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Naturalistic Decision Making in Power Grid Operations: Implications for Dispatcher Training and Usability Testing

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Executive Summary

The Blackout of 2003 demonstrated that the North American interconnected electric system is vulnerable to cascading outages and widespread blackouts. Investigations of large-scale outages often attribute the causes to the three T's: Trees, Training, and Tools. The focus of the present study is on improved training approaches to accelerate learning and improved methods for analyzing effectiveness of tools within a high-fidelity power grid simulated environment. A theory-based model has been developed to document and understand the mental processes that an expert power system operator uses when making critical decisions. The theoretical foundation for the method is based on the concepts of situation awareness, the methods of cognitive task analysis, and the naturalistic decision making (NDM) approach of Recognition Primed Decision Making. The method has been systematically explored and refined as part of a capability demonstration of a high-fidelity real-time power system simulator under normal and emergency conditions. To examine NDM processes, we analyzed transcripts of operator-to-operator conversations during the simulated scenario to reveal and assess NDM-based performance criteria. The results of the analysis indicate that the proposed framework can be used constructively to map or assess the Situation Awareness Level of the operators at each point in the scenario. We can also identify the mental models and mental simulations that the operators employ at different points in the scenario. This report documents the method, describes elements of the model, and provides appendices that document the simulation scenario and the associated mental models used by operators in the scenario.

The methodology described and advanced in this report can be used to identify improved training strategies to accelerate learning as well as to structure human factors testing of analytical and visualization tools for power system operators. It is concluded that the NDM approach provides an ideal framework for human factors evaluations of decision aids and for systematic training management of team-based training scenarios using high-fidelity power grid simulators. As a result of this test case, we recommend the following research and applied thrusts to advance human factors theory and practice within the power industry:

1. Continue application of this HF framework and analysis approach to advance and demonstrate the value of the analyses, in conjunction with simulation capabilities of the EIOC, to further the DOE mission in improving and strengthening the electric power utility infrastructure.

2. Continue to advance the HF framework and methodology to provide direct benefits to stakeholders within the electric power grid community, specifically to accelerate training programs for new power system operators and to systematically evaluate the usability of next generation of tools for managing a Smart Grid.

3. Conduct evaluations and enhance the design of Wide Area visualization/decision support tools.

4. Engage directly with utility operators to apply the methodology toward improving their operations, conducting demonstrations and evaluations of advanced training concepts, and providing a testbed and associated HF methods to assess the effectiveness of tools and procedures.

5. Pursue opportunities to exploit the PNNL EIOC for training workshops, based on the framework described in this report, and as a test bed for evaluating new procedures, decision aids, and visualization techniques.

In conclusion, this research demonstrates the capability to meet critical mission objectives of the DOE as well as strengthen the role of PNNL and the EIOC as a resource and test bed for power grid training and visualization analysis.

Acknowledgments

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1 Introduction

Despite advances in technology, power system operators must assimilate overwhelming amounts of data to keep the grid operating. Analyses of recent blackouts have clearly demonstrated the need to enhance the operator's ability to understand the state of the system and anticipate possible problems. Engineers, computer scientists, and human factors (HF) experts have borrowed from other experiences to discover or apply new tools and techniques to transform data into information and facilitate the decision making process of operations personnel. With increasing complexity and interconnectivity of the grid, the scope and complexity of power grid operations continues to grow. To address this escalation of complexity, new paradigms are needed to guide research, tool development, and training to enhance and improve operations. This report applies current models and theories of decision making and situation awareness (SA) from a power grid perspective and offers a more detailed framework, based on this theoretical perspective, to guide development of tools and training approaches to increase grid operator SA and enhance operational performance.

2 Situation Awareness

In a widely accepted definition, situation awareness (SA) is described as the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future (Endsley, 1988; 1995). In this empiricist view of SA, stimuli (information elements) are processed to yield meaning, and a common solution to human information processing limitations is to design methods to facilitate processing of more information through limited processing channels. Naturalistic Decision Making (NDM) is a research domain that takes a slightly different approach to the SA problem, adopting an ecological view where awareness is an intrinsic feature of the functional relationship between the environment and the person (Dekker et al, 2004). While the NDM perspective acknowledges the existence of "elements," its focus is on the role the elements play in constructing a plausible "story" of what is going on, not for building an accurate mental model of an external world. In this sense, the NDM perspective on SA is consistent with current ideas about sensemaking as an active strategy for dealing with a complex world (Weick, 1995), (Klein *et al*, 2006). Thus, in studying SA, in addition to examining the lack of correspondence between actual and experienced worlds, one should examine the decision makers' "unfolding experience of the situation in which they found themselves."

The NDM/sensemaking perspective on SA is distinct from the traditional branch of HF research, which focuses more on ergonomics and the transactional relationship between the human operator and the systems. This transactional relationship is a prime source of complexity in system design that focuses on the form and literal content of isolated transactions (e.g., friendly input/output formats) rather than their function in the larger system (Greitzer *et al.*, 1985). Interaction in this transactional approach is at best only locally optimal and the user is left somehow to configure a host of local transactions to meet the broader system goals.

The conventional SA and NDM/sensemaking perspectives tend to lead us to ask different questions. The traditional information processing/empiricist view of SA compels the investigator to identify what the decision makers failed to notice, what they did not know, or what they should or should not have done (which is in some ways a retrospective analysis). In contrast, the NDM/sensemaking perspective suggests that it is not about providing more information (more data, more elements), but rather about clarifying priorities to help the decision maker understand what matters. Thus, from the point of view of the decision maker in the situation, deficiencies such as failures to notice an element in the environment or perform a critical action may not even exist—they may be artifacts of retrospective hindsight.

Another way of thinking about the differences between the more empirical/information processing and the more ecological NDM/sensemaking perspectives on SA is to consider the way we approach the design of information analysis and decision support systems. In focusing on the information processing issues, we tend to think about design enhancements for human-system "transactions" embodied in features of displays and visualizations that seek to overcome human information processing limitations (attention, perception, memory limits) at the expense of considering deeper (e.g., goal-directed) cognitive processes engaged in sensemaking and critical decision making—transactions between goals, observations, and actions—that might also be implicated in the loss of SA. Consider, for example, the frequently cited human limitation described as Miller's (1956) magical number seven, plus or minus two: Miller's insightful observation that humans have a limited capacity in the number of items or "chunks" of information they can maintain in working memory tends to be interpreted as a hard limitation (information processing bottleneck). This factor is situation-dependent; research has shown that experts have the ability to reduce complex stimuli into coherent chunks so that the 7+2 constraint is rarely a limit on expert performance in natural environments.

Relating to the cognitive and sensemaking underpinnings of SA, it has been suggested that poor SA reflects the lack of a basis for decomposing complex data or information into coherent chunks (Klein, 1993). Thus, we should ask our models of SA to (a) explain how skilled decision makers chunk information so they can navigate smoothly through the problem space; (b) to point out where experts might make poor judgments and interpretations; and (c) to describe how a novice's understanding of a situation would differ from that of an expert. A major feature of a leading NDM model of decision making, Klein's (1993) Recognition-Primed Decision Model (RPDM), specifically calls out some important differences between the expert and non-expert in decision making tasks; namely, that experts tend to "see" solutions early—i.e., they do not engage in formal analyses of alternative options or hypotheses but instead identify a plausible solution and proceed to examine and execute it, while looking for potential inconsistencies that would lead them to reject the solution and find another.

The RPDM has great potential for guiding research in decision making that follows this ecological perspective; still, additional detail and specification of a more normative implementation of the model is needed to support the development of specific/prescriptive techniques to enhance training effectiveness or assess new decision support systems. In the case of user interface design approaches to SA, one goal of a more prescriptive model is to define more explicit connections across levels of abstraction to improve awareness of patterns and relationships (Flach *et al.*, 2004). Such specification of connections among patterns and relationships would also improve the precision of training mitigation options. The main objective of the present research was to develop the additional depth of detail within a NDM/sensemaking approach, embodied within the RPDM framework, to achieve a more systematic and rigorous training management methodology to apply in power grid operations training.

3 Naturalistic Decision Making Models

3.1 Recognition-Primed Decision Model

The RPDM has been successfully applied to training mission critical teams in a number of industries including crews of airline pilots and teams of nuclear plant operators. Following the August 14, 2003 blackout, the RPDM was introduced to the power industry and was successfully applied to the planning, development, and implementation of grid operator training systems such as the *Virtual Instructor* and *PowerSimulator* (Podmore et al., 2008). A descriptive diagram of the RPDM is shown in Figure 1 (after Hunter *et al*., 2000).

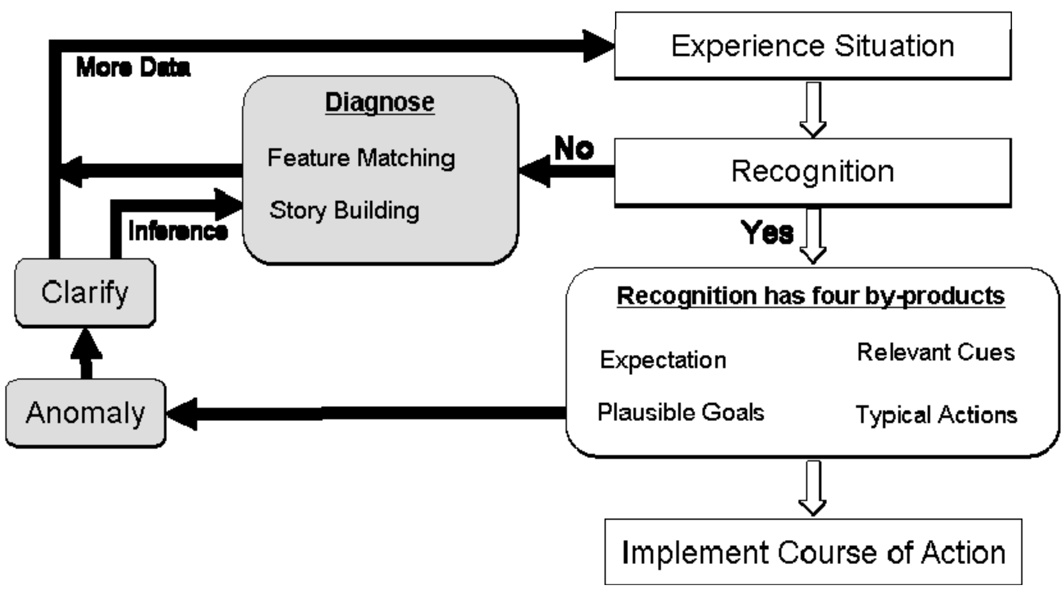

Figure 1. Klein's Recognition-Primed Decision Model

This figure shows that while experts may typically immediately recognize the situation and see the applicability of associated actions (following the path of the unshaded process in Figure 1), in some cases—such as novel/unfamiliar situations—the cues in the environment do not immediately match known or expected patterns and problems. In this case, a diagnostic process must intervene to assess the situation (this is depicted in the shaded portions of the figure). This requires more mental resources and utilization of knowledge stored in the decision maker's long-term memory, and the assessment would be limited or hampered if there were severe time constraints.

3.2 Recognition/Metacognition (R/M) Model

In addressing the diagnostic process used to reconcile conflicting or missing data, Cohen and colleagues (Cohen *et al.*, 1997) point out that NDM approaches to decision making, which emphasize recognition processes, may be inadequate when no familiar pattern of cues fits the current situation. They argue that processes that improve SA in novel situations are *metarecognitional* in function. Their NDM approach therefore highlights metarecognitional skills. This follows the line of thinking that metacognition involves splitting cognitive processes into three levels. The *object* level comprises recognitional processes that activate schemas in response to internal and external cues. The *metalevel* monitors the object level and maintains a model or description of the object level. This level includes processes that identify problems with the recognition schemas and processes that correct or modify the situation model and plan. A higher-level process, called the *quick test*, controls both the object level and metalevel processes by taking into account the time available, costs of an error, degree of uncertainty, and novelty. When stakes are high and time is available, the quick test process is used to critique the situation in order to find incomplete, unreliable, or conflicting information. Skills used in the critiquing process include identifying key assessments and the recognition support for them, checking stories and plans based on those assessments for completeness; noticing conflicts among the recognition meanings of cues; elaborating stories to explain a conflicting cue (rather than discarding it); etc. The process also regulates the use of these skills based on available time, stakes, and novelty of the situation.

The R/M framework builds upon the NDM foundation provided by the RPDM model and offers a mechanism to account for how experienced decision makers test and improve the results of initial recognition-primed decisions. The R/M framework focuses on critical thinking processes within situation assessment that direct the decision maker to look for gaps and conflicts in the "story" so that when unexpected or conflicting events occur, the mental model and/or action script can be adjusted.

3.3 An Integrated Model for Power Grid Operations

An integrated model of NDM integrates concepts of SA (Endsley, 1997), recognition-primed decision making (RPD) (Klein, 1993), metacognition (Cohen *et al.*, 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 *et al.*, 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; they do not need to interpret and integrate cues or consider possible alternate actions but instead respond 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 uses 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 2 depicts an integrated NDM model that we find useful in training of power grid operational decision making. It is strongly influenced by insights of Weick (1995) on sensemaking concepts that have been applied to power grid operations (Greitzer *et al*., 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 works as anticipated. The main advantage of this characterization is that it acknowledges the role of mental models in the SA component of decision making as well as in response selection.

The shape-coding in Figure 2 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 cues are monitored by the system operator's five senses,

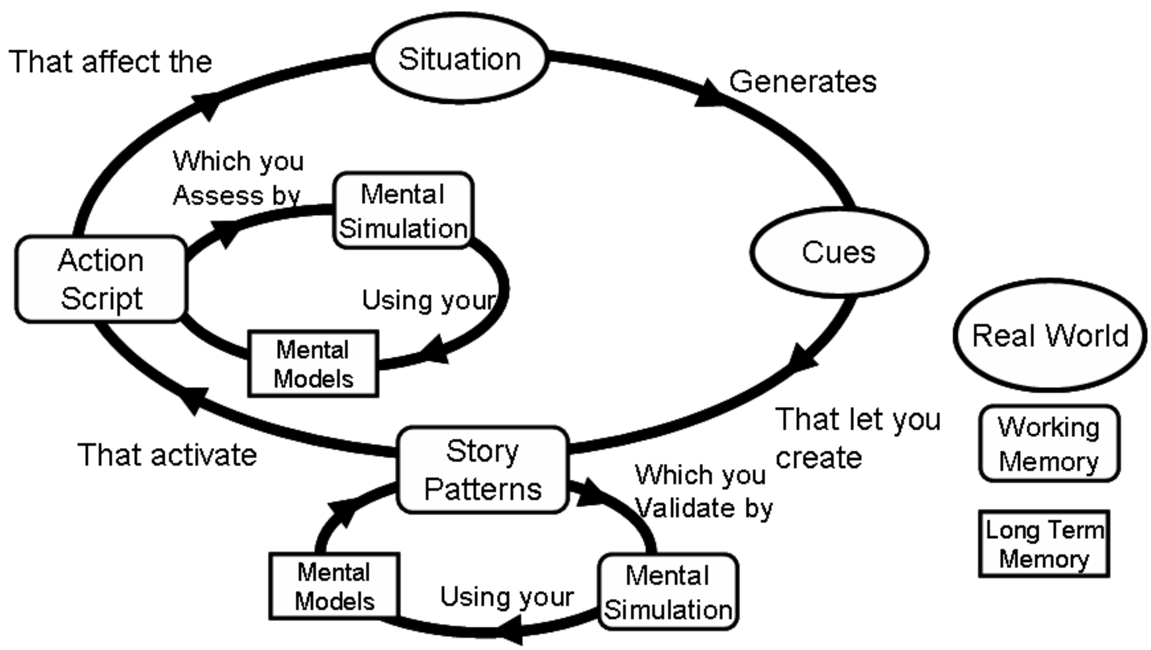

Figure 2. Proposed Integrated Naturalistic Decision Making Model.

primarily sight and hearing. 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 quick test is accommodated in the initial 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. The following sub-sections describe the main concepts and components of the model from a power grid operations perspective.

3.3.1 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.

The situation or state of the system is presented to the system operator from a variety of sources, including:

- measurements from the SCADA system and data links
- communications with plant operators, substation operators, line crews, distribution operators, and neighboring control area operators
- reports on results of on-line analysis programs, results from operation planning studies, and operation planning engineers.

3.3.2 Cues

The Cues describe the operator's level of awareness regarding the current situation. The Cues are analogous to a sphere of understanding. A more experienced operator will have a larger sphere of understanding. He or she will be more sensitive to and will have a greater appreciation for various explicit and sometimes subtle inputs. Cues for the system operator are generated from system summary displays, alarm logs, abnormal summaries, charts, map boards, system overview displays. There are potentially thousands of variables for a Transmission Operator to look at. The saying "Too much data and not enough information" is often used to describe this situation. The more experienced operators can extract and focus on the key variables to summarize the overall situation. Examples include:

- MVAR reserves in an area
- voltage stability P-V margin
- sustained ramping capacity
- spinning reserves
- Area Control Error (ACE).

3.3.3 Patterns

Using the cues to recognize key patterns is a critical step in the decision making process. Only by recognizing the correct patterns can the operator determine the appropriate actions. Some examples of the patterns that can be recognized from the various cues include:

- The system is vulnerable to a single line contingency; branch overloads are about to cause cascading thermal outages.
- The voltages in an area are very weak.
- A neighboring system is experiencing voltage problems and is drawing excessive MVARs from our system.
- The system is on the verge of voltage collapse.
- The system has large standing phase angles.
- A unit in our own control area has tripped and the generation reserves are insufficient to comply with the NERC CPS2 criteria.

The more experienced operators will be able to recognize a wider range of patterns and will more quickly detect when a new pattern has emerged.

3.3.4 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 *et al.*, 1997**)**.

3.3.5 Action Scripts

Action scripts are stored in our memory based upon past experience. The more experienced operators will have a wider range of action scripts. Based upon the different patterns that we recognize, our mind selects one or more action scripts for us to execute. Examples of action scripts include corrective actions such as:

- generator rescheduling
- adjusting control area interchanges
- adjusting phase shifters

- line switching
- changing transformer taps
- switching shunt capacitors or reactors.

The NERC (2004) policy states that these corrective actions should be implemented as quickly as possible without regard to the economic cost. 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.

3.3.6 Mental Models

As operators decide which corrective actions to implement, they test the prospective actions using various mental models to anticipate their impacts on the system. The experienced operator can usually estimate the directional trends that will occur for various control actions. Examples of mental models are[1]:

- 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.

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 operator's mental models. But in many cases, even if simulation or contingency analysis tools are available, the operator may not have sufficient time to use them. Experienced operators possess mental models and scripts that reflect the art of how to control the system a little at a time, monitor the changes, and then decide on a more definitive action. But unusual situations and abnormal events are problematic because required intuitive knowledge and scripts may not be readily available. Such conditions trigger a slightly different set of tactical, analytic thought processes and techniques—mental simulations represent this more controlled, analytic, and deliberative level of decision making.

3.3.7 Mental Simulations

The experienced system operator performs a mental simulation by first retrieving certain relevant mental models from long-term memory. 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 long-term memory. There is sometimes difficulty in connecting or associating mental models to see what in retrospect was an obvious consequence. An operator's understanding of the mental model is reflected in the depth and nature of the mental simulation.

As the operator processes the cues, he or she runs consistency checks such as:

"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?"

[1] Many more examples of mental models relevant to power grid operations are described in Appendix 2 of this report.

Once the operator decides which corrective actions to implement, he or she tests the actions using mental models to anticipate their impact on the system. The experienced operator can usually estimate the directional trends that will occur for various control 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, when the system is in an unfamiliar/unusual operating state, estimating the quantitative effects of control actions 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 how to control the system a little at a time, monitor the changes, and then decide on a more definitive action. When faced with such unfamiliar or complex situations in which time does not allow contingency analysis or relevant analyses or simulations are not available, operators will turn to each other to discuss and get other perspectives. Developing and maintaining this shared SA is another critical factor in successful performance.

4 Illustration and Application of the Model: A Power Grid Restoration Scenario

The abstract concepts of NDM are best described, as well as tested and extended, when applied to real-world problems. To illustrate the analysis, we have developed an illustrative scenario.

The scenario involves a system restoration. Put simply, system restoration involves in part connecting islands to the entire system. At this point, operators are several days into the scenario and they 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.
In summary, the real-world problem is that data must be assimilated, voltages matched, and then the island can be connected to restore the system. A complete script of the scenario is provided in Appendix 1.

The problem is shown in Figure 3: 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 (RC) oversees the West, East, and Central Systems.

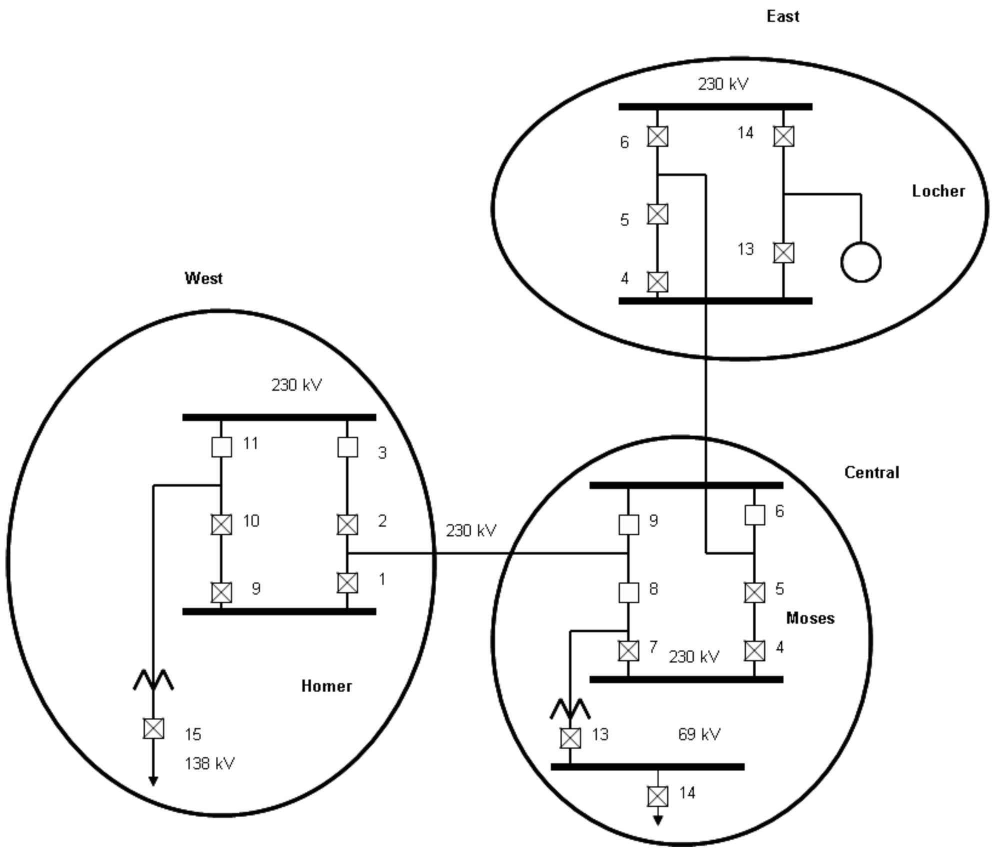

Figure 3. A Real-World Problem

4.1 Cognitive Task Analysis

We use cognitive task analysis (CTA) to capture and describe operator knowledge that relates to a real-world decision making task. CTA includes a number of methods to describe cognitive processes underlying performance as well as patterns of reasoning, problem solving, decision making, and collaborating and domain expertise and skill (Hoffman & Militello, 2008, p. 5). CTA is challenging because experts have accumulated large bodies of knowledge through experience, and their perceptual and cognitive skills are hard to verbalize, especially when described by experts who are not performing the task in a realistic environment (Gordon & Gill, 1997).

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

- A very realistic environment can be created using simulation. The thoughts and reactions of operators under these conditions are therefore also very realistic.
- By having multiple role players and scenarios that force interaction between the roles, operators are required 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 4. 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 will cover near misses and difficult, tough, or unusual cases.
- Audio recording of conversations between operators will document the thought processes of each operator.
- Historical data recording and playback system will allow state of system to be rewound and reviewed.
- System operator vital signs including body temperature, pulse rate, respiration rate, blood pressure, perspiration, and brain activity can be optionally measured and recorded.

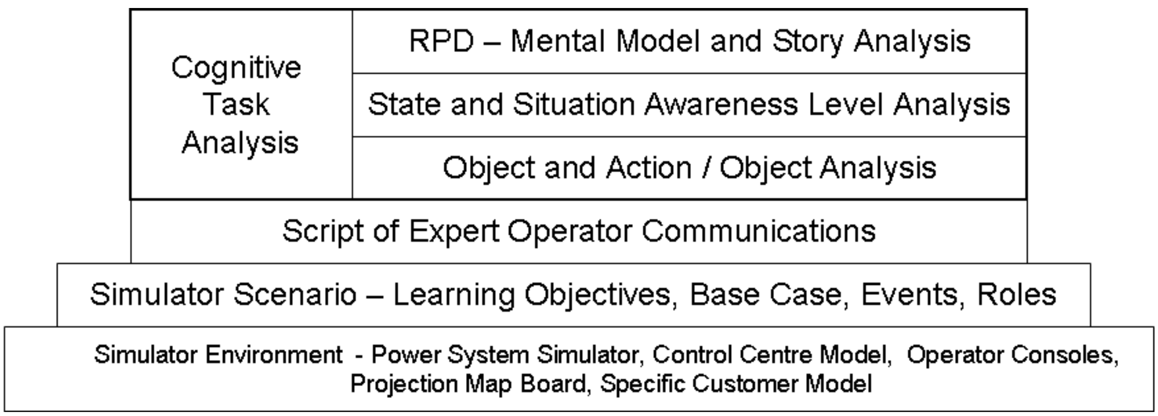

Figure 4. NDM Framework

4.2 Object and Action / Object Analysis

To support observation and analysis, we have applied object-oriented modeling methods to analyze the script of operator conversations. Object-oriented models are useful to understand problems, communicate with application experts and model enterprises (Rumbaugh, 1991). 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:

- Object Analysis – derived by listing all the nouns in the conversations
- Action Analysis – derived by listing all the verb and noun combinations referenced in the conversations.
- State Analysis – derived by listing all the observations or questions about the past, current, and projected future system state.

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. Tables 1, 2 and 3 show the results of the Object Analysis, Action Analysis, and State Analysis (respectively).

Table 1. Object Analysis Results

Object	Object	Object
1 kV limit	indications of line flows	request
138 kV load centers	indications on breakers	required level
50 MVAR increment in output	island	requirements of interconnection check list
adjacent substations	level	resources to raise voltage
angle specification	level to allow closing	restoration check list
another six hours	line breaker	restoration plan
breaker	line capacitance	SCADA
breakers on both sides of line	line crews	SCADA indications
bus breaker	line ends	status boards
cap banks	megawatt flow	substation
central area	megavar flow	substation voltage
concurrence from RC	megavar injections	system voltage
current island	megavar transfers	the 230 kV
distribution load centers	megavars at no load	visual inspection
end of line	megawatt transfers	voltage
fault indication	method to raise voltage	voltage control devices
faulted micro switch	megavar constraints	voltage differential
faulty breaker position indicator	mvar reserves remaining	voltage differential across breaker
frequency specification	note in system	line flows
generator	open position	line status
generator MVAR output	other restoration efforts	local voltage increase
generator nominal levels	outside substation	voltage mismatch
independent islands	personnel	voltage specification
indications	position of breaker	west area

Table 2. Results of Action Analysis

Actions
adjust voltage
back down megavar output
begin to lower substation voltage
check with RC for consistency
close breaker
close breaker our side
coordinate
coordinate and raise voltage
discovered not connected to east
equalize voltage
facilitate closing of breaker
fix faulty indication
increase megavar output
increase megavar output
increase voltage
interconnect west and central areas
interconnect with west
interfere with restoration efforts
isolate line
lower system voltage
lower voltage
make a note in system
monitor voltage
open breaker your end
open while indicating closed
raise system voltage
raise voltage
reduce voltage ourselves
restoration to lower voltage
restoring distibution load centers
seeing indications
seeing megawatt and megavar transfers
send personnel to manually inspect position of breaker
show line closed
show power transfers
show voltage mismatch
switch cap banks out of service
syncrhonize islands
tie islands
transfer line capacitance
transfer line capacitance from your system to our system
trying to synchronize across breaker
update status boards
visually inspect position of breaker
will not interconnect

Table 3. Results of State Analysis

Order	Step	State	Phase
1	21	no way to raise voltage	current
2	25	locher generator connected	current
3	25	locher generator operating at nominal levels	current
4	25	can increase megavar output to raise voltage	future
5	25	make sure changing voltage will not interfere with other restoration efforts	future
6	26	230 kV line is lightly loaded	current
7	26	230 kV is able to handle additional megavar flow	current
8	30	will there be sufficient reserves remaining	future
9	47	voltage is unchanged	current
10	47	line flows are not changed	current
11	47	indications that breakers are closed	current
12	51	seeing local voltage increase	current
13	51	not seeing indications of increased line flows	current
14	51	breakers both sides indicate closed	current
15	53	breakers are closed	current
16	53	voltage is not changing	current
17	61	megavar output has been reduced	current
18	65	have visually inspected breaker	current
19	65	have found breaker open	current
20	65	SCADA is indicating breaker is closed	current
21	66	operating as independent islands	current
22	67	areas are not connected	current
23	71	line is out of service	current
24	71	in process of repairing faulty micro-switch	current
25	71	have micro-switch replaced by end of day	future
26	76	there was a faulty breaker position indicator	current
27	76	we will have to reduce voltage difference ourselves	future
28	77	restoration for distribution load centers is taking longer	past
29	77	line crews are stretched thin	current
30	77	central to take 6 hours to restore 138 kV load centers	future
31	79	only megavar injections at Homer are from Homer-Moses line at our end	current
32	79	Homer-Moses line is connected at our end but open at your end	current
33	81	Opening the Homer breaker to isolate the Homer - Moses line would lower the voltage at Homer	future
34	82	Open the breaker your end, isolate the line, close the break our side. Transfer line capacitance from your system to our system. Lower voltage at Homer, raise voltage at Moses	future
35	87	We can interconnect on the 230 kV system using Homer breaker 1	future
36	100	Homer breaker 1 indicates open	current
37	102	Moses breaker 8 indicates closed	current
38	106	All requirements of Interconnection Checklist have been met	current
39	107	The interconnection checklist is complete	current
40	113	Voltage, frequency, phase are within spec	current
41	113	We are seeing megawatt and megavar transfers across the line	current
42	118	west and central are now interconnected	current

4.3 State and Situation Awareness Level Analysis

The SA Level Analysis is performed by listing in a separate column all the observations or questions about the past, current, and projected future system state. No elaboration is required. This is simply a matter of extracting relevant portions of the conversation.

The entries for the SA Level Analysis are color coded to indicate the SA Level (Endsley 1997) for the operator that is speaking.

- 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
- Red: identifies a point when there is an opportunity for the operator to exhibit or develop Level 2 SA, but this is not occurring.

As the scenario unfolds, the color codes progress from Orange to Blue to Green as we would expect. The color codes clearly show the quality of communication and shared SA among the operators. In the first scenario that we analyzed with four operators, the communications were clear, met the criteria to be considered excellent, and the colors all tended to be consistent at different points in the scenario. The SA Levels should be analyzed by someone familiar with the technique, but an expert power system operator is not necessary for analysis. Refer to Appendix 1 for the complete analysis table for the illustrative scenario.

4.4 Mental Model and Story Analysis

The theoretical proposition put forth in this report 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.

In the illustrative scenario, 72 objects and 55 action / object combinations were identified. Examples of objects were *faulty breaker position indicator*, *frequency specification*, *generator*, *generator MVAR output*, *independent islands*, *indications of line flows*, *line breaker*, *line capacitance*, and *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*, and *update status boards*. For the illustrative scenario that we analyzed, the 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 quickly accepted and used by the 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.

Another result of the analysis is to identify tacit knowledge of operators. The illustrative scenario was designed for experienced system operators who, by definition, possess a wealth of tacit knowledge, including how to recognize cues, a vast array of mental models, an ability to conduct a variety of mental simulations to predict what will happen on their system, and an ability to make intuitive decisions for reasons that are not at all obvious to the novice. Thus, the analysis helps to distinguish between expert and non-expert performance, which informs the instructional process.

4.5 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 are naturally captured in their conversations.
- 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 SA 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 models that are crucial to solving the particular operating problem are very clearly identified along with the time when the operators retrieve this model from long-term memory.
- The mental simulations and mental models used by the operators can be identified.
- The action scripts that are considered and selected are clearly identified.

The results of this cognitive task analysis test case have significant implications for training, as will be discussed in Section 5.

4.6 Benefits of the Model and Analysis

The potential benefits of the RPD analysis can be summarized as follows:

- The RPD analysis provides a systematic approach for conducting a session debrief.
- The RPD provides a framework for the expert and novice operator to answer the question "What were you thinking at the time you made such and such a decision."
- The RPD analysis converts all the tacit assumptions and knowledge of the expert operator into an explicit, clearly documented description.

It is well known that with "Monday morning quarterbacking" we can always gain more insight compared to when the players are in the middle of the game. The framework and associated analysis method that we have established provides a systematic means of identifying such insight and behaviors requiring training intervention or mitigation during or immediately following execution of the scenario.

5 Application to Training on Power Grid Critical Decision Making

The training development/training management process is depicted in Figure 5. 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 over an operator's career. Typically, 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. When informed by the more specific and rigorous concepts and performance criteria available in cognitive task analysis and naturalistic decision making approaches, the instructional design team is able to prepare a detailed training management and mitigation plan that is based on the operator's demonstration of understanding (or lack of understanding) of requisite cues, patterns, mental models, action scripts, etc. that are involved in critical decision making solutions to the scenario. That is, instead of reacting to relatively gross behavior or outcomes, the training manager/instructor is armed with specific guidelines or behavioral/performance "targets" (indicators) that identify possible deficiencies. With this detailed information, the trainer may choose to interrupt the exercise immediately to discuss problems, or he/she may note the discrepancies between actual and optimal performance 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 instill greater understanding in trainees that may be taken away and applied in the field.

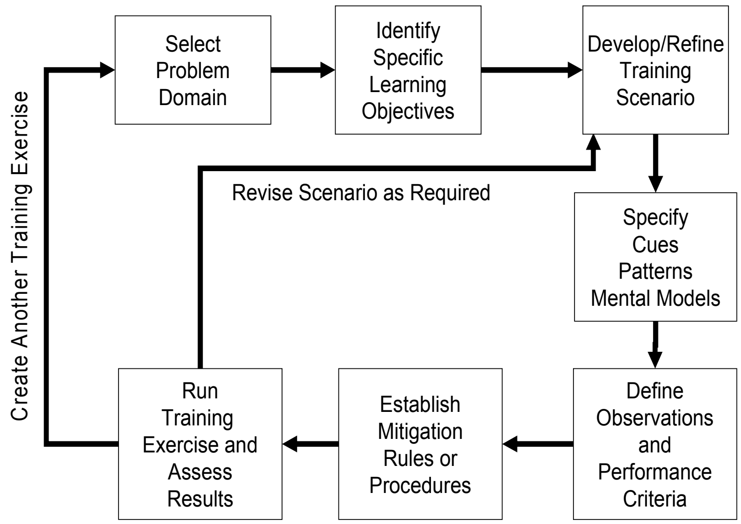

Figure 5: General Training Development/Management Process

Since the RPD model was introduced to the power industry following the blackout of 2003, training has been structured so that there is a much stronger 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. Currently, over 2000 system operators are trained each year using the PowerSimulator (Podmore et al., 2008).

Cognitive debriefing resulting from simulation training is critical to capturing the knowledge and expertise of the expert participants. In the simulation environment, very little explicit knowledge is captured (Nonaka, 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 *et al.*, 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 recorded and transcribed conversations will allow the instructor to conduct a detailed analysis of the training sessions. From this analysis, additional scenarios and training curricula can be developed with increasingly more precision with the goal of minimizing cognitive errors, or the root biases and failed heuristics underlying them. Thus, the methodology described here significantly strengthens and informs the feedback loop in Figure 5.

If we can really measure the operator thought processes in terms of Cues Monitored, Levels of Situational Awareness, Mental Models retrieved, Mental Simulations being run, and Stories being built as accurately and as simply as this example suggests, then this could have some fairly profound impacts on how we develop training curricula and programs.

Of course, more scenarios need to be analyzed to see if this one is typical or atypical.

5.1 Measuring Performance of Experts versus Rookies

It has been noted in general that experts spend more time and care in observing and orienting themselves to their environment and situation before making a decision and taking an action (Endsley, 1997). The authors have also personally noted that expert power system operators like to spend more time thinking through the plan and developing a complete and consistent story compared to rookie operators. The addition of the loop to "Validate the Story with a Mental Simulation Using Your Mental Models" was added at the insistence of Mr. Chuck Johansson to stress the importance of this step. Time and again in simulator scenarios we see the rookie attitude of "let's close it in a see what happens" (no doubt encouraged by their time with video games) balanced by the more experienced operator's cautions of "no let's look a little further and be sure we can anticipate what will happen." As we perform more experiments with groups of Rookie and Expert operators, we will be able to use the Human Factors Analysis to clearly document their level of SA at each step of the scenario.

5.2 Identifying Gaps in Knowledge

The draft NERC PER 005 Personnel Standard requires that Reliability Coordinators, Transmission Operators, and Balancing Authority Operators measure the competency gap for their individual system operators. The Object and Action Analysis provides a list of basic concepts for both rookie and expert operators to review and make sure that they have mental models for all of the objects and actions. The Object and Action Analysis implements and accelerates an informal approach that is sometimes used in on the job training. System operators sometimes teach themselves by noting every term that is unfamiliar and then asking their mentor to explain this when they have the time. The Object and Action Analysis can be performed simply without requiring a complete transcript of the conversations. During the scenario, the instructor can designate that one of the team members should take note of all the new objects and action / object combinations are they occur in the conversations. This assignment is a good one for the most junior member in the class.

5.3 Developing More Advanced Scenarios

There is an art to being a simulator instructor that can adapt on the fly and introduce the right amount of complexity into a scenario as it evolves. This art and intuition are needed to answer questions such as:

- How well are the students keeping up with the current scenario?
- If I add this event, how do I expect the system and the students respond?
- What concepts can I add in addition to the ones currently being covered?

The Object and Action Analysis can be a useful tool for identifying and communicating how complexity can be added to scenarios. The analysis identifies the Objects and Actions that were used and communicated in the particular scenario, but there may be other important Objects and Actions that were not used and/or not relevant to this scenario.

A review of the scenario object and action list can trigger an instructor to identify areas where the scenario may be taken to another level. For example, in the illustrative island synchronization scenario, there was no mention of the terms *weak bus*, *runaway transformer taps* or the *tap changers*. A more detailed review of the scenario might raise the following questions:

- What if the Moses bus is very weak compared to the Homer bus? Could transferring the line capacitance from Homer to Moses create an over-voltage on the Moses bus?

- What if there is no synchronizing breaker at Moses and we are forced to synchronize at Homer? Can the voltage at Moses be lowered by adjusting tap settings at Homer?

- What about runaway transformer taps? Leave the tap changers in auto mode. Make sure the system operators put them in manual mode; otherwise, tap will run away and create extreme high side voltages.

- What if the Moses island has limited megavar reserves? It may not be able absorb the charging megavars from the Homer – Moses line and could cause over-excitation and generator damage.

In summary, the object, action, and state analysis gives the instructor a low-cost tool to review what the students were thinking during the scenario. It provides a vehicle to close what is otherwise an open loop for the instructor.

6 Application to Usability Testing of Power Grid Analytical and Visualization Tools

There is a trend in the industry where vendors are supplying data display subsystems that can be retrofitted onto existing SCADA and Energy Management Systems. Each of these systems can potentially present usability challenges when integrated into operational environments. The framework and methodology described in this report may be used to systematically evaluate the usability of these tools and visualizations. Examples of commercial products in this general category of enhanced displays and subsystems include:

- *PI Historian* from OSIsoft. The PI system brings all operational data into a single system that can deliver it to users at all levels of the company—from the plant floor to the enterprise level.

- *PowerWorld Retriever* from PowerWorld. PowerWorld Retriever gives operators a real-time or historic view of the power system and its various parameters quickly, accurately, and in a format that increases situational awareness.

- *eterravision* from Areva. eterravision helps operators anticipate and prevent potential problems by enabling them to fully visualize their networks in real time.

- *PowerVisuals* from Incremental Systems and PowerData is a family of Net-enabled graphical user interface products that can be used for monitoring and controlling real-time event-driven processes as well as maintaining and accessing their underlying databases. PowerVisuals supports user-defined display types that are typically found in modern Energy Management, SCADA, and process control systems including:

- system overview schematic diagrams
- substation one-line diagrams
- Repeat tabular (spreadsheet) displays.

In addition, there are several products being developed as part of U.S. government research that present similar challenges for usability testing. The U.S. government is investing significant resources into research and development of advanced methods for Grid Visualization:

- *Visual Analytics Centers*. In 2004, the U.S. Department of Homeland Security (DHS) chartered the National Visualization and Analytics Center™ (NVAC™) at the Pacific Northwest National Laboratory to define a long-term research and development agenda for visual analytics. NVAC established the family of Visualization and Analytics Centers (VACs) through academic, government, and industrial partnerships.[2] The U.S. government faces critical challenges in identifying and preventing attacks on U.S. soil. At the same time, businesses have a driving need to understand rapidly changing markets to remain financially healthy. Disaster management requires rapid assessment of complex and dynamic situations to save lives and property. The VACs are a national and international resource, fulfilling a fundamental need to provide advanced analytical tools to make progress in understanding and addressing these challenges. VACs will provide high throughput visual analytics that are accessible to all, enabling anticipation and prediction of, preparedness for, and response to man-made and natural disasters and terrorist incidents for resilient national freedoms and security. VACs' primary task is supporting DHS's mission by giving analysts and emergency responders technology and capabilities to detect, prevent, and reduce the threat of terrorist attacks; identify and assess threats and vulnerabilities to the United States; and recover and minimize damage from terrorist attacks, should they occur.

- *VERDE*. Visualizing Energy Resources Dynamically on Earth (VERDE) is a U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability sponsored effort.[3] The VERDE project was initiated by DOE in response to the devastating hurricanes in 2005. The goal of VERDE is to coordinate federal response to natural disasters or major events. The project is being performed by Oak Ridge National Laboratory (ORNL), in partnership with the Tennessee Valley Authority (TVA). VERDE is a real-time grid visualization tool that will initially assess status of transmission lines in the Southeast. VERDE provides real-time status of transmission lines, real-time weather overlays, predictive impact models and animated replay data analysis, and energy infrastructure interdependencies (such as coal delivery and rail lines, refinery and oil wells, natural gas pipelines, transportation and evacuation routes, and population impacts). VERDE is connected via an ICCP data link to NERCnet, which provides real-time data every minute. TVA extracts data and translates line status—in or out of service. ORNL provides an electric dynamic grid analysis that overlays weather,

[2] http://nvac.pnl.gov/docs/VisualizingAnalytics.pdf
[3] http://phasors.pnl.gov/Meetings/2007_may/presentations/verde_brief.pdf

population, transportation, and electrical network data; visual displays are sent to DOE every minute.

Another trend is specialized vendors supplying add-on analytical tools with their own closely coupled user interfaces. Examples of such analytical tool systems include:

- The DSATools from PowerTech, Vancouver, Canada. DSATools provides the complete assessment of system security including all forms of stability. The key components in the suite, VSAT, TSAT, and SSAT, have also been designed to be used for on-line dynamic security assessment (DSA). In this mode, the software is connected directly to a power system's energy management system (EMS) and computes system security in a continuous cycle. The software provides system operators with important information about system security limits, critical contingencies, and remedial actions needed to prevent system failures.

- Secure Suite from Bigwood Systems. Secure Suite includes: Transient Stability Analysis and Enhancement (TEPCO-BCU), Voltage Stability Analysis and Enhancement (VSA&E), Small-Signal Stability Analysis and Enhancement (ECLIPS), Static Security Assessment and Corrective Control (SSA&C), and Security-Constrained Available Transfer Capability Analysis (SC-ATC).

- Physical and Operational Margins (POM) from V and R Systems. POM-RT is a powerful voltage stability and contingency analysis tool that provides real-time solutions for the operations environment. POM-TS is an add-on module integrated into POM. It is a fast and comprehensive dynamic simulation program that offers the capability to simulate balanced and unbalanced faults and determine transient stability limits after any disturbance is applied to a power system network.

The Human Factors framework that has been outlined in the previous sections can be used for the systematic evaluation of usability for existing and new analytical and visualization tools—those described above as well as other displays, analysis, and visualization tools that are in development at the Pacific Northwest National Laboratory. The evaluation methodology, based on the framework presented in this report, is described in the following subsections.

6.1 Evaluation of Analytical Tools

The RPDM has been successful and widely adopted because it really does describe how an expert human makes a decision for many fields. A big problem for Power System Analytical Tools is that they often do not include the operator in the decision making loop and they provide recommendations that are counter-intuitive. This can be a problem even when the counter-intuitive recommendations are correct. There is a spiral of trust that must be built between the system operator and the analytical tool.

This is the case with PowerSimulator. There may be cases where the system will black out due to an action by the power system operator. If the cause of the blackout is not obvious, there is a tendency to blame the program. The robustness of the program has now developed to the point where, in almost all cases, we can point to operating error as the cause. This has greatly increased the trust that operators have in the program compared to the early days when islands would black out due to various non-physical reasons. The problem is aggravated for the Power System Analytical Tool Developer when we tell him or her that the program does not work like an expert operator, but we can not give any specifics on how an expert operator makes a decision. With the Human Factors Framework, we can record and analyze the performance of an expert team of operators with and without the Analytical Tool. We can also record and analyze the performance of a rookie team of operators with and without the Analytical Tool. A good Analytical Tool should make a measurable improvement in the performance of the expert operators and an even more significant improvement in the performance of the rookie operators.

The Human Factors Framework will allow analysts to provide much more specific feedback on how Power System Analytical Tools should be enhanced for usability, robustness, and performance.

6.2 Evaluation of Visualization Tools

Visualization Tools have been developed almost universally from the viewpoint of presenting a complex system state to the power system operator. This in itself is a complex problem. An operator essentially has to be able to visualize the system in three dimensions.

- *Spatial*—what is the pattern of voltages and flows across the current system state?
- *Temporal*—how will the system change over the course of a shift as the load picks up or drops off and transactions come and go? What will the pattern of voltages and flows across the system look like in the future?
- *Contingency*—how will the system respond to the most severe single contingency and certain multiple contingencies? What will the pattern of voltages and flows across the system look like if these events occur right now? What will the pattern of voltages and flows across the system look like if these events occur in the future?

The true effectiveness of the advanced display techniques can only be really tested when the system moves into an emergency or restorative state. Under these conditions, when large volumes of data are rapidly changing on a wide-area basis, it is critical that the system remain responsive. Ideally, the system should allow the operator to understand the root-cause events that created the current situation and help him/her quickly evaluate options for restoring the system to a normal state.

The Human Factors framework developed in the present study can provide an excellent test bed for evaluating a range of visualization tools:

- The Areva System can naturally be used to test the Areva eterravision system on customers that have an Areva DTS operational.
- Some Areva customers, e.g.. ISO New England and Southwest Power Pool, have integrated PowerWorld Retriever with the Areva Energy Management System.

- PowerSimulator can be used to demonstrate the effectiveness of the PowerVisuals System Map and Station displays for a wide range of models under normal, emergency, and restoration conditions.

PowerSimulator has been designed in such a way that it can be linked to third-party Visualization Tools and third party Analytical Tools with relative ease. PowerSimulator includes an openly published real-time Application Program Interface (API) so the third-party display systems and third-party applications can retrieve the following data from the simulator:

- breaker oriented model of the power system
- bus branch oriented model of the power system
- real-time simulation of the SCADA data.

The third-party Visualization Tools and Analytical Applications are not meant to replace the basic user interface that is being supplied by existing EMS vendors for SCADA operations. They are focused on providing a view of the big picture. PowerSimulator includes the basic SCADA and AGC functions so that system operators can implement the necessary control actions in a real-time closed loop fashion after they have developed the required level of situational awareness with the third party Visualization and Analytical Tools.

6.3 Industry Track Record

The Energy Management industry has a spotty track record in prototyping, developing, and implementing widespread deployment of advanced analytical tools and visualization methods. Even steady state network applications such as state estimator and contingency analysis are notoriously difficult to commission and then maintain. Customers often use the phrases:

- “Designed by engineers for engineers.”
- “An engineer’s dream and operator’s nightmare.”
- “Too many tabular displays.”

The Eastern U.S. blackout of 2003 is an indication of the complexity these programs. The MISO state estimator was turned off by the application engineer, but the MISO system operator was not aware of this.

These problems are not unique to the power business. They occur in many industries. Operators shape tools based on their interests, constraints, and task demands. They stick with stereotypical routines to avoid getting lost in large and complex menu structures and complex sets of alternative methods (Miller and Woods, 1997).

6.4 Benefits of a Human Factors Framework

A systematic Human Factors based analysis of the analytical tools and visualization methods for mission critical real-time environments has been a major focus of research conducted at the Pacific Northwest National Laboratory (PNNL) in support of power grid operations (Greitzer *et al.*, 2008; Guttromson *et al.*, 2007) as well as in the broader naturalistic decision making community.

As stated earlier, Visualization Tools have been developed almost universally from the viewpoint of presenting a complex system state to the power system operator. While this is a very important part of the problem, it is only a partial solution. The other, equally important, part of the problem is how to stimulate the operator to recall the correct mental models that are required to solve the problem. This is certainly a challenge and goal for training, but it also may be considered a possible contribution of operator aids and decision support systems. A possible operator aid would be a collection of mental models that would be indexed to certain types of problems, so they would be readily available for reference during off-normal operations. This might increase the likelihood that the decision aids would be applied appropriately. Appendix 2 is an initial step toward documenting mental models—a more interactive implementation could conceivably serve as a decision aid or cueing function to prompt and enable decision makers to consider appropriate mental models earlier.[4]

Some of the benefits of using the Human Factors Framework to perform usability testing are:

- Ensure that the interface design is compatible with an expert operator's mental model of the system. These mental models will be precisely identified.
- Ensure ease of navigation through menus by both novice and experienced users.
- Usability testing can be done on the back end of the development cycle for existing systems.
- Usability testing can be done one the front end of the development cycle for new applications, especially ones that use Phasor Measurement Units (PMUs).
- It decreases the time to market success and increases the acceptance rate of these applications.
- It is transition oriented—providing better displays about events, targets, and transitions.
- It is future oriented—while existing systems focus on capturing current configuration, this approach supports methods and mind-sets for projecting the state of the system into the future.

[4] Imagine, for example, if we were to show the operator a picture of a transmission line mental model (example 2 or 4 in Appendix 2) as a prompt early in the restoration scenario illustrated in this report. This would likely have led to the consideration of the most important mental model earlier in the process.

- It is pattern based—system operators can scan at a glance and pick up possible unexpected or abnormal system conditions about the transmission grid rather than having to read and integrate each individual piece of data to make an overall assessment.

7 Discussion

In this report, the processes and principles of Recognition Primed Decision Making, Recognition/Meta-Recognition, and SA have been combined into an integrated decision making model. This integrated model has been applied along with a Cognitive Task Analysis to develop a more detailed approach to electric power system operator training for emergency scenarios within a grid simulation environment. 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 the development of new training scenarios as well as to establish a more rigorous environment for testing and evaluating new operator decision aids or displays. The key findings are that the framework described in this research can explain the thought processes of the system operators at **all the steps** in an operational scenario; it supports the identification of key mental models that are critical to solving power grid operations problems; and it provides a basis from which to inform and enhance training programs for power grid operations and accelerate learning of key learning objectives.

Among the most significant findings are:

- The enhanced RPD model is able capture the thought processes of the system operators at all steps in the scenario.

- 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 models crucial to solving the particular operating problem may be clearly 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 are clearly identified.

8 Conclusions and Recommendations

Some of the benefits of using the Human Factors Framework to inform design, perform usability testing, and improve training for power grid operations are:

- ensures that the interface designs will be compatible with an expert operators mental model of the system. These mental models will be precisely identified

- ensures ease of navigation through menus by both novice and experienced users.
- can be done on the back end of the development cycle for existing systems
- can be done at the front end of the development cycle for new applications
- can decrease the time to market success and increase the acceptance rate of these applications
- transition oriented—better displays about events, targets, and transitions
- future oriented—existing systems focus on capturing current configuration and how to project state of system into the future
- pattern based—system operators can scan at a glance and pick up possible unexpected or abnormal system conditions about the transmission grid rather than having to read and integrate each individual piece of data to make an overall assessment
- more effective training scenarios, keyed to specific learning objectives and naturalistic decision making components (mental models, etc.)
- more effective performance measures and criteria for training management and accelerated learning for power grid critical decision making.

Our theoretical proposition regarding the application of RPDM to power grid operational training and decision making, and to assessment of the usability and effectiveness of new tools and visualizations, has produced interesting and promising findings. We have shown how to develop strong linkages among simulated learning opportunities, integrated feedback, and debriefings that are informed by the theoretical framework outlined here. Analysis of usability and effectiveness appears to be enhanced and informed by the application of the RPDM framework.

As a result of this test case, we recommend the following research and applied thrusts to advance human factors theory and practice within the power industry:

1. Continue application of this HF framework and analysis approach to advance and demonstrate the value of the analyses, in conjunction with simulation capabilities of the EIOC, to further the DOE mission in improving and strengthening the electric power utility infrastructure. Specifically, this objective may be accomplished by identifying strategies for improving training and providing HF analyses to guide the development of next-generation Wide Area Display technologies.

2. Continue to advance the HF framework and methodology to provide direct benefits to stakeholders within the electric power grid community. Specific aims are to more precisely measure the cognitive gaps in novice and expert power system operators; apply the results of this analysis to accelerate the training programs for new power system operators; and systematically evaluate the usability of the next generation of tools for managing a Smart Grid.

3. Conduct evaluations and enhance the design of Wide Area visualization/decision support tools. Bring together the HF analysis methods with the capabilities of the EIOC to provide a unique platform for researching, developing, and deploying technologies to better manage and control the grid. Ongoing PNNL research focuses on developing real-time tools and supporting their integration into operating systems. New tools can provide a better view of the power grid, as well as faster and more accurate predictions of what might be happening so operators can quickly respond. We can use our human factors methods and advanced evaluation framework to examine the potential effectiveness of such tools. Examples are the Modal Analysis of Grid Operations (MANGO) tool that allows grid operators to "see" in real-time, the oscillations on the grid such as those that led to the 1996 West Coast and 2003 East Coast blackouts; the newly conceived Transient Analysis of Grid Operations (TANGO) tool that will allow grid operators to anticipate in real time the transient stability margins; and other new computational and visualization techniques.

4. Engage directly with utility operators. We have identified several commercial utilities whose models we can get running quickly in the EIOC. We can offer an attractive package for improving their operations, conducting demonstrations and evaluations of advanced training concepts, and providing a testbed and associated HF methods to assess the effectiveness of tools and procedures that will address both technical and human-factor issues such as those experienced during the August 2003 Blackout event and its restoration process.

5. Pursue opportunities to exploit the PNNL EIOC for training workshops, based on the framework described in this report, and as a test bed for evaluating new procedures, decision aids, and visualization techniques. Implementing a comprehensive HF Framework within the EIOC will provide a systematic foundation for validating and verifying that system operators will perform their jobs better with the proposed new tools and training. Because the EIOC is a safe setting, researchers can work through the iterative process of developing and refining technology more quickly.

In conclusion, this research demonstrates the capability to meet critical mission objectives of the DOE as well as strengthen the role of PNNL and the EIOC as a resource and test bed for power grid training and visualization analysis.

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Appendix 1: Analysis of the Restoration Scenario

Note: Typically, performance assessment would be done based on actual operator behaviors that are observed during the simulated scenario. For illustrative purposes, here we examine the hypothetical script that we constructed for this scenario.

Summary of the Main Story

The scenario involves a system restoration. Put simply, system restoration involves in part connecting islands to the entire system. At this point, operators are several days into the scenario and they 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.
In summary, the real-world problem is that data must be assimilated, voltages matched, and then the island can be connected to restore the system. A complete script of the scenario is provided in the "Text of Scenario" section below.

The problem is shown in Figure 1-1: Three power system operators are responsible for different sections of the power system:

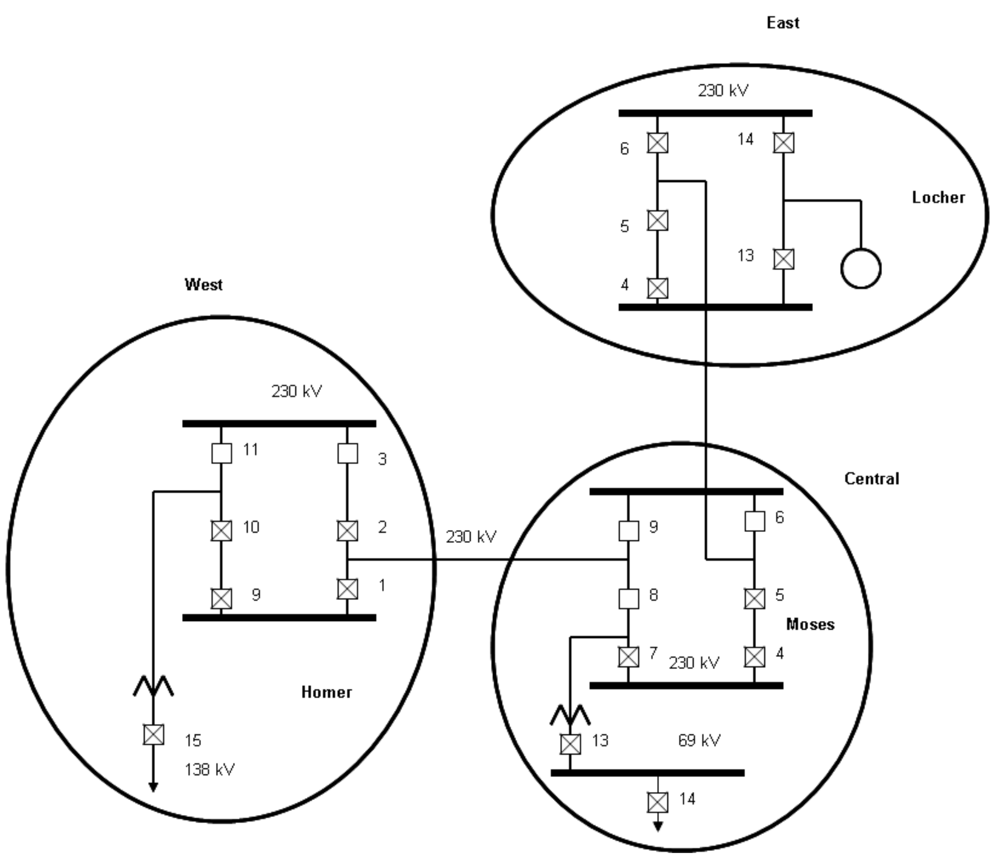


Figure 1-1. A Real-World Problem

- 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 (RC) oversees the West, East, and Central Systems.

Overview: The operators are able to synchronize the islands. They communicate clearly; RC provides overall direction of goals. Central, West and East work as a team to meet the goals. The RC is informed before Central, West, or East takes any actions. After missing a critical mental model that the unloaded Homer–Moses line acts as a capacitor (Steps 11-37), the operators work through their process until they recognize that the cues do not match their initial mental model (Steps 38-42). The Central Operator (Steps 47-66 and 79) successfully applies the mental model of MVAR flow and bus voltages to detect that the Homer–Moses line must be open, in spite of the breaker indications showing that it is in service; and the solution for the interconnection then becomes apparent (Steps 106-120).

West's Homer station is operating as a separate island from the Central Moses station. The Homer–Moses line is acting as shunt capacitor. It is about 75 miles long. Each mile of 230 kV generates about 0.3 MVAR of charging.

The Homer 230 kV bus is a weak bus. It is energized from the 115 kV side of the Homer 230/115 kV transformer.

The situation at Homer is unusual. The 230 kV bus will normally be stronger than the 115 kV bus. Bus strength can be measured by the sum of the reactances in series to the closest generator. The charging from the Homer–Moses line is going through a number of reactances in series before it can be absorbed by a generator somewhere. MVARs have to flow downhill on voltage. So the Homer 230 kV voltage has to be raised to support the downhill flow.

Text of the Scenario

Step	Speaker	Conversation
1	RC:	RC to West. RC to Central:
2		*<West Acknowledge> <Central Acknowledge>*
3		Per the restoration plan the next step is to tie the West Island and the Central Island together. To do this it will be necessary to close the 230kV Moses to Homer breaker, breaker 8..
4	Central:	10-4. This is Central. We acknowledge
5		My indications show voltage mismatch across the 230kV Moses to Homer breaker 8. The value exceeds the 1 kV limit indicated in the restoration checklist. I cannot close the breaker.
6	West:	West to RC
7		*<RC Acknowledge>*
8		I am seeing the same indications

Step	Speaker	Conversation
9	RC:	10-4 West. RC to West and Central:
10		*<West Acknowledge> <Central Acknowledge>*
11		Coordinate to equalize voltage across the 230kV Moses to Homer breaker 8. Once you've agreed on a plan, contact me prior to synchronizing the two islands.
12	West:	This is West: 10-4
13	Central:	This is Central: 10-4
14	West:	West to Central:
15		<Central acknowledge>
16		Is there anything you can do at the Moses substation to raise the voltage?
17	Central:	No, is there anything you can do to lower the voltage at Homer?
18	West:	We don't have any voltage control devices at Homer, or any adjacent substation.
19	Central:	West, do you have an estimate on how long it will take for the restoration to lower voltage by that level?
20	West:	I would estimate at Central another six hours before we can begin to lower the Homer sub-station voltage to a level that would allow closing the 230kV Moses breaker 8. Are there any actions that you can take outside of the Moses substation to raise the voltage?
21	Central:	Within our current island we have no way to raise the voltage. We are connected to East. I can check with them and see if they can help raise the voltage on our side.
22	Central:	East this is Central
23		<East Acknowledges>
24		We are trying to synchronize our island with West but the voltage differential is too high to synchronize across the breaker. West is not able to lower their system voltage due to Megavar constraints and we do not have any method to raise voltage. Do you have any resources to raise the voltage in our system?
25	East	Central, at present we have Locher generator connected and operating at nominal levels. We could increase its Megavar output to raise voltage. We will need to check with the RC to make sure that changing the voltage by this level will not interfere with other restoration efforts.
26	Central:	Sounds good. Let's proceed. The 230kV is lightly loaded, it should be able to handle additional Megavar flow.
27	East:	RC this is East
28		<RC Acknowledges>
29		I have a request from Central to increase the Megavar output of Locher in order to raise their system voltage so they can connect to West. I am checking to make sure that raising the voltage in our island will not negatively impact other restoration efforts.
30	RC:	East, this is RC. After the Locher unit has increased the voltage at Central's Moses substation, will there be sufficient Megavar reserves remaining?
31	East:	RC this is East. Locher has the Megavars reserves to sufficiently raise the voltage at Moses.
32	RC:	East and Central, this is RC.
33		*<East Acknowledge> <Central Acknowledge>*
34		Coordinate and raise voltage at Central's Moses substation.
35	East:	RC this is East: 10-4.
36	Central:	RC this is Central: 10-4.
37	East:	Central this is East. Since we have concurrence from the RC I suggest we increase the output Locher in 50 MVAR increments until your voltage differential is reduced to the required level.
38	Central:	East this is Central: 10-4, we'll monitor voltage while you change the output at Locher.
39	East:	Central, the output at Locher has been increased by 50MVAR; by how much did that affect the voltage at Moses?
40	Central:	East this is Central. We are still seeing the same voltage level at Moses, there is no apparent change. Could you try raising the output by another 50MVAR?
41	East:	10-4 Central. Raising increasing Locher reactive output an additional 50MVAR
42		Central this is East. We are seeing an increase on the output of Locher and increased voltage at Moses.
43	Central:	East, could you try raising the output by another 50MVAR
44	East:	10-4. Give me a minute.
45	Central:	10-4. Appreciate it.
46	East:	Central, Locher output has been increased another 50 MVAR and the voltage at Locher

Step	Speaker	Conversation
		has increased further. Are you seeing any increase in voltage at Moses?
47	Central:	East this is Central. The voltage is still unchanged at Moses. I also noticed that the line flows on the 230kV Moses to Locher line has not changed, even though I have indications that the breakers at both ends are closed. I will check with the RC to see if their indications are consistent with what we are seeing.
48	East:	Central, I agree.
49	Central:	Central to RC.
50		<RC Acknowledges>
51		East has increased the Megavar output on the Locher unit and is seeing local voltage increase. The voltage on the Moses, however, has not changed. Additionally, we are not seeing indications of increased line flows on the Moses to Locher line, but the breakers on both sides indicate that they are closed. Can you confirm what you are seeing?
52	RC:	Central this is RC… wait one.
53		My system is indicating that the bus and line breakers at the Locher end of the Moses to Locher line are closed and the bus breaker at the Moses end of the Moses to Locher line are closed. But there is no Megawatt flow and only a small amount of Megavar flow. This seems to indicate that breakers t Moses amight be open. The fact that the voltage at Moses is not changing seems to confirm this.
54	Central:	RC this is Central. Since we are all seeing the same indications I suggest that we send personnel to manually inspect the position of Moses breaker 5..
55	RC:	Central this is RC. That's a good idea. I think we should visually inspect the position of breaker 5 at Moses
56	Central:	Central to RC. Agreed. We will visually inspect the breaker at Locher and Moses and report back.
57	RC:	East this is RC.
58		<East Acknowledges>
59		East, we suggest you back down the Megavar output of Locher in order to facilitate the closing of any breaker that is found to be open while indicating closed.
60	East:	RC this is East. 10-4
61		RC this is East. Locher 1 MVAR output has been reduced 150MVAR.
62		<RC Acknowledges>
63	Central:	RC this is Central.
64		<RC Acknowledges>
65		We have visually inspected the Moses to Locher breaker 5 and found that it is actually open even though our SCADA is indicating that it's closed. So Central and East are currently not connected.
66	RC:	Central this is RC. Confirming, visual inspection has shown the 230kV Moses to Locher breaker 5 in the open position contrary to SCADA indications. East and Central are operating as independent islands.
67	East:	RC this is East. East concurs. We are not connected to Central.
68	RC:	Central this is RC.
69		<Central Acknowledges>
70		We will update our status boards and make a note in our system that the present line status was incorrect. Central, what are your plans to fix this fault indication?
71	Central:	RC this is Central. Since this line is already out of service we are in the processes of having the faulty micro-switch repaired. We hope to have the faulty micro-switch replaced by the end of the day.
72	RC:	10-4 Central. Since the line will be out of service for repairs to the breaker we will not interconnect Central and East at this time. Central, you will need to find a way to adjust voltage to interconnect with West without the aid of East.
73		*<East Acknowledge> <Central Acknowledge>*
74	Central:	West this is Central.
75		<West Acknowledges>
76		We attempted to coordinate with East to raise the voltage in our island but it was discovered that we are not currently connected to East. We thought that we were but there was a faulty breaker position indicator at Moses. We will have to determine how to reduce the voltage difference ourselves.
77	West:	Central this is West. The restoration of the distribution load centers is taking longer than expected, the line crews are stretched pretty thin; it will still be at Central 6 hours to

Step	Speaker	Conversation
		restore 138 kV load centers.
78	Central:	10-4. The voltage difference is still too high and we can't wait for restoration of the 138kV load centers. Do you have any cap banks at Homer that can be switched out of service?
79	West:	No, the only Megavar injections at Homer are from the 230kV Homer-Moses line which is connected at our end but open on your end.. The Homer - Moses 230 kV line produces about 15 MVAR at no load.
80	Central:	If you opened the 230kV Homer breaker and isolated the 230kV Homer-Moses line, would that significantly impact the voltage level at any of the other substations in your island?
81	West	It would lower the voltage at Homer but the voltage level at the other sub-stations shouldn't cause any problems.
82	Central:	Ok West. I suggest that you open the 230 kV Homer breaker 1, isolate the 230 kV line and we close the 230 kv breaker on our side. This will transfer the line capacitance from your system to ours and should lower the voltage at Homer and raise the voltage at Moses.
83	West:	West-(to Central): I agree. Let's confirm with the RC before we proceed.
84	Central:	Central to RC.
85		<RC Acknowledges>
86		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.
87		West will open the 230 kV Homer breaker 1. 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.
88	RC:	Central 10-4. West are you listening in?
89		<West Acknowledges>
90		This seems like a valid plan. Let me confirm: West will open breaker 1 at Homer. Central will then close the breaker 8 at Moses. This will switch the proposed tie point to the Homer end of the 230kV Moses to Homer line. The capacitance of the 230 kV line will be used to enhance the voltage on the Central side while lowering the voltage on the West side. Is that correct, Central?
91	Central:	RC, Central. That is correct.
92	RC:	RC to West, do you concur with this plan?
93	West:	RC this is West. We concur.
94	RC:	Central and West, this is RC. Proceed with that plan. Please keep me informed.
95		<Acknowledge West> <Acknowledge Central>
96	West:	West to Central.
97		<Central Acknowledges>
98		Central, we will now open the Homer breaker 1. Standby
99		The Homer breaker, 1, indicates open.
100		The Homer breaker 1 now indicates open on our system. The voltage at Homer is _____kV.
101	Central:	1-4, West. Breaker 1 at Homer now indicate open. We are now closing the 230kV Moses breaker 8. Standby.
102		The 230kV Moses breaker 8, indicates closed. The voltage at Moses is reading _____kV.
103	West:	Roger that, Central. Our EMS confirms breaker 8 at Moses closed with a voltage of _____kV.
104	RC:	West and Central this is RC
105		<Central Acknowledges> <West Acknowledges>
106		Since all requirements of the Interconnection Checklist have been met, West and Central, you are clear to interconnect your islands. Inform me when it is complete so we can continue with the restoration plan.
107	Central:	RC this is Central: 10-4. The Interconnection Checklist is complete and Central and West will attempt to connect our two islands.
108		Central to West.
109		<West Acknowledges>
110		RC has given approval to connect our two islands. The last step is for you to close the 230 V Homer breaker, breaker 1. Do you agree?
111	West:	Central this is West. West agrees that the voltage, frequency and phase are within spec according to the Interconnection Checklist for closing the 230 kV breaker, 1.

Step	Speaker	Conversation
112		Closing. Homer 1. Standby
113		The 230 kV Homer breaker, 1, is now indicating closed on our end and we are seeing Megawatts and Megavar transfers across the line.
114		<Central Acknowledge>
115	Central:	10-4, West. Our SCADA is also indicating breaker 1 is closed and that there are Megawatt and Megavar flows on the line.
116	West:	West to RC:
117		<RC Acknowledges>
118		We have closed the 230 kV Homer breaker 1 and the 230kV Homer-Moses line is now in service. West and Central are now interconnected.
119	RC:	RC-(to West): 10-4 West and Central. We also show the 230 kV Homer to Moses line closed and power transfers on that line. The West and Central areas are connected.

RPD Analysis of the Scenario Script

The RPD analysis is performed by examining the Script, step by step, and adding "analysis" columns that point out critical observations that reflect correct, incorrect, or missing cues, mental models, and actions:

- The cues that are actually monitored in comparison to the cues that should be monitored.
- The mental models that are actually applied in comparison to the mental models that should be applied.
- The actions that are actually considered in comparison to the actions that should be considered.
- The actions that are actually applied in comparison to the actions that should be applied.
- The story that is actually developed in comparison to the story that should be developed.

The full analysis is summarized in Table 1-1.

Table 1-1. Analysis Summary

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
1	RC:	RC to West. RC to Central:									
2		*<West Acknowledge> <Central Acknowledge>*									
3		Per the restoration plan the next step is to tie the West Island and the Central Island together. To do this it will be necessary to close the 230kV Moses to Homer breaker, breaker 8..	Restoration plan, Island, Breaker	Tie islands, Close breaker					Know there are two islands		
4	Central:	10-4. This is Central. We acknowledge				Tie two islands together		Two electrical islands rotating asynchronously			
5		My indications show voltage mismatch across the 230kV Moses to Homer breaker 8. The value exceeds the 1 kV limit indicated in the restoration checklist. I cannot close the breaker.	voltage mismatch, 1 kV limit, restoration checklist	show voltage mismatch			Voltage difference across open breaker	Line charging into weak bus causes voltage rise	Monitoring bus voltages		*For this scenario it is assumed that the voltage differential must be less than 1 kV in order to safely synchronize and close a breaker.*
6	West:	West to RC									
7		*<RC Acknowledge>*									
8		I am seeing the same indications	indications	seeing indications							
9	RC:	10-4 West. RC to West and Central:									
10		*<West Acknowledge> <Central Acknowledge>*									
11		Coordinate to equalize voltage across the 230kV Moses to Homer breaker 8.. Once you've agreed on a plan, contact me prior to synchronizing the two islands.	voltage	equalize voltage, coordinate, synchronize islands		Coordinate and equalize voltage		Misses mental model that the unloaded Homer - Moses line is a capacitor	Misses mental model that the unloaded Homer - Moses line is a capacitor		
12	West:	This is West: 10-4									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
13	Central:	This is Central: 10-4									
14	West:	West to Central:									
15		<Central acknowledge>									
16		Is there anything you can do at the Moses substation to raise the voltage?	voltage	raise voltage							
17	Central:	No, is there anything you can do to lower the voltage at Homer?		lower voltage				Misses mental model that the unloaded Homer - Moses line is a capacitor	Misses mental model that the unloaded Homer - Moses line is a capacitor		
18	West:	We don't have any voltage control devices at Homer, or any adjacent substation.	voltage control devices, adjacent substations					Homer 230 kV is a weak bus, because it is being fed from the 69 kV system. Misses mental model that the unloaded Homer - Moses line is a capacitor. Misses the standard operating procedure on Open Weak end First or Close the Strong End First.	Homer 230 kV is a weak bus, because it is being fed from the 69 kV system. Misses mental model that the unloaded Homer - Moses line is a capacitor. Misses the standard operating procedure on Open Weak end First or Close the Strong End First.		
19	Central:	West, do you have an estimate on how long it will take for the restoration to lower voltage by that level?	level	restoration to lower voltage							

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
20	West:	I would estimate at Central another six hours before we can begin to lower the Homer sub-station voltage to a level that would allow closing the 230kV Moses breaker 8. Are there any actions that you can take outside of the Moses substation to raise the voltage?	substation voltage, level to allow closing, outside substation, another six hour	begin to lower substation voltage				Substation operators are restoring feeders as MW MVAR load is added voltages will decrease			
21	Central:	Within our current island we have no way to raise the voltage. We are connected to East. I can check with them and see if they can help raise the voltage on our side.	current island	raise voltage, connected to East	no way to raise voltage			Again misses mental model that the unloaded lineHomer-Moses Line is a capacitor	Again misses mental model that the unloaded lineHomer-Moses Line is a capacitor		*At this point the Central operator believes that they are connected to the East system through the 230kV Locher - Moses line. What none of the operators realize is that the 230kV Moses to Locher line is open but due to a faulty micro switch on the breaker it indicates closed. Since status indication is in the micro switch, all remote indications of the breaker are incorrect.*
22	Central:	East this is Central									
23		<East Acknowledges>									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
24		We are trying to synchronize our island with West but the voltage differential is too high to synchronize across the breaker. West is not able to lower their system voltage due to Megavar constraints and we do not have any method to raise voltage. Do you have any resources to raise the voltage in our system?	voltage differetial across breaker, MVAr constraints, method to raise voltage, resources to raise voltage	trying to synchonize, synchronize across breaker, lower system voltage, raise system voltage					Know voltage difference across breaker is too high to synchronize		
25	East	Central, at present we have Locher generator connected and operating at nominal levels. We could increase its Megavar output to raise voltage. We will need to check with the RC to make sure that changing the voltage by this level will not interfere with other restoration efforts.	generator, nominal levels, generator MVAR output, other restoration efforts	Increase Megavar output, raise voltage, changing the voltage, interfere with restoration efforts	Locher generator connected and operating at nominal levels. We could increase its Megavar output to raise voltage. We will need to check with the RC to make sure that changing the voltage by this level will not interfere with other restoration efforts.			Locher generators can raise voltage and increase MVAR output	Understand how Locher generators can raise voltage and increase MVAR output but this will not be applicable		*Locher Power Station contains 1 1200 MW unit. Sincethe units is already running, they are able to change reactive power output in a short period of time.*
26	Central:	Sounds good. Let's proceed. The 230kV is lightly loaded, it should be able to handle additional Megavar flow.	The 230 Kv, megavar flow		230 kV line is lightly loaded, Able to handle additional Megavar flow			230 KV line is closed at both ends and is serving some small load	Assme 230 KV line is closed at both ends and is serving some small load but it is really open		*At this point the operators are seeing that the line appears in service, and are misinterpreting reactive line charging as a light load. The light reactive loading is due to the transmission line characteristics.*
27	East:	RC this is East									
28		<RC Acknowledges>									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
29		I have a request from Central to increase the Megavar output of Locher in order to raise their system voltage so they can connect to West. I am checking to make sure that raising the voltage in our island will not negatively impact other restoration efforts.	Request, System Voltage,						Normally would be a good mental model of future but not applicable in this case.		
30	RC:	East, this is RC. After the Locher unit has increased the voltage at Central's Moses substation, will there be sufficient Megavar reserves remaining?	voltage, substation, MVAR reserves remaining	increase voltage,	Will their be sufficient Megavar reserves remaining			D curve for Locher units. Needs MVAR reserves to add more load and handle contingencies			
31	East:	RC this is East. Locher has the Megavars reserves to sufficiently raise the voltage at Moses.						Unit has MVAR reserves - D curve. Unit AVR control Loop in Auto	Unit has MVAR reserves - D curve. Unit AVR control Loop in Auto		
32	RC:	East and Central, this is RC.									
33		*<East Acknowledge> <Central Acknowledge>*									
34		Coordinate and raise voltage at Central's Moses substation.		coordinate and raise voltage							
35	East:	RC this is East: 10-4.									
36	Central:	RC this is Central: 10-4.									
37	East:	Central this is East. Since we have concurrence from the RC I suggest we increase the output Locher in 50 MVAR increments until your voltage differential is reduced to the required level.	concurrence from RC, 50 MVAR increment in output, voltage differential, reqquired level	increase MVAR output				Increasing MVARs at Locher will raise voltage Locher and at Moses. MVARs flow downhill on voltage. Tent and pole analogy. Based on Locher being connected to Moses being connected to	Normally would be a good mental model by not applicable in this case.		

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
								Moses			
38	Central:	East this is Central: 10-4, we'll monitor voltage while you change the output at Locher.		mointor voltage							
39	East:	Central, the output at Locher has been increased by 50MVAR; by how much did that affect the voltage at Moses?								Locher raised by 50 MVAR	
40	Central:	East this is Central. We are still seeing the same voltage level at Moses, there is no apparent change. Could you try raising the output by another 50MVAR?					No increase in voltage at Moses.	The cues are not matching with the assumed Mental Model	The cues are not matching with the assumed Mental Model		
41	East:	10-4 Central. Raising increasing Locher reactive output an additional 50MVAR								Locher raised by 50 MVAR	
42		Central this is East. We are seeing an increase on the output of Locher and increased voltage at Moses.					Increase in MVAR output of Locher.				
43	Central:	East, could you try raising the output by another 50MVAR									*At this point the operators are not considering the possibility that the interconnecting transmission line might not be in service.*
44	East:	10-4. Give me a minute.									
45	Central:	10-4. Appreciate it.									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
46	East:	Central, Locher output has been increased another 50 MVAR and the voltage at Locher has increased further. Are you seeing any increase in voltage at Moses?								Locher raised by 50 MVAR	
47	Central:	East this is Central. The voltage is still unchanged at Moses. I also noticed that the line flows on the 230kV Moses to Locher line has not changed, even though I have indications that the breakers at both ends are closed. I will check with the RC to see if their indications are consistent with what we are seeing.	line flows, indications on breakers, line ends	check with RC for consistency	voltage is unchanged, line flows not changed, indications that breakers are closed		No voltage increase at Moses. No increase in flows on Moses-Locher line. Breakers closed at both ends	Flows and voltages are not agreeing with mental model of lines between Locher and Moses	Flows and voltages are not agreeing with mental model of lines between Locher and Moses		
48	East:	Central, I agree.									
49	Central:	Central to RC.									
50		<RC Acknowledges>									
51		East has increased the Megavar output on the Locher unit and is seeing local voltage increase. The voltage on the Moses, however, has not changed. Additionally, we are not seeing indications of increased line flows on the Moses to Locher line, but the breakers on both sides indicate that they are closed. Can you confirm what you are seeing?	local voltage increase, indications of increase line flows, both sides		seeing local voltage increase, not seeing indications of increased line flows, breakers both sides indicate closed				Are suspecting pattern of line end open even though the breakers indicate closed.		
52	RC:	Central this is RC… wait one.									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
53		My system is indicating that the bus and line breakers at the Locher end of the Moses to Locher line are closed and the bus breaker at the Moses end of the Moses to Locher line are closed. But there is no Megawatt flow and only a small amount of Megavar flow. This seems to indicate that breakers t Moses amight be open. The fact that the voltage at Moses is not changing seems to confirm this.	bus breaker, line breaker, end of line, Megawatt flow, Megavar flow		breakers are closed, voltage is not changing			Flows and voltages are not agreeing with mental model of lines between Locher and Moses			
54	Central:	RC this is Central. Since we are all seeing the same indications I suggest that we send personnel to manually inspect the position of Moses breaker 5..	indications, personnel, position of breaker	send personnel, personnel to manually inspect position of breaker							
55	RC:	Central this is RC. That's a good idea. I think we should visually inspect the position of breaker 5 at Moses		visually inspect position of breaker		Visually inspect breakers					
56	Central:	Central to RC. Agreed. We will visually inspect the breaker at Locher and Moses and report back.									*At this point Central sends linemen to visually inspect the breaker at Moses. As we'll see in a moment, the 230kV Moses breaker 5 is found to be open, contrary to indications.*
57	RC:	East this is RC.									
58		<East Acknowledges>									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
59		East, we suggest you back down the Megavar output of Locher in order to facilitate the closing of any breaker that is found to be open while indicating closed.		back down Megavar output, facilitate closing of breaker, open while indicating closed		Back MVAR output of Locher			Correctly projecting that backing down		
60	East:	RC this is East. 10-4									
61		RC this is East. Locher 1 MVAR output has been reduced 150MVAR.			Mvar output has been reduced					Locher output decreased by 150 MVAR	
62		<RC Acknowledges>									
63	Central:	RC this is Central.									
64		<RC Acknowledges>									
65		We have visually inspected the Moses to Locher breaker 5 and found that it is actually open even though our SCADA is indicating that it's closed. So Central and East are currently not connected.	SCADA		have visually inspected, found actually open, SCADA indicating closed		Visual inspectio n confirms breaker is open and telemetr y is incorrect		Confirmed that breaker is showing closed but is really opened.		
66	RC:	Central this is RC. Confirming, visual inspection has shown the 230kV Moses to Locher breaker 5 in the open position contrary to SCADA indications. East and Central are operating as independent islands.	visual inspection, open position, SCADA indications, independent islands		operating as independent islands						

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
67	East:	RC this is East. East concurs. We are not connected to Central.			are not connected						
68	RC:	Central this is RC.									
69		<Central Acknowledges>									
70		We will update our status boards and make a note in our system that the present line status was incorrect. Central, what are your plans to fix this fault indication?	status boards, note in system, line status, fault indication	update status boards, make a note in system, fix fault indication		Update status boards and note status incorrect					
71	Central:	RC this is Central. Since this line is already out of service we are in the processes of having the faulty micro-switch repaired. We hope to have the faulty micro-switch replaced by the end of the day.	fault micro switch		line is out of service, in process of repairing faulty micro-switch, hope to have replaced by end of day.						
72	RC:	10-4 Central. Since the line will be out of service for repairs to the breaker we will not interconnect Central and East at this time. Central, you will need to find a way to adjust voltage to interconnect with West without the aid of East.		will not interconnect, adjust voltage, interconnect with west						Decision to leave line out of service	*Due to other restoration concerns East will not be involved any further in the attempts to connect West with Central.*
73		*<East Acknowledge> <Central Acknowledge>*									
74	Central:	West this is Central.									
75		<West Acknowledges>									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
76		We attempted to coordinate with East to raise the voltage in our island but it was discovered that we are not currently connected to East. We thought that we were but there was a faulty breaker position indicator at Moses. We will have to determine how to reduce the voltage difference ourselves.	faulty breaker position indicator	discovered not connected to east, reduce voltage ourselves	We are not currently connected to East. We thought we were connected. There was a faulty breaker position indicator at Moses. We will have to reduce voltage difference ourselves.						
77	West:	Central this is West. The restoration of the distribution load centers is taking longer than expected, the line crews are stretched pretty thin; it will still be at Central 6 hours to restore 138 kV load centers.	distribution load centers, line crews, 138 kV load centers	restoring distribution load centers	Restoration for distribution load centers is taking longer. Line crews are stretched thin. Central to take 6 hours to restore 138 kV load centers			Substation operators are restoring feeders as MW MVAR load is added voltages will decrease			
78	Central:	10-4. The voltage difference is still too high and we can't wait for restoration of the 138kV load centers. Do you have any cap banks at Homer that can be switched out of service?	cap banks	switch cap banks out of service			Voltage differenc e remains high		Observes again that voltage difference is too high to close breaker.		
79	West:	No, the only Megavar injections at Homer are from the 230kV Homer-Moses line which is connected at our end but open on your end.. The Homer - Moses 230 kV line produces about 15 MVAR at no load.	megavar injections, MVAR at no load	line connected our end, line open your end, line produces MVARs at no load	The only Megavar injections at Homer are from the 230kV Homer-Moses line which is connected at our end but open on your end.. The Homer - Moses 230 kV line produces about 15 MVAR at no load.			Observes that Homer - Moses line is really a capacitor	Observes that Homer - Moses line is really a capacitor		

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
80	Central:	If you opened the 230kV Homer breaker and isolated the 230kV Homer-Moses line, would that significantly impact the voltage level at any of the other substations in your island?		Open breaker, isolate line and impact voltage level at substations				Opening the line and removing its charging will reduce the voltage	Realizes that opening the line and removing its charging will reduce the voltage		
81	West	It would lower the voltage at Homer but the voltage level at the other sub-stations shouldn't cause any problems.		lower voltage	Opening the Homer breaker to isolate the Homer - Moses line would lower the voltage at Homer			Voltage at Homer will be lowered	Voltage at Homer will be lowered		
82	Central:	Ok West. I suggest that you open the 230 kV Homer breaker 1, isolate the 230 kV line and we close the 230 kv breaker on our side. This will transfer the line capacitance from your system to ours and should lower the voltage at Homer and raise the voltage at Moses.	Line capacitance	Open breaker your end, islolate line, close breaker our side. Transfer the line capacitance form your system to our system. Lower voltage at Homer, raise voltage at Moses	Ok West. I suggest that you open the 230 kV Homer breaker 1, isolate the 230 kV line and we close the 230 kv breaker on our side. This will transfer the line capacitance from your system to ours and should lower the voltage at Homer and raise the voltage at Moses.			Engergizing line from Moses will raise voltage at Moses	Engergizing line from Moses will raise voltage at Moses		
83	West:	West-(to Central): I agree. Let's confirm with the RC before we proceed.									
84	Central:	Central to RC.									
85		<RC Acknowledges>									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
86		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.	west area, central area	interconnect west and central areas, transfer the line capacitance	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.				RC is confirming the mental model of line acting as capacitor and plan to transfer capacitance from West to Central.		
87		West will open the 230 kV Homer breaker 1. 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.			West will open the 230 kV Homer breaker 1. 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.						
88	RC:	Central 10-4. West are you listening in?									
89		<West Acknowledges>									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
90		This seems like a valid plan. Let me confirm: West will open breaker 1 at Homer. Central will then close the breaker 8 at Moses. This will switch the proposed tie point to the Homer end of the 230kV Moses to Homer line. The capacitance of the 230 kV line will be used to enhance the voltage on the Central side while lowering the voltage on the West side. Is that correct, Central?			This seems like a valid plan. Let me confirm: West will open breaker 1 at Homer. Central will then close the breaker 8 at Moses. This will switch the proposed tie point to the Homer end of the 230kV Moses to Homer line. The capacitance of the 230 kV line will be used to enhance the voltage on the Central side while lowering the voltage on the West side. Is that correct, Central?			RC: Confirms to plan - Everyone has the same mental model	RC: Confirms to plan - Everyone has the same mental model		
91	Central:	RC, Central. That is correct.									
92	RC:	RC to West, do you concur with this plan?									
93	West:	RC this is West. We concur.									
94	RC:	Central and West, this is RC. Proceed with that plan. Please keep me informed.									
95		<Acknowledge West> <Acknowledge Central>									
96	West:	West to Central.									
97		<Central Acknowledges>									
98		Central, we will now open the Homer breaker 1. Standby			The Homer breaker, 1, indicates open.					CB 999 Opened	
99		The Homer breaker, 1, indicates open.					Breaker 999 shows open			CB 679 Opened. Homer-Moses line now deenergized	

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
100		The Homer breaker 1 now indicates open on our system. The voltage at Homer is _____kV.			The Homer breaker 1 now indicates open on our system. The voltage at Homer is _____kV.		Breaker 679 shows open. Voltage at Homer is lowered		Operator monitors voltage at Homer		
101	Central:	1-4, West. Breaker 1 at Homer now indicate open. We are now closing the 230kV Moses breaker 8. Standby.			1-4, West. Breaker 1 at Homer now indicate open. We are now closing the 230kV Moses breaker 8. Standby.					Moses Breaker 94 closed. Homer - Moses line energized from Moses	
102		The 230kV Moses breaker 8, indicates closed. The voltage at Moses is reading _____kV.			The 230kV Moses breaker 8, indicates closed. The voltage at Moses is reading _____kV.		Breaker 94 shows closed		Operator monitors voltage at Moses		
103	West:	Roger that, Central. Our EMS confirms breaker 8 at Moses closed with a voltage of _____kV.					Voltage at Moses is raised				*At this point, the Interconnection Checklist between West, Central, and RC has been successfully completed.*
104	RC:	West and Central this is RC									
105		<Central Acknowledges> <West Acknowledges>									
106		Since all requirements of the Interconnection Checklist have been met, West and Central, you are clear to interconnect your islands. Inform me when it is complete so we can continue with the restoration plan.	Requirements of Interconnection checklist		Since all requirements of the Interconnection Checklist have been met, West and Central, you are clear to interconnect your islands..	Connect the two islands					

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
107	Central:	RC this is Central: 10-4. The Interconnection Checklist is complete and Central and West will attempt to connect our two islands.			The interconnection checklist is complete				Projection that islands can be successfully connected.		
108		Central to West.									
109		<West Acknowledges>									
110		RC has given approval to connect our two islands. The last step is for you to close the 230 V Homer breaker, breaker 1. Do you agree?									
111	West:	Central this is West. West agrees that the voltage, frequency and phase are within spec according to the Interconnection Checklist for closing the 230 kV breaker, 1.	Voltage, frequency, phase, spec		Voltage, frequency, phase are within spec			Sychroscope with voltage, frequency and phase in tolerance	Sychroscope with voltage, frequency and phase in tolerance		
112		Closing. Homer 1. Standby									
113		The 230 kV Homer breaker, 1, is now indicating closed on our end and we are seeing Megawatts and Megavar transfers across the line.	megawatt and megavar transfers	seeing megawatt and megavar transfers	The 230 kV Homer breaker, 1, is now indicating closed on our end and we are seeing Megawatts and Megavar transfers across the line.		Homer breaker 999 closed				
114		<Central Acknowledge>									
115	Central:	10-4, West. Our SCADA is also indicating breaker 1 is closed and that there are Megawatt and Megavar flows on the line.	megawatt and megavar flows	seeing megawatt and megavar flows			MW and MVAR flows on Homer - Moses Line				
116	West:	West to RC:									
117		<RC Acknowledges>									

Step	Speaker	Conversation	Objects	Action	State - current, past, projection	Objectives	Cues	Mental Models/ Simulations	Level of Situation Awareness	Actions	Narration
118		We have closed the 230 kV Homer breaker 1 and the 230kV Homer-Moses line is now in service. West and Central are now interconnected.			We have closed the 230 kV Homer breaker 1 and the 230kV Homer-Moses line is now in service. West and Central are now interconnected.			Two islands are connected with increase inertia and capacity	Two islands are connected with increase inertia and capacity		
119	RC:	RC-(to West): 10-4 West and Central. We also show the 230 kV Homer to Moses line closed and power transfers on that line. The West and Central areas are connected.		show line closed and show power transfers	west and central are interconnected						That concludes this demonstration. Please stand by while we enable your telephones to ask questions.

Illustration of Operator Performance Assessment Based on Scenario Script

SA Level 1: Perceiving critical cues

Prior to Step 79, the SA of the West, Central, and RC operators is at Level 1. They perceive the critical factors: The voltage at Homer is high and the voltage at Moses is low, but they do not seem to understand why this is happening and how it can be corrected.

SA Level 2: Understanding what the critical cues mean

In Step 79, the West operator's SA increases to Level 2. He is focusing on the MVAR injections from the closed end of the Homer–Moses line into the Homer bus and he states, "…the only Megavar injections at Homer are from the 230kV Homer–Moses line which is connected at our end but open on your end. The Homer-Moses 230 kV line produces about 15 MVAR at no load."

SA Level 3: Understanding what will happen in the near future

In Step 82, the Central operator's SA increases to Level 3. He states: "Ok West. I suggest that you open the 230 kV Homer breaker 1, isolate the 230 kV line and we close the 230 kV breaker on our side. This will transfer the line capacitance from your system to ours and should lower the voltage at Homer and raise the voltage at Moses." The Central operator understands why the voltage at Homer is high and is proposing an action to lower the voltage at Homer and increase the voltage at Moses by transferring the line capacitance from Homer to Moses.

Shared understanding

The level of coordination and sharing of information between the system operators is high.
In Steps 78 to 83, the Central and West operators interact and jointly increase their SA from Level 1 to Level 3. In Step 86 and 87, the SA of the RC is also brought up to Level 3 and the RC reiterates his Level 3 understanding in Step 90.

Finding the right mental model

The simple mental model of transferring line capacitance is the crux of the whole scenario.
The operators increased their SA from Level 1 to Level 3 only after they retrieved the mental model that an open line acts as a capacitor from their long-term memory.

Finding the correct action

This scenario reinforces the point (Endsley 1997) that when an operator has a high level of situational awareness, then the correct action can be very obvious.

Conclusion

The fact that the SA Level can be tracked for each operator in this scenario with such high precision and the fact that we can correlate this improvement in SA so directly to the retrieval of such a basic mental model suggest that the Human Factors Framework will be very useful for many applications.

More detailed monitoring of cues

The cues that were monitored during a scenario could be enumerated at a more detailed level if the simulation software were able to recreate the displays that were opened along with the state of the system as part of the playback feature. The operator and instructor could then play back the scenario and highlight the variables that were key indicators. However, this level of detailed review does not seem to be needed when there are good communications between multiple role players.

Short-Term Working Memory versus Long-Term Memory

The authors have categorized the elements in the RPD Model as follows:

- The situation and the cues are real-world elements. The situation is either the real world or some mathematical model in the simulator. The cues are also part of the real world. They are variables that are observable by the system operator through his monitoring systems (SCADA, map boards, weather, television, relays, etc.) and conversations with other system operators and his environment.

- The mental models are stored in long-term memory.

- The mental simulations, story, and action scripts are built up in real time in short-term memory.

The mental model of a line acting as a capacitor was in long-term memory for the West, Central, and RC operators. However, it was not until Step 78 that we see it being retrieved and used in short-term memory. A summary of the analysis is as follows:

- In Step 17, Central asks West, "Is there anything you can do to lower the voltage at Homer?"

- In Step 18, West responds, "We do not have any voltage control devices at Homer or any adjacent station."

  This shows that they had not considered the mental model at that time.

- In Step 78, Central asks West, "Do you have any cap banks that can be switched out of service?"

- In Step 79, West responds, "No, the only Megavar injections at Homer are from the 230 kV Homer–Moses line."

Once the connection had been made, the West, Central, and RC operators all agree immediately on a common solution with virtually no discussion. And they all accept the common mental model of transferring the line capacitance from Homer to Moses.

Underlying Premise of RPDM

The operators in this scenario reinforced the underlying premise of the RPDM. Once they identified a viable plan, they tended to quickly validate it and then attempt to put it into action.

They did not spend any time in the scenario weighing the pros and cons of different options. This was true even though the first solution that they chose was not the simplest and most effective one:

- After they found that the first solution of using the generator to raise voltage would not work because of the open breaker, they were forced to develop an alternative.
- At this point, they again quickly identified the solution to transfer the line charging capacitance for Homer to Moses.
- At no point did any operator suggest the option of changing taps at Homer.

This willingness to go with the first feasible solution is remarkable, especially given the number of participants and potential for more diversity of opinions.

Conclusion

This section has used the processes and principles of Recognition Primed Decision Making and Cognitive Task Analysis to analyze the script for the Island Synchronization Scenario. The results are very promising:

- The enhanced RPD model seems to explain the thought processes of the system operators at all the steps in the scenario.
- The system operators' SA can be rated using Endsley's three Levels at each step of the scenario.
- The mental model that is key to solving the voltage problem is very clearly identified.
- The mental simulation that the operators run using this mental model is very clearly identified.

Later in the scenario, the West Operator (Steps 79 and 81) and Central Operator (Steps 80 and 82) correctly observe that voltage at Homer can be lowered and voltage at Moses can be raised by disconnecting the Homer–Moses line from Homer and then re-energizing it from Moses. An excerpt from the scenario analysis is shown in the following figure.

79	West:	No, the only Megavar injections at Homer are from the 230kV Homer-Moses line which is connected at our end but open on your end.. The Homer - Moses 230 kV line produces about 15 MVAR at no load.		Observes that Homer - Moses line is really a capacitor
80	Central:	If you opened the 230kV Homer breaker and isolated the 230kV Homer-Moses line, would that significantly impact the voltage level at any of the other substations in your island?		Opening the line and removing its charging will reduce the voltage
81	West	It would lower the voltage at Homer but the voltage level at the other sub-stations shouldn't cause any problems.		Voltage at Homer will be lowered
82	Central:	Ok West. I suggest that you open the 230 kV Homer breaker 1, isolate the 230 kV line and we close the 230 kv breaker on our side. This will transfer the line capacitance from your system to ours and should lower the voltage at Homer and raise the voltage at Moses.		Engergizing line from Moses will raise voltage at Moses

Possible Areas for Improvement

Central and West operators could have observed earlier in the scenario that voltage at Homer can be lowered and voltage at Moses can be raised by disconnecting the Homer–Moses line from Homer and the re-energizing it from Moses. The RC directs (Step 11) the West and Central operators to coordinate to equalize the voltage. He could have advised them at this point that the voltage at Homer could be lowered and voltage at Moses could be raised by disconnecting Homer–Moses line from Homer and then re-energizing it from Moses. The Central operator states (Step 17) that he does not have any way of controlling voltage at the Moses station. He overlooks that the Homer–Moses line can be used to raise voltage at Moses. He does not take the time to consider if there are taps on adjacent transformers that can be used to control the weak bus at Moses.

	A	B	C	E
1	**Speaker**	**Conversation**	**Objectives**	**Mental Models/Simulations**
15	SPP RC:	Coordinate to equalize voltage across the 230kV East Manhattan to Concordia breaker, breaker 230-94. Once you've agreed on a plan, contact me prior to synchronizing the two islands.	Coordinate and equalize voltage	Misses mental model that the unloaded Concordia - E. Manhattan line is a capacitor
16	Sunflower:	This is Sunflower: 10-4		
17				
18	Westar:	This is Westar: 10-4		
19				
20	Sunflower:	Sunflower to Westar:		
21		<Westar acknowledge>		
22		Is there anything you can do at the E. Manhattan substation to raise the voltage?		
23				
24	Westar:	No, is there anything you can do to lower the voltage at Concordia?		Misses mental model that the unloaded Concordia - E. Manhattan line is a capacitor
25				
26	Sunflower:	We don't have any voltage control devices at Concordia, or any adjacent substation.		Concordia 230 kV is a weak bus, because it is being fed from the 115 kV system. Misses mental model that the unloaded Concordia - E. Manhattan line is a capacitor. Misses the standard operating procedure on Open Weak end First or Close the Strong End First. Misses fact that voltage of 230 kV bus is fed from the 115 kV side and could be controlled by the 230 - 115 kV transformer taps

The West operator states (Step 18) that he does not have voltage control devices at the Homer station.

- The Homer–Moses transmission line is in fact a voltage control device.

- The taps on the 230 / 115 kV transformer might also be used to control the 230 kV bus when the 230 kV bus is weak.

Possible Areas for Enhancing the Scenario

Include the enabling learning objectives: monitor and control transformer taps and auto regulation modes.

- The base case would be set up with the transformer taps in auto regulation mode.

- Operators would need to monitor tap settings and ensure regulation modes are set to manual.

- The instructor could fail to put a tap into regulation mode to reflect a bad control point.

- The operator would have to detect the tap moving over time.

- The enabling learning objectives could be extended to include identifying possible points of synchronization that have synch-scopes.

Lessons Learned for Voltage Control Under System Restoration

Lessons learned that could be pointed out during debriefings:

- Under islanded light load conditions, everything responds differently compared to normal integrated operating conditions.
- The system operates like nothing you have seen before: unless you have seen a real restoration or run a simulator.
- 230 kV buses that are normally strong may be very weak.
- Ferranti rise into a weak bus is greatly increased compared to Ferranti rise into a strong bus.
- Lines are operating close to zero MW load. They are like large capacitors.
- Cables can be even bigger capacitors.
- Watch out for runaway transformer taps.
- Put all regulators in MAN mode before energizing transformers.
- Monitor the ability to absorb reactive power in each island before energizing HV lines.

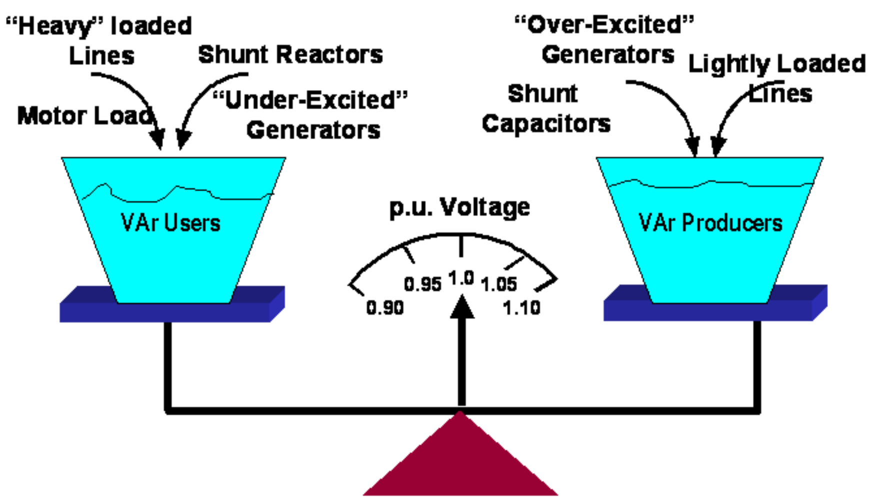
Appendix 2: Relevant Mental Models

This section enumerates the mental models that are relevant to managing power system voltages under system restoration conditions. The diagrams have been taken from the following Modules in the Emergency Operations with PowerSimulator (EOPS) Curricula:

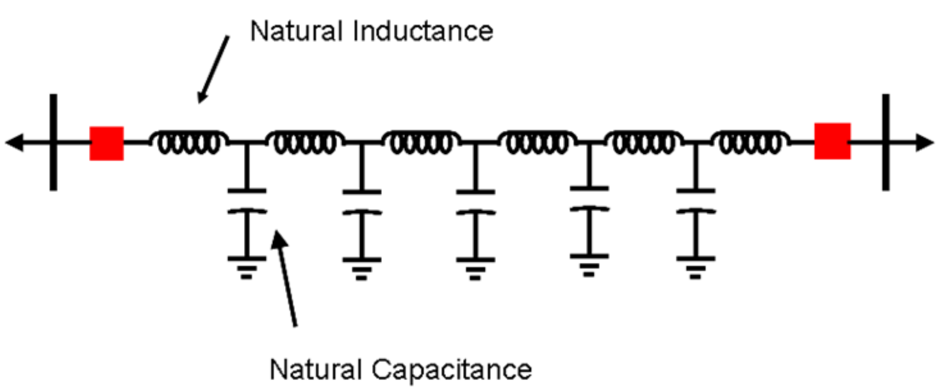
- Course 5: Preventing Voltage Collapse: Module 5.2: Voltage and MVAR Characteristics of Generators
- Course 5: Preventing Voltage Collapse: Module 5.6: Transformers
- Course 7: System Restoration: Module 7.4: Voltage and MVAR Control.

These mental models are therefore also relevant to operating the illustrative restoration scenario described in Appendix 1.

MVAR and Voltage Balance



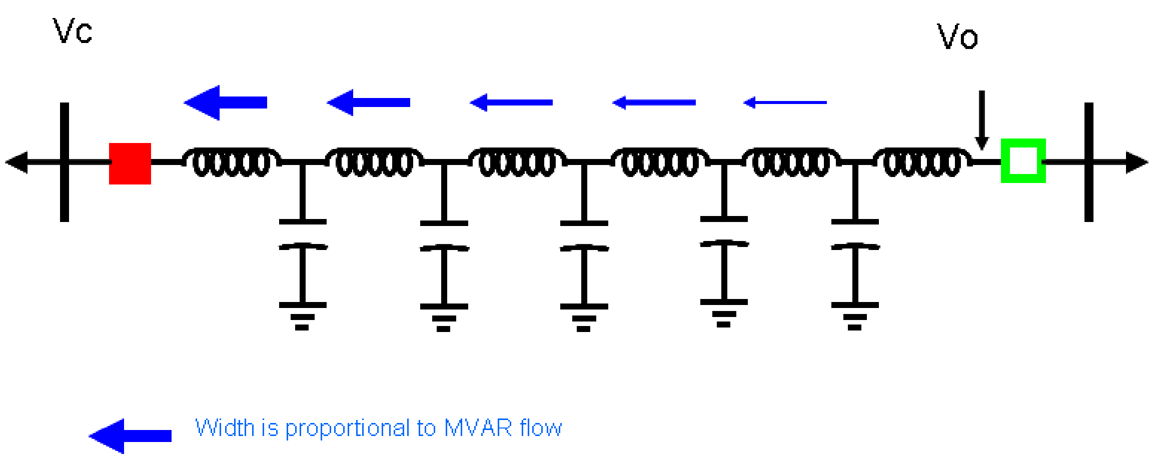
Equivalent Circuit for Overhead Transmission Line



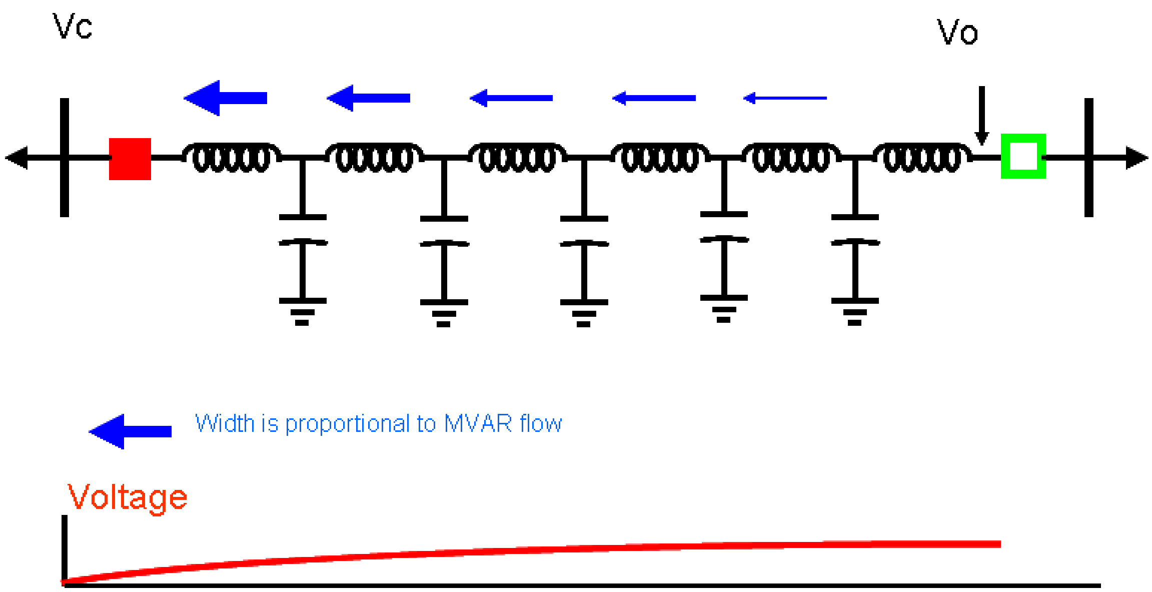
MVAR Charging for Different Voltage Lines and Cables

Transmission Line Charging	
Nominal Voltage	**MVAR/Mile**
69 kV Line	0.025
115/138 kV Line	0.1
230 kV Line	0.3
345 kV Line	0.8
500 kV Line	1.7
115/138 kV Cable	2.0-7.0
230 kV Cable	5.0-15.0
345 kV Cable	15.0 - 30.0

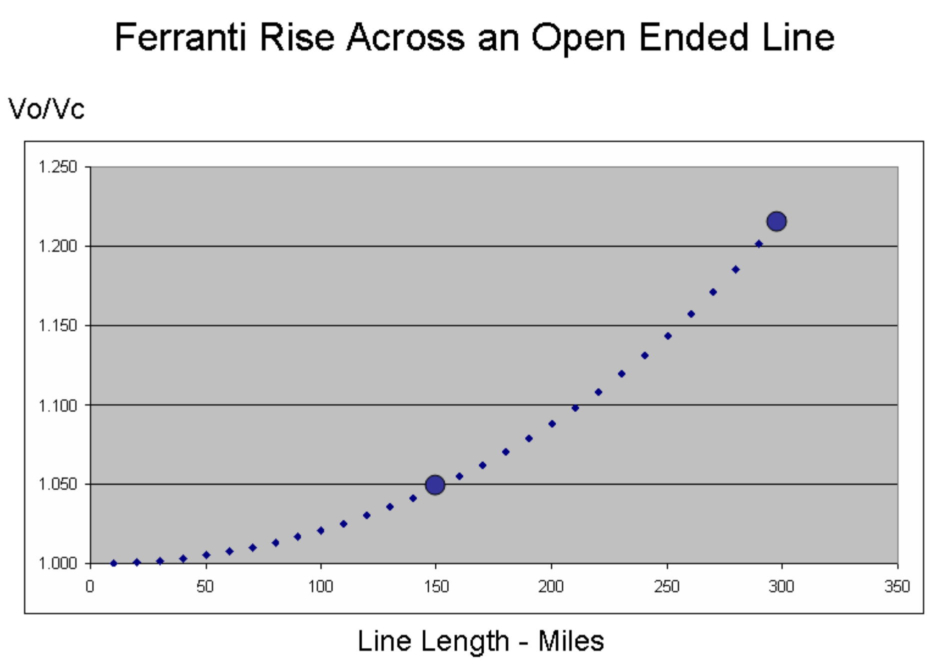
MVARs Flowing out of Open-Ended Line



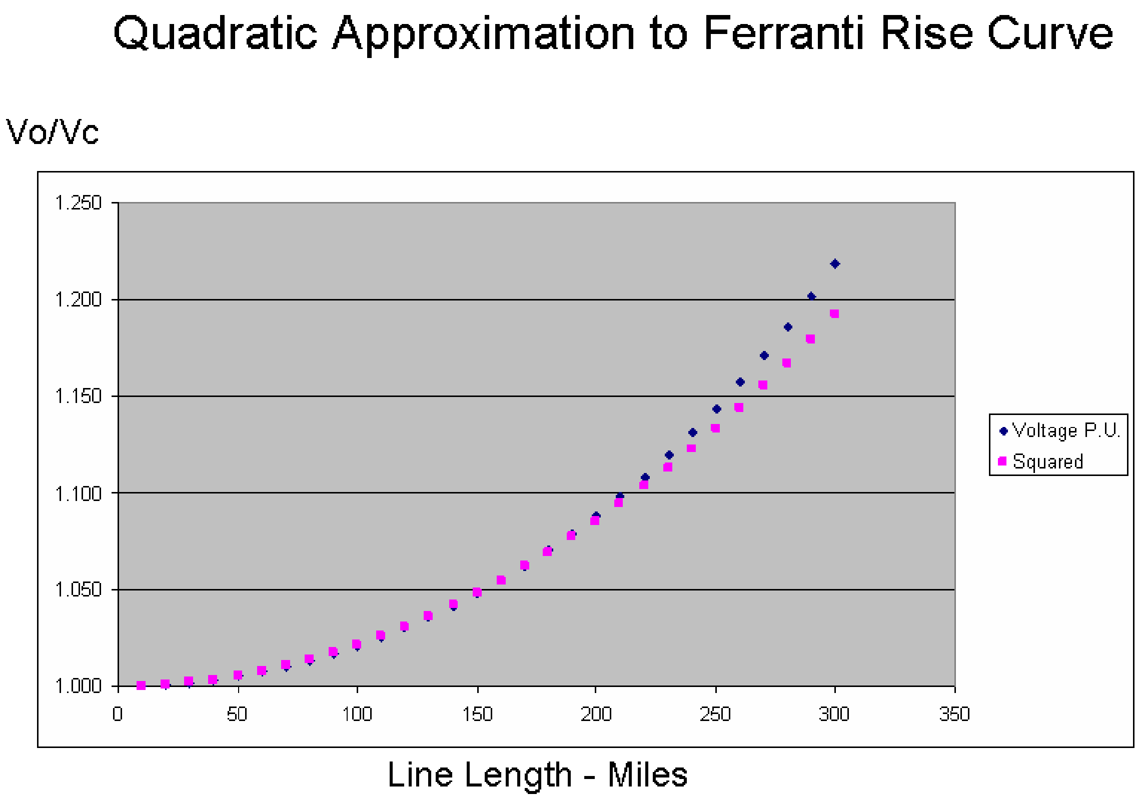
Voltage Profile Along Open-Ended Line



Ferranti Rise for Different Line Lengths



Rule of Thumb Using Quadratic Approximation



Rule of Thumb

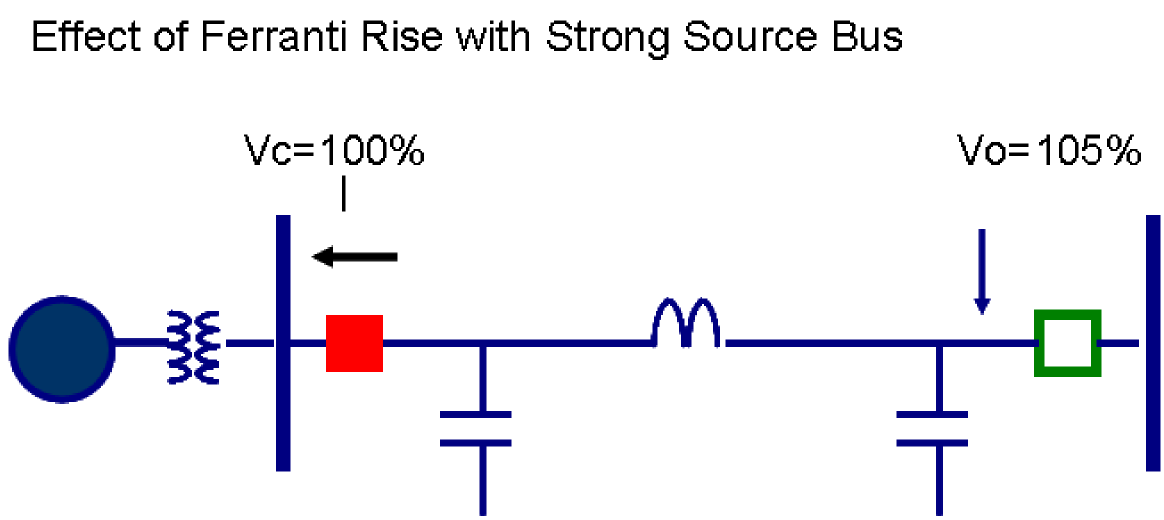
A 150-mile line of ANY voltage level produces Ferranti rise at open end of 5%.
From this you can calculate Ferranti rise for other lengths.

Strong Bus and Weak Bus

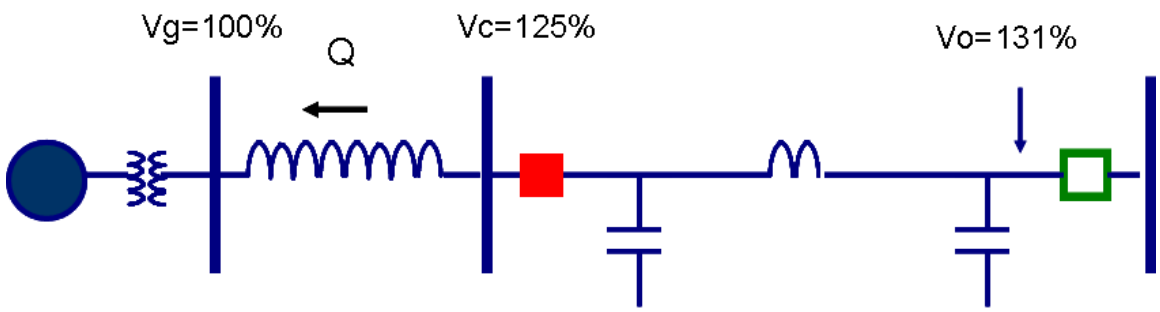
Strength of bus is measured by the per unit reactance in series to the closest regulating generator bus.

Source Bus Strength	Equivalent Impedance Between Bus at Closed End of Line and Generator Bus - Per Unit	Description	Transmission Line Example	Charging MVARs that will produce 1% Voltage Increase
1	1	Weak	Bus is attached to generator via 200 miles of 115 kV line	1
10	0.1	Strong	Bus is attached to generator via 80 miles of 230 kV line	10
100	0.01	Very Strong	Bus is attached to generator via 10 miles of 230 kV line	100
1000	0.001	Extremely Strong	Bus is attached directly to generator	1000

Effect of Ferranti Rise with Weak and Strong Source Bus



Effect of Ferranti Rise with Weak Source Bus



The voltage rise on bus at the closed end has to be added to the voltage rise along the line.

Generator MVAR Capability Curve

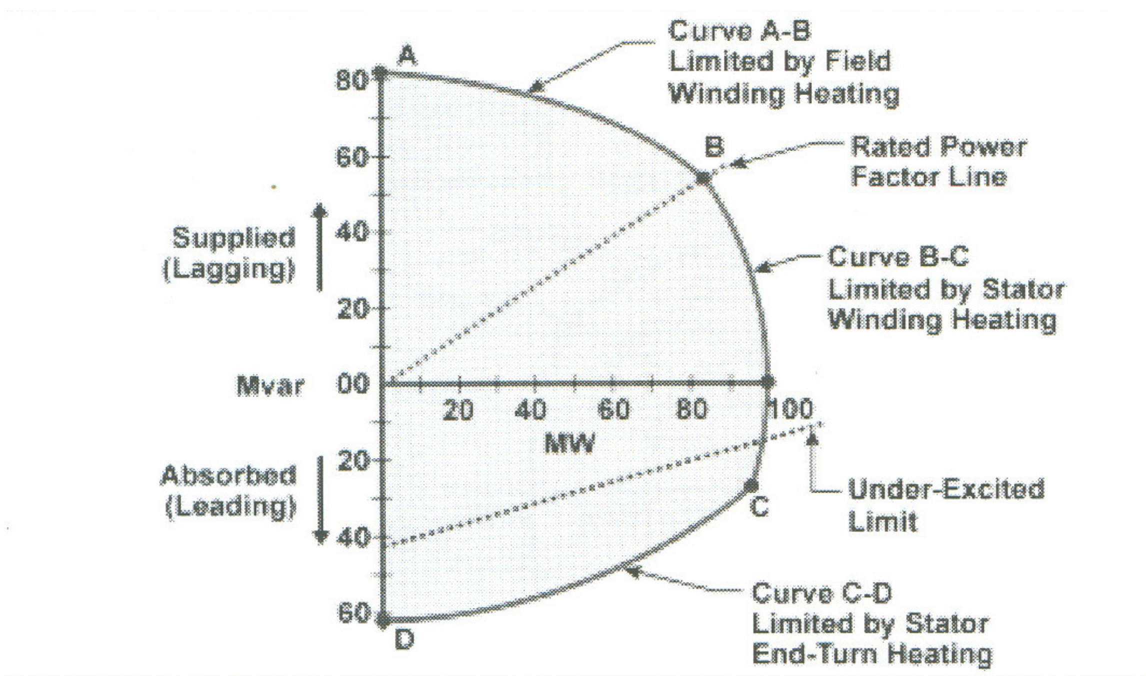
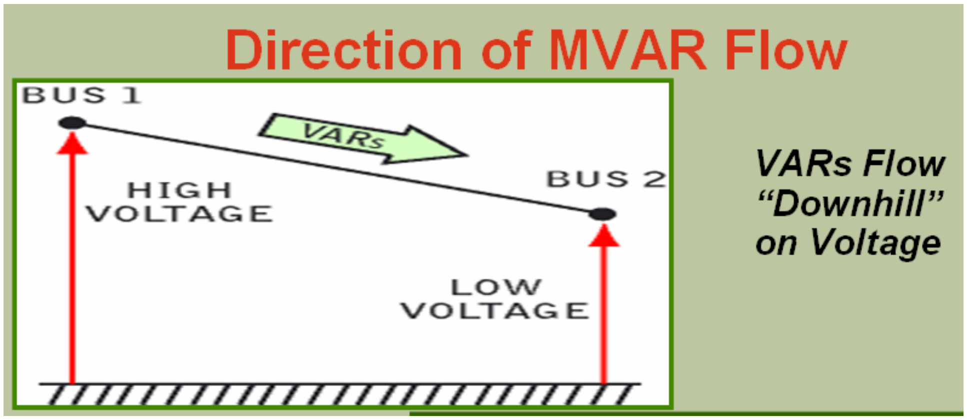
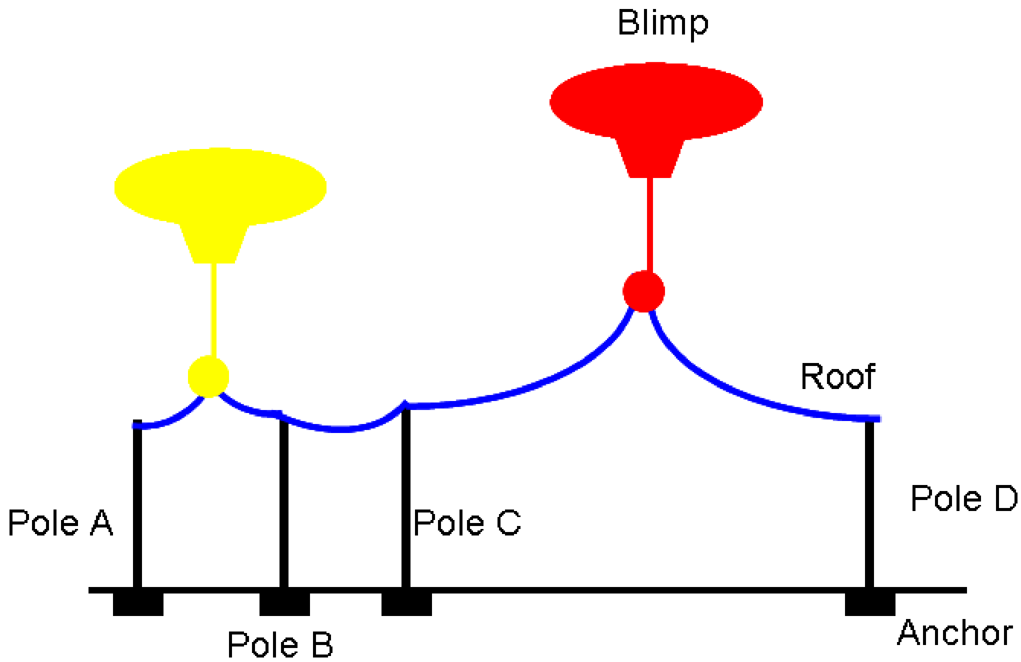


Figure 5-40
Reactive Capability Curve

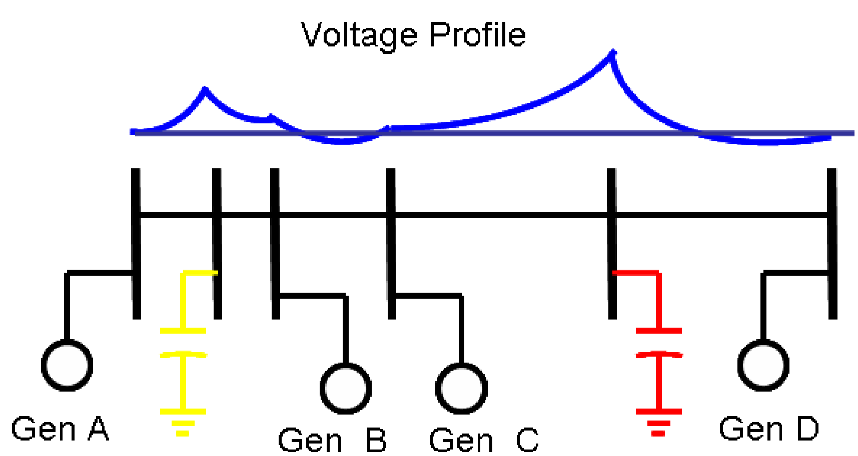
MVARs Flow Down Hill on Voltage Magnitude Difference



Tent, Pole, and Blimp Analogy for Voltage Rise

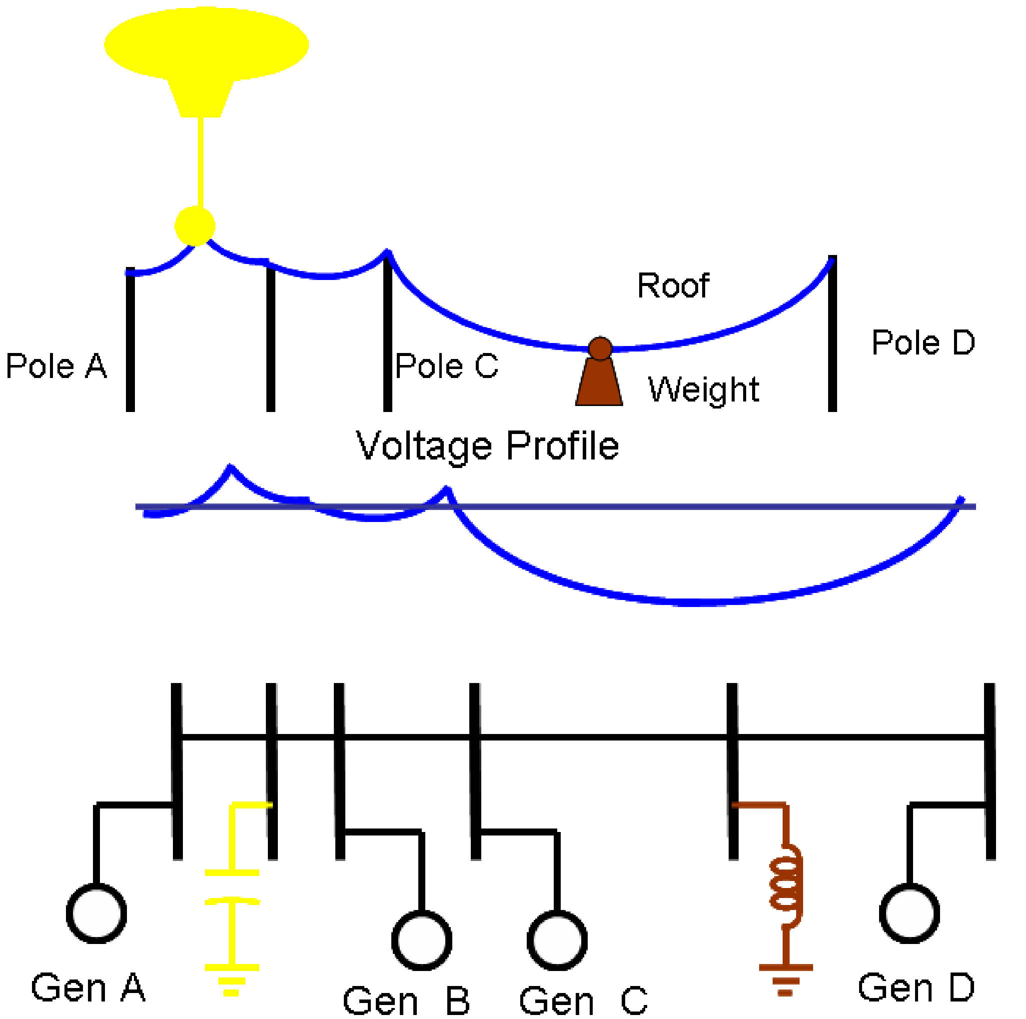


The blimp that is attached to the point in tent roof without adjacent poles raises the roof the most



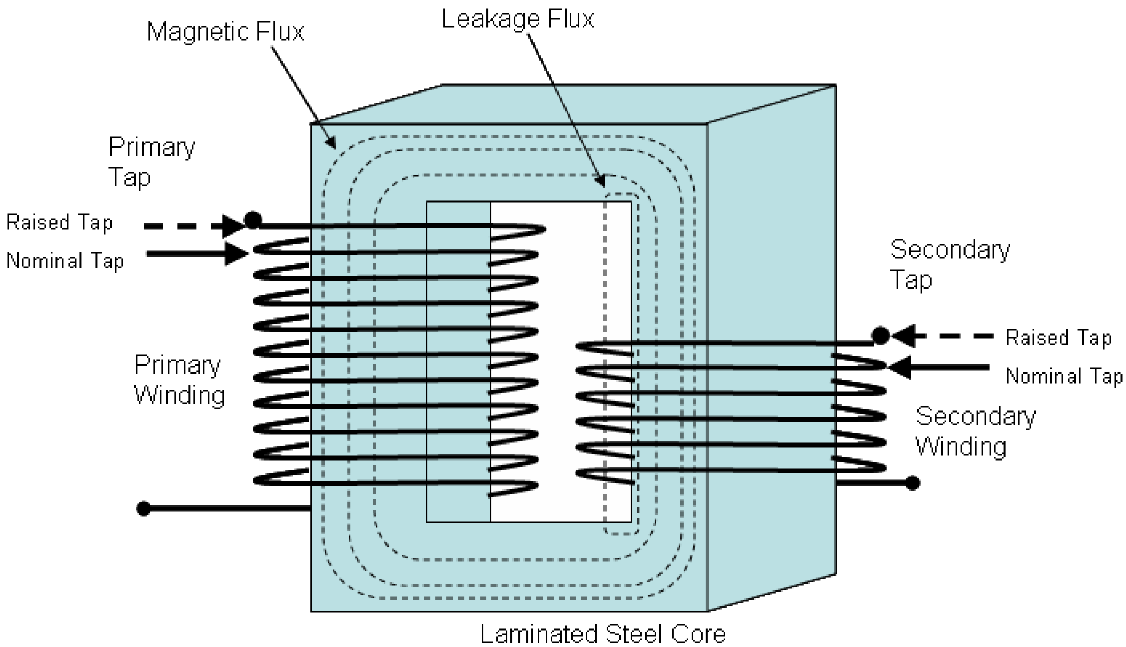
The capacitor that is attached to the point in the network without adjacent generators raises the voltage profile the most

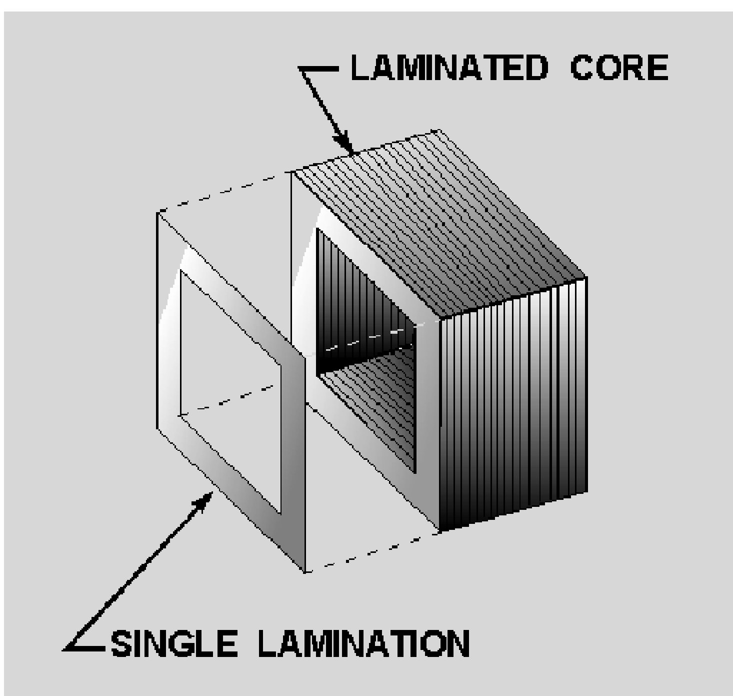
Tent, Pole, and Weight Analogy for Voltage Sag



The voltage will sag way down when an inductive load is applied at the weak bus

Diagram of Physical Arrangement of Transformer Core, Windings, and Taps

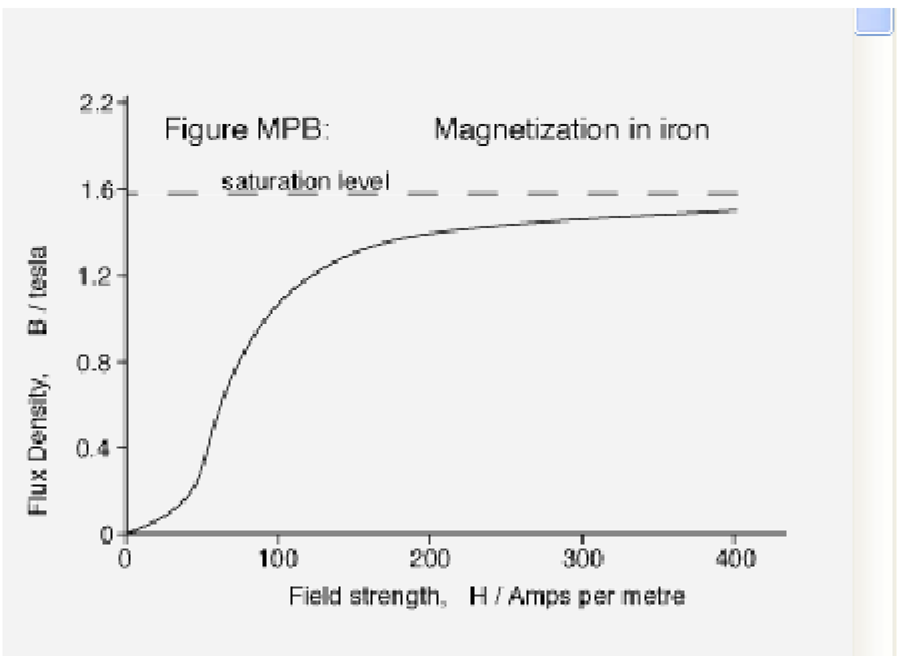




Transformer Damage with Exposure to High Voltages

The flux in the transformer core is directly proportional to the voltage and inversely proportional to the frequency. The measured Volts per Hertz ratio is therefore an excitation indication. For almost all transformers, damage occurs at an over-excitation or Volts-per-Hertz level of 1.25 pu. When the allowable Volts per Hertz ratio is exceeded, the magnetic core saturates. During saturation, excessive core flux increases the inter-lamination voltages causing iron damage (burning, pitting). Also, at this high level, the normal magnetic path cannot accommodate the increased flux, which then flows in leakage paths neither laminated nor designed to carry it, causing heat damage.

Transformer magnetizing currents increase dramatically when the transformer becomes saturated at high voltage levels. These large currents can destroy the transformer. The damage builds up over time. Transformers must not be subjected to prolonged over-voltage.



Runaway Transformer Taps

There is a danger of runaway transformer taps under the conditions shown at both the Homer and Moses stations. The Homer 230 kV and 115 kV buses are both higher than their normal operating limits. The Moses 230/115 kV transformer would normally have its automatic tap changer set to regulate the low side voltage within a specified range. If the low side voltage is high, then the regulator will adjust the tap changer to lower the low side tap based on the assumption that the 230 kV bus is a strong bus. However, in the restoration scenario, the 115 kV bus is the stronger bus. So lowering the low side tap will raise the high side voltage. This is going to aggravate the situation and could cause even more damage to the transformer.

Runaway Tap with Regulation of Low Side Bus

Low side Bus is Strong – High side Bus is Weak