# Naturalistic Decision Making for Power System Operators

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## ABSTRACT

**Motivation** – Investigations of large-scale outages in the North American interconnected electric system often attribute the causes to three T's: Trees, Training and Tools. To document and understand the mental processes used by expert operators when making critical decisions, a naturalistic decision making (NDM) model was developed. Transcripts of conversations were analyzed to reveal and assess NDM-based performance criteria. **Findings/Design** – An item analysis indicated that the operators' Situation Awareness Levels, mental models, and mental simulations can be mapped at different points in the training scenario. This may identify improved training methods or analytical/ visualization tools. **Originality/Value** – This study applies for the first time, the concepts of Recognition Primed Decision Making, Situation Awareness Levels and Cognitive Task Analysis to training of electric power system operators. **Take away message** – The NDM approach provides a viable framework for systematic training management to accelerate learning in simulator-based training scenarios for power system operators and teams.

### Keywords

*power system operators, naturalistic decision making*

## INTRODUCTION

Despite advances in technology, power system operators must assimilate overwhelming amounts of data to keep the electric utility grid operating. Analyses of recent blackouts have demonstrated the need to enhance the operator's ability to understand the state of the system and anticipate possible problems. With increasing complexity and interconnectivity of the grid, the scope and complexity of power grid operations continues to grow. To confront this escalation of complexity, new paradigms are needed to guide research, tool development, and training to enhance and improve operations. This study applied current models and theories of decision making and situation awareness (SA) from a power grid perspective and offers a more detailed framework than current decision models, based on this theoretical perspective, to guide development of tools and training approaches to increase grid operator SA and enhance operational performance.

## BACKGROUND

The North American electricity system is one of the great engineering achievements of the past 100 years. This electricity infrastructure represents more than $1 trillion (U.S.) in asset value, more than 200,000 miles—or 320,000 kilometers (km) of transmission lines operating at 230,000 volts and greater, 950,000 megawatts of generating capability, and nearly 3,500 utility organizations serving well over 100 million customers and 283 million people (U.S.-Canada Power System Outage Task Force, 2004). Customers have grown to expect that electricity will almost always be available when needed at the flick of a switch. Most customers have also experienced local outages caused by a car hitting a power pole, a construction crew accidentally damaging a cable, or a lightning storm. What is not expected is the occurrence of a massive outage on a calm, warm day. Widespread electrical outages, such as the one that occurred on August 14, 2003, are rare, but they can happen if multiple reliability safeguards break down.

Providing reliable electricity is an enormously complex technical challenge, even on the most routine of days. It involves real-time assessment, control and coordination of electricity production at thousands of generators, moving electricity across an interconnected network of transmission lines, and ultimately delivering the electricity to millions of customers by means of a distribution network. To meet the demands and expectations of this industry, effective training and maintenance of a high level of mastery are required of the system operators and decision makers.

Prior to the black out of August 14, 2003, only a small fraction of power system operators had ever trained with realistic operator training simulators. Following the blackout, the North American Electric Reliability Council (NERC) Emergency Operations Recommendation No. 6 required that: "All reliability coordinators, control areas, and transmission operators shall provide at least five days per year of training and drills in emergencies, *using realistic simulations*, for each staff person with responsibility for the real-time operation or reliability monitoring of the bulk electric system. This system emergency training is in addition to other training requirements."

Because of the importance of keeping the electric grid running reliably at all times, simulation is the best, and perhaps the only learning approach (Aldrich, 2004). The simulated environment is risk-free, enabling learners to integrate theory and practice without fear of causing system reliability issues. From a cognitive learning point of view, simulation provides a unique modality and environment for experiential learning in an active and immersive learning environment (Kolb, 1984, p. 236). To provide effective training that develops and maintains competencies, a systematic approach is needed to take account of the mental processes that come into play when making critical decisions. We have applied and performed some preliminary tests on a naturalistic decision making model that draws upon recognition primed decision making, and cognitive task analysis to yield a framework to more efficiently train power system operators.

## A INTEGRATED DECISION MODEL

An integrated model of NDM incorporates concepts of situation awareness (Endsley, 1997), recognition-primed decision making (RPD) (Klein, 1993), metacognition (Cohen, Freeman & Thompson, 1997), and considerations about levels of expertise. Levels of expertise refer to distinctions between skill-based, rule-based, and knowledge-based behavior—reflecting the fact that decision makers perform at different levels of expertise (Hammond, Hamm, Grassia & Pearson, 1987; Rasmussen, 1993). People who are highly experienced with a task tend to process information at the skill-based level, reacting to the raw perceptual elements at an automatic, subconscious level; without the need to interpret and integrate cues or consider possible alternate actions, but instead responding to cues and patterns that are already associated with actions. If the decision maker is familiar with the task but lacks extensive experience, he or she must process input and perform at the rule-based level. Rules are if-then "recipes" for action that are associated with cues and patterns (or they may be available as written procedures that a less experienced decision maker can follow at the rule-based level of processing). In novel situations where there are no stored rules based on previous experience, even expert decision makers operate at the knowledge-based level that comprises analytical processing. Effective decision making utilizes all three levels of processing. The goal of training for critical decision making is to provide the learner with experiences and instruction on cues, patterns, mental models, and actions that effectively establish a repertoire of well-learned concepts that enable the operator to perform predominantly at the skill-based level of processing, while providing a sufficient knowledge-based foundation to perform well in novel situations.

Figure 1 is a depiction of an integrated NDM model that we purport will be useful in training of power grid operational decision making. It can be seen that this is strongly influenced by insights of Weick (1995) on sensemaking concepts that have been applied to power grid operations (Greitzer, Schur, Paget, & Guttromson, 2008), and largely based on the RPD model; it incorporates the metacognitive/critique portion of the R/M model by invoking additional mental models and mental simulations in the pattern recognition process. Here the initial processing of cues and patterns may be modulated by a critiquing process (using mental models and simulations) that occurs early in the recognition-primed process of situation assessment. Additional mental simulation processes occur following selection of a course of action (action script), as the decision maker examines or tests whether the proposed response action work as anticipated. The main advantage of this characterization is that it acknowledges the role of mental models in the situation awareness component of decision making as well as in response selection.

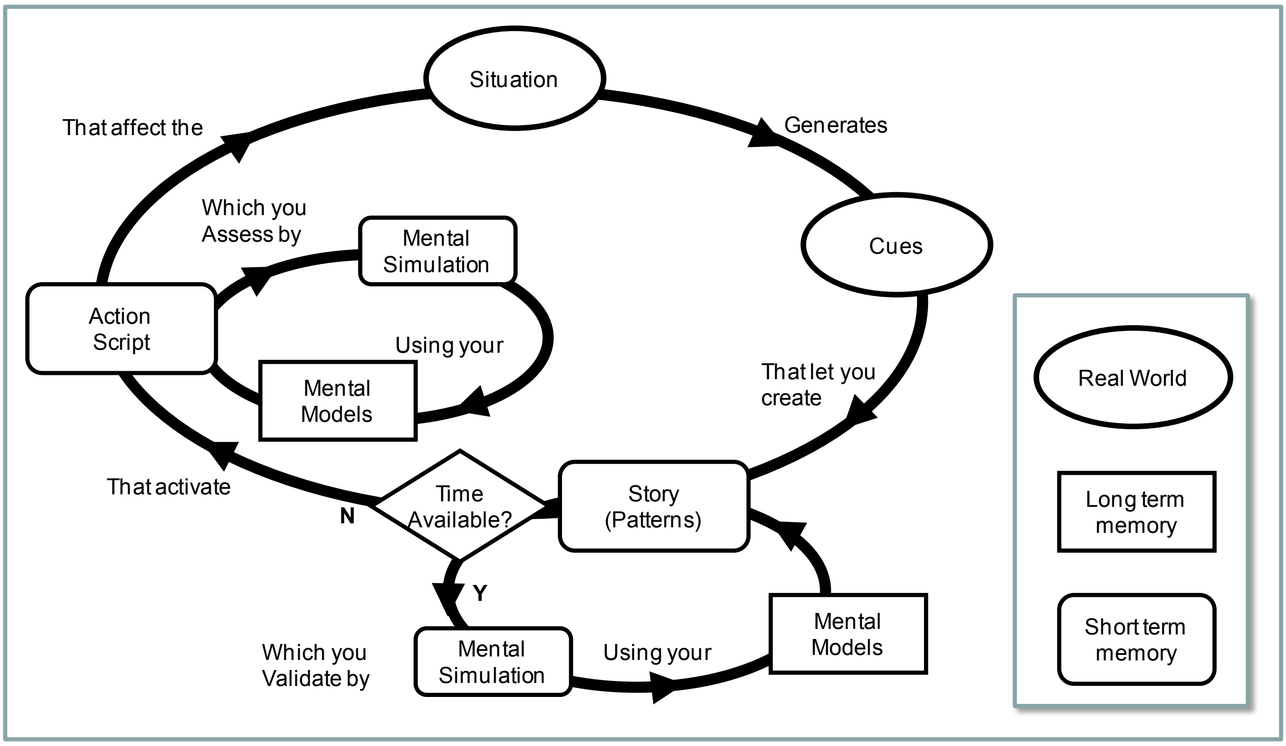


**Figure 1. Integrated Naturalistic Decision Making Model.**

The shape-coding in Figure 1 is meant to suggest the primary locus and role of each of the processes in the human information processing system. The ellipses represent the external real world environment. The cues are part of the real world. They are also the boundary between the real world and the system operator. The rectangles with rounded corners represents deliberate controlled processes carried out in working memory (WM)—these may reflect rule-based activity or analytical/knowledge-based activity depending on the decision maker's experience with the situation. The pure rectangles depict mental models that are retrieved from long-term memory (LTM). The metacognitive R/M Time Available or Quick Test is accommodated in the first mental simulation loop. The second mental simulation loop reflects the need for the system operator to assess and anticipate the impacts of their control actions.

## RECOGNITION PRIMED DECISIONS FOR POWER SYSTEM OPERATORS

### Situation

The situation or state of the system will vary based upon a number of factors including, time of day, current and forecasted system load and weather conditions for local and interconnected areas, current and forecasted generation and transmission maintenance outages for local and interconnected areas, current and forecasted interchange levels and flow patterns.

### Cues

The situation or state of the system is presented to the system operator from a variety of sources including: measurements from the system and data links, communications with personnel within and outside of the control room, reports on results of on-line analysis programs, results from operation planning studies and planning engineers. The electric power grid control system contains cues on numerous displays including system summary displays, alarm logs, abnormal summaries, charts, map boards and system overview displays that reflect thousands of variables. The saying "too much data and not enough information" is often used to describe the user interface problem.

An experienced operator will be more sensitive to and will have a greater appreciation for various explicit and sometimes subtle inputs than a novice operator. The more experienced operators can extract and focus on the key variables that summarize the overall situation.

### Mental Models

An expert power system operator has thousands of relevant mental models in LTM. Mental models range along a continuum from simple to complex. They are required for but not limited to:

- Physical, mechanical and electrical characterizations of different system components and how they work together

- The abilities, sensibilities, limitations and motivations of the system operator's extended team.
- Operating procedures and policies

The mental models are used to validate that a complete and consistent Story has been built to explain the current situation. They are also used to anticipate the effects of candidate control actions.

#### Story

Using the cues to build a Story is a critical step in the decision making process. By using the mental models and the mental simulations to build a complete and consistent story the operators increase their SA. The building of the Story corresponds to increasing the operator's level of SA from Level 1 through Level 3 (Endsley, 1997):

- Level 1: perceiving critical factors in the environment.
- Level 2: understanding what those factors mean, particularly when integrated together in relation to the person's goals.
- Level 3: understanding what will happen in the near future.

The more experienced operators are able to monitor a wider range of cues and are able to build a more complete and consistent Story compared to less experienced operators. Experienced decision makers work with evolving situation models or stories. They assimilate new cues with these models as a reference, while at the same time looking for gaps and conflicts while being prepared for surprises. When an unexpected or conflicting event occurs, they elaborate the story to take it into account. They maintain an awareness of their elaborative efforts and stay alert to the danger of going too far (Cohen, 1997).

#### Action Scripts

Based upon the development of a complete and consistent story concerning the current situation, the experienced operator will develop an action script to correct the existing situation and any anticipated contingencies. Regulatory requirements state that these corrective actions should be implemented as quickly as possible without regard to the economic cost. For example, if there are lines or transformers that are exceeding their Short Term Emergency Ratings or buses that are exceeding their voltage limits, the System Operator has the authority and responsibility to implement the necessary remedial actions, including shedding load, to alleviate these overloads and violations.

#### Mental Simulations

The experienced system operator performs a mental simulation by first retrieving relevant mental models from LTM. The operator then runs a mental simulation using these mental models and checks to see if there is consistency with the cues that are being observed. Sometimes these mental models need to be triggered to be activated and retrieved from LTM. There is sometimes difficulty in connecting mental models together to see what in retrospect is an obvious consequence.

While processing the cues, the operator runs consistency checks.[1] "*Are the MVARs flowing downhill on voltage? Is the total MW into the bus equal to the total MW out of the bus? Is the line loaded above or below the surge impedance loading level? Are the MVARs for the open ended line flowing into the bus?*"

The operator uses mental models to test the impact of candidate corrective actions. For example, *adding capacitance will increase local bus voltages*; *a line will be unloaded by decreasing generation at the sending end and increasing generation at the receiving end*. However, estimating the quantitative effects of control actions when the system is an unusual operating condition can be very difficult. A simulation or contingency analysis tool may be able supplement the mental models of the operators. However, in many cases even if they are available, there may not be sufficient time to use these tools. Experienced operators know the art of controlling the system a little at a time, monitoring the changes and then deciding on a more definitive action. Training simulations can increase the depth of an operator's understanding of mental models that increase SA by facilitating understanding of why certain outcomes are expected or by identifying exceptions.

### EXAMPLE OF A CONCRETE PROBLEM

The abstract concepts of NDM are best tested and extended when they are applied to real-world problems. A useful example is a system restoration problem following a blackout in which disconnected "islands" must be reconnected to

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[1] In the following, MW (megawatts) refers to actual power output of a power generation station or system and MVAR (megavars) refers to reactive power. Power grid dispatchers work to maintain a certain level of MW output for the system. Reactive power, the result of the magnetic coupling needed to produce work with a machine, is used to maintain and control the voltages on the system.

the entire network. An illustrative problem is shown in Figure 2. Three power system operators are responsible for different sections of the power system:

- The West Operator monitors and controls the west system, which includes the Homer Substation.
- The East Operator monitors and controls the East System, which includes the Locher generating substation.
- The Central operator monitors and controls the Central system, which includes the Moses substation.
- The Reliability Coordinator oversees the West, East and Central Systems.

As the scenario begins several days into the blackout restoration, the operators need to connect the West system, operating as a separate electrical island, to the Central system. The voltages at the Homer station are high and the voltages at the Moses station are low. The voltages have to be matched more closely before the Breakers 8 and 9 at Moses can be closed to tie the West and the Central system together, thus connecting the island to the system. The challenge for the operators is to assimilate the data and match voltages so the connection can be made safely.

## TEST METHODOLOGY

To assess the efficacy of applying the NDM framework to power grid decision making and training, we formulated the following research hypothesis: Initial processing of cues and patterns may be modulated by a critiquing process (using mental models and simulations) that occurs early in the recognition-primed process of situation assessment. Additional mental simulation processes occur following selection of a course of action (action script), as the decision maker examines or tests whether the proposed response action work as anticipated. These processes may be inferred from control actions and captured conversations. The method used to examine these transactions is object/action analysis, described below.

### Qualitative Testing: Object and Action / Object Analysis

Object-oriented modeling methods may be used to analyze the script of operator conversations. Object-oriented models

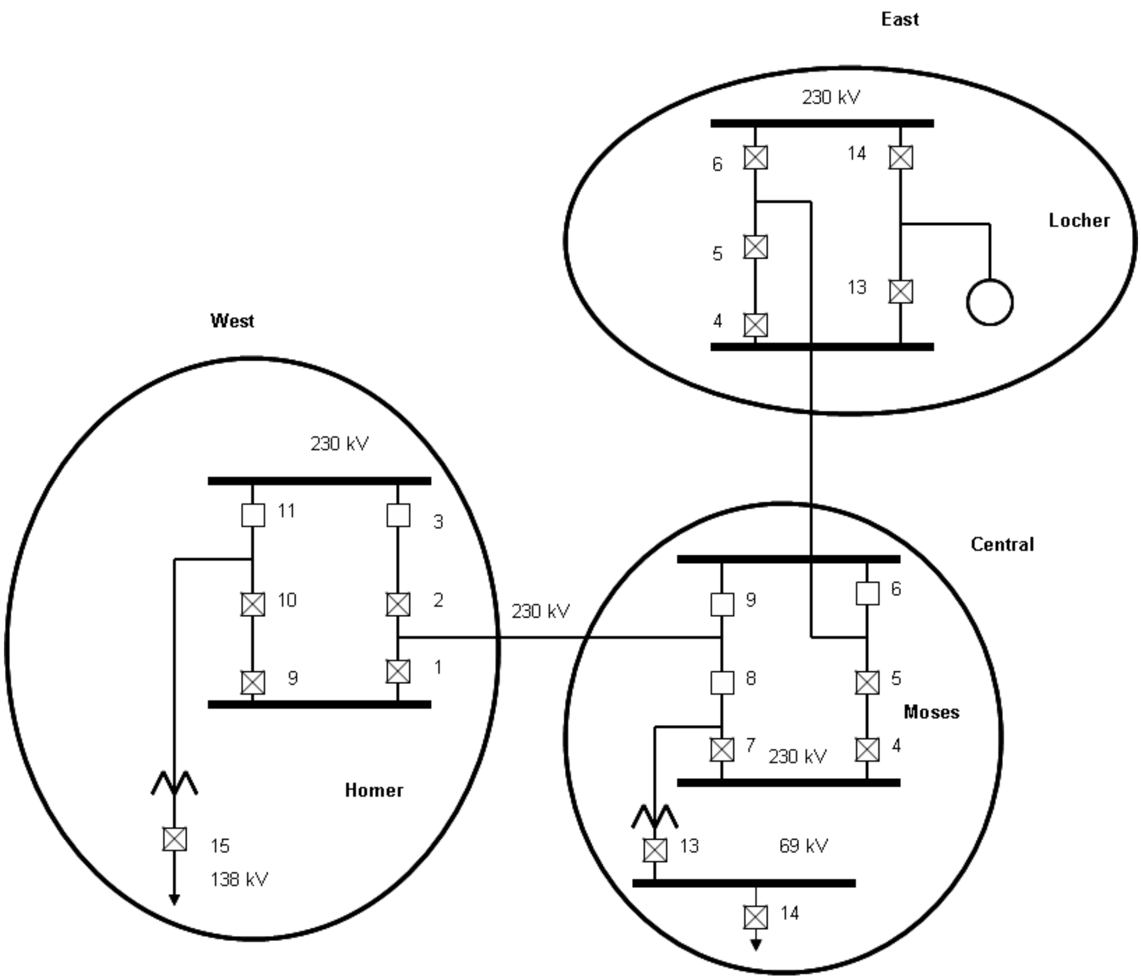


**Figure 2. A Real World Problem**

are useful to understand problems, communicate with application experts and model enterprises (Rumbaugh, 2001). A script developed by subject matter experts (SMEs) in the electric utility industry was used. At the most basic level, the following analyses have been developed:

The Object and Action / Object analysis is performed as follows:

- Object Analysis – derived by listing all the nouns in the conversations
- Action / Object Analysis – derived by listing all the verb and noun combinations in the conversations.

These analyses can all be performed rather mechanically by processing the script of operator communications when this is available. They can also be performed without a written script. One can listen to the operator communications and note the new objects, the new action / object combinations as the scenario evolves.

The method thus begins with a qualitative component grounded in generative theory (e.g., Bryman & Burgess, 1999; Drasgow & Schmitt, 2002) of openness to the way in which stories, patterns, cues, and decision making are observed by experts as it unfolds and is illuminated through cognitive task analysis. Consistent with scientific theory modeling, rather than manipulation of variables, the goal is to understand decision making in its real-world setting, resulting in the construction of an environment, or model (Moorthy, 1993). The underlying rationale of the nomothetic view is to suggest that the model reflects a cohort of individual thought processes. The prefix "semi" is used to indicate that not everyone will process decisions in precisely the same way.

### COGNITIVE TASK ANALYSIS (CTA)

Cognitive task analysis has evolved as a number of methods to describe cognitive processes underlying performance as well as patterns of reasoning, problem solving, decision making, collaboration and domain expertise and skill (Hoffman & Militello, 2008, p. 5). CTA is challenging because experts have large bodies of knowledge accumulated through experience; their perceptual and cognitive skills are hard to verbalize, especially without performing the task in a realistic environment (Gordon and Gill, 1997).

The use of a high fidelity Electric Utility Grid Simulator effectively overcomes the major challenges of CTA for the following reasons:

- A realistic environment can be created using simulation. The thoughts and reactions of operators under these conditions have face validity.
- By having multiple role players and scenarios that force interaction between the roles, operators are motivated to explain thought processes to each other. The process that Klein (1993) calls Knowledge Elicitation or extracting information through observations, about cognitive events, structures, or models is therefore maximized.

The manner in which the NDM processes have been integrated and applied to perform the CTA is shown in Figure 3. In this NDM Framework, experts can perform a wide variety of normal, emergency and system restoration tasks under simulated conditions. Tasks are performed under very realistic conditions. To truly capture expertise, the framework should cover near misses and difficult or unusual cases.

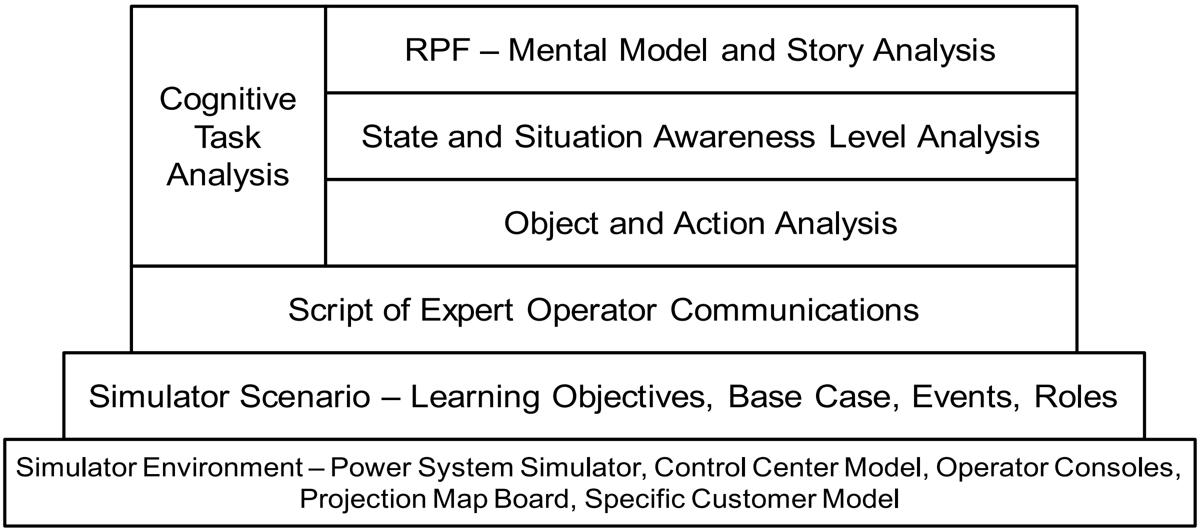


**Figure 3. NDM Framework**

### State and Situation Awareness (SA) Level Analysis

The SA Level Analysis is performed by listing in a separate column, all the observations or questions about the system state. No elaboration is required. The entries for the SA Level Analysis are color-coded to indicate the SA Level for the operator that is speaking (Endsley, 1997):

- Orange/Level 1: perceiving critical factors in the environment.
- Blue/Level 2: understanding what those factors mean, particularly when integrated together in relation to the person's goals.
- Green/Level 3: understanding what will happen in the near future.

As the scenario unfolds the color codes progress from Orange to Blue to Green as we would expect. Preliminary testing on the color coding of items suggest the quality of communication and shared SA among the operators. In the scenario analyzed with four operators, the communications were distinct.

### Mental Model and Story Analysis

A working assumption of the theoretical proposition put forth in this paper is that a competent system operator should have a basic mental model of all the objects and action / object combinations that are used in the expert operator conversations. The analysis of our illustrative scenario identified 72 objects and 55 action / object combinations. Examples of objects were faulty breaker position indicator, frequency specification, generator, generator MVAR output, independent islands, indications of line flows, line breaker, line capacitance, line crews.

Examples of action / object combinations included interconnect west and central areas, interfere with restoration efforts, isolate line, lower system voltage, make a note in system, synchronize islands, transfer line capacitance from your system to our system, try to synchronize across breaker, update status boards.

In the first scenario analyzed, a critical mental model of transmission line acting as a capacitor was not mentioned by the participants until Step 82 in the scenario. After this mental model was mentioned, it was accepted and used by all the operators. An effective solution was then quickly developed and agreed upon, specifically:

- Step 86: Central Operator to RC Operator: "We have a plan that should reduce the voltage mismatch across the 230kV Moses to Homer line and allow us to interconnect West and Central service areas. We propose to transfer the line capacitance of the 230kV Homer - Moses line from West to Central."
- Step 87: Central Operator to RC Operator: "West will open the 230 kV Homer breakers 1 and 2. Central will close the 230kV Moses breaker 8. This should lower the voltage at Homer and raise the voltage at Moses. If all goes according to plan, we can then interconnect on the 230 kV system, using the Homer breaker 1."

The most essential element of this scenario can be found in the Action / Object combination: "transfer the line capacitance of the 230kV Homer - Moses line from West to Central." This key mental model did not seem to be in working memory of any operators until well into the scenario.

**Summary of the Cognitive Task Analysis**

The Cognitive Task Analysis is a useful tool for explaining the thought processes of the system operators at all the steps in the scenario. The results from the scenario analysis can be summarized as follows:

- When expert power systems operators participate in a team based simulator scenario that requires them to coordinate operations, their thought processes can be captured in their conversations with instructions that direct them to say what they are thinking.
- The script of operator conversations can be analyzed with an Object and Action / Object Analysis to determine the mental models used by the operators.
- The script of operator conversations can be analyzed to extract comments on the system state. These comments can be used to rank the Situation Awareness Levels of each participant at each step of the scenario using the three levels defined by Endsley (1997).
- The analysis of the SA Levels seems to demonstrate the effectiveness of the operator communications.
- The mental model(s) that are crucial to solving the particular operating problem are identified along with the time when the operators retrieve this model from long term memory when the thoughts of the operators are verbalized. They may also be inferred from control actions, given sufficiently specified mental models.

**APPLICATION TO POWER GRID CRITICAL DECISION TRAINING**

The results of this cognitive task analysis test case have potential implications for training. The training development/training management process is depicted in Figure 4. The process is continually and dynamically updated, but may begin with selection of a problem domain from a list of operational issues and training requirements that must be addressed. Traditionally, power system operator learning objectives are specified only at a general level, such as "the operator will demonstrate skills in interpersonal communication protocols in multi-balancing authority coordinated operations." Based on the selected problem area and learning objectives, a training scenario is developed that includes problems that exercise the desired skills. In contrast, when informed by the more specific and rigorous concepts and performance criteria available in cognitive task analysis and naturalistic decision making approaches, a detailed training plan may be developed based on the operator's demonstration of understanding (or lack of understanding) of requisite cues, patterns, mental models, action scripts, etc. That is, instead of reacting to relatively gross behavior or outcomes, the trainer has specific guidelines or behavioral/performance indicators that identify possible deficiencies. With this information, the trainer may choose to interrupt the exercise immediately to discuss problems, or note performance gaps and review the incorrect or missing concepts in an after-action debriefing. In this way, we believe that training will progress more efficiently, and with an enhanced ability to identify deficiencies and enable greater transfer of training.

Since the RPD model was introduced to the power industry following the blackout of 2003, training has been structured so that there is a strong linkage between the classroom content and the simulator based exercises. This includes explicit training about cues, patterns, and mental models that are critical to perform various operating tasks. For example, currently, over 2000 system operators are trained each year using the PowerSimulator (Podmore, Robinson, Sadinsky & Sease, 2008).

Cognitive debriefing resulting from simulation training is critical to capturing the knowledge and expertise of particularly the expert participants. In the simulation environment, very little explicit knowledge is captured (Nonaka,

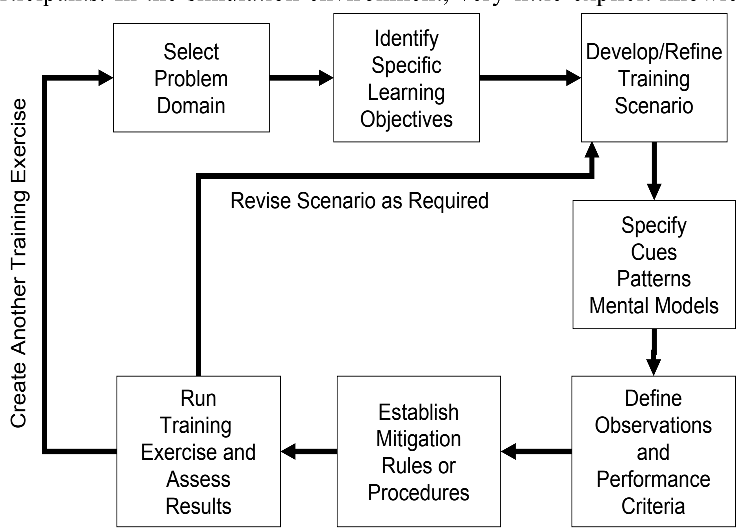


**Figure 4: General Training Development/Management Process**

1987). In the medical field, which also heavily uses simulation training, the literature points to *Cognitive dispositions to respond* (CDR) as patterns of thought that may lead to suboptimal decisions. These patterns have three components: heuristics, affective and emotional (Bond, Deitrick, Barr, Kane, Worrilow, Arnold & Croskerry, 2006). A debrief to identify these patterns as well as styles of thinking such as "thinking in silos," a vertical line failure, are essential in reducing decision errors.

The NDM analysis of critical control actions and recorded/transcribed conversations will allow the instructor to conduct a detailed analysis of the training sessions, provided the conversations include "thinking out loud." From this analysis additional scenarios and training curricula can be developed with increasingly more precision to minimize cognitive errors and biases. Thus, the methodology described here significantly strengthens and informs the feedback loop in Figure 4.

## CONCLUSION

This paper has described an integrated decision making model that combines the processes and principles of Recognition Primed Decision Making, Recognition/Meta-Recognition, and Situation Awareness. This integrated model has been initially analyzed along with a Cognitive Task Analysis to develop a more detailed approach to electric power system operator training. The theory and approach described how conversations that occur when expert power systems operators participate in a team-based scenario may be used to inform the analysis and specify critical learning criteria that are tied to a model-based framework for naturalistic decision making. Results are promising and are being applied to develop new training scenarios and to establish a more rigorous environment for testing and evaluating operator decision aids or displays. Among the most significant findings are:

- The enhanced RPD model can capture the thought processes of the system operators at all the steps in the scenario, given think-aloud protocols or specification of critical control actions
- The Situational Awareness of the system operators can be measured using Endsley's three Levels of SA at each step of the scenario.
- The mental model(s) crucial to solving the particular operating problem may be identified along with the time when the operators either retrieve or fail to retrieve the model from long term memory.
- The mental simulations that the operators deploy using this mental model may be identified.

Our theoretical proposition has produced interesting and promising findings. Simulated learning opportunities that integrated feedback and debriefing have a strong linkage between theory and practice. As a result of this test case, we recommend more rigorous research given our preliminary indicators of the potential to: more precisely measure the cognitive gaps in novice and expert power system operators, accelerate the training programs for new power system operators, and more systematically evaluate the usability of the next generation of tools for enhancing the decision making and training of power system operators.

## ACKNOWLEDGMENTS

The authors wish to thank Ross Guttromson at PNNL, who made it possible for this collaboration through an internally funded PNNL project, Human Factors for Situation Awareness in Power Grid Operations. We acknowledge Doug Harrington for encouraging us to apply the Recognition Primed Decision Model to power grid human factors; and Chuck Johansen, Senior Trainer with SOS Intl, for motivating us to integrate concepts of the R/M Model, and Jeffrey Sill for his contributions to testing and item analysis. We also wish to thank our other respective colleagues at PNNL, Southwest Power Pool, Incremental Systems Corporation, PowerData Corporation and SOS Intl for their support, ideas and discussions. This work was supported by the Pacific Northwest National Laboratory operated for the U.S. Department of Energy by Battelle under Contract DE-AC05-76RL01830. [Information Release No.: PNNL-SA-62694].

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