PNNL-32362

High Value Opportunities to Advance Automation in Electric Grid Control Rooms

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U.S. DEPARTMENT OF ENERGY

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Acronyms and Abbreviations

ACAT	AI-based Contingency Analysis Tool
AGC	Automatic Generation Control
AI	Artificial Intelligence
ANM	Active Network Management
ANN	Artificial Neural Network
BA	Balancing Authority
BES	Bulk Electric System
CAISO	California Independent System Operator
CENACE	Centro Nacional de Control de Energía
CIP	Critical Infrastructure Protection requirements (NERC)
CPS	Control Performance Standard
DCAT	Dynamic Contingency Analysis Tool
DCS	Disturbance Control Standard
DER	Distributed Energy Resource
DNN	Deep Neural Network
DOE	Department of Energy
DTS	Dispatcher Training Simulator
EMP	Electromagnetic Pulse
EMS	Energy Management System
ES	Expert Systems
FL	Fuzzy Logic
GA	Genetic Algorithms
GMD	Geomagnetic Disturbance
GUI	Graphical User Interface
HADREC	High Performance Adaptive Deep-Reinforcement-Learning-based Real-time Emergency Control
IROL	Interconnection Reliability Operating Limit
ML	Machine Learning
NAERM	North American Energy Resilience Model
NERC	North American Electric Reliability Corporation
PNNL	Pacific Northwest National Laboratory
RAS	Remedial Action Scheme
RC	Reliability Coordinator
RTA	Real-time Assessment
RTCA	Real-Time Contingency Analysis
SCADA	Supervisory Control and Data Acquisition

SDG&E	San Diego Gas and Electric
SE	State Estimator
SLAC	Stanford Linear Accelerator Center, or SLAC National Accelerator Laboratory
SOL	System Operating Limit
TOP	Transmission Operator
TRAST	Transformative Remedial Action Scheme Tool
TSAT	Transient Stability Assessment Tool
VSAT	Voltage Stability Assessment Tool

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1.0 Purpose

This paper explores high-value opportunities to advance automation in electric grid control rooms for the purpose of improving grid safety, reliability, and resiliency during normal and emergency operating conditions.

2.0 Introduction and Background

Electric industry system operators and operations support personnel, herein referred to as System Operations staff, are inundated with data from different systems and sources and often struggle to derive meaning from the information that is presented to them. Furthermore, the continued evolution of the electric power system due to Distributed Energy Resource (DER) penetration, renewable resource integration, ongoing grid modernization initiatives, and emerging threats has changed the operating characteristics of the system and made problem-solving for operators more nuanced and complex.

As a result, grid operators and electric utilities are increasingly driven to develop automated processes and introduce decision support tools to reduce cognitive demand on System Operations staff and aid in the operational decision-making process. However, System Operation staff are traditionally hesitant to implement and accept new solutions, automation processes, and tools within the control room.

There are multiple attributes that a new solution or tool has to possess in order to be accepted by System Operation staff, such as:

1. It has to address real, existing, or future foreseen issues.
2. It has to be accurate so that users can develop and maintain trust in the tool
3. It has to be efficient in resolving specific issues without ambiguity
4. It has to deliver a clear message via a friendly Graphical User Interface (GUI)
5. It has to be maintainable since control room tools used in decision making must be available 24/7
6. It has to allow the users to take manual control in the event that the tool malfunctions or fails to function in the desired manner

For those reasons, based on our multiple decades of experience in control room operation, deployment of new solutions and tools in control rooms, and current industry trends, we are addressing opportunities for improvement of control room experience to support power system operators in an informed decision-making process and ameliorate their control room experience.

The remainder of this technical report:

1. Analyzes the nature of electric industry system operations and considers the critical systems and tools that functional entities rely upon to perform reliability-related tasks;
2. Assesses emerging trends, challenges, and opportunities that affect the way grid operators and electric utilities operate the power grid in the current and expected future state; and
3. Identifies high-value opportunities to leverage advanced automation for the purpose of improving grid safety, reliability resiliency during normal and emergency conditions.

3.0 Electric Industry System Operations

3.1 Functional Roles & Responsibilities

The North American Electric Reliability Corporation (NERC) Reliability Functional Model defines the set of functions that must be performed to ensure the reliability of the Bulk Electric System[1]. This paper focuses primarily on the Reliability Coordinator (RC), Balancing Authority (BA) and Transmission Operator (TOP) functions since these entities are responsible for performing reliability-related tasks in operation time framework. While there is no NERC-defined term for "reliability-related task", it's generally considered to be any task that has the potential to impact Bulk Electric System (BES) reliability if the task is not performed or is performed improperly.

In accordance with *NERC Reliability Standard PER-005 – Operations Personnel Training*, each RC, BA, and TOP must create a list of BES company-specific real-time reliability-related tasks and implement a training program to validate the capabilities of its personnel to perform each task.

Table 3-1 summarizes a generic set of reliability-related tasks that were considered in conducting this analysis.

Table 3-1. Reliability-Related Task Summary

Reliability-Related Task Description	Functions
1. **Generation Resources.** System Operators monitor generation resources and dispatch those resources to provide Real and Reactive Power and reliability-related services per contracts or arrangements.	BA, RC, TOP
2. **Transmission Resources.** System Operators monitor transmission resources and deploy transmission assets within their area of responsibility.	BA, RC, TOP
3. **Reactive Resources.** System Operators monitor reactive resources and deploy those resources for voltage control and/or Reactive Power balancing.	BA, RC, TOP
4. **Demand-Resource Balancing.** System Operators maintain Demand-resource balance and comply with Control Performance and Disturbance Control Standards (CPS/DCS).	BA, RC
5. **Operating Reserve.** System Operators maintain adequate Operating Reserve and respond when reserve values fall below the required amount.	BA
6. **System Frequency.** System Operators monitor system frequency and respond to Frequency Trigger Limit exceedances.	BA, RC, TOP
7. **SOL & IROL Monitoring.** System Operators monitor System Operating Limits (SOL) and Interconnection Reliability Operating Limits (IROL) and respond to exceedances.	RC, TOP
8. **Energy Emergencies.** System Operators identify and respond to actual or potential Energy Emergencies.	BA, RC
9. **System Restoration Events.** System Operators identify Disturbances that require initiation of restoration plans and determine the actions required to return the system to normal operation.	RC, TOP

1 https://www.nerc.com/pa/Stand/Pages/FunctionalModel.aspx

3.2 Critical Systems and Tools

System Operations staff rely upon a number of critical systems and tools to monitor and control the electric system. Table 3-2 summarizes a generic set of critical systems and tools that were evaluated for this analysis.

The primary objectives of the evaluation were to:

1. Recognize how the loss, degradation, or compromise of a particular system or tool could affect a System Operator's ability to perform reliability-related tasks; and
2. Identify advances in automation that could help improve system or tool performance; reduce the impact of a loss, degradation, or compromise of a system or tool; or assist users with evaluating system or tool outputs and recognizing events or scenarios that should be addressed.

Table 3-2. Critical Systems & Tools Summary

Critical Systems & Tools Description	Prime Users
1. **Supervisory Control and Data Acquisition (SCADA).** The primary tool for observing and controlling equipment remotely.	BA, RC, TOP
2. **Automatic Generation Control (AGC).** The program used to dispatch generating Facilities to maintain scheduled Interchange and system frequency, and to comply with CPS and DCS.	BA
3. **Reserve Programs.** The programs used to maintain Operating Reserve and Reactive Reserve and dispatch reserve to address Real/Reactive Power shortages.	BA, RC, TOP
4. **Alarming.** The programs used to alert staff to changes to system topology, and abnormal conditions or unacceptable system performance that may require further analysis.	BA, RC, TOP
5. **State Estimator (SE).** The tool used to estimate load and generation at all locations, backup metered locations in the event of a failure, and provide a base case for further analysis.	RC, TOP
6. **Real-Time Contingency Analysis (RTCA).** The tool used to monitor post-Contingency operating conditions and identify unacceptable system performance.	RC, TOP
7. **Study Tools.** The tools used to perform power system studies to assess expected system performance for a given condition.	RC, TOP
8. **Stability Tools.** The tools used to perform steady-state stability analysis and conducts a comprehensive assessment of dynamic behavior to identify transient stability issues.	RC, TOP
9. **Market Software.** The software used to run day-ahead and real-time markets and enable the buying and selling of electricity and ancillary services on a day-to-day basis.	BA
10. **Synchrophasor Applications.** The applications that use sub-second, time-synchronized measurements to identify excessive power system oscillations, low damping levels and other abnormal conditions that could impact BES reliability.	BA, RC, TOP
11. **Energy Scheduling Tools.** The tools used to buy/sell power and schedule Interchange.	BA
12. **Reliability Communications Systems.** The tools used to convey operational information. These tools include but are not limited to messaging systems, phone systems and FM radio.	BA, RC, TOP
13. **Outage Scheduling Systems.** The tools used to coordinate and track equipment outages.	BA, RC, TOP
14. **Physical Facilities.** All generation, transmission and distribution facilities and their associated equipment.	BA, RC, TOP

3.3 Summary of Key Findings

The key findings of PNNL's analysis of the critical systems and tools that functional entities use to perform reliability-related tasks and of the tasks themselves are as follows:

Communication & Coordination Between Entities – There's a significant amount of communication and coordination that must take place between functional entities to perform their assigned tasks. In many instances, the System Operations staff of one company is dependent on that of another to aid in the performance of tasks that are necessary to achieve common operational goals and objectives.

<u>Advanced Automation Opportunities</u>: Advancements in automation to help improve communication and coordination between functional entities and reduce the likelihood of miscommunication or lack of coordination will provide significant value. Specifically, automation that gathers and synthesizes information from the various functional entities can be displayed to form a common operational picture. The common operational picture supports shared situation awareness to facilitate efficient coordination and prevent breakdowns in the common ground between functional entities. An example of this is PNNL's Shared Perspectives, an application based on a scalable web architecture that supports a highly interactive collection of visualization components[2] and part of PNNL's Grid Operation and Planning Technology Integrated Capabilities Suite (GridOPTICS™).

Task Association & Time Constraints – Several of the reliability-related tasks that System Operations staff perform are associated with other tasks. In other words, it's common for staff to perform multiple tasks at or around the same time during an event. Furthermore, these tasks typically have associated timeframes for completion that vary and interdependencies that require staff to prioritize the performance of one task over another or perform the tasks in a certain sequence. These requirements can become quite complex during major system events.

<u>Advanced Automation Opportunities</u>: Advances in automation to help System Operations staff recognize task dependencies and associated time constraints and determine the most effective and efficient order in which to perform tasks will provide significant value.

Data Requirements – The amount of data and information required to perform reliability-related tasks varies. Furthermore, the amount of information and data required to perform any particular task can vary depending on actual or expected system conditions. A major system disturbance can generate hundreds if not thousands of alarms and overwhelm System Operations staff by inundating them with information.

<u>Advanced Automation Opportunities</u>: Advances in automation to assist System Operations staff with managing data and locating information that's critical to the operational decision-making process will provide significant value. This technology will help operators quickly diagnose the source of the alarms to prevent cascading alarms from inundating the operator. Another advanced automation opportunity is alarm management systems designed to help with alarm prioritization and false alarm/violations detection.

Task Impact & Frequency of Performance – The impact that reliability-related tasks can have on safety and system reliability and the frequency at which each task is performed vary. There

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[2] Shared Perspectives: Actionable Visualization Tool for Power Grid Situation Awareness, Gosink, Luke and Dowson, Scott, 2015, PNNL-SA-112261.

are several tasks that System Operations staff are expected to perform on a routine basis that could have a significant impact on reliability if they are not performed or are performed improperly. This is important to note as tasks that demand repetitive action can be monotonous and considered boring, which can result in an inadequate level of mental activity while performing the task thereby increasing the risk of error.

There are also high-impact, low-frequency tasks that are performed so infrequently that a staff member may go his or her entire career without having to perform that task yet must remain competent to do so if the need arises.

<u>Advanced Automation Opportunities</u>: The repetitive, mundane tasks are typically good candidates for at least partial automation. Monitoring will be required to assess automation reliability especially if the tasks are high impact. Advances in automation that aid System Operations staff in the performance of high impact tasks by eliminating the need for staff to perform redundant tasks will provide significant value.

Risk Evaluation – The level of risk to the employee and public safety, system reliability, and continuity of service can vary from task to task and from event to event. Risk evaluation is typically performed by System Operations staff without the use of risk assessment tools.

<u>Advanced Automation Opportunities</u>: Advances in automation to introduce decision support tools that assist System Operations staff with evaluating risk will provide significant value. It will be important for a tool of this kind to have sufficient transparency into the factors it relies on to calculate risk as well as the algorithm it uses to combine these factors into overall risk. Transparency can help operators develop appropriate trust and reliance on the technology.

Correlation of Critical Systems & Tools – System Operations staff are highly dependent on their critical systems and tools to perform reliability-related tasks. A failure, degradation or compromise of a system/tool can reduce or eliminate the staff's ability to perform certain tasks and adversely impact safety and system reliability. In addition, PNNL noted that there is limited correlation between systems/tools which requires staff to view the outputs independently in order to draw conclusions.

<u>Advanced Automation Opportunities</u>: Advances in automation to correlate the outputs of critical systems/tools and improve the situational awareness of System Operations staff to help identify the loss, degradation or comprise of a system or tool will provide significant value. Such tools reduce the workload required to mentally integrate data from multiple tools and allow operators to spend their cognitive resources on higher level cognitive activities such as anticipating future trends.

4.0 Electric Industry Trends, Threats and Opportunities

PNNL considered several electric industry trends, threats and opportunities while conducting its analysis. The primary objectives of this exercise were to:

1. Gain a better understanding of how these trends, challenges and opportunities may affect the current and future state of the electric system.
2. Identify advances in automation that could help grid operators and electric utilities prepare for changes associated with the identified trends and threats or take advantage of recognized opportunities.

Table 4-1 summarizes the trends, threats and opportunities that were considered for this analysis.

Table 4-1. Summary of Electric Industry Trends, Threats, and Opportunities

Category	Description
Generation Trend	1. **Increased Renewable Resource Penetration.** Approx. 17 percent of total electricity demand in the U.S. is supplied by renewable resources at this time. That percentage is expected to increase to 39 percent within two decades. The highest growth of renewables is predicated for solar/wind generation.
Generation Trend	2. **Generation Profile Changes.** The generation profile is changing as renewable resource use continues to increase and traditional generation types (e.g., coal) are becoming less economical to run and are often retired. These changes are resulting in a greater percentage of load being served by non-dispatchable generation and an increased reliance on natural gas to balance the variable nature of renewables.
Generation Trend	3. **Integration of DERs.** Tremendous change is taking place in consumers' adoption of DER to supply a portion of their energy needs. DER displace energy that was traditionally supplied by the BES, contributing to declining load on the grid, but adding complexity to operations, market design efforts, and system planning needs.
Transmission Trend	4. **Aging Infrastructure.** The last forty years have seen limited investment in the North American transmission grid figures showing that approx. 70 percent of transmission lines and power transformers are 25 years or older, and 60 percent of circuit breakers are 30 years or older. Catastrophic failures of transmission assets threaten system reliability and changing system dynamics may increase the likelihood of such events. In addition, regulations to build large-scale transmission lines has become more onerous and utilities often have difficulty attaining the local and state permits required to build new lines.
Transmission Trend	5. **Evolving Utility Structure.** Several states and regulators have move aggressively towards breaking up vertically integrated utilities separate ownership of generation, transmission and distributions systems. This has resulted in a patchwork of restructured and vertically integrated utilities across the U.S. with more than 2000 utilities now owning and/or operating some part of the electric system. This increase in owners/operators requires significant communication and coordination between entities to ensure the system in a safe and reliable manner.
Transmission Trend	6. **Improved Operational Toolset.** The set of tools used by System Operations staff to monitor and control the grid is improving at a substantial pace. As grid modernization efforts progress, new architectural concepts, tools, and technologies will be used to measure, analyze, predict, protect, and control power systems. Introducing more sophisticated tools with enhanced analytical and predictive capabilities will improve the operators' ability to proactively identify and address issues that could adversely impact grid safety, reliability and resiliency. However, significant training will be required to ensure the operators are knowledgeable of how the tools function and can analyze and validate their outputs to address potential failures and degradations.
Emerging Threats	7. **Cyber-Physical Attacks.** In the age of the automation and the ever-increasing connectivity and ease of low-cost communication, there is greater visibility and control of electricity assets. There is also greater cyber exposure of critical industrial control systems, which were previously disconnected from the outside world. This exposure has resulted in increased vulnerabilities in the power grid to cyber-attacks. These vulnerabilities impose a high risk to grid operations and increase the likelihood of not being able to restore the system to its previous state after an intrusion.
Emerging Threats	8. **Geomagnetic Disturbances (GMD).** GMDs have also been known to have an impact on the power transmission system through the induction of geomagnetically

Category	Description
	induced current causing saturation on transformers. This is especially prevalent in the grids that are near the magnetic north and south. This combined with high-resistant soil types (namely igneous rock) makes an area more susceptible to GMD.
Emerging Threats	9. **Electromagnetic Pulses (EMP).** An EMP, which is a short burst of magnetic energy, is a transient phenomenon compared to the more steady-state GMD. These events can be natural (e.g., lighting strike), man-made (e.g., voltage transients due to motors starting) or caused by military-grade weapons (high altitude nuclear blast). Protecting against these effects require everything from hardened electronics, surge protection and transformer neutral blocking.
Emerging Threats and Extreme Weather Conditions	10. **Wildfires and Extreme Weather Conditions.** Climate change is posing a greater threat to the nation's infrastructure as more severe, natural disasters start to become the norm. Warm, dry conditions are becoming common place leading to longer fire seasons and increased risk to electric system reliability and resiliency due to wildfires. The subsequent recovery from these events is extremely expensive, time-consuming, and requires specialized approaches for addressing each disaster.
Opportunities	11. **Human Performance Improvement.** Human error is cited as the main cause for up to 80 percent of all incidents and accidents in complex, high-risk systems that exist in the aviation, petrochemical, healthcare, construction, mining, and nuclear power industries. Human Performance is critical in the electric industry as System Operations staff perform tasks on a daily basis that could impact employee safety or that of the public, or system reliability. As technology advances at an unprecedented rate and the grid rapidly evolves, grid operators and electric utilities must endeavor to improve operational tools, processes and training to help eliminate error precursors and arm personnel with critical thinking skills needed to improve human performance and avoid errors when possible.
Opportunities	12. **Real-Time Simulation Capabilities.** Grid operators and electric utilities prefer to use Dispatcher Training Simulators (DTS) to conduct simulation training exercises as they provide the most realistic environment for training on response to specific types of events. However, entities often find it difficult to maintain their own DTS due to the amount of work required to develop simulations and maintain a functional simulation model. In addition, most simulation cases are rigid in that you must perform the scenario as scripted and have limited ability to vary the difficulty level of a particular scenario to match your audience (i.e., all learners must complete the same exercise). Advances in simulation technology could provide a significant value to the electric industry, especially when it comes to preparing personnel to operate the grid of the future.

5.0 High-Value Opportunities for Advanced Automation

Four primary areas have been identified that can be leveraged to advance automation and improve grid safety, reliability, and resiliency:

Operational Systems & Tools – Opportunities to improve performance and increase the value of critical systems and tools that System Operations staff rely upon to perform their duties.

Operating Processes & Procedures – Opportunities to automate Operating Processes and Procedures that System Operations staff execute in the performance of their duties. For the purpose of this report, Operating Processes and Procedures are considered to be general or specific steps taken by an operating position to achieve a defined operational goal.

Operational Decision-Making – Opportunities to better support the operational decision-making process.

Human Performance & Training – Opportunities to reduce the likelihood of human performance errors and improve the quality and effectiveness of operations training.

The following subsections go into more detail to explain each of these areas of opportunity. However, it is important to note that there are vast amounts of research today looking to use the BES, or sub-components thereof, as real-world use cases for applying Machine Learning (ML) and Artificial Intelligence (AI). Each of these areas of opportunity may have unique solutions in the realm of ML/AI research. To our knowledge, despite the massive amounts of research being done in this space, there is very little of it that has actually been validated and deployed functionally in a live operating electric grid system. Our research endeavored to perform a cursory evaluation of what we believe to be the current state of the art for ML/AI research for the U.S. BES. A summary of that work is included in Appendix 1 (Section 7.1) of this report.

5.1 Operational Systems & Tools

There are several critical systems and tools that System Operations staff rely upon to monitor and control the electric system. There are also non-critical systems/tools that provide staff with data and information that's meant to inform the operational decision-making process (e.g., weather services, security monitoring systems).

<u>Problem Statement</u>: System Operations staff rely upon critical systems and tools to identify and address abnormal conditions and unacceptable system performance as required to maintain safe and reliable operation of the electric system.

A significant loss of generating or transmission Facilities can generate hundreds of alarms and result in multiple operating parameter exceedances, which may have different timeframes for required response (e.g., immediate action to address IROL exceedances, five minutes to address severe frequency deviations, thirty minutes to address voltage-based SOLs).

These types of events require staff to triage in real-time to determine which mitigating actions to prioritize based on the actual or potential risk to safety and/or reliability. Such scenarios can be further complicated by the fact that staff often have dependencies on people, processes, and tools that can affect their ability to perform certain actions.

The remainder of this section summarizes the opportunities that were identified to improve operational systems and tools.

5.1.1 Intelligent Alarming Systems

Grid operators and electric utilities have traditionally relied on Energy Management System (EMS) alarming applications to alert System Operations staff to system topology changes and conditions that require analysis or corrective action. A major system disturbance can generate hundreds if not thousands of alarms and overwhelm staff by inundating them with information.

As a result, some companies have identified the need for intelligent alarming systems to help System Operations staff identify, prioritize and react to critical issues.

Intelligent alarming systems can be developed to adjust the way alarms are processed and presented to staff based on the nature and severity of a particular event.

In addition, these systems can be used to:

1. Eliminate or suppress false and nuisance alarms.
2. Highlight data and information that's critical to the decision-making process.
3. Eliminate or hide data and information that doesn't need to be in the users' purview.

Furthermore, these types of intelligent alarming systems can be coordinated with other systems or tools that help System Operations staff assess risk and prioritize corrective action based on prevailing conditions. Refer to Sections 5.1.4 and 5.3.2 for a more detailed description of those opportunities.

5.1.2 System Reconfiguration Options

When an operational scenario occurs where System Operations staff must act to mitigate or prevent unacceptable system performance, there are three primary actions that can be taken:

1. Redispatch generation.
2. Reconfigure system topology.
3. Adjust load.

Reconfiguring system topology by changing the status of substation and field devices is often underutilized due to the fact that the traditional toolset used by staff doesn't typically include an application that analyzes how the power system can be reconfigured to mitigate certain conditions.

Appendix 2 (Section 7.2) contains an example of a novel substation switching methodology that could be deployed to aid with on-the-fly topology reconfiguration that might be implemented to execute automatically under certain operating conditions.

Tools can be developed to analyze how equipment can be reconfigured to achieve defined objectives, which may include, but shouldn't be limited to:

1. Reposturing the system to improve pre- and post-Contingency performance.
2. Mitigating an actual or potential exceedance of an operating limit or parameter.
3. Minimizing the risk of electrical contact for personnel performing work.
4. Reducing the customer minutes of interruption associated with planned/forced outages.
5. Maximizing the effectiveness of reactive devices to support system voltage.

5.1.3 Correlation of Applications

Grid operators and electric utilities use several different applications to monitor system conditions and identify unacceptable system performance or abnormal conditions. In many instances, these applications have their own alarming functionality and present their outputs independent of other tools.

Advancements in automation could assist entities with correlating the output of multiple applications. Many violations detected and alarmed by different applications can have a common cause. For example, the outputs of synchrophasor-based applications that are used to monitor oscillatory behavior and system damping, and inertia/stress levels could be correlated with the Voltage and Transient Stability Assessment Tools (VSAT/TSAT) that are used to establish stability margins. Correlating the outputs of these applications would provide System Operations staff with a clearer picture of the dynamic behavior of the power system and potential stability issues in the pre- and post-Contingency state.

5.1.4 Model Validation and Advanced Applications

Grid operators and electric utilities must maintain accurate system models to drive the network analysis and study tools that they rely upon to assess actual and expected system conditions. These tools may include but are not limited to:

1. State Estimator (SE)
2. Real-Time Contingency Analysis (RTCA)
3. Voltage and Transient Stability Assessment Tools (VSAT/TSAT)
4. Real-time and offline study tools [see Appendix 3 (Section 7.3) for a more detailed description of power system studies]

Modeling errors and discrepancies can degrade performance and result in false alarms or, even worse, a failure to identify system performance that warrants corrective action.

Advanced Applications such as RTCA, VSAT, and TSAT typically use node-breaker models which, in some instances, are developed and maintained by multiple entities. However, the SOLs that TOPs establish are typically based on studies that are conducted using bus-branch models. This being the case, many entities elect to rely on offline studies or nomograms that are based on offline studies rather than Real-time applications. In short, it's not uncommon for the models used to establish SOLs to be different from those used to detect SOL violations. Digital twin can be a promising technology to link modeling tools with advanced applications, resulting in second-level RTCA performance[3]. Digital twin can be developed to:

1. Compare multiple sets of real-time and offline models to identify differences in topology and parameters.
2. Detect modeling errors that are reducing model accuracy, generating false alarms, or causing variances in calculated current, voltage, and phase angle values.
3. Recognize patterns and determine the probability of certain violations based on expected and prevailing system conditions.

PNNL also believes that AI can be leveraged to develop contingency analysis tools to detect false alarms in the following manner:

1. Create a training set consisting of offline studies that used the same model as Real-time studies used to calculate SOLs, including a wide range of representative operating conditions.
2. Conduct the learning phase until the tool is able to calculate the probability of certainty for any given violation, which can then be used to consider alarm validity.

[3] https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8779809

3. Run this tool in parallel with traditional model-based contingency analysis tools as a means to verify result accuracy (see Figure 5-1).

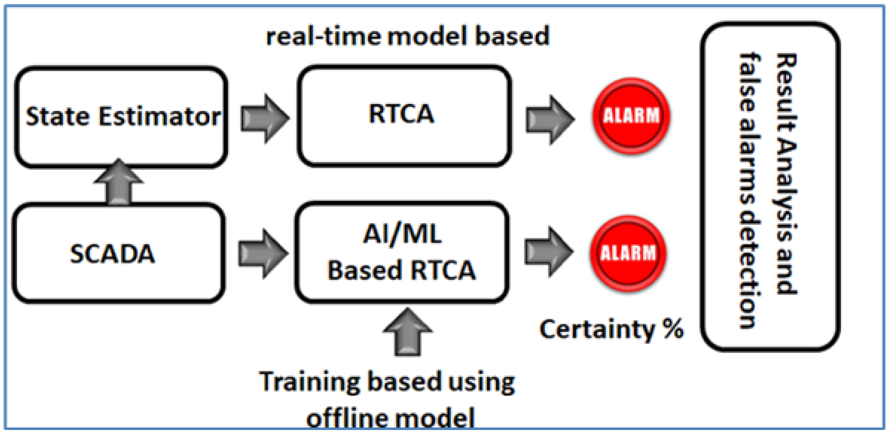


Figure 5-1. Model Diagram

5.2 Operating Processes & Procedures

There are numerous requirements for functional entities to maintain Operating Plans, Procedures, or Processes to address certain types of events. Operating Plans, Procedures, and Processes are defined in the Glossary of Terms Used in NERC Reliability Standards, shown in Figure 5-2.

Continent-wide Term	Acronym	BOT Approved Date	FERC Approved Date	Definition
Operating Plan [Archive]		2/7/2006	3/16/2007	A document that identifies a group of activities that may be used to achieve some goal. An Operating Plan may contain Operating Procedures and Operating Processes. A company-specific system restoration plan that includes an Operating Procedure for black-starting units, Operating Processes for communicating restoration progress with other entities, etc., is an example of an Operating Plan.
Operating Procedure [Archive]		2/7/2006	3/16/2007	A document that identifies specific steps or tasks that should be taken by one or more specific operating positions to achieve specific operating goal(s). The steps in an Operating Procedure should be followed in the order in which they are presented, and should be performed by the position(s) identified. A document that lists the specific steps for a system operator to take in removing a specific transmission line from service is an example of an Operating Procedure.
Operating Process [Archive]		2/7/2006	3/16/2007	A document that identifies general steps for achieving a generic operating goal. An Operating Process includes steps with options that may be selected depending upon Real-time conditions. A guideline for controlling high voltage is an example of an Operating Process.

Figure 5-2. NERC Definitions for Operational Documentation

Problem Statement: System Operations staff are expected to adhere to the Operating Plans, Procedures, and Processes that their respective companies develop as they identify the actions that must be taken to achieve defined operational goals while complying with regulatory and statutory requirements. In some instances, the direction provided in these documents is also reflective of contractual agreements that the company has entered into to operate the electric system in a certain manner.

The amount, type, and complexity of operating documentation that grid operators and electric utilities maintain vary. However, it's not uncommon for System Operations staff to reference multiple documents during a single event, some of which may have conflicting information. It's also not uncommon for these documents to provide high-level direction and depend on the knowledge and experience of an operator to determine the most effective actions to take based on the nature and scope of an event. Please note that these operating documentations are typically developed offline in a conservative way due to the time-consuming process of model development and computation. This is another place that AI/ML could be helpful to develop more efficient and effective documentation. Another opportunity is to digitalize the operating documents using knowledge graphs and/or decision modeling and notation technologies such that the relevant rules and processes be easily accessed by the operators depending on the actual system conditions and further integrated into other on-line analyses and applications.

The remainder of this section summarizes the opportunities that PNNL has identified to automate certain Operating Processes and Procedures.

5.2.1 Voltage and Frequency Control Coordination

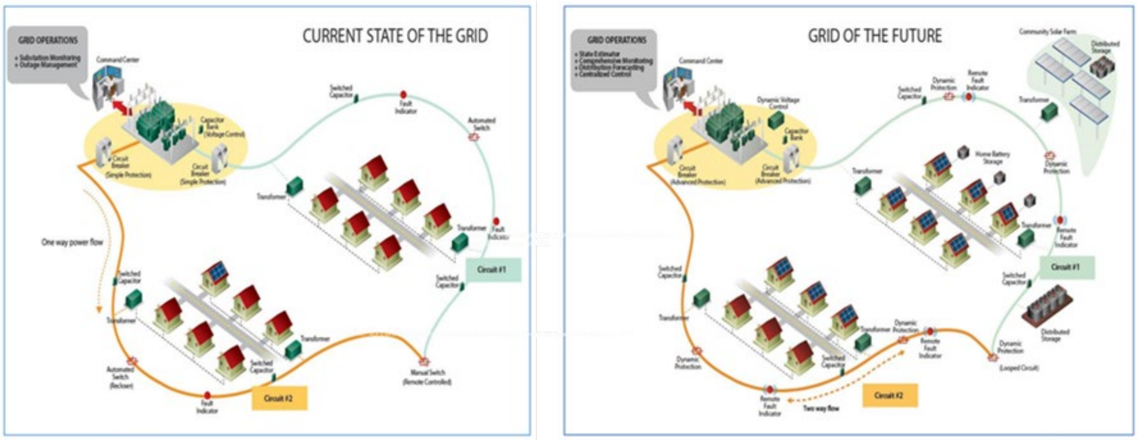
Functional entities must use reactive resources to maintain system voltages within acceptable limits in order to avoid damage to system Equipment and customer devices and tripping of generation and Transmission Facilities.

Traditionally, TOPs deployed reactive resources on the transmission and sub-transmission systems to maintain BES voltage levels and had limited interaction with Distribution Providers as distribution systems had minimal generation injection points and were typically radial in nature.

However, the operating characteristics of distribution systems have changed due to the continued integration of DERs as illustrated in Figure 5-3. The bi-directional power flow resulting from increased power sources, accompanied by a variety of energy efficiency and demand response programs that drive customers to manage power consumption on a more local level, require improved situational awareness and deeper insight into distribution system conditions and performance.

PNNL believes that robust automatic voltage and frequency control programs can be developed to more effectively:

1. Coordinate the automatic deployment of static and dynamic reactive resources on the distribution, sub-transmission, and transmission systems to maintain nominal voltage across all systems in the most efficient manner.
2. Recognize voltage patterns and avoid over-deployment of reactive resources.
3. Mitigate potential post-Contingency voltage violations in a manner that presents minimal risk of pre-Contingency voltage violations.



Source: *SCE's Grid Modernization Distribution System Concept of Operations* paper dated January 17, 2016

Figure 5-3. Current Vs. Future State of Distribution System

5.2.2 Validation of Switching Programs

Grid operators and electric utilities perform switching programs on a daily basis to accommodate scheduled and forced outages. The complexity and degree to which these programs are coordinated with other functional entities varies.

While some companies have programs in place to mimic switching beforehand and validate the intended results, PNNL believes that more advanced tools can be developed to more effectively identify and address conflicts that may arise due to overlapping outages and abnormal system conditions.

Specifically, PNNL believes a tool can be developed to perform the following actions with minimal operator intervention:

1. Mimic all switching programs to take place during a defined period of time in the order that they're expected to occur to identify unintended results and potential conflicts.
2. Mimic all switching programs to take place out of order to identify where the performance of one program before another could result in undesirable conditions.
3. Mimic each switching program to determine if there is a more effective way to achieve the intended results (i.e., reduce steps, limit the impact to adjacent equipment).
4. Recommend actions that can be taken before or after the performance of a switching program to improve expected pre- and post-contingency performance.

5.2.3 Execution of Operating Processes & Procedures

The Operating Plans, Procedures, and Processes that grid operators and electric utilities develop to provide System Operations staff with direction on how to address certain operational conditions and scenarios are typically based on operational planning studies. In many instances, these documents aren't overly perspective and rely on the knowledge and expertise of operations personnel to analyze actual system conditions and devise a specific course of action.

PNNL believes that advanced tools can be developed to:

1. Identify conditions and scenarios that require execution of specific Operating Processes and Procedures.
2. Compare the system conditions mimicked in the planning studies that were conducted when drafting the processes and procedures to actual and forecasted system conditions to identify significant differences that warrant further analysis.
3. Determine if the steps found in the processes and procedures can be executed to meet the defined operational goal(s).
4. Suggest additional or other steps that can be taken to meet the defined operational goal(s) in a more effective, efficient manner.

5.2.4 Troubleshooting Demand-Resource Balancing Issues

BAs are responsible for integrating resource plans ahead of time, maintaining Demand and resource balance within their respective BA areas, and supporting interconnection frequency in real-time.

There are also entities that coordinate with their respective BAs to take additional measures to maintain balance within their local areas (sometimes referred to as local BAs or sub-BAs). There are additional entities that buy and sell power to others and schedule Interchange as required.

BAs typically use AGC to control generation and regulate Real Power output to generating Facilities to maintain Net Scheduled Interchange and Interconnection system frequency, and to comply with CPS/DCS.

It’s not uncommon for AGC to automatically suspend due to a data point failure or bad value, which typically requires the BA to manually dispatch generation to maintain Demand and resource balance until the issue is resolved. There have also been occasions where an Interchange schedule is entered incorrectly causing a deviation between Net Scheduled and Net Actual Interchange and resulting in an increase of inadvertent Interchange.

PNNL believes that advanced tools can be developed to evaluate multiple systems, identify discrepancies between load-generation-Interchange values that could cause AGC to suspend or result in inadvertent Interchange, and assist with troubleshooting and limiting the impact of such events.

5.3 Operational Decision-Making

The average person makes approximately 35,000 decisions each day yet only makes about 120 mistakes a year on the job. System Operations staff make decisions on a daily basis that can significantly impact to grid safety and reliability. In some instances, a failure to make the right decision can result in cascading outages, a partial or total system shutdown or even death.

<u>Problem Statement</u>: The Operating Plans, Procedures, and Processes that grid operators and electric utilities develop to provide direction on the operation of the electric system cannot address every operational scenario that may occur. As previously stated, these documents are general in nature and often rely on the knowledge and expertise of System Operations staff to analyze system conditions and decide on a course of action to achieve their operational goals.

As the operating characteristics of the system continue to change due to grid modernization and problem-solving becomes more complex, the need for System Operations staff to practice critical thinking and perform non-routine tasks will grow resulting in a marked increase in cognitive demand. As a result, functional entities must develop more advanced decision support tools to aid in operational decision-making and reduce cognitive demand.

The remainder of this section summarizes the opportunities that PNNL has identified to develop tools to better support the operational decision-making process.

5.3.1 Automatic Mitigation Plans

In accordance with mandatory reliability standards, functional entities must develop Operating Plans to address actual or expected system conditions that could result in a SOL exceedance or operating Emergency. These plans are typically developed upon discovering such conditions in the Operations Planning Horizon. However, there are times when such plans are developed in the Same-day or Real-time Operations Horizons, which allows for less time to assess the condition and determine the most effective course of action.

PNNL believes advanced tools can be developed to:

1. Analyze actual and expected system conditions to identify abnormal behavior or unacceptable system performance that warrants the development of a mitigation plan and link associated Operating Processes and Procedures.
2. Identify mitigating actions that can be taken in accordance with mandatory standard requirements and contractual obligations to achieve defined reliability goals.
3. Order viable mitigating actions based on reliability benefit and economic impact.
4. Generate system studies to determine the expected outcome of performing certain mitigating actions for further analysis by System Operations staff.

5.3.2 Risk Assessment Tools

System Operations staff must manage risk to ensure that employee and public safety, system reliability, and continuity of service are not unduly compromised during normal and emergency operations.

While the existing operational toolset includes applications for analyzing actual and forecasted system conditions to identify actual or potential SOL/IROL exceedances and energy shortages, there is no tool in place that specifically assists System Operations staff with evaluating risk to support the decision-making process.

PNNL believes risk assessment tool that receives qualitative and quantitative data from operational and non-operational sources can be developed to:

1. Analyze historical data alongside actual and forecasted system conditions to recognize patterns and identify abnormal conditions or unacceptable system performance that warrants further analysis.
2. Run a risk evaluation model to analyze the following factors for a given scenario or condition and assign a risk score:
    a. Greatest negative impacts and probability of those negative impacts occurring.

   b. Greatest positive impacts and probability of those positive impacts occurring.
   c. Absorption and recovery capabilities.
3. Generate a risk analysis report that summarizes the results and highlights qualitative and quantitative factors to be considered in the operational decision-making process.

5.4 Human Performance & Training

In accordance with mandatory standard requirements, certain functional entities must use a systematic approach when designing, developing, and delivering training to their System Operators and Operations Support Personnel. The overreaching goal of these entities' training programs is to ensure personnel who are tasked with performing reliability-related tasks are able to do so as expected.

Problem Statement: Grid operators and electric utilities have experienced significant turnover in the last 10 years leading to a decrease in experience and increased need for training. Furthermore, the pace at which the grid is being modernized and advancing technologies are being integrated into the control room is changing the amount and type of training needed to ensure System Operations staff have the knowledge and skills required to operate the electric system in a safe, reliable, and economic manner.

While not specific to any particular reliability-related task, entities are recognizing the need to incorporate Human Performance training into their respective training programs to ensure System Operations staff have the critical thinking skills required to perform their respective duties in the appropriate manner. A failure to engage in critical thinking often can lead to operating errors that undermine the performance of a task and adversely impact grid safety and reliability.

5.4.1 Human Performance Error Detection & Prevention

There are several factors that can lead to human performance errors, such as time pressure, distractions, changes in job scope, the simultaneous performance of multiple tasks (i.e., multitasking), and lack of guidance. Included in this is a lack of trust in the measurements or of the tools/algorithms being used to trigger alerts/alarms, particularly if they have high false-positive rates.

The *U.S. Department of Energy Human Performance* Improvement *Handbook, Volume 1: Concepts and Principles* defines an error-likely situation as, "A work situation in which there is greater change for error when performing a specific action or tasks in the presence of error precursors."

Error precursors are unfavorable conditions embedded in a job site that create mismatches between a task and the individual. Error precursors interfere with successful performance and increase the probability for error. Simply stated, they are conditions that provoke error. They can be organized into one or more of the following four categories: Task Demands, Individual Capabilities, Work Environment, and Human Nature.

Error precursors are, by definition, prerequisite conditions for error and, therefore, exist before an error occurs. If discovered and removed, job-site conditions can be changed to minimize the chance for error. In accordance with the handbook, the second principle of human performance states that error-likely situations are predictable, manageable, and preventable.

PNNL believes that advanced tools can be developed to analyze historical data alongside actual and forecasted system conditions as well as System Operations staff performance to identify error precursors in the Same-day and Real-time Operations Horizons and raise awareness before an operating error actually occurs. This tool could also be leveraged in the simulation training environment to identify potential learning opportunities.

5.4.2 Smart Dispatcher Training Simulator

As described in the *NERC Continuing Education Administrative Manual*, training simulations can include tabletop exercises, operator training simulators, emergency drills, or the practice of emergency procedures, restoration, blackstart, or other reliability-related scenarios.

Grid operators and electric utilities prefer the use of DTS to conduct simulation training exercises as it provides the most realistic environment for training on response to specific types of events. However, entities often find it difficult to maintain their own DTS due to the amount of work required to develop simulations and maintain a functional simulation model. Furthermore, most simulation cases are rigid in that you must perform the scenario as scripted and have limited ability to vary the difficulty level of a particular scenario to match your audience (i.e., all learners must complete the same exercise).

PNNL believes that a Smart DTS can be developed to gauge a learner's level of expertise based on their performance in a simulation and vary the degree of difficulty to provide a better training experience. PNNL also believes this simulator could be used to:

1. Recognize learner actions that indicate a lack of knowledge or skill that requires additional training (e.g., adjusting generation that increases the severity of SOL exceedance, placing reactor in service prior to removing capacitor from service).
2. Recognize learner habits that must be changed or improved (opening multiple circuit breakers to quickly indicating failure to self-check, failing to navigate to all of the displays needed to collect the information needed to inform an operational decision).

6.0 Conclusion

The fast-changing landscape of the BES is presenting challenges in the complexity of operations and deployment of new technologies. Advances in telemetry and grid measurements, as well as high performing operational networks, are enabling new opportunities for data-driven algorithms for decision support that have, until now, never been possible. The objective of this report was to take a look at control room operations and identify high-value opportunities for automation. This report approached this evaluation from both a control room operator's perspective, as well as from a power systems engineering perspective. Both are essential for effective improvements in the Real-time Operations Horizon.

The opportunities identified in this report will require further evaluation for feasibility and most certainly will require collaboration between grid operators and electric utilities, equipment manufacturers and vendors, regulatory agencies, and researchers. The electric industry cannot afford to wait to address these challenges and utilities will not be able to do so on their own. The Department of Energy (DOE) is uniquely positioned to begin making investments in these areas to secure a more reliable and resilient grid for the future.

7.0 Appendices

7.1 Appendix 1: ML/AI Current State of the Art

What is AI and ML?

Artificial Intelligence (AI) is a science and engineering of making machines and software behave in such a way that, until recently, it was believed requires human intelligence. AI has evolved over time, meaning that something that was considered AI until recently, might now just be a simple task with today's technology and thus not considered AI any longer. Some of the techniques that belong to artificial intelligence are expert systems (ES), artificial neural networks (ANN), fuzzy logic (FL) and genetic algorithms (GA).

Machine learning (ML) is a subset of AI and is a "science" that enables systems (software) to adjust and improve through experience, without being explicitly programed to do so using neural network models. Deep learning employs a deep neural network (DNN) as the model that typically has dozens of layers, millions and even billions of free parameters.

State-of-the-art in short

ML has long been studied since the 1950s with the objective to enable machines to "think" as human brains. The idea to apply AI-based techniques and methods to solve the power system problems is not new as well, and it dates back more than 30 years. Since then, significant research efforts have been conducted, and a large number of techniques and solutions were investigated for a wide range of problems. A potential of AI to facilitate and accelerate the use of clean energy sources, lower the energy cost, to reduce energy waste, and to improve the planning, operation and control of power systems is projected. When designed carefully, AI systems could be particularly useful in the automation of structured tasks and routines in control room environments as well, allowing humans (operators) to focus on more important tasks.

However, it was not until recently that AI started to deeply impact many domains with tremendous advancement, where the most successful branch of ML is deep learning. In last few years, there has been a significant increase in proposed AI/ML applications to the power system (see Figure A1.1)[4], driving up the volume of publications. Due to enormous volume of the publications, quite a few survey (review) papers have been generated as well. Surveys are mostly focused on the AI applications in the particular area in the power system such power

[4] M. S. Ibrahim, W. Dong, and Q. Yang, "Machine learning driven smart electric power systems: Current trends and new perspectives," Applied Energy, Volume 272, 2020, 115237, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2020.115237

system such as security and stability[5], resiliency[6], demand response[7], forecasting[8], optimization[9], on-line voltage stability assessment[10], online security assessment[11], with few exceptions such as Reference 8 that covered more than 200 recent publications in all domains of smart grids.

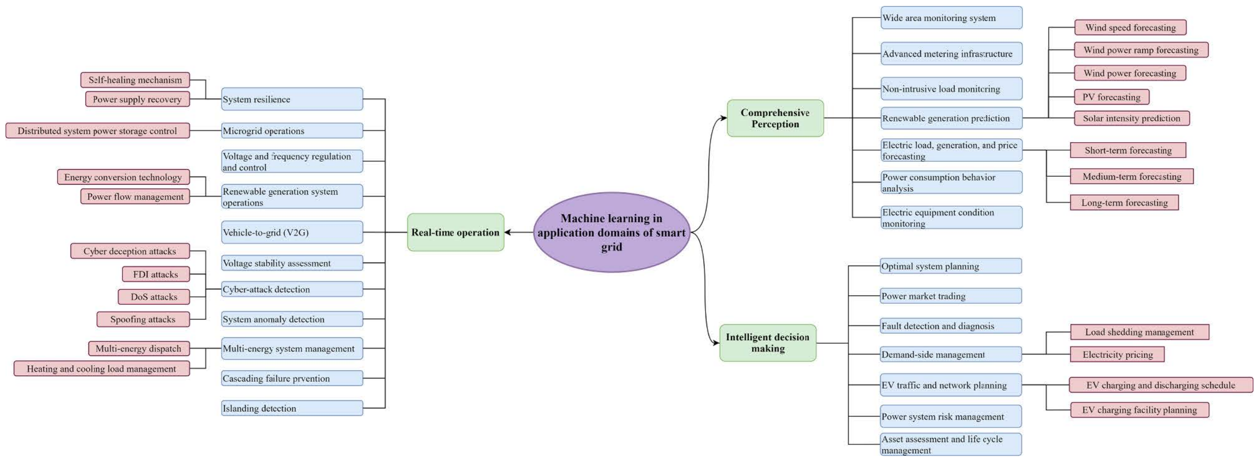


Figure A1.1. ML in application domains of smart grid[4]

Despite the extensive research efforts, it is recognized that the majority of these proposed techniques never found their application and are not being implemented in the real world. The following section tries to identify the cause for technologies adoption delay.

Why the AI/ML deployment is not following the AI/ML research "boom"?

The purpose of this review is not "to discourage" the future research efforts but rather to investigate the main causes and to highlight the requirements that applications need to satisfy before being considered for the real-world implementation.

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[5] O. A. Alimi, K. Ouahada, and A. M. Abu-Mahfouz, "A Review of Machine Learning Approaches to Power System Security and Stability," IEEE Access, Volume 8, pp. 113512–113531, 2020, https://doi.org/10.1109/ACCESS.2020.3003568

[6] J. Xie, I. Alvarez-Fernandez and W. Sun, "A Review of Machine Learning Applications in Power System Resilience," 2020 IEEE Power & Energy Society General Meeting (PESGM), Montreal, QC, Canada, 2020, pp. 1–5, https://doi.org/10.1109/PESGM41954.2020.9282137

[7] I. Antonopoulos, V. Robu, B. Couraud, D. Kirli, S. Norbu, A. Kiprakis. Flynn, S. Elizondo-Gonzalez, S. Wattam, "Artificial intelligence and machine learning approaches to energy demand-side response: A systematic review," Renewable and Sustainable Energy Reviews, Volume 130, 2020, 109899, ISSN 1364–0321, https://doi.org/10.1016/j.rser.2020.109899

[8] E. Vivas, H. Allende-Cid, and R. Salas, "A Systematic Review of Statistical and Machine Learning Methods for Electrical Power Forecasting with Reported MAPE Score," Entropy, Volume 22, no. 12, p. 1412, Dec. 2020

[9] Review of Learning-Assisted Power System Optimization 2020. arXiv:2007.00210v2

[10] Amroune, M. Machine Learning Techniques Applied to On-Line Voltage Stability Assessment: A Review. Arch Computat Methods Eng 28, 273–287 (2021). https://doi.org/10.1007/s11831-019-09368-2

[11] N. V. Tomin, V. G. Kurbatsky, D. N. Sidorov, A. V. Zhukov, "Machine Learning Techniques for Power System Security Assessment.", IFAC, Volume 49, Issue 27, 2016, Pages 445–450, ISSN 2405-8963, https://doi.org/10.1016/j.ifacol.2016.10.773 (**This work was supported by the Russian Scientific Foundation under Grant No. 14-19-00054 and the 2015 Endeavour Scholarship and Fellowship program.)

Challenges for the implementation of ML algorithms and techniques are diverse and can be put in one of the following categories: technology maturity, governance, transparency, security, safety, privacy, employment, and economic impacts.

Following is the list of some main challenges:

1. Technology maturity
    a. Not properly verified and validated in terms of:
        i. Size (scalability)
        ii. Different operating conditions (normal vs adverse)
        iii. Flexibility (grid topology is constantly changing)
        iv. Success rate
        v. Operational risk
        vi. Security risk (AI is a black box)
        vii. Lack of domain knowledge and physics representation in existing AI
        viii. Out-of-the-box use of AI/ML for complex grid applications
2. Data (gathering and processing)
    a. Lack of large datasets for validation and verification of proposed methods (proprietary information)
    b. Lack of realistic datasets representing grid adverse conditions to enable proper verification and validation studies (rare events in general), in particular, protection modeling data such as Remedial Action Scheme (RAS).
    c. Integration challenges for the data sets from different domains/applications
    d. Data sanitization and cleaning (data quality)
    e. Data unbalance (mostly normal operation conditions, only a very small percentage of large events that are of particular interest)
3. Complexity
    a. A lot of proposed ML methods require massive computational and data management resources
    b. Calls for cloud computation that brings in regulatory restrictions and latency in the picture
4. Cyber-attacks vulnerability (there is not enough research done on how much such algorithms will increase overall risk)
5. Benefits vs risk studies (in terms of economy primarily)
6. Gap between domains: AI companies while have expertise in math and computer science, they often lack the understanding of specifics of power systems.
7. Regulatory restrictions (restrictions on cloud-based applications use in the power industry)
8. Data sharing between parties
9. Operators/Users (trust issues, fear of becoming obsolete, cognitive overload, reduction of the overall system understanding, etc.)

Some examples of the real-world implementations using AI in the power industry are given as follows:

1. IBM under DOE’s SunShot initiative (reliable prediction of the renewable resources such as solar wind and hydro);

In this effort, IBM blends a great number of weather and solar energy prediction models with historical data to accurately predict renewable energy generation at a given weather situation, forecast horizon and location.

2. IBM - equipment efficiency and health monitoring tool;

IBM developed ML based equipment efficiency and health monitoring tool for preventative and predictive maintenance based on large amounts of data gathered through instrumented assets and advancements in analytics. The ML technique would allow the system to learn from data on its own without on-field examination. This is extremely useful for devices/assets that located remotely or unsafe to reach.

3. DeepMind (a subsidiary of Google) – wind generation (36h ahead) forecast;

A DeepMind system has been configured to predict wind power output 36 hours ahead Using a neural network trained on widely available weather forecasts and historical turbine data. This is very useful to develop a unit-commitment plan and make optimal hourly delivery commitments in advance.

4. IFC for CENACE (Centro Nacional de Control de Energía) – cloud effect on solar generation;

IFC for CENACE developed an AI algorithm to model the effect of cloud coverage on solar generation to accurately predict solar generation and help balance the grid with batteries, which assists with reacting to variances and providing primary regulation support in real-time.

5. Florida - Restoration support and critical load prioritization
6. Siemens: Siemens has released a software package to operate grids autonomously known as Active Network Management (ANM). ANM tracks how a grid interacts with different loads of energy and tweaks its adjustable parts to increase efficiency. While this was previously carried out with manual adjustments, ANM adjusts grids responsively when new energy producers become available, like a solar park, or when new energy consumers come online. This ANM can play an important role in future renewable integration effort.
7. In September 2017, the DOE granted a research award to SLAC National Accelerator Laboratory researchers at Stanford University to use AI to improve grid stability. By programming it with past data on power fluctuations and weak spots on the grid, the new “autonomous grid” will identify and strength those spots, absorb the fluctuation brought by solar energy, and be able to respond to major events on its own.
8. INL+Teness: The purpose of this project is to integrate into a single system a variety of AI based systems (ES, neural networks, fuzzy systems, and GA) that can provide plant specific information to the plant operators in an intelligent, simple, understandable and non-intrusive manner regarding the status of the nuclear power plant.
9. Argonne National Laboratory a research team has developed a novel approach to help system operators understand how to better control power systems with the help of AI. Their new approach could help operators control power systems in a more effective way, which

could enhance the resilience of America’s power grid, according to a recent article in IEEE Transactions on Power Systems.

10. PNNL has ongoing research in power system operation and control. For example, one project team specifically focus on big data analytics for cascading analysis, prevention and restoration and developed an AI-based contingency analysis tool (ACAT) to aid operators identify suitable corrective actions, while another team aims to develop a robust artificial-intelligence-based online controller parameter optimization and adaption framework for enhancing the resilience of power grids with increasing uncertainties and dynamics. Moreover, a ML framework has been added to PNNL’s in-house Dynamic Contingency Analysis Tool (DCAT) to enhance analytics of large volumes of results and direct the selection of scenarios and support power system engineers to perform numerous planning studies. Last but not least, PNNL researchers developed a Transformative Remedial Action Scheme Tool (TRAST) for adaptive RAS control parameter setting, and also haven been developing high-performance adaptive deep-reinforcement-learning (DRL)-based real-time emergency control (HADREC) to enhance power grid resilience against large contingencies or extreme events in stochastic environments.

Finally, we can conclude that AI/ML based applications cannot replace existing real-time applications, however they can help in analyzing the power system in real-time, crunching large amount of data, and enhancing the decision-making processes in control rooms, providing assistance to operators. A human-factor study is recommended before deploying AI/ML tools in a control room.

The opportunities of AI/ML applications in control room are listed below:

- Analyze historical data helping to enhance operator experience, such as the AI-assisted power system model conversion between node-breaker model and bus-branch model developed in the North American Energy Resilience Model (NAERM) project
- Analyze current operating conditions and provide diagnosis of the system state pointing at the weakest point of the system, such as PMU-based grid event detection and prediction
- Analyze output of real-time applications and eliminate false threats based on system operating conditions and historical data, such as intelligent alarming system
- Analyze future expecting conditions using load forecast, renewable energy forecast, unit commitment data, schedules, outages and provide diagnosis of the system for anticipating system conditions, such as afore-mentioned correlation of applications
- Analyze results of performed system studies that are used in preparation for real-time operations, such as the afore-mentioned validation of switching programs
- Provide virtual AI assistants for preventive control, and mitigation plans based on system conditions, system studies, operator procedures and real-time application results, such as the ongoing ARPA-E funded HADREC project and the afore-mentioned ACAT work.
- Recommend the control or operation tasks to suitable operators based on the task impact, priorities and operator experience, etc.
- Provide a personalized perspective of the system or user interface to reduce cognitive load and improve decision making.

7.2 Appendix 2. A more detailed look at a system reconfiguration option

When an operational scenario occurs where System Operations staff must act to mitigate or prevent unacceptable system performance, there are three primary actions that can be taken:

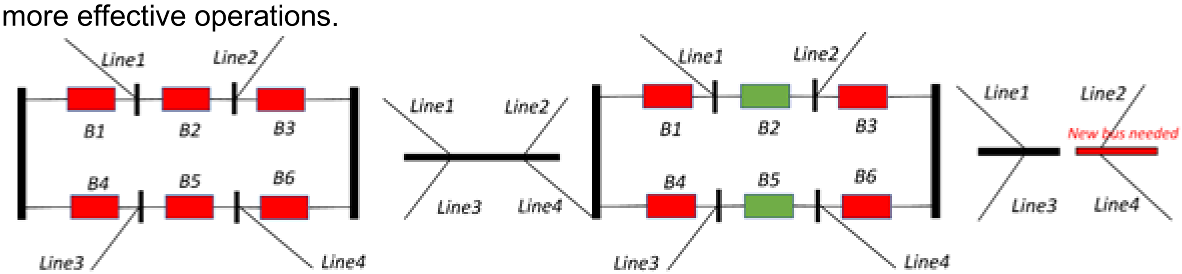
- redispatch generation
- reconfigure system topology, and/or
- adjust load.

Reconfiguring system topology by changing the status of substation and field devices is often underutilized due to the fact that the traditional toolset used by System Operations staff doesn’t typically include an application that analyzes how the power system can be reconfigured to mitigate certain conditions.

Algorithms and tools should be developed to analyze how equipment can be reconfigured to achieve defined objectives, which may include, but are not limited to:

- re-posturing the system to improve post-Contingency performance
- mitigating an actual or potential exceedance of an operating limit or parameter
- minimizing the risk of electrical contact for personnel performing work
- reducing the customer minutes of interruption associated with planned/forced outages
- maximizing the effectiveness of reactive devices to support local/wide area voltage.

The figure below shows how opening of breaker can split a simple substation (one bus) into two buses. There are many large substations that can be reconfigured in many different ways for more effective operations.



A real-world example is when a busbar coupler in Europe split a substation into two separate parts (two buses). As the system configuration changed, powerflow on the lines changed, overloading multiple lines. Consequently, cascading failures resulted, and the system separated into two islands within 20 seconds. This was a known N-1 Contingency but as a node-breaker model was not used for system studies, such contingencies are neglected. Multiple substations can be reconfigured to more readily mitigate risks like this, however, if node-breaker models are not used, the system study engineers do not analyze the possibility of substation reconfiguration. Consequently, there is no planning for how the system can be reconfigured.

7.3 Appendix 3. Power System Studies

Power system studies include seasonal studies, outage studies, week-ahead studies, next-day studies, look-ahead studies, and real-time studies, and these occur at different timelines leading up to real time operations. The main objective of performing studies in the Operations Horizon (i.e., seasonal and outage planning sub-horizons) is to ensure system operators are prepared for real-time operation and to establish SOLs. When studies are first performed in the Operations Horizon, there are a lot of unknown variables such as weather forecast data, emergency and forced outages, and many unforeseen circumstances. The Operations Horizon is typically defined as a rolling 12-month period starting at real-time (now) through the last hour of the twelfth month into the future. The figure below illustrates the timelines for the studies.

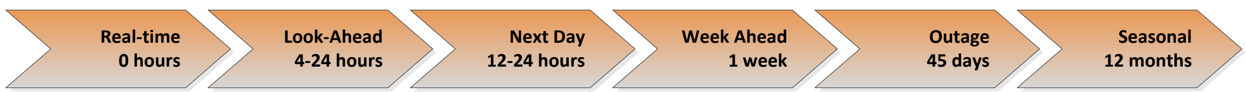


Figure 6-1 Operations Horizon Timeline for Power System Studies

Typically, operational studies start with seasonal studies that are performed up to a year in advance. These studies are followed by outage studies that must be performed up to 45 days in advance. As the timeframe to real-time approaches, there are less unknowns and higher confidence. Scheduled outages are coordinated within the TOPs, with the RC, and, if needed, SOLs are derated and mitigation plans are developed. The representation of the expected real-time system improves while approaching real-time operations and the studies become more realistic. Next-day studies are performed for a day ahead and look ahead studies are performed up to 24 hours ahead. Finally, near real-time and real-time studies are performed in the near real-time timeframe, with forecast data ideally becoming more accurate, resulting in more realistic studies.

The type of studies and how often they are conducted must fit within the requirements as defined by NERC standards. While NERC does not specify what real-time studies need to be performed, NERC does specify that Real-Time Assessments (RTA) must be performed at least once every 30 minutes (see NERC standards TOP-001-5 R13 and IRO-008-2 R4, where the TOP standard sets the requirement for TOPs and the IRO standard sets the requirement for RCs).

Typical near-real time and real-time studies include power-flow, voltage stability (margin to voltage collapse), and transient stability studies, all for N-1 and credible N-2 Contingencies.

SOLs are established by TOPs, not by RCs. The RC performs different types of studies in Operation Horizon making sure that pre-established limits are not violated in operation preparation due to planned outages, unplanned outages or during real-time operation. At the same time, real-voltage stability and transient stability applications are used to assure sufficient margin to voltage collapse or instability is achieved in real-time operations.

Operators are required to keep system within SOLs/IROLs. SOLs are established to achieve acceptable system performance. The BES is expected to be operated so that acceptable system performance is achieved in both the pre- and post-Contingency states (N, N-1, N-1-1, credible N-2). Pre-Contingency acceptable system performance requires that the BES demonstrates transient, dynamic and voltage stability, and that all facilities remain within their normal facility ratings and within System Voltage Limits.

Post-Contingency acceptable system performance requires that BES demonstrates transient, dynamic and voltage stability, that all facilities are within their emergency facility ratings, that all facilities are within their emergency System Voltage Limits and that there is no cascading or uncontrolled separation.

SOLs/IROLs are entered into the SCADA and other real-time applications and monitored against violations. If some of the limits are violated alarms (sound and visual) are sent to operator. All alarms are available at the same place (EMS). Each alarm has its own message stating what limit has been violated.

The main objective of performing studies in the Operations Horizon is to:

- Ensure existing operational or mitigation plans are valid
- Assess whether added outages (planned and/or forced) conflict with the previously studied topology
- Review and refine previously established generation requirements
- Determine whether changes in the load forecast result in newly identified reliability issues

Ideally, operational or mitigation plans needed to ensure acceptable system performance will be established prior to the Near-term Study phase; however, new operational or mitigation plans can also be developed in the Near-term Study phase or in real-time. Those new plans would typically be driven by a late change in forecast data or unpredicted circumstances such as forced outages or faults. Operation plans are stored in form of precoders or operating bulletins in paper and electronic format. System studies create operational framework. This framework can be seen as multidimensional space consisting of pre-determined system limits operators are constrained to operate within. The volume of the space can change in real time due to new unpredicted circumstances. Operators are continuously trained, and they are expected to know when and how to apply specific procedure. However, in real life it is more complicated due to unforeseen situations, loss of tool, interaction among operators or cognitive overload. In that context, real-time operation tools may be very helpful. However, real-time operation tools must be accurate and robust at the same time, though sometimes one conflicts with another.

7.4 Appendix 4. Additional Thoughts on the Introduction of Advanced Technologies into Real-Time Operations

There are many reasons why some of the most advanced tools are not used in controls rooms to inform the operational decision-making process, such as:

- In order to deploy a specific tool in the control room, it has to address a real, existing or future problem. System Operations staff have many displays and tools they have to pay attention to, so adding a new tool and/or multiple new additional displays can add significantly to their cognitive efforts and result in cognitive overload. During system emergencies, operators must swiftly analyze multiple situations and communicate with their peers and external entities in a timely manner.
- Apart from addressing real, existing problems, a new tool needs to be accurate. Typically, it can take many years to deploy a new tool into the control room, first for testing and, after extensive testing, in production for operator use. Inaccuracy of deployed tools can manifest in two ways:
  - Generation of false alarms that are an annoyance. In this is the case, the operator may turn the tool off and ignore the alarms. An Example is a contingency alarm in RTCA that proves to be false, which may result in the operator disabling the contingency in the tool.
  - Even worse, after gaining trust, erroneous results may lead to unnecessary action that proves costly.
- When a tool is deployed into the control room and its outputs are used to inform RTAs, then it becomes subject to NERC compliance obligations and part of Critical Infrastructure. If the tool becomes non-operational longer than 30 minutes, TOP may need to self-report to NERC. Real-time decision-making grade tool requires 24/7 support meaning additional personal and additional training would be needed. There are NERC Critical Infrastructure Protection (CIP) requirements that must be fulfilled.
  - SE and downstream application based on SE snapshots, such as RTCA, Real-time Voltage Stability and Real–time Transient Stability are model based. They require a large maintenance efforts and expertise. While it might not be difficult to maintain internal model, the problem becomes significant for maintenance of external models. Traditionally real-time operation applications such as the SE and RTCA use different network models than power system study engineers who are responsible for operation and planning studies (evaluation of SOLs). Models used in real-time are node-breaker models having analog measurements and breaker statuses mapped to the model allowing the model to follow power system operating conditions in real time. Models used for operation and planning studies are bus-branch models (basecase) that need to be adjusted to represent desired system study conditions. Since the two models have evolved separately, there are differences between them. Postmortem analysis of the Arizona-Southern California outage in 2011 has indicated that these differences can lead to conflicting results. The main difference between those two above-mentioned models are:
  - Node-breaker model contains switching devices while basecase does not.
  - Basecase is approved by regional entities to use for system studies so all system studies are performed using basecase
  - Node-breaker model is developed by individual TOPs and is used in real-time operation only

- As node-breaker model is developed by individual TOPs independently, this model contains different levels of details and different level of the accuracy
- Basecase (bus-branch) model represents overall interconnection while node-breaker model used in real-time might not represent overall interconnection.

Consequently, system limits that are set based on system studies using basecase but evaluation of violation against these limits in real-time operation applications are based on SE model that is different. SE also introduces mismatches into the system. Mismatches are inserted as positive and negative loads all around the system where loads do not exist. While individual mismatches are relatively small, they add up and can influence SE solution significantly.

Finally, the more applications used, the more notifications and alarms need to be processed resulting in increased cognitive load. In other words, in order to deploy a single application in control room and use it for decision making, the system operators must be sure that the application will perform accurately and provide sufficient benefits.

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