

Real-time Online Analysis of Power Grid

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Abstract—The unprecedented operational complexity and security risks in operating the Chinese UHV AC/DC power grid calls for a new generation of real-time (sec-order) online analysis systems to provide decision support. Our recent Digital Twin based online analysis research and development work to address the needs is presented. In addition, a high-level solution architecture for the future real-time online analysis systems is proposed for realizing: a) The delay of the virtual model to mirror the physical power grid is in sub-sec range; b) The downstream online analysis applications could have sec-order responsiveness.

Index Terms—Grid online analysis, security assessment, digital twin, security constraint dispatching.

I. INTRODUCTION

CHINA has built the world's largest UHV AC/DC interconnected power grid- the State Grid, which can be categorized as a "strong DC and weak AC" system [1], where the long-distance UHV transmission network is dominated by the DC links. The State Grid also features a high penetration of distributed renewable generation and a huge volume of power electronic loads. As a consequence, a disturbance caused by an outage or a sudden change of renewable generation output, in one part of the grid is much more likely to be spread to or affect other parts of the grid in a much quicker way. Therefore, the State Grid is facing unprecedented operational complexity and security risks [2].

Real-time in online analysis commonly refers to using online measurement info (RTU) to perform security assessments. In addition, in this article, real-time also refers to the response/variation speed in the order of seconds (sec-order). The generation and the load in a power grid are constantly balanced, in general passively, in real-time by the variation of the system frequency. The process to transit to a new balanced point/state after a disturbance in a power grid develops at a sec-order speed. The goal of power grid dispatching is to adjust the generation to balance the anticipated load and also satisfy the security constraint (SC) of the grid operational limits. Currently, grid dispatching systems are running at speeds in the order of minutes (min-order), issuing dispatching signals to the Automatic Generation Control (AGC), for example, at a 5 min interval, to actively balance the generation/load. The

dispatching system is supported by online security assessment systems, such as DSA, for decision support purposes. The assessment systems currently also have a min-order end-to-end response speed. In the State Grid dispatching center, an online analysis round-trip now takes about 10 minutes to complete [2].

Grid generation output could be adjusted through AGC in real-time (sec-order). However, in the traditional AC grid, grid-wide power transmission and load distribution adjustment could only be actively performed with a min-order speed. Therefore, the current EMS is designed to issue min-order dispatching signals. For "strong DC and weak AC" grids, such as the State Grid, it is both feasible and desirable to implement active real-time grid-wide power transmission/distribution adjustments. In other words, it becomes physically possible to implement a SC dispatching system with the sec-order response speed. The dispatching signals, when necessary for certain situations, could be issued to UHV DC links, renewable generation stations, battery-based energy storage systems and active electronic loads, in addition to AGC to implement an SC active real-time grid-wide power dispatching system to take advantage of these new flexible, sec-order response capable devices, which are not available in the traditional AC grid.

With such a real-time dispatching system, the grid-wide active SC generation and load balance process could be achieved in real-time, in sec-order, and in synchronization with the frequency variation state transition process of the physical grid. The implementation of such a real-time SC dispatching system requires a new generation of sec-order online analysis systems to provide real-time decision support.

II. DIGITAL TWIN

A Digital Twin (DT) contains three main parts: a) physical products in the real space, b) virtual models in the virtual space, and c) the connections of data and information/process that ties the virtual models and real products together [3], [4]. In the DT approach, the virtual model could be updated to "mirror" the physical system in real-time. The analysis and simulation could be performed on the virtual model for real-time decision support purposes. In the online analysis research and development (see Section-III), an online analysis DT is proposed and implemented. In the implementation, the network analysis model (NAM) [5], or the virtual model in DT term, connects to the power grid, or the physical system, through the SCADA RTU message subscription. The NAM, therefore, could mirror the power grid for online analysis purposes. The NAM implementation is based on the extension of InterPSS core simulation engine [6]. In addition, In-Memory Computing (IMC) based grid analysis algorithms [7]

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and Complex Event Processing (CEP) based grid operation monitoring rules [8] are applied to the virtual model to perform the situation awareness analysis for the real-time decision support.

III. ONLINE ANALYSIS RESEARCH & DEVELOPMENT

Based on the DT approach, a new real-time online analysis system development initiative, sponsored by the State Grid, was started in 2016 and concluded in 2018 [9]. The primary goal was to reduce the online analysis overall round-trip computation time, from data acquisition to completing the analysis, from the current approximate 10 minutes to less than 60 seconds in order to achieve, what was called, sec-order responsiveness. In the development, a new online analysis solution architecture was proposed [2], in which a parallel data processing path is added to the existing online analysis system. In the new path, a data grid is used to host a NAM. The NAM is updated in real-time by subscribing to the grid change events published by the SCADA system. The update to the NAM is also published as model change events. These model change events are subscribed by a CEP engine to perform situation awareness analysis.

A pilot online analysis system was developed and deployed in a provincial dispatching center in China, with an online network data model of size ~ 1 K-bus. The NAM consists of a physical (node/breaker) model and a simulation (bus/branch) model. The RTU info, published by the SCADA system, is subscribed by the physical model to continuously update itself. Topology analysis is performed to map the physical model state changes to update the simulation model to keep itself in-synch with the physical model. The online analysis is performed periodically at an interval of 20 seconds. When performing the online analysis, an IMC based State Estimation (SE) algorithm is applied to the simulation model to create a converged Loadflow snapshot, which is then used to provide input data for two online analysis applications: 1) a Neural Network (NN) -model based Critical Clearing Time (CCT) prediction application; 2) a grid operational rule evaluation application. It is observed, based on the actual field measurement data, that the overall round-trip computation time, including the model updates, SE algorithm execution, and the execution of two applications, was less than 300 ms [9]. The SE computation could be completed in approximately 50 milliseconds with a Qualification Measurement Rate (QMR) of $\sim 98\%$. The QMR difference between the new IMC based SE and the existing SE in the EMS production system is less than 0.5%.

IV. HIGH-LEVEL SOLUTION ARCHITECTURE

Base on the pilot project experience, a high-level solution architecture for the future real-time online analysis systems has been designed, as shown in Fig. 1. The RTU and PMU measurement info are routed on to a data bus (BUS in the figure) in the dispatching center. The NAM, hosted inside a Data Grid, subscribes to the RTU/PMU info to update itself continuously in real-time with a sub-sec delay to track or mirror the grid operational state. Based on the CEP approach, dispatching

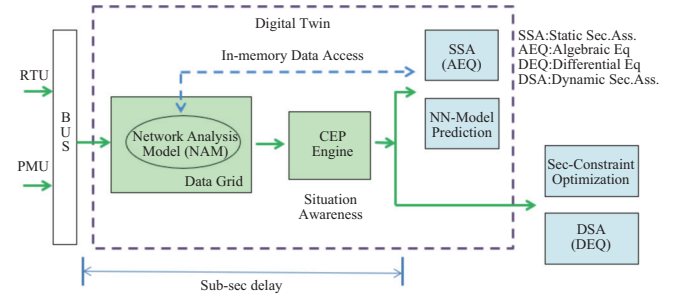


Fig. 1. Architecture for Future Real-time Online Analysis System.

rules are executed inside the CEP engine to perform situation awareness analysis. If a significant situation, for example, a switching event, is detected, a Loadflow snapshot with a sub-sec delay with respect to the RTU/PMU info would be created to drive the downstream online analysis applications. The execution path or the online analysis process flow of the applications are dynamically formed and coordinated by the CEP engine. Downstream applications in an online analysis system could be broadly divided into two categories: 1) Light-weight applications, such as algebraic equation (AEQ) based static security assessment (SSA), NN-model based prediction; 2) Heavy-duty applications, such as, security constraint optimization, differential equation (DEQ) based dynamic security assessment (DSA). The light-weight applications could be hosted inside the Data Grid to get the IMC support. In the IMC approach, the application and the NAM can exchange info through in-memory data access, to achieve what is called a “moving algorithm instead of moving data” strategy to minimize the data movement in the analysis process. The heavy-duty applications are usually hosted outside the Digital Twin environment. Through application integration, the Loadflow snapshot could provide the initial condition or base case for these types of analysis and simulations.

Since the NAM is hosted in the Data Grid, multiple base case model copies could be made instantly in memory to evaluate “what if” scenarios for a looking-ahead online analysis. For example, the predicted grid operation state change, planned dispatching actions, or proposed preventive controls could be superposed on these base case model copies to perform security assessments of the potential future grid operational states.

V. CONCLUSION

The State Grid makes the implementation of security constraint real-time (sec-order) dispatching possible, which requires real-time online analysis systems to provide decision support. In the proposed Digital Twin (DT) based real-time online analysis approach: a) The NAM, or virtual model in DT terms, subscribes to the RTU/PMU measurement info to keep itself updated continuously to mirror the physical power grid to track the operational state; b) Through IMC, the light-weight applications, which are hosted inside the Data Grid, could have direct in-memory data access to the NAM to achieve sub-second end-to-end responsiveness; c) The virtual model could provide the heavy-duty applications, which are running outside

the DT environment, with an initial condition or base case Loadflow snapshot with a sub-second delay; d) The situation awareness analysis and the process flow for the analysis are controlled by the CEP engine, based on a set of predefined rules. The primary goal was set to be: a) The delay of the virtual model to mirror the physical grid is in sub-sec range; b) The downstream online analysis applications could have sec-order responsiveness. The new online analysis system is targeted to be deployed in the State Grid dispatching center in the future.

In the Aug 2019 UK incident, the generation losses combined exceeded the amount of frequency containment reserve and led to system frequency falling so far that the protection devices were triggered, disconnecting 1.1 million electricity customers, within approximate 80 sec [10]. Generally speaking, the causes of electricity supply interruptions could be due to: 1) Extreme weather to cause multiple outages in the transmission and distribution networks; 2) An unfortunate combination of events within a short space of time, where none of the contributing events on their own should normally have caused any interruption. It was asserted in Ref [10] that the Aug 2019 UK incident was not caused by lack of power generation resources, rather, by the ways in which resources were controlled and the system was operated in the disturbance period. We argue that for the current min-order dispatching systems, 80 sec definitely seems to be a short space of time. In the current dispatching systems, the resources are controlled and the system is operated in the emergency period according to a set of fixed passive logic. However, with the upcoming sec-order dispatching system, it is possible to control and operate a grid in a span of ~ 80 sec emergency period based on the DT approach and system-wide real-time online analysis, and according to the resulting active and dynamic logic, so that some combination of events within a short space of time, similar to the UK incident, could be dealt with as a set of complex events according to pre-defined operation rules [8], rather than “unfortunate” combination of events.

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