An Integrated Online Dynamic Security Assessment System for Improved Situational Awareness and Economic Operation

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This work was supported by SGCC Jiangsu Science and Technology Program under project Development and Application of Massive Smart Load Monitoring and Control Device Cloud Platform.

ABSTRACT The ever-increasing penetration of centralized and distributed renewable energy, power electronics-based transmission equipment and loads, advanced protection and control systems, storage devices and new power market rules all contribute to the growing dynamics and stochastic behaviors being observed in today’s grid operation. Understanding operational risks and providing prompt control actions are of great importance to ensure secure and economic operation of a bulk power system. In this paper, a novel integrated online dynamic security assessment system (DSAS) is developed that intakes real-time EMS snapshots combining both bus/branch and node/breaker network models, performs dynamic contingency analysis under various conditions, calculates real-time transfer limits, and provides online control suggestions to mitigate operational risks. Several unique and innovative features are developed to address practical challenges, including: (1) real-time stitching of power flow information from both node/breaker and bus/branch models covering different geographical regions of interest; (2) online corrections and enhancements to power flow and dynamic models; (3) equipment-name-based modelling approaches for complex contingencies and control systems; and (4) distributed computing capabilities for significant computational speed enhancement. The developed DSAS has been deployed in the control center of State Grid Jiangsu Electric Power Company with hundreds of HVAC and 8 (U)HVDC transmission lines, which has been running reliably since Sept. 2018, achieving satisfactory performance in improving situational awareness and economic operation of the power grid.

INDEX TERMS Co-simulation, Distributed computing, Dynamic security assessment, EMS, Node/Breaker model, Transient Stability, User defined model

I. INTRODUCTION

A. BACKGROUND

Dynamic security of a bulk power system is the ability to maintain system synchronism with acceptable bus frequencies and voltage profiles within a short time frame following a large disturbance, which needs to be maintained at all times when operating a power grid [1]. It is typically threatened by extreme weather conditions, tree contacts, terrorism, cyber-attacks, equipment malfunction, protection system mis-operation, operator errors, etc. The fast-growing stochastics and dynamics observed in today’s grid, including renewable energy, bi-directional power flows caused by demand responses and storage devices, hybrid HVAC/HVDC systems with heavy power transfers, growing power electronic devices, increased applications of advanced protection and control systems, and new market behavior, may break the power balance in a short time period. In extreme cases, cascading failures and large-scale blackouts may occur if the disturbances are not evaluated thoroughly and mitigated in a timely manner [2]. It is therefore of critical importance to assess dynamic security and operational risks
of the system in near real time to address these new challenges.

B. PREVIOUS WORK ON DSA

To assess dynamic security, direct methods were proposed decades ago to assess transient stability using transient energy function (TEF) [3]-[4]. The main idea is to evaluate the injected energy of a disturbance and compare it with the maximum permissible energy. If the injected energy is smaller than the threshold, this disturbance will not cause transient instability. The authors in [5] introduce the concept of corrected transient energy function (CTEF) and show that the value of CTEF maintains constant during post-fault transient period. The criterion to detect the first swing stability margin is developed based on the concept. In [6], the transient energy function is leveraged to estimate the transient stability margin after a fault using the phasor measurement unit (PMU) at the generator buses. The post-fault control action is determined by a look-up table built offline. The application of transient energy function method in real-time environment is limited by the difficulty of calculating TEFs.

With the fast development of modern computers, mathematical algorithms, differential and algebraic (DAE) solvers, and system monitoring techniques such as synchronous phasor measurements, various efforts for transient stability monitoring and detection, margin identification and prediction have been reported, among which using time-domain simulations to obtain transient trajectories under contingencies became the fundamental and dominant technology [7]. In [8], a method for transient stability simulation based on a semi-analytical solution (SAS) of power system DAE derived from the Adomian decomposition method (ADM) is proposed. The authors in [9] establish the mapping between the system trajectory and individual-machine equal area criterion. A direct time-domain approach that is based on the individual-machine equal area criterion is proposed. Reference [10] introduces Differential Transformation (DT) to investigate the power system dynamic simulation. In [11], the holomorphic embedding method (HEM) is utilized to develop an efficient dynamic simulation framework.

Recent research regarding online dynamic security assessment focuses more on applying machine learning based methods in estimating transient stability in real time [12]-[17]. In [18], the system transient stability margin is evaluated by the long short-term memory (LSTM) network. The prediction accuracy is improved by learning the temporal data dependencies of the input data. Reference [19] leverages twin convolutional support vector machine to investigate the size and type of independent transient stability margin. To compute the total transfer capability (TTC) of the interconnected system, the authors in [20] propose a real-time measurement-based TTC estimator. The group Lasso regression is utilized for the offline training process. Typically, massive offline simulations are conducted to train models to be used for real-time environment. However, for such approaches to be effective and robust in real environment, a few challenges need to be resolved, including: (1) lack of sufficient high-quality sampling cases that can represent majority of the possible operating conditions, especially those insecure or problematic ones; (2) the overfitting problem being observed by many supervised machine learning-based approaches; and (3) lack of ability of analyzing massive simulation results and generating actionable information in real time. Thus, most of these proposed approaches are at their early stages; and improving the quality and speed of time-domain simulation-based dynamic security assessment is necessary to provide better situational awareness for secure and economic grid operation.

C. PROPOSED NOVEL SOLUTIONS FOR ONLINE DSA

To solve the above issues, this paper presents an integrated online dynamic security assessment system (DSAS) with several innovative solutions for resolving practical issues when conducting DSA for a bulk power system in online environment. The DSAS has been deployed in the control center of the State Grid Jiangsu Electric Power Company for more than 12 months. The key innovations of this work comparing to existing solutions are summarized below:

1) It adopts the high-fidelity modeling platform and scalable time-domain simulation engine, TSAT, developed by Powertech Labs [21] for online security assessment and control, which supports hundreds of approved stability models used for planning and operational studies across the world and makes it easier to design and test new models and controller performance without the need for rewriting all the stability models for a real power grid from scratch. Various security criteria are supported to allow for a more comprehensive evaluation of dynamic security, including transient stability, transient voltage, damping, transient frequency and relay margin.

2) It uses a hybrid network modeling approaches, which intakes and combines real-time EMS snapshots in both bus/branch and node/breaker models covering different regions of the power system. For the region of interest inside a bulk power grid, full topology (node/breaker) models are used while conventional bus/branch models are used for the rest of the system. This novel approach provides in-depth modeling and simulation capabilities with equipment names as the unique IDs, and it can significantly accelerate the adoption of node/breaker-based modeling and simulation practices to enable more precise modeling of power equipment and contingency sequence.

3) It adopts an adaptive approach to correcting and enhancing real-time models for DSA implementation, including: (1) mapping between power flow, dynamic models, contingency definition and monitored
information; (2) correcting problematic models and parameters on the fly; and (3) inserting full modeling details for power equipment and control systems, e.g., HVDC control system, special protection system, and composite load models, which are typically modelled as equivalent loads or generators.

4) It enables distributed computation techniques to significantly speed up massive dynamic simulations for real-time computation by utilizing dozens or hundreds of computer CPU processors via Ethernet.

5) It provides a user-friendly user-defined-modeling (UDM) platform so that complicated control systems like high voltage direct current (HVDC), flexible alternating current transmission system (FACTS), and special protection system (SPS) can be included in addition to the existing standard models for a power system.

With these innovative solutions, the developed DSAS can enable several advanced applications for improving situational awareness and economic operation for a real power system, including: security assessment under N-1 or N-k contingencies, transfer limit calculation, remedial action scheme (RAS) or special protection system (SPS) modeling, high-fidelity dynamic models of complex control system via user defined models (UDMs), etc.

D. OUTLINE OF THE PAPER

The remainder of this paper is organized as follows. Section II introduces the principles and main challenges in designing and implementing the online DSAS in real world. Section III provides the details of the proposed integrated DSAS, including architecture design, use of node/breaker models and distributed computing capability. Section IV provides realistic case studies and computational performance using the real-time snapshots from Jiangsu province. Finally, conclusions are drawn in Section V, with future work identified.

II. PRINCIPLES AND CHALLENGES OF ONLINE DSAS
A. PRINCIPLES OF DSA VIA TIME-DOMAIN SIMULATIONS

Time-domain simulations, a.k.a. dynamic simulations, are typically conducted in order to obtain transient trajectories of a system, such as generator rotor angles, bus voltages, and bus frequencies, under system disturbances for assessing dynamic security. Various security criteria can be applied, including system synchronism, transient voltage recovery, frequency profile, damping, etc. Typical system component models used in such simulations include generators, exciters, governors, PSS, dynamic loads, DC converters, protection relays and UDMs, shown in Fig.1, where information exchange and model interactions are provided.

In dynamic simulations, mathematical models are used to describe the transient behavior of the above-mentioned power equipment over a period of time (e.g., 10 seconds to 30 seconds). The dynamic behavior of a multi-machine power system can be described by the nonlinear Differential-Algebraic Equations (DAEs), as provided in Eq. 1.

\[
\begin{align*}
\mathbf{x} &= \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{u}) \\
\mathbf{0} &= \mathbf{g}(\mathbf{x}, \mathbf{y}, \mathbf{u})
\end{align*}
\]

where \( \mathbf{x} \) is a vector of order \( n_x \times 1 \) containing state variables in the entire power system, such as generator rotor speed, rotor angle, flux, and states of excitation system, governor, PSS, dynamic loads, and DC components. \( \mathbf{y} \) is a vector of order \( n_y \times 1 \) consisting of algebraic variables, i.e., bus voltage magnitude and angle. \( \mathbf{u} \) is a vector of order \( n_u \times 1 \) containing input variables such as the reference voltage magnitudes for the automatic voltage regulator (AVR). \( \mathbf{f} \) is the differential equation set, where the derivatives of state variables are normally discretized. The definitions and control block diagrams of those commonly used generators, exciters, governors, PSS and DC models can be found in [7],[21],[22], so they are not provided here due to space limitation. The algebraic equations \( \mathbf{g} \) consist of the network equations based on Kirchhoff’s current law, i.e., the sum of all currents flowing into a bus must be equal to zero, which provides an interface between the algebraic variables and the state variables. The following equation is used to synchronize dynamic behavior of all components in the network at each time step during a dynamic simulation:

\[
I = YV
\]
where $I$ contains current injections at each bus from generators, dynamic loads and user defined dynamic models; $Y$ stands for the admittance matrix of a power network, which should also include generator equivalent impedance and static load components; and $V$ is the vector of complex bus voltages of the network.

In order to solve the above DAEs and obtain time-domain curves for assessing transient stability, there are two types of integration methods adopted by commercial software vendors, namely, explicit and implicit methods. These methods are summarized in Table I.

**Table I: Integration Methods Used for DSA**

<table>
<thead>
<tr>
<th>Types of Integration</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explicit integration</td>
<td>Euler</td>
</tr>
<tr>
<td></td>
<td>Modified Euler (or Runge-Kutta 2nd order)</td>
</tr>
<tr>
<td></td>
<td>Runge-Kutta 4th order</td>
</tr>
<tr>
<td></td>
<td>Mixed Adams-Bashforth</td>
</tr>
<tr>
<td>Implicit integration</td>
<td>Trapezoidal</td>
</tr>
</tbody>
</table>

Explicit approaches include Euler, Modified Euler, 4th order Runge-Kutta and Mixed Adams-Bashforth, which are easy to implement and can support very complex UDMs. The discretized differential equations and algebraic equations are solved alternatively multiple times within one time step to achieve the specified tolerance. A relatively small time step, e.g., 1/4 or 1/2 cycle is required to ensure numerical stability. In North America, the dominating commercial vendors’ dynamic simulation programs all adopt explicit integration methods for power system planning and operational studies, such as TSAT developed by Powertech Labs.

In contrast, implicit integration methods can support larger time steps while maintaining numerical stability, e.g., 1 cycle. The Trapezoidal method is commonly used in commercial software packages used in China and Europe. In such a method, DAEs are combined and solved simultaneously at each time step, using Newton’s method where Jacobian matrices are calculated many times during a dynamic simulation through derivation of DAEs or perturbation methods. For a large power network, good initial guess at each time step is critical to ensure rapid convergence; otherwise, the increasing number of iterations would significantly slow down the dynamic simulation, especially when many switching actions exist within a short time period.

Both explicit and implicit methods have their pros and cons. In this work, we adopt the commercial simulator, TSAT, which enables both integration methods, as the platform for implementing the proposed DSAS with practical considerations.

**B. INDICES FOR DETERMINING TRANSIENT SECURITY**

To interpret the trajectory of a system following a disturbance, TSAT provides two types of transient stability index to effectively assess the severity of a disturbance, using generator rotor angles. The first one is called power swing-based stability index (swing margin, “SM”), which is based on the Extended Equal Area Criterion (EEAC) approach proposed in [26]. This method contains three steps to determine the stability index:

1) Identify critical cluster of generators (CCG). This is the group of generators that are likely to become unstable at more stressed system conditions.

2) Form parametric one-machine-infinite-bus (OMIB) equivalent. The parameters of the equivalent are updated based on the simulation results of the system.

3) Evaluate the stability of the system and compute the stability index.

The other index is named power angle-based stability index (angle margin, “AM”). The index is defined as follows for each electric island in the system:

$$\gamma = \frac{360 - \delta_{\text{max}}}{360 + \delta_{\text{max}}} \times 100, \quad 100 < \gamma < 100$$

where $\delta_{\text{max}}$ denotes the maximum angle separation of any two generators in each AC island in the post-disturbance response. The smallest index among all islands is selected as the transient stability index for the system. Hence, $\gamma > 0$ and $\gamma \leq 0$ indicate stable and unstable conditions, respectively. Since AM is proportional to the system angle separation, it serves as a good indicator regarding how severe a system is after a disturbance. One can select either index to determine security of a transient simulation following a disturbance.

To speed up computations, early termination techniques are also adopted in the simulation engine for those very secure and very insecure cases. For stable conditions, SM and the maximum peak-to-peak power angle swing are calculated to compare with the specified thresholds. The calculation is terminated only if SM is larger than the set threshold and the maximum angle swing is less than the set threshold. Similarly, for unstable conditions, SM and AM are computed and compared with the specified thresholds. The simulation is terminated only if both margins are less than the set thresholds simultaneously.

In addition to transient stability indices shown above, this platform also supports checking the following criteria for a more comprehensive evaluation of a simulation case:

1) **Damping**: to calculate modes of oscillations within a desired range of frequency from generator responses.

2) **Transient voltage**: to evaluate bus voltage drop/rise duration indices during a dynamic simulation.

3) **Transient frequency**: to evaluate frequency drop/rise duration for buses and generators during a dynamic simulation.

4) **Relay margin**: to check apparent impedances of monitored lines against impedance/distance relay zone settings for potential tripping actions.
C. KEY CHALLENGES FOR IMPLEMENTATION IN REAL TIME

To perform dynamic security assessment reliably in real time, several challenges need to be resolved effectively, including:

1) **Naming convention**: Real-time power flow information is typically handled by energy management system (EMS), where state estimation results are obtained periodically (every 1-5 minutes) using SCADA measurements across the entire system. For planning studies, DSA can be conducted on system planning cases that are projected operating scenarios for future conditions. For online DSA, linking the EMS information (in node/breaker format) with DSA solver (in bus/branch format) in real time can be a challenge, given the naming convention can be totally different, although they represent the same physical system.

2) **Information mapping**: Tables can be developed offline to map and convert the information from EMS to DSA format. This approach works well most of the time, except for scenarios where network topologies are changed that cause major changes in bus names or numbers, e.g., due to bus splitting. This affects dynamic models providing current injection to the network, contingency definition, monitored system information, user defined dynamic models, etc.

3) **Fidelity of models**: High-fidelity power flow and dynamic models are required to obtain accurate system responses following various contingencies. For power flow models, the accuracy can be relatively easy to maintain if enough details are provided to model various power equipment, e.g., HVDC, ZIP loads, etc. For dynamic models, getting the correct parameter set for the entire system is a challenging task, given each generator, dynamic load, and HVDC can contribute to the system dynamic responses. In North America, NERC standards (MOD 26, 27 and 33) are enforced to verify dynamic models of large generators and their controllers. If large mismatches are identified between model performance and actual measurements, calibration process is needed via stage testing or PMU based approaches [23].

4) **Selection of contingencies and post processing**: Within a desired interval (e.g., 15 minutes), all transient stability analyses and advanced applications need to be completed. Thus, users need to be careful when selecting an appropriate number of contingencies either statically or dynamically for screening system operational risks, by considering computational speed, available computing resources and communication network conditions. Thorough testing and tuning are required to ensure reliable operation of DSAS. In addition, converting insecure simulation results with suspicious behavior and risks into actionable information to ensure system security can be also very challenging in real-time environment.

III. PROPOSED SOLUTION WITH PRACTICAL CONSIDERATIONS

To resolve the above issues considering practical constraints, an integrated DSAS with several innovative features is proposed in this paper.

A. OVERALL FLOWCHART – AN INTEGRATED SOLUTION

The overall flowchart for each computing cycle (every 15 minutes) is depicted in Fig. 2, consisting of several key steps:

- **Step 1**: at the beginning of the process, the main program checks if the computational engines are ready for taking new power flow information before running various simulation tasks. A flag file can be used for this purpose.

- **Step 2**: an EMS interface is needed to transfer the correct power flow information to the main DSAS program, which includes EMS output and/or solution files. In this work, we adopt a novel approach that enables mixture of two types of data files with different network models, BPA (bus/branch) and CIM-e (full topology/node/breaker representation) so that the areas of interest can be modeled using the detailed node/breaker models while external systems can be represented by bus/branch models.

- **Step 3**: the information from EMS is further processed to achieve a full AC power flow solution. If successful, DSAS will link contingency definitions, dynamic models, UDMs, and monitored quantity list with the current operating condition, and then allocate simulation cases to computing processors, using distributed computing techniques for significant speed up.

- **Step 4**: advanced applications can then be started, including contingency screening for operational risks, calculation of transfer limits for critical corridors, derivation of preventive control measures (PCM) if insecure contingencies are detected, scanning for potential cascading failures with protection relay modeled, design and verification of SPS, and system wide or component model validation.

The following subsections provide more details of each main step.

B. ADOPTION OF NODE/BREAKER MODEL WITH EQUIPMENT NAME AS UNIQUE ID

In order to effectively resolve the naming convention and information mismatch issues, full network topology information, namely, node/breaker model, is used in this work that can provide precise details across the power system. Such models are commonly used in EMS and an example is provided in Fig. 3 to explain the difference between the traditional bus/branch model and node/breaker model in modeling two neighboring substations.

As can be seen, using bus/branch models, the two substations can be modeled as 4 buses; while in node/breaker models, the same substations are modeled as 6 busbars, 13 breakers and several nodes. Thus, much more detailed information becomes available to precisely model the network topology and contingency/RAS action consequences. For example, when breakers BR2, BR5 and
BR8 are disconnected simultaneously, the corresponding two buses (103 and 101 in bus/branch model) are split into four buses, causing totally different topology for power grid analysis. Such a phenomenon cannot be captured using bus/branch model.

The node/breaker models also adopt equipment names (instead of bus numbers) as unique IDs for all power equipment, and these IDs do not change from one operating condition to another. This novel feature can significantly reduce the efforts in maintaining the models to represent reality for online application because all the supporting files for dynamic simulations don’t need to be updated frequently and can thus be easily maintained off-line.

C. PROCESSING REAL-TIME INFORMATION FOR DSA

Ideally, node/breaker models should be used to cover the entire power grid for real-time operational studies; where topology processing is conducted to reduce the node/breaker models to bus/branch models to achieve highly efficient internal calculations.

1) Real-time stitching of power flow information with different formats

However, in reality, not all utilities or independent system operators have access to real-time full-topology information outside their service areas; in some scenarios, like the Jiangsu EMS, node/breaker information is available only for part of the power system, and for the rest of the system bus/branch information is available. A novel “real-time stitching” technique is developed in this work that can identify the boundary buses between internal and external network using zone definitions so that node/breaker models are used for modeling internal network using equipment names, and bus/branch models for representing external networks. Then, the two models are combined to get a more accurate power flow solution for further applications without over-simplifying the system, e.g. using equivalent generators or loads to represent the external power system.

![Figure. 2. Simulation procedure of the proposed DSAS for each computing cycle.](image)

The node/breaker models are disconnected simultaneously, the corresponding two buses (103 and 101 in bus/branch model) are split into four buses, causing totally different topology for power grid analysis. Such a phenomenon cannot be captured using bus/branch model.

![Figure. 3. Comparison of bus/branch model and node/breaker model representing two substations.](image)

Fig. 4 illustrates this “stitching” process, where the zone in the middle has detailed node/breaker model available while the surrounding zones have bus/branch model. Two files are periodically generated by two different EMS applications. It is worth mentioning that due to communication delays, the two types of files may not represent precisely the same system condition; thus, special logic is needed to ensure synchronism between the two. In this process, a 1-minute (or 3 minute) threshold is used, which can be adjusted by users. If the two files are generated more than 1 minute apart, the case is ignored and the DSAS will wait for the next snapshot.

![Figure. 4. Flowchart of stitching node/breaker model and bus/branch model.](image)

2) Enhancement of power flow information to support high-fidelity complex models

Certain equivalencing methods are used in today’s EMS tools when solving state estimation problems, e.g., using equivalent loads to represent HVDC links, using shunts for synchronous condensers, etc. Without accurate power flow...
models, the dynamic behavior of such complex equipment cannot be simulated. To resolve this issue, the proposed DSAS allows the users to enhance the power flow information by adding more details to the real-time snapshots. For HVDC injection into a bus, EMS may simply use a large dummy load for power flow studies. In the online DSAS, the dummy loads are removed on the fly, and rectifier and inverter models, DC buses, DC lines are added to the AC system so that dynamic simulations with detailed HVDC models are possible.

3) Dynamic model patches in real time

Dynamic model information also needs to be updated periodically to match reality at the current operating condition, represented by the converged power flow. In the proposed DSAS, offline models and parameters can be overwritten by online data patches when issues are identified on certain dynamic models. In addition, UDMs can be added to simulate the dynamics of complex components like HVDC systems, SPS or composite loads, etc.

D. DISTRIBUTED COMPUTING FOR ENHANCED COMPUTATIONAL SPEED

For online DSAS, there may be thousands of contingencies that need to be simulated for an operating condition. Using a single-processor computer cannot achieve the desired computational speed in most cases. Thus, the developed DSAS adopts state-of-the-art distributed computing techniques that can automatically allocate computing tasks to available computation servers, which can significantly reduce the total computational time for a computing cycle.

E. IMPLEMENTATION AND DEPLOYMENT IN THE CONTROL CENTER OF THE SGCC JIANGSU ELECTRIC POWER COMPANY

The commercial software platform, DSATools™, developed by Powertech Labs, is adopted for implementing the proposed new features discussed above, which supports both BPA format [25] and CIM/e format data. The deployment configuration of the DSAS in the control center of the SGCC Jiangsu Electric Power Company is shown in Fig. 5. There are four computing servers in this system. Each is equipped with 48 physical CPU cores (with hyper threading enabled) running at 2.2 GHz, 64 GB of memory, and 1 TB SSD hard drive. One of the servers runs the main program, DSA Manager, which is the brain of the entire process; while the remaining servers provide TSA computing services. Forty TSA services are enabled on each of the servers, making 160 simulation cores available for online DSA tasks. Workstations can be used by grid operators in the control room to observe operational risks at the current operating condition and evaluate the suggested control actions. Compared to the existing techniques deployed in real-world applications, the proposed DSAS with novel features can enable more comprehensive and accurate dynamic security assessment for the control center of Jiangsu power grid. More details are provided in Section IV below.

IV. ADVANCED APPLICATIONS AND CASE STUDIES USING REAL SCENARIOS

The Jiangsu power grid is part of the interconnected power system in the East China. It serves 40,000,000 customers with high-quality electric energy on a daily basis. The peak load in Jiangsu power grid reached 102.88 GW in the summer of 2018. The Jiangsu grid is connected with several provincial power grids using both HVAC and HVDC transmission lines, including Zhejiang, Anhui, and the City of Shanghai. The key transmission network (~55,000 miles) consists of around 20 1000-kV Ultra high voltage AC (UHVAC) lines with a thermal capacity of 7,000-10,000 MVA each, four Ultra high voltage DC (UHVDC) systems with a thermal capacity of 3-8 GW each, more than 600 500-kV AC lines, and more than 2900 substations (35kV and above).

The EMS system in the East China area outputs state estimation results every 5 minutes. The state estimation cases contain 35 kV and above transmission network that includes over 3800 buses, ~450 generators, ~2300 loads, ~300 shunt elements, ~5000 AC lines and ~1700 transformers. For Jiangsu’s grid, the EMS state estimation outputs cases with full node/breaker topology information every 15 minutes. The real-time stitching method introduced in Section III.C is used to combine both node/breaker and bus/branch models. After the stitching process, the power flow network to be processed contains more than 13,000 nodes and 12,000 lines with breakers and disconnectors.

Most of the dynamic models including generators, exciters, governors, and PSS used in the online EMS applications for the East China area are supported by TSAT, which are summarized in Table II. These are standard stability models used in the BPA software program and the detailed control block diagrams can be found in the BPA software manual.
[25]. For all the wind generators in Jiangsu province, the WECC 2nd generation doubly-fed induction generator model (Type 3_DFIG, REGC_A) is adopted in the DSAS that can realistically represent the dynamic behavior of the corresponding wind generator and controller models used in the BPA software program (converted models are: MM, ME, MR, TG, ES, EV, GF, EP, EZ, LP and LQ) [25]. HVDC system models are developed as UDM using the following procedures, which then enable several advanced applications deployed in the Jiangsu Electric Power Company. The deployed DSAS has been running reliably since Sept. of 2018.

A. MODELLING LINE COMMUTATION CONVERTER (LCC) UHVDC SYSTEMS VIA UDMS

1) Power flow modification

The power flow information merged from two types of EMS programs does not contain detailed DC models. It is necessary to add DC components to power flow as well as dynamic models. Using the procedure introduced in Section III.C, the positive and negative poles of the UHVDC systems are automatically added to the real-time power flow case to replace the equivalent dummy load connected to ACbus2, shown in Fig. 6. The active power and reactive power injections of the two added DC inverters will match the equivalent load. One equivalent generator and one AC bus (ACbus1) are added to represent the network on the rectifier side. Note that if the active power of the equivalent load is less than 10% of the rated capacity of the DC line, DC components are not added to respect reality.

<table>
<thead>
<tr>
<th>Types of Models</th>
<th>Supported Models in BPA Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>generator</td>
<td>M, MF, MG</td>
</tr>
<tr>
<td>exciter</td>
<td>EA, EJ, F#, FF, FG, FJ, FK, FM, FN, FS, FU, FV, FZ</td>
</tr>
<tr>
<td>governor</td>
<td>GA, GH, GJ, GS</td>
</tr>
<tr>
<td>turbine</td>
<td>TB</td>
</tr>
<tr>
<td>load</td>
<td>LB, LN</td>
</tr>
<tr>
<td>PSS</td>
<td>SA, SB, SG, SI, SP</td>
</tr>
</tbody>
</table>

Table II. BPA models supported by TSAT

![Figure 6](image)

Figure 6. Example of UHVDC system models added to the onlineights flow data.

The LCC HVDC model used in the developed DSAS is provided below [27]:

\[
P = -V_d I_d \quad (3)
\]

\[
Q = -V_d q \tan (\phi) \quad (4)
\]

\[
V_d = k_c V_d \cos (\alpha) - \frac{3}{\pi} N_b X_d I_d = k_c V_d \cos (\gamma) + \frac{3}{\pi} N_b X_d I_d \quad (5)
\]

\[
V_{dd} = \frac{3\sqrt{2}}{\pi} N_b n_t \alpha_t V_{LL} \quad (6)
\]

\[
\mu = \pi - \alpha - \gamma \quad (7)
\]

\[
\tan (\phi) = \frac{2\mu + \sin (2\alpha) + \sin (2\gamma)}{\cos (2\alpha) - \cos (2\gamma)} \quad (rectifier) \quad (8)
\]

\[
\tan (\phi) = \frac{2\mu + \sin (2\alpha) + \sin (2\gamma)}{\cos (2\alpha) - \cos (2\gamma)} \quad (inverter) \quad (9)
\]

Where \( V_d \) is the converter DC voltage; \( I_d \) is the converter DC current; \( \alpha \) is the converter firing angle; \( \gamma \) is the converter extinction angle; \( X_c \) is the commutating reactance per bridge; \( V_{dd} \) is the open-circuit DC voltage; \( V_{LL} \) is the AC line-line voltage on converter side; \( N_b \) is the number of bridges in series on the DC side; \( n_t \) is the transformer nominal voltage ratio of DC to AC side; \( a \) is transformer off-nominal tap ratio; \( k_c = 1 \) for rectifier and -1 for inverter; \( \phi \) is the angle by which line current lags the line-to-neutral source voltage, and \( \mu \) is the commutation angle.

2) Dynamic model of LCC HVDC

UDMs are developed to follow the control block diagram and operation logics of the LCC (U)HVDC system, known as DA/DZ/DA# cards in the BPA software program. In particular, the master control, VDCOL for rectifier and inverter, current control amplifier for both rectifier and inverter, firing angle limit calculation for rectifier and inverter are modeled using control blocks. Eventually, the \( \alpha_{ord} \) (alpha order) signals are sent to rectifier and inverter for regulating DC voltage and DC line power, respectively. The architecture of this control system is given in Fig. 7, where details can be found in [24]-[25] and not repeated here due to space limitation.

![Figure 7](image)

Figure 7. Control block diagram of the LCC UHVDC system model, DA/DZ/DA# in BPA program [15].

3) Model verification against the BPA software program

To verify the accuracy of the developed UDM for LCC UHVDC control system, a power grid model with 9 buses and one DC line is used to compare the DC control system performance given by the BPA program (used for planning
studies in Jiangsu power systems) to that provided by DSAS program with the UDM HVDC model. The one-line diagram is shown in Fig. 8. The parameters of the DC line and both converters are extracted from real (U)HVDC models, used in the East China power grid. A 3-phase to ground fault is applied to the AC bus connecting to the inverter. The dynamic responses obtained in both programs are shown in Fig. 9, which demonstrate the comparison in rectifier firing angles, converter active power, inverter firing angles and DC voltage profiles of the rectifier. As indicated in the figures, very close match between the two time-domain curves is obtained, which verifies the validity of the developed UDM (U)HVDC models.

With the power flow modification function and the UDM LCC (U)HVDC models, one can insert all the (U)HVDC and their control systems to the real-time scenarios in the Jiangsu power grid for performing comprehensive DSA as well as advanced applications. This enables much more accurate modeling practice of hybrid AC/DC bulk power systems, to evaluate the impact of potential disturbances on both AC and DC sides.

**B. MASSIVE CONTINGENCY SCREENING WITH MULTIPLE SERVERS**

Every 15 minutes, when the required power flow and dynamic model information is available, the developed DSAS performs contingency scan via dynamic simulations on a pre-selected list of contingencies. Equipment name is used to specify N-1 contingencies on all the 220 kV and above transmission lines within Jiangsu province, yielding more than 2100 contingencies. Each contingency has a simulation length of 5s, and a fault is applied at 0.1s, then cleared after 5 cycles followed by a single circuit tripping. The 4th order Runge-Kutta method is used for numerical integration. To save hard drive space and gain speed up, no monitored information is specified, which does not affect security criteria checking of each contingency scan. In DSAS, various security checking options supported by TSAT can be enabled, including transient security index, damping ratio, and transient voltage recovery, to identify potential system issues.

Using 160 simulation cores, all the computation tasks for the base case screening considering N-1 contingencies can be completed within 4.5 minutes. Once each computing cycle is completed, all the results indicating security or insecurity of each contingency are archived for further analysis. The developed DSAS with the proposed new features has been running reliably in the control center of the Jiangsu power system since Sept. 2018. Vast majority of the simulation cases are processed successfully. However, there are issues identified in rare situations, which are summarized below along with the corresponding solutions:

(a) Synchronization issue between the node/breaker model file representing Jiangsu province and the bus/branch model file representing East China area. In rare situations, one of the two files got delayed or missing for one computation cycle, preventing the DSA simulations from being conducted. Thus, the current calculation cycle is put on hold until both of the most recent matching power flow files are received.

(b) Failure in real-time stitching of both files. In some cases, power flow failed to converge. Two causes are identified: the time difference between a bus/branch model and the corresponding node/breaker model is larger than 3 minutes; and some EMS snapshots contain fatal modelling errors (e.g., missing critical power equipment). To resolve these issues, EMS system outputs need to be further improved to ensure better mapping of both models.

(c) Failure in running dynamic simulations due to dynamic model errors. Due to certain fatal model parameter issues (e.g., very small time constants in generator models), dynamic simulations fail to start. To resolve this issue, one need to identify the problematic parameters and insert a dynamic model correction file to ensure successful operation of DSAS for each computing cycle.

**C. TRANSFER LIMIT SEARCHING OF CRITICAL TRANSMISSION CORRIDORS LIMITED BY TRANSIENT STABILITY**

Another useful application of online DSAS is to search for transfer limits of critical transmission corridors affected by transient stability under various contingencies. The outputs can be used as constraint inputs to run power market...
simulations and to determine generation schedules. This feature can directly support the operation of power markets for safely transferring a desired amount of power between different areas towards more economic operation.

To perform such a study, source and sink groups (with the combined generation/load increase or decrease) at the two ends of the transfer need to be specified. Two critical corridors are selected to test this capability, one corridor is transferring power from north to south of Jiangsu province and the other is transferring power from Anhui province (west) to Jiangsu province (east). In both cases, the source of power transfer is a group of generators whose MW outputs can be moved upward; while the sink group contains generators that can be move downward at the same time. Generator active and reactive power limits are enforced when adjusting their outputs to stress the transmission corridors. A variable step searching algorithm (combination of linear and quadratic interpolation/extrapolation) is used in this process [21]. The same set of N-1 contingencies are used in this study. The afternoon of one summer day in 2019 was selected to demonstrate the transfer limit calculation, with the results shown in Fig. 10 and Fig. 11. Regarding computational time, searching for both transfer limits considering the full N-1 contingency list (~2100), in addition to the base case screening, takes less than 12 minutes using 160 simulation cores (within the 15-minute EMS cycle).

V. CONCLUSIONS AND FUTURE WORK

In this paper, a novel integrated dynamic security assessment system is proposed and deployed in one of the largest power utilities in China for enhancing situational awareness and economic operation. Principles and challenges of implementing DSA in real-time environment are discussed. Comparing with existing methods, the novelty of this work is summarized below:

1) real-time stitching of power flow information using both node/breaker models and bus/branch models; this will help accelerate the adoption of node/breaker-model-based simulations for high-fidelity DSA in the power industry.

2) using equipment names as unique IDs for component matching with EMS snapshots; this will help reduce the labor-intensive efforts in maintaining real-time models.

3) real-time correction and enhancement to both power flow and dynamic models to support more accurate dynamic simulations.

4) high-fidelity models via UDM are developed to represent the dynamic behavior of LCC UHVDC systems in Jiangsu; the dynamic behavior of the created UDM models demonstrates acceptable performance.

These innovative techniques were not implemented in the previous online DSA systems deployed in many of the control centers. With these new features, advanced applications can be enabled to screen N-k contingencies in real time, search for transfer limits of critical corridors, design and tune effective special protection systems for effectively enhancing situational awareness and economic operation of today’s power grid.

For future work, additional research and development efforts will be conducted to develop more advanced applications including hybrid electromagnetic and electromechanical simulations, modeling SPS/RAS, developing more high-fidelity dynamic models, and others.

ACKNOWLEDGMENT

The authors would like to acknowledge Ms. Xunhui Hu and Ms. Mengqi Zhou from the NARI group for their contributions and support in providing the EMS interface.

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Figure 10. Transfer limit calculated for the North-South corridor in Jiangsu.

Figure 11. Transfer limit calculated for the Anhui-Jiangsu corridor.
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