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Hybrid Simulation/Measurement-Based Framework for Online Dynamic Security Assessment

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SUMMARY

This paper presents a hybrid simulation/measurement-based framework for online dynamic security assessment, providing the foundation for new generation of real-time tools needed for operators to assess in real-time the system's dynamic performance and operational security risk. The proposed approach combines high-performance dynamic simulation analysis tools and synchrophasor-based stability assessment algorithms, and integrates the results to provide real-time situational awareness on available operating margins against major stability problems. The major components are 1) a simulation-based module which uses high-performance dynamic simulation software to simulate the effect of potential contingencies, calculates N-1 contingency margins and tests the effect of preventive or corrective actions; 2) synchrophasor-based voltage and angular stability algorithms to monitor in real time the dynamics of the system and compute operating margins; 3) a synchrophasor-based dynamics prediction module which is used to identify vulnerable areas in the system and to provide a simplified equivalent model of the external system outside the boundaries of the study area of the system; 4) an integrator module which analyzes, manages, coordinates, and post-processes results from various modules of the proposed framework to generate actionable information; and 5) cutting-edge visualization technology to display various system quantities and to visually process the results of the hybrid measurement/simulation-based security-assessment tool.

KEYWORDS

Angular Stability, Dynamic Security Assessment, High-Performance Computing, Synchrophasors, Transient Stability, Visualizations, Voltage Stability.

INTRODUCTION

Given the rapid growth of regional electricity markets, the increasing integration of intermittent resources (such as renewable generation and demand response), and the lack of corresponding growth in transmission infrastructure, the grid is often operated under stressed conditions and increased likelihood of cascading outages. On-line Dynamic Security Assessment (DSA) is becoming a major need for system operators and several tools have been developed so far which are based on execution of dynamic simulations. However, despite the advances in computing technologies, computing capability is a major barrier for successful implementation of an online DSA and it requires computational efficiency several orders of magnitude greater than today's state-of-the-art. An online DSA needs to perform hundreds of nonlinear time-domain simulations in a very limited time frame (usually 5 to 15 minutes) in order to meet the needs of reliable grid operation. The present state-of-the-art on real-time stability assessment relies heavily on steady-state power flow-based simulations. Time-domain simulation tools are used sparingly and often in prototype operational mode. Time-domain studies generally involve 10- to 20-second simulations for a limited number of contingencies with reduced-order system models. Even with these reduced-order simulations, these simulations require 20 to 30 minutes of clock time, without accounting for appropriate levels of time horizon and associated modelling complexities for analyzing cascading contingencies or variable generation ramping impacts [1].

Recent advances in synchrophasor technology and the continuing growth of Phasor Measurement Units (PMUs) which provide high-resolution real-time synchronized phasor measurements, offer significant opportunities for on-line dynamic monitoring and stability assessment of the grid. Grid operators need advanced applications that utilize the synchrophasor data and online stability analysis results to obtain more meaningful knowledge such as operating margins, risks, and locations of potential stability problems, as well as suggestions on remedial actions. Methodologies based on high-resolution real-time measurements that track the dynamic performance of a power system have been proven to be effective in understanding the current state of the system, including potential operating margins under varying system conditions. However, these methodologies cannot predict performance under contingency conditions or for changes in operating scenarios. Hence, simulation-based approaches are needed for comprehensive DSA to simulate "what-if" scenarios, including contingencies.

Based on that, it is clear that novel online DSA tools are needed that are based on a hybrid platform that takes advantage of the complementary nature of both simulation and measurement based approaches and capitalizes on the strengths of each approach. Towards this goal, this paper presents an integrated hybrid approach for on-line DSA which combines outstanding features of both measurement-based and simulation-based approaches in order to accomplish the high-performance tools demanded by operators of modern grids.

PROPOSED FRAMEWORK FOR ONLINE DSA

Figure 1 provides a high level overview of the proposed framework for real-time DSA. The framework combines high-performance dynamic simulation with synchrophasor data to assess in real-time the system dynamic performance and operational security risk. It is designed to take advantage of complementary benefits of simulation-based and measurement-based approaches.

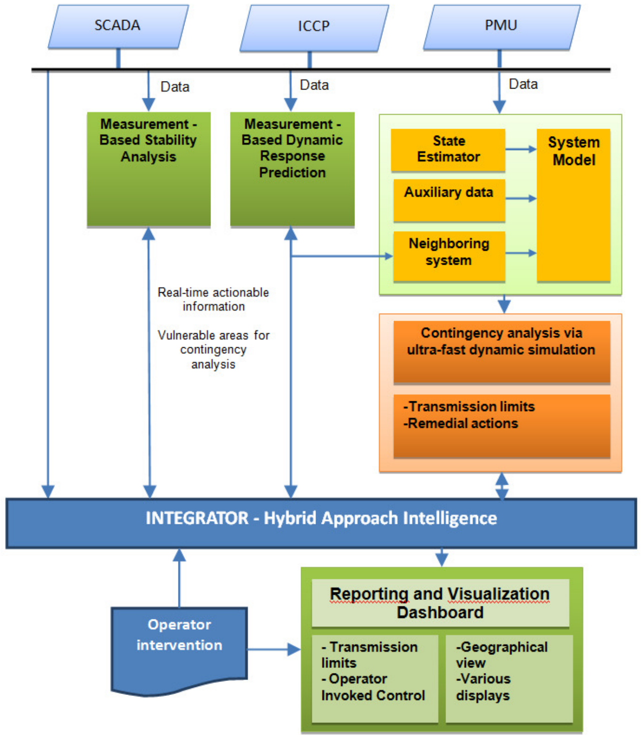

Figure 1: Framework of proposed real-time DSA.

A short description of the framework building modules is given next:

a) Simulation-based module: This module provides information for "what if" scenarios such as stability limits and margins during N-1 contingency conditions. The core of this computation module is a high-performance dynamic simulation tool, capable of processing thousands of contingencies, to provide real-time situational awareness and "look ahead" capability on available operating margins against major stability problems (such as angle separation and voltage collapse), as well as to evaluate possible preventive or corrective control actions to mitigate instability problems. This module determines the transmission limits of selected corridors that need to be observed during operation, and voltage and frequency violation indexes caused by potential contingencies. Under this work, EPRI's Extended Transient Midterm Simulation Program (ETMSP) was upgraded and tested in a high performance computing environment by enabling parallelization of contingencies, thread-parallelization of the linear solver and a variable time step size scheme. Details on the performance improvement can be found in [1].

b) Measurement-based stability assessment module: A measurement-based module continuously assesses voltage and angular stability conditions and estimates operating margins of a power system in real time using high-resolution field data such as synchrophasors. This module utilizes a measurement-based voltage stability analysis (MBVSA) algorithm and a measurement-based angular stability analysis algorithm (MBASA) for real-time stability margin calculations, and does not need to run a contingency simulation, so the calculations are fast and model-independent. The calculated stability margins can be expressed as the total amount of real or reactive power (i.e. the security margin) that can be further transferred through the interface lines and boundary buses without causing any voltage stability problem under the current operating conditions. Therefore, it can be used as a real-time indicator of the area's overall stability level. If after a contingency or significant change in system conditions, the monitored area or interfaces are found short of margin (i.e. below a prescribed threshold), different remedial actions can be initiated to mitigate the risk of instability or cascading outage. The MBVSA and MBASA algorithms that have been developed as part of this work are described in detail in [2-3].

c) Measurement-based dynamic response prediction module: This module incorporates algorithms to dynamically estimate a reduced model of the power system using only synchrophasor data and then feed the model with anticipated changes in the inputs of the model to estimate system responses as model outputs. The module is used for two main purposes: a) to dynamically identify vulnerable portions in the grid, and b) in combination with the dynamic simulation software to represent the external grid. One of the hurdles for accurate dynamic simulation is the lack of appropriate representation of the neighbouring grids, that is, the portions of the interconnected system that are outside the borders of the control are being studied. This technique can be effectively used to produce a simplified model of the external grid with minimal information and data. Only synchrophasor measurement data at the boundary nodes are used to produce the reduced model that interfaces with the full dynamic model of the study region. The autoregressive with exogenous input (ARX) model structure is used in this work for this purpose [4-5].

d) Integrator: The integrator is a key component of the proposed framework. The integrator platform implements the intelligence to manage the different modules in an integrated fashion. It analyzes, manages, coordinates, and post-processes results from the different algorithms to generate actionable information. It is envisioned that expert systems will be used to materialize the integrator in production-grade implementations. Expert systems are software systems designed to emulate the problem solving behaviour of human experts in narrow, specialized domains. Expert systems are sometimes referred to as knowledge-based systems. This is due to the fact that expert systems contain knowledge bases that incorporate domain knowledge or experience. In this work, a simple rule-based approach is used to prove the concept and applicability of the integrated framework. A rule-based system is a category of expert systems in which the knowledge base is represented in the form of 'IF-THEN' rules. An inference engine is the search mechanism that identifies the rules that are applicable for each case. Once the applicable rules are found by the inference engine, the rules are 'fired,' i.e., the actions included in the THEN part of the rules are taken. These actions may include the conclusions reached by the rule-based systems. It is also possible that the THEN part triggers further analysis by the rule-based system, in which case the inference engine cycles continue until a conclusion is reached.

e) Reporting and visualization dashboard: The function of this module is to present the results of security assessment in the appropriate manner for each type of user, which may include not only system dispatcher but also reliability or operation engineers. The level of detail and type of information that needs to be passed along to these users is significantly different. Certainly, system dispatchers need concise information about system current conditions and trends, operational limits to observe, and alarms including specific remedial or preventive control actions to implement. The reliability engineer on the other hand analyzes results of the DSA in detail to evaluate the impacts of potential contingencies, conduct root cause analysis, and define the remedial and/or preventive actions to be passed to the dispatcher. Therefore, the reliability engineer needs access to more detailed results of system analysis. Visualization has been a powerful mechanism to dramatically improve situational awareness in control centers. As operational complexity continues to increase, the limitations of existing snapshot-based, control-center visualization tools are becoming apparent. The visualization dashboard should allow the user to display data or results from any of the modules in a meaningful manner. A prototype visualization platform that meets the criteria of the visualization module of the proposed online DSA framework has been developed under this work and snapshots will be demonstrated during the presentation.

This paper focuses on the integration module and will demonstrate through examples in the next section how information from the different modules can be analyzed, managed, coordinated, and post-processed to generate actionable information and visualizations with focus on the operator needs. A simple rule-based approach is used in the form of "if-then" rules that triggers either automatic actions such as contingency simulation triggering, or issues alerts to the operators to inform them on the criticality of the system and recommends manually triggered control actions.

DEMONSTRATING RESULTS

The use of the proposed hybrid framework is demonstrated through a few illustrative examples. The objective is to walk the reader through the entire process, simulating how the system would evolve during a contingency situation, how the operator would react based on the information from the DSA scheme, and how operator's intervention would impact the system. A voltage stability assessment example will be presented. The proposed framework applies also for angular stability assessment and real-time contingency analysis using dynamic simulations. Examples of those will be given in future publications.

A 140-bus NPCC system, shown in Figure 2, is used as the test system. The focus will be on a load center located in Connecticut which is supplied by three interface lines: one from New York area and the other two from the New England region. A voltage collapse scenario was simulated, resulting after 2 contingencies in the load center, a first line trip (line 31-32) at t=200 seconds and a second line trip (line 30-31) at t=400 seconds. The voltages of the load center for this scenario are shown in Figure 3.

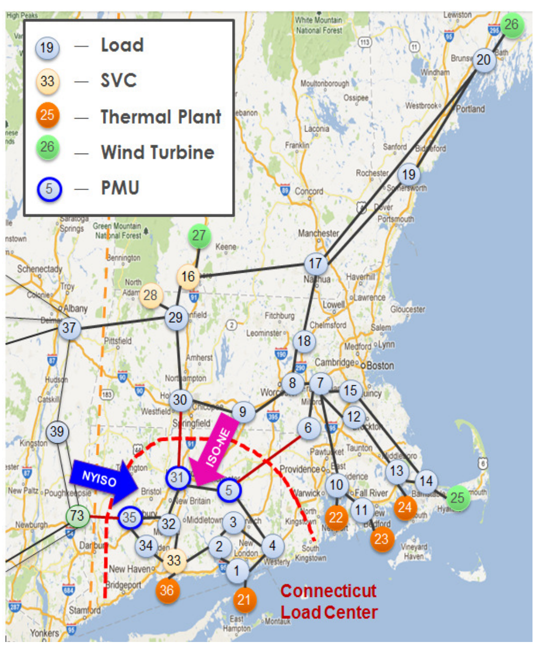

Figure 2: NPCC test system and the study area

The scenario is separated in three stages, corresponding to the three operating conditions of the system before and after the contingencies, as shown in Table 1.

Table 1: Stages of the simulated instability scenario

Stage 1	No Contingency
Stage 2	Line 31-32 tripped
Stage 3	Lines 31-32 & 30-31 tripped

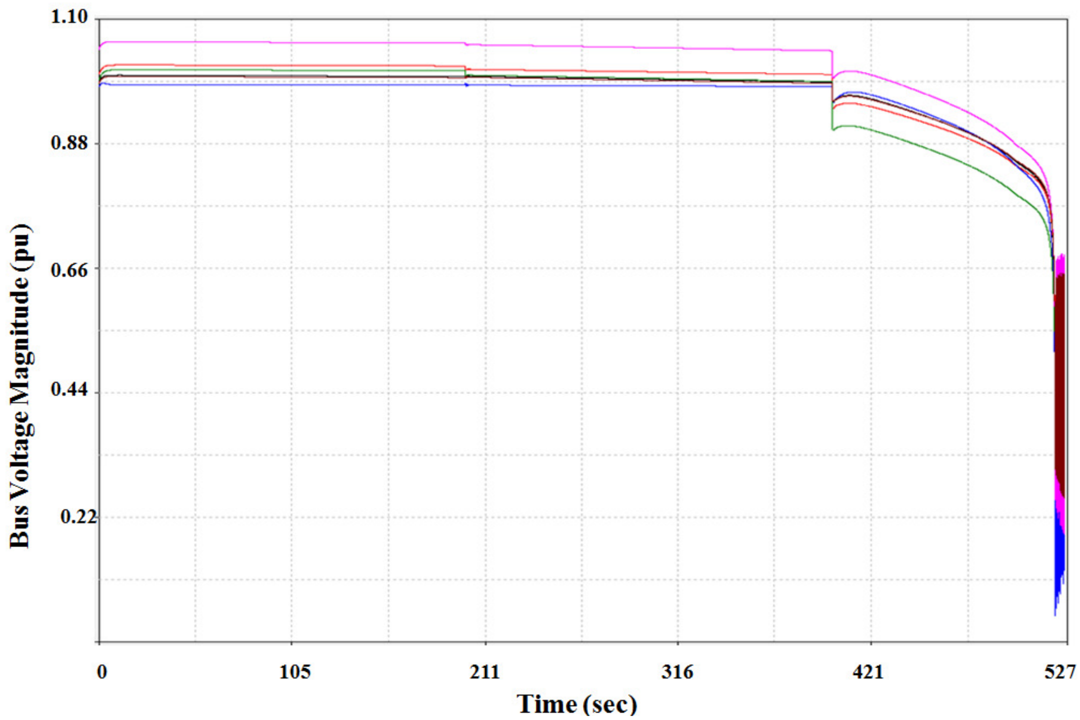

Figure Error! No text of specified style in document.**: Load Center Voltages - Voltage collapse scenario**

At the first stage, there is no contingency and the system is operating securely under N-1 criteria, with the total transfer on the interface lines being below the N-1 limit (limit under worst contingency). The critical contingencies can be either predefined in a critical contingencies list based on compressive off-lines studies, or alternatively through an online contingency screening process. Highly efficient algorithms for contingency screening have been developed and are available for on-line applications [7]. It is worth to mention that the proposed hybrid framework considers the use of high-performance computing that enables the analysis of relatively large number of contingencies in a very short period of time[1]. Hence, the list of critical contingencies to be processed could be expanded without affecting the feasibility of the scheme.

Note that the N-1 limit for the worst contingency (in this scenario the worst contingency is the line 73-35 trip) is provided to the operator by the simulation-based module of the proposed online DSA. In addition the limit for the current operating condition is calculated by the measurement-based module (MBVSA algorithm [2]) and the simulation-based module.

[1] Reference [1] shows that through parallelization, the runtime for 4096 contingencies in a 20,502 buses system model can be reduced to less than 400 seconds with a 500 cores computer.

Note that in this case MBVSA underestimates the N limit (limit at present operating condition). This inaccuracy of MBVSA algorithms far from the instability point has been also reported in [6], however at this stage the stability limit value is not important since the margin is quite adequate. At this stage, the value of MBVSA for the operator is to monitor the trend of the limits and take an action if there is a big change. A simple visualization is shown in Figure 4, illustrating the total power transfer on the three tie-lines, the N and N-1 limits as computed by the simulation-based module, and the N limit computed by the measurement-based module. Note that the grey box indicates that the operator is "blind" at this stage of the upcoming contingency.

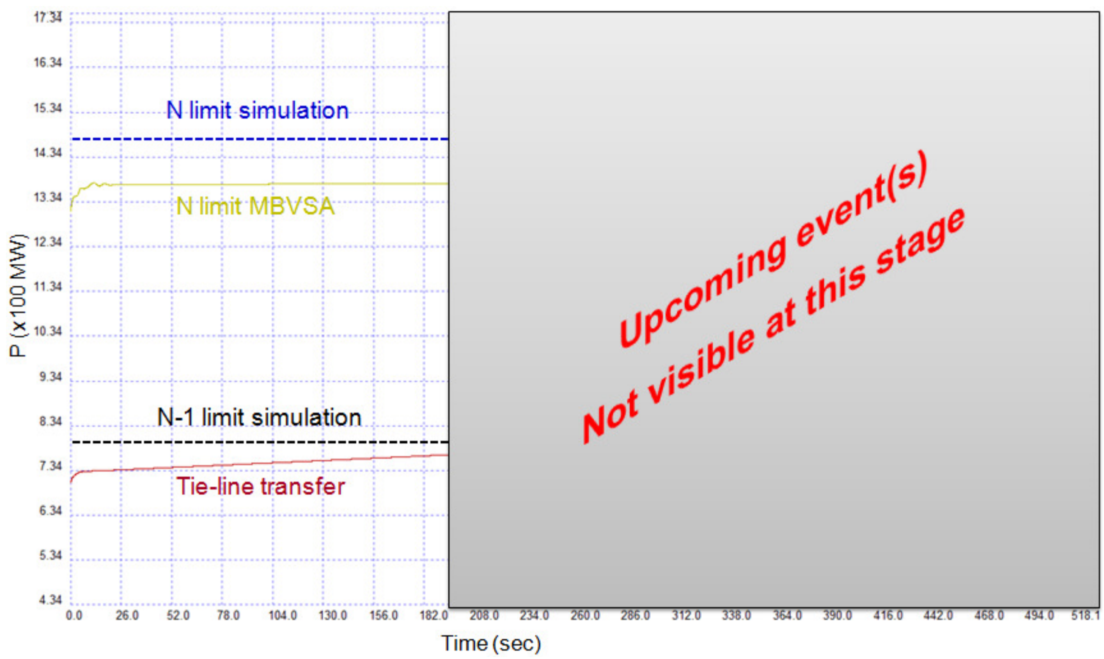

Figure 4: Stage 1 of scenario

During Stage 2, upon the line 31-32 trip, the system operates under a contingency. Immediately upon the contingency, the limit for the current operating condition as calculated by the MBVSA is slightly increased, indicating to the operator that an event took place. Note that the limit is actually reducing as indicated by the simulation-based computed limits, but since the MBVSA gets more accurate that is why actually its value is increasing, getting closer to the value computed by the simulation. Based on the MBVSA results, the integrator module of the proposed scheme automatically triggers recalculation of the N-1 limit based on simulations or provides an alert to the operator to manually trigger simulations. Note that an important value of the MBVSA at this stage is that immediately after the event, and before the computations performed by the simulation-based module are completed, the operator is informed that there is still sufficient margin for the present operating condition, so no emergency actions are needed. Once the updated N-1 limits are calculated, the results are superposed on the MBVSA results and the additional information is provided to the operator. A simple visualization is shown in Figure 5. Note that the operating condition under Stage 2 violates the N-1 criteria, so upon computation of the new N-1 limit, the integrator module, based on the results given by the other modules, issues an alert to the operator to inform him of this violation so that corrective actions can be taken to bring the system back to a secure operating point.

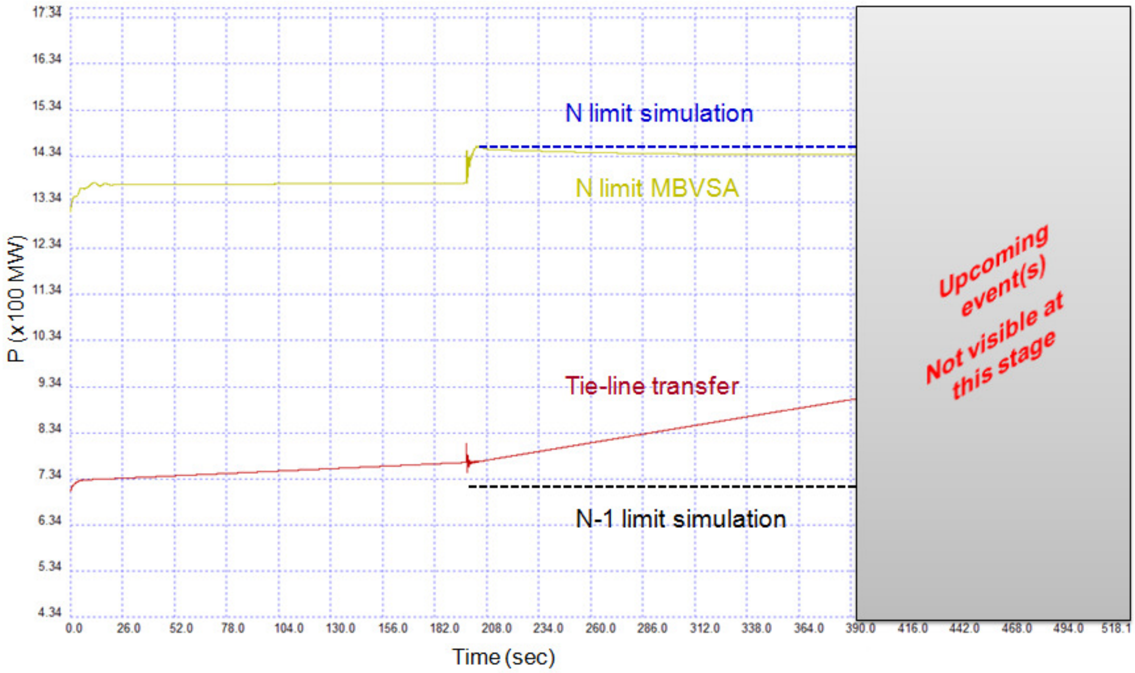

Figure 5: Stage 2 of scenario

Assuming that another contingency occurs (line 30-31 trip) before the operator took any corrective action, the system enters Stage 3 of operation. Immediately after the second contingency, simulations are triggered again by the integrator module to recalculate the N-1 limits, however, assuming a fast evolving event in which there is not sufficient time to get the simulation results, the integrator module is using the results from the MBVSA module to indicate to the operator the criticality of the system and suggests emergency control actions if a specific threshold is violated. In this case we had set the threshold to be 150 MWs, but it has to be emphasized that this is system dependent and its value has to be defined upon multiple offline studies and based on the operator's experience on the system. Note that the value of MBVSA at this stage is significant since it provides situational awareness for the operator on the criticality of the system condition when there is no sufficient time to perform simulations to assess the system condition. A simple visualization is shown in Figure 6, with the system response without any emergency control action, resulting in the voltage collapse.

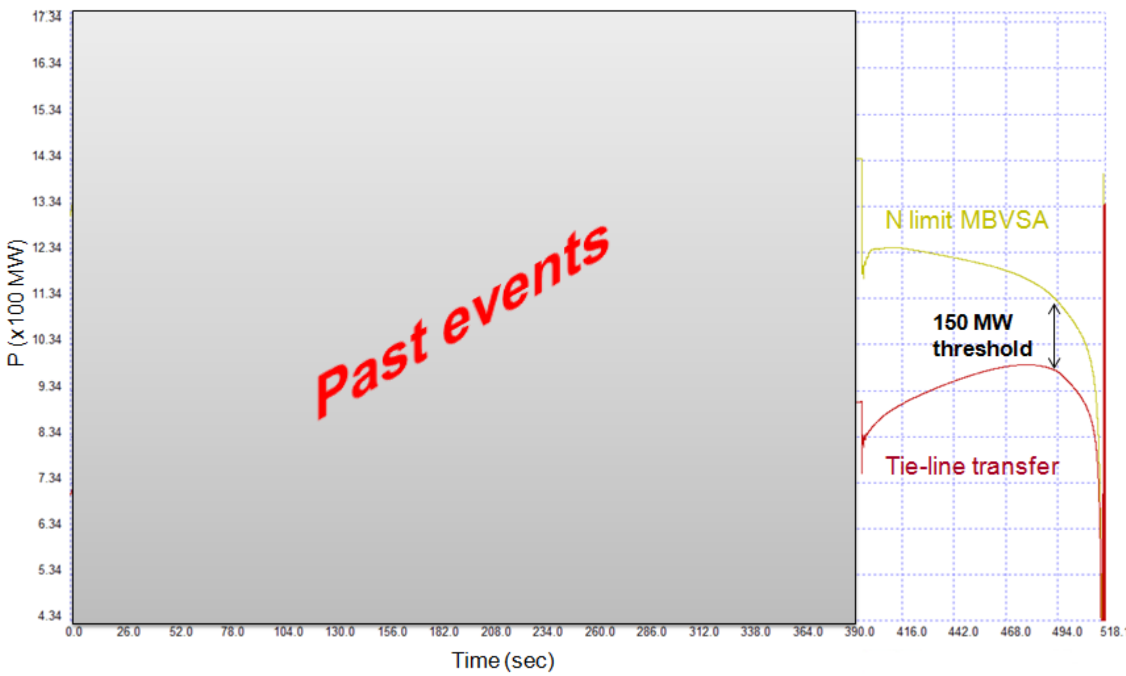

Figure 6: Stage 3 of scenario

The effect of a corrective action, suggested by the integrator module, was also simulated and is shown in Figure 7. In particular, additional reactive power was dispatched from the wind farms in the system (shown in Figure 2) when the threshold was reached. It can be observed that the voltage collapse is prevented, the system is no longer under emergency condition and the operators can take additional actions to bring the system in a secure operating condition. Note that this action is not the optimal, since the wind farms are not inside the load area. However, it was assumed that the system was stressed and there was no additional reactive power support that could be provided by other voltage control devices.

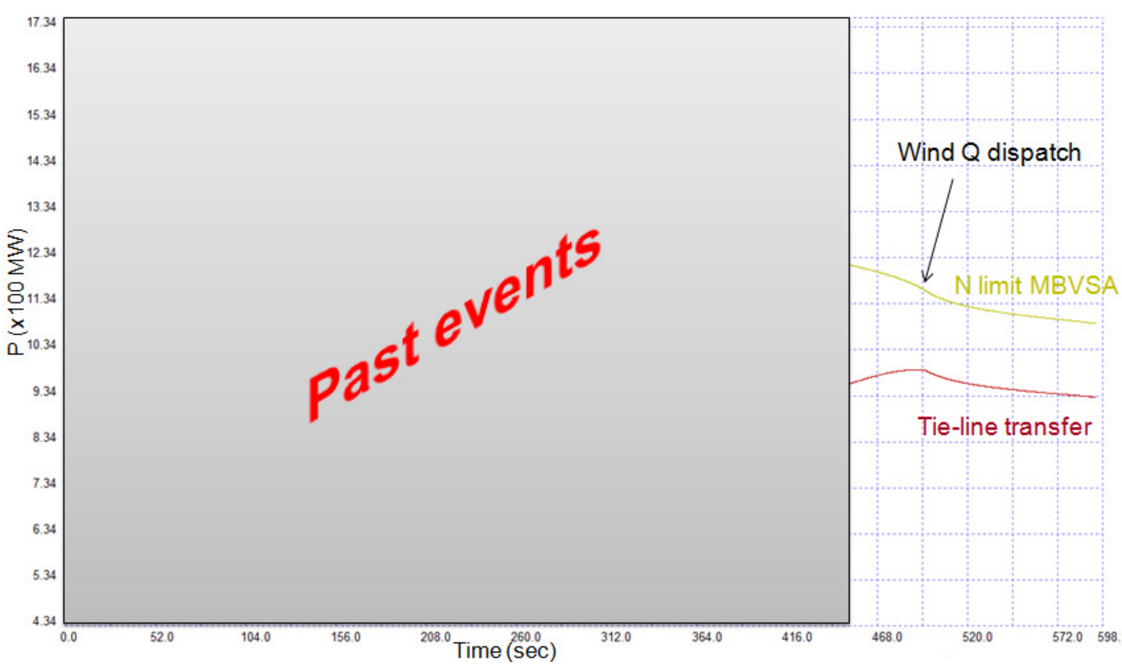

Figure 7: Effect of emergency control action

CONCLUSIONS

A hybrid simulation/measurement-based framework for online dynamic security assessment is proposed in this work. It combines the strengths and features of simulation and measurement-based approaches in such a way to develop a tool capable of: (i) providing operator with superior situational awareness of current conditions and trends; (ii) providing operator real-time preventive and remedial actions to maintain system security under potential foreseen contingencies; and (iii) evaluating potential system harmful events and potential remedial actions after the first event actually occurred and the system is evolving toward a cascading outage scenario. The proposed framework is expected will help providing solid foundation for new generation of real-time tools that are needed for operators to assess in real-time the system's dynamic performance and operational security risk.

The next steps include development of the software platform to integrate the different modules in a common data and model framework, demonstration of the integrated tool in a pilot mode in a real control center, and the development of an industry roadmap for attaining the integrated tool ready for production-grade deployment in real-time operations.

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