy, scalability, and computational efficiency, which enables an online application in every PMU data frame. A simple but comprehensive visualization is suggested, where the energy control center

operator is informed of the qualitative security state of the power system (Normal, Alert or Emergency) with the quantitative security index and can easily locate any insecure areas or components. D-DSA provides a comprehensive power system dynamic security assessment that enhances operational situational awareness. Future work includes integrating generation units (conventional and renewable) and transformers at the component level of the D-DSA to enhance the comprehensive understanding of power system security.

APPENDIX

See Tables 8–12.

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