Next Generation Monitoring and Control Functions for Future Control Centers

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Abstract—This paper presents a vision of the next generation monitoring, assessment and control functions in a future control center, which will be fully automated, decentralized and based on wide-area measurement. The paper points out the technology and infrastructure gaps to fill to fully implement future control centers, as well as a roadmap towards the proposed vision. This vision is expected to be a critical part of the future smart transmission grid.

Index Terms—Power system control, power system monitoring, power system operation, smart grid, smart control center.

I. INTRODUCTION

The present technology in power system operation such as state estimation and contingency analysis was initially developed back to 1960s. The technology advance in communication, computing and power system algorithms has made it possible to re-think the way to perform real-time monitoring and control [1-4]. The typical present technology of monitoring and control may be briefly summarized as follows:

- The monitoring system is based on the output from state estimation, which is subject to a considerable delay at the scale of tens of seconds to minutes. It is usually based on the local information of a control area. Interaction with neighboring system is limited.
- The security assessment is based on contingency screening, which is mainly a steady-state power flow analysis.
- The protection and control system is mostly based on local information. Some recent work considering global impact using Special Protection Schemes (SPS) is based on offline studies to adjust control strategies. In general, the coordination of different protection and control systems is limited.

To eliminate these limitations, the future control centers are expected to utilize wide-area information for online, measurement-based security assessment to implement automatic and decentralized control strategy. Hence, the system will be more hybrid, integrated, coordinated, supervisory and hierarchical. This is shown in Figure 1. This vision for future control centers, also referred to as smart control centers, can be a critical part to implement the overall framework of the future smart grid.

![Fig. 1. Vision of Next Generation Monitoring, Assessment, and Control in a Smart Control Center.](image)

The functions of future smart control centers can be classified as monitoring functions, assessment functions, and controllability. The discussion in this paper compares the vision with the present technology of these three aspects, and points out the technology and infrastructure gap to fully implement the future vision. Also, a roadmap towards a full implementation of this vision is presented.

This paper is organized as follows. The vision of each of the three categories (monitoring, assessment, and control) is described in detail in Sections II, III, and IV, respectively. Section V discusses the infrastructure and technology needs to implement the future smart control centers. Then, Section VI presents a roadmap towards this vision. Finally, concluding remarks are provided in Section VII.

II. MONITORING FUNCTIONS

A. From separate system models to one unified system model

The present system models for planning and operation are different even within a control area or region. In the future, it will be highly beneficial to have one unified model for both
planning and operation purposes. An interface function is needed to seamlessly transfer the EMS real time data to/from planning model. This will reduce the discrepancy between planning studies and real-time operations. Although the actual data used or the way to utilize the data by planning and operation will be still different, the unified system model will significantly eliminate the data maintenance and synchronization that must be repeated regularly. Presently, a control area maintains and updates its own data. The outside areas are usually simplified and different from the actual models used by other control areas. In the future, a single system model across different regions and areas will be implemented such as having a unified model of the entire Eastern Interconnect (EI) for planning as well as operation.

B. From state estimation to state measurement

The present monitoring system in a control center depends on state estimator, which is based on data collected via SCADA and remote terminal units. In the future control center, the system-level information will be obtained from the state measurement module based on Phasor Measurement Unit (PMU) [5-6]. The PMU-based state measurement is expected to be more efficient than the present state estimation since synchronized phasor signals give the state variables, in particular voltage angles. As a comparison, the present state estimation demands more running time and is less robust, since the data collected from Remote Terminal Unit (RTU) are not synchronized and significant effort must be taken for topology checking and bad data detection.

C. From one-line diagram to wide-area GIS

The present technology displays the system configuration with one-line diagrams that can show which buses are connected with a specific bus. However, it is not exactly matched to the geographic location. Also, it is typical that only buses in the control area, together with some boundary buses, are displayed in the monitoring system. In the future, the results from state measurement shall be combined with a wide-area geographical information system (GIS), which is currently popular for distribution systems but not at the transmission level, for visual display of the network on the screen of the control center. The wide-area GIS shall cover a broad region including the control center’s own service territory as well as all interconnected areas, and even the whole Eastern Interconnect or WECC system. This will increase the situational awareness across a very broad scope and prevent inappropriate operations when neighboring system is not fully known.

D. From limited stability margin monitoring to true stability margin monitoring

With the state variables obtained from state measurement, it is more feasible to display the true system stability measures in real time. The present technology typically displays the voltage magnitude, which presents limited information of voltage stability margin. As the system is more stressed and voltage collapse is a recurring threat, the voltage magnitude is no longer a good indicator of voltage stability. Hence, a true indicator of voltage stability margin is needed for better monitoring [5]. Similarly, the present technology monitors the local frequency. However, if the global frequency and particularly the frequency change can be monitored and traced, it is possible to identify the fault location even in remote location through possible frequency wave technology. With these research works and the assistance of the wide-area GIS data and continuous development, the voltage stability margin and frequency variation trend can be displayed in real time on a top layer of the actual wide-area GIS map. Compared with the present technology of simulation-based, local visualization, the future measurement-based stability margin monitoring system will greatly help the operators identify potential problems in real-time operation.

E. From mixed communication system to dedicated communication system

Since the future visualization and monitoring technology will cover a much broader scope, better information exchange is needed. The present technology for inter-area communication includes a mix of traditional and new technologies, such as telephone lines, wireless, microwave, fiber optics, etc [3]. In the future, the communication channel is expected to be more dedicated such as employing a fiber optic network for communication with Qualify of Service (QoS) implemented. Not surprisingly, this also demands a unified protocol for better communication among different control areas.

F. From limited customization to more flexibility

Another technology that is usually overlooked is the monitoring and visualization system. The present monitoring technology in control centers does not offer much flexibility in customization for better human-machine interface. The future control center should offer easy customization capability and be more user-friendly such that the monitoring system can be configured to match the focus and to address specific concerns at different control centers.

The above discussions of the future monitoring functions are briefly summarized in Figure 2 below.
III. ASSESSMENT FUNCTIONS

A. From un-prioritized alarm system to prioritized alarm system

The present alarm system gives various types of alarms; however, no priority is given to each message. When a severe disturbance occurs, there can be many alarm signals such that the operators may be overwhelmed. In the future, the alarm system should assign priority to each alarm message based on root cause analysis, which is essentially a preliminary security assessment. Therefore, the operators may follow top priority to solve the root cause of the disturbance. This can reduce the chance of potential mis-operation by operators and enhance the capability to handle true emergencies.

B. From steady-state security assessment to dynamic security assessment

The present on-line analysis in control centers typically performs steady-state contingency analysis. Each credible contingency event is analyzed using contingency power flow studies, and line flow violations will be identified. In future control centers, it is expected that online time-domain-based analysis such as voltage stability and transient angular stability can be carried out in real time. Also, online small-signal stability analysis is expected.

C. From analysis of the next operational interval to look-ahead analysis

The present technology is for the online analysis (contingency screening) for the next operational time interval such as every five minutes. This does not address the possible short-to-mid term (like within an hour) variation of system conditions. In the future, online analysis should not only perform dynamic analysis as previously mentioned, but perform look-ahead simulation such that future system conditions will be considered. Then, possible short-to-mid term strategic actions can be considered.

D. From deterministic approach to probabilistic approach

The present technology applies N-1 contingency in a deterministic approach. In future control centers, N-x or cascading failure should be considered with probabilistic risk analysis. When the system is more stressed than ever, the higher order contingency and possible cascading failures after an initial contingency event are more likely to happen than before. Since the dimension of complexity grows drastically with higher order contingencies, it is necessary to consider the probability of occurrence and the impact of contingency. Therefore, a probabilistic approach is desired.

E. From offline model validation to online model validation

The present analysis is based on pre-defined generator and transmission models, which may be validated in offline studies. This does not represent the real-time dynamic characteristics of the system. Therefore, the future online analysis in control centers shall perform dynamic model update and validation. The updated and validated data will be used for the online stability analysis previously mentioned.

The above discussions of the future assessment functions are briefly summarized in Figure 3 below.

IV. CONTROL FUNCTIONS

A. From local control actions to globally coordinated control actions

The present technology lacks the coordination of protection and control systems [1-2]. Each component takes actions based on its own decision. Sometime this uncoordinated control may lead to over reaction under contingency. For instance, the load increase in a load center may cause the voltage to decrease. This may cause the tap-changing transformer to attempt to raise voltage, which will increase the power consumption and eventually lower the system voltage further. If the tap changers are aware of the load increase with a signal from its control center, a coordination strategy can be implemented. Hence, future
control centers shall have the capability to coordinate many control devices distributed in the system such that the optimal coordination can be achieved for better controllability.

B. From offline-based parameter settings to online reconfigured parameter settings

Presently, the protection and control setting are configured as fixed values based on offline studies. In the future, these settings should be configured in real-time in a proactive and adaptive way such that it will better utilize the generation and transmission asset when the system is not stressed. Also, it will better protect the system under extremely stressed conditions. For instance, when the system load is decreasing and online security shows a comfortable margin of stability, the control parameters can be set to a new value such that more economic power can be transferred. As a comparison, if the system is more stressed, the control parameters may be adjusted such that less economic power is transferred to ensure the security.

C. From offline-based control strategy to online restorative plans

In the present control centers, the ultimate control action like separation is taken based on offline studies. In the future, the system separation will be performed in real time to better utilize the dynamic system condition. Similarly, the present restoration plan based on offline studies should be replaced with online restorative plans.

The above discussions of the future control functions are briefly summarized in Figure 4 below.

![Fig. 4. Vision of future control function](image)

V. INFRASTRUCTURE AND TECHNOLOGY NEEDED

The previous section provides visions of future real-time monitoring, assessment, and control systems. To fully implement the visions, a number of implementation factors of infrastructure must be considered. Several key challenges are summarized as follows:

- The present EMS system has a state estimation function based on data collected from Remote Terminal Units (RTU), while the future EMS system may have a real-time synchronized state measurement such as PMU-based measurement to have better accuracy and speed.
- The present communication infrastructure is a mix of telephone lines, Broadband over Power Lines (BPL), wireless communication, microwave, optical fiber, and so on, while the future communication infrastructure should be fast, dedicated communication system like optical fiber such that the communication delay will be minimized. Also, communication protocol standard and Quality of Service (QoS) should be fully implemented.
- The present computing technology in most control centers is based on sequential computing, while the future work may be based on dedicated parallel computing resources with proper prioritizing and scheduling of different real-time simulation tasks.
- There is a lack of online coordination schemes of different control systems. The present technology like Special Protection Scheme (SPS) is based on a large amount of offline studies, while the proposed work requires a fast, robust approach to coordinate the controls in real time.
- The present technology is mainly controlled by local signals, while the proposed work requires the protective relay to respond to extensive, adaptive system signals.
- The present control is performed in a centralized mode, while the future control can be based on a distributed intelligence to efficiently localize some disturbance under emergency.

The above key technology/infrastructure needs can be found in Figure 5 below. At the bottom of the figure, substations, power plants and transmission lines are equipped with PMU-based measurement device. At some key substations, local intelligence is also performed to distribute some assessment function to the local level. Hence, some disturbance may be handled locally in an efficient way. Meanwhile, the synchronized signals are forwarded to the control center via dedicated communication system. Then, the control centers can perform a system-wide monitoring and assessment. If control actions are needed, the instruction will be sent to substations, power plants or transmission lines for global control.
Fig. 5. The needed infrastructure to implement the future monitoring, assessment and control systems.

Tables 1 to 3 present a full picture of the infrastructure and technology needs to implement the future monitoring functions, assessment functions, and control functions, respectively.

Table 1. Infrastructure and technology needed to advance the present monitoring functions to future monitoring functions

<table>
<thead>
<tr>
<th>Present</th>
<th>Infrastructure and Technology Needed</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>State estimation</td>
<td>PMU deployment</td>
<td>State measurement</td>
</tr>
<tr>
<td>One-line diagram for displaying local area</td>
<td>Incorporate GIS information, data exchange standard</td>
<td>GIS-based display, wide area including neighboring system or entire EI/WECC</td>
</tr>
<tr>
<td>Mixed communication channel, lack of protocol</td>
<td>Communication infrastructure, Standardization of Protocol</td>
<td>Dedicated communication network, unified protocol, quality of service</td>
</tr>
<tr>
<td>Monitoring voltage magnitude</td>
<td>Var management, voltage stability monitoring &amp; control</td>
<td>Monitoring reactive reserve or voltage stability margin</td>
</tr>
<tr>
<td>Monitor local frequency</td>
<td>Real-time frequency excursion monitoring technologies</td>
<td>Monitoring frequency and frequency change across a wide area</td>
</tr>
</tbody>
</table>

Table 2. Infrastructure and technology needed to advance the present assessment functions to future assessment functions

<table>
<thead>
<tr>
<th>Present</th>
<th>Infrastructure and Technology Needed</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Online contingency analysis</td>
<td>Tools to perform online comprehensive stability analysis</td>
<td>Online voltage stability analysis Online transient stability analysis Online Small Signal Stability</td>
</tr>
<tr>
<td>Alarming without prioritization</td>
<td>Alarm management tool</td>
<td>Prioritization of alarming messages by indentifying root causes</td>
</tr>
<tr>
<td>Pre-defined generation and transmission model</td>
<td>Tools to perform real-time load modeling and generator dynamic model update and validation</td>
<td>Dynamic models updated and validated in real-time</td>
</tr>
</tbody>
</table>

Table 3. Infrastructure and technology needed to advance the present control functions to future control functions

<table>
<thead>
<tr>
<th>Current</th>
<th>Infrastructure and Technology Needed</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-1 Contingency Analysis</td>
<td>Fast simulation Methods to enable N-k analysis</td>
<td>Investigate cascading failures</td>
</tr>
</tbody>
</table>

VI. TECHNOLOGY ROADMAP

Figure 6 illustrates the technology roadmap towards the real-time monitoring, assessment, and control systems in a future control enter.

In the short term (before 2015), the monitoring system shall implement the alarming message management or prioritization such that the operators will not receive too many overwhelming messages, which will literally block the operators from performing any meaningful corrective actions. Also, a comprehensive security assessment should be implemented such that true real-time security signals will be displayed. This is very important since the voltage magnitude is no longer a good indicator of voltage stability. As
previously mentioned, true stability margin assessment in terms of voltage stability as well as transient stability and oscillatory stability must be evaluated. In addition, automatic voltage control is expected to be implemented. This is because voltage stability is an increasing concern in the U.S. power system and the trend of the time to voltage collapse tends to be decreasing.

In the mid term (by 2020), the future system shall be equipped with the capability to monitor wide-area frequency and voltage stability. This requires the communication protocol standardization. Also, security assessment should be combined with cost or impact such that a risk evaluation will be implemented. In the control part, a coordinated protection and control shall be implemented to replace the present SPS.

In the long term (by 2030), the system should have the capability to identify the fault location and type with the large penetration of PMU-based state measurement. Also, the assessment function should have the capability to perform look-ahead simulation such that the system will be well prepared for potential disturbance. Then, online controlled separation and restoration can be implemented.

![Roadmap](image)

**Fig. 6. Roadmap towards the future monitoring, assessment and control systems.**

**VII. CONCLUSIONS**

This paper presents the vision of future control centers for real-time operation. Comparison of the present technology and the future vision is discussed. Infrastructure and technology gaps, as well as the roadmap towards the propose vision, are discussed. Future work may lie in research and demonstration of the feasibility of the proposed concept of future smart control centers, including the monitoring functions, the assessment functions, and controllability.

**VIII. ACKNOWLEDGMENT**

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**IX. REFERENCES**


**X. BIOGRAPHIES**

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