Power System Restoration Following a High-Altitude Electromagnetic Pulse (HEMP) Induced Blackout

3002014579

Power System Restoration Following a High-Altitude Electromagnetic Pulse (HEMP) Induced Blackout

3002014579

Technical Update, October 2018

EPRI Project Manager

R. Horton

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

ACKNOWLEDGMENTS

The Electric Power Research Institute (EPRI) prepared this report.

Principal Investigators
N. Bhatt
V. Singhvi
R. Horton

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Power System Restoration Following a High-Altitude Electromagnetic Pulse (HEMP) Induced Blackout. EPRI, Palo Alto, CA: 2018. 3002014579.

ABSTRACT

High-altitude electromagnetic pulse (HEMP) refers to an electromagnetic pulse created by the detonation of a nuclear weapon in space. HEMP has the potential to damage the power grid over a wide area, thus interrupting power delivery. The current knowledge of HEMP impacts indicates that damage to the communications infrastructure and to the electronic-based protection and control devices known as intelligent electronic devices (IEDs) could occur should a HEMP event take place. HEMP can also damage end-use loads and distribution system components. The Electric Power Research Institute (EPRI) is engaged in a multi-year research and development (R&D) effort to investigate the potential HEMP threat by providing technically-based research results to inform assessments and mitigation decisions. One aspect of this investigation focuses on power system restoration, should a HEMP event trigger a blackout.

This report presents the state-of-the-art in power system restoration by discussing global principles and practices currently followed in the development and implementation of plans for power system restoration following a widespread blackout. The possible impacts of a HEMP event on restoration processes are identified during discussion of current restoration practices. Suggestions to improve the restoration process to be prepared for a potential HEMP event are provided. To include broader coverage (beyond HEMP) of power system restoration, appendices describe: a) the lessons learned during restoration following major global blackouts; and b) suggestions for future work in the restoration area.

Keywords

High-altitude electromagnetic pulse (HEMP)
Power system restoration
Electromagnetic pulse
Power system blackout
Blackstart resources
Cranking paths

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Background

High-altitude electromagnetic pulse (HEMP) refers to an electromagnetic pulse created by the detonation of a nuclear weapon in space. It has the potential to damage power grid assets over a wide area, thus, interrupting power delivery [1]. The current knowledge indicates that HEMP can potentially damage communications infrastructure and electronic-based protection and control devices known as intelligent electronic devices (IEDs). HEMP can also damage end-use loads and distribution system components. EPRI is engaged in a multi-year R&D effort to investigate the potential HEMP threat by providing technically based research results to inform system assessments and decisions regarding mitigation. One aspect of this investigation focuses on power system restoration, should a HEMP event trigger a widespread blackout.

This report presents the state-of-the-art in power system restoration by discussing the global principles and practices that are currently followed in developing and implementing plans for restoring a power system following a widespread blackout. During the discussion of current restoration practices, possible impacts of a HEMP event on the restoration process are indicated at appropriate places. Suggestions to improve the restoration process to be prepared for a potential HEMP event are provided. Lastly, to conclude a broader coverage (beyond HEMP) on power system restoration, appendices are included, which describe: a) experiences during restoration following major global blackouts; and b) suggestions for future work in the restoration area.

1.2 Objectives

The objective of this report is to identify the potential impacts of a HEMP event on current restoration practices and processes and provide suggestions for future work to be prepared for a HEMP event.

1.3 Report Organization

Chapter 2 discusses power system restoration principles and practices that are followed globally. The discussion is designed to provide an understanding of various elements of a power system restoration plan. At appropriate places, potential impacts of a HEMP event on the restoration process are highlighted. Chapter 3 provides a summary, with suggestions to improve the restoration process to be prepared for a HEMP event.

Two appendices are added to provide a broader perspective, beyond HEMP, of power system restoration. Appendix A summarizes restoration experiences following global blackouts, with focus on the effectiveness of restoration plans that are developed for such events. Appendix B lists suggestions to improve the effectiveness of the current power system restoration processes and practices irrespective of the underlying cause of a blackout, as well as to investigate new restoration approaches to address emerging issues such as renewable generation, distributed energy resources and high-impact low-frequency (HILF) events.

1.4 Glossary

Several terms are defined below to facilitate common understanding of key aspects of power system restoration.

- **Blackstart Resource:** A generator that can be started without an external source or can remain in service while connected to its auxiliary load
- **Council on Large Electric Systems (CIGRE):** An international non-profit association for promoting collaboration with experts from all around the world by sharing knowledge and joining forces to improve electric power systems of today and tomorrow
- **Cranking Path:** A transmission path from a blackstart generator to a non-blackstart generator or a critical load (Note: A cranking path could also extend from a cranked and online non-blackstart generator to an un-cranked non-blackstart generator.)
- **Distribution Provider:** Provides and operates the "wires" between the transmission system and the end-use customer
- **East Central Area Reliability Coordination Agreement (ECAR):** A Regional Entity that merged in 2005 within the Reliability First Corporation (RFC). RFC is one of the eight Regional Entities responsible for ensuring the reliability of the North American Bulk-Power System
- **Energy Management System (EMS):** A system made up of software/hardware/firmware used by transmission control centers to monitor and control power system performance
- **Electric Reliability Council of Texas (ERCOT):** An entity that manages the flow of electric power to more than 25 million Texas customers -- representing about 90 percent of the state's electric load (Note: As the independent system operator for the region, ERCOT schedules power on an electric grid that connects more than 46,500 miles of transmission lines and 600+ generation units.)
- **European Network of Transmission System Operators (ENTSO-E):** An entity that represents 43 electricity transmission system operators from 36 countries across Europe (Note: ENTSO-E was established and given legal mandates by the EU's Third Legislative Package for the Internal Energy Market in 2009, which aims at further liberalizing the gas and electricity markets in the EU.)
- **Extra High Voltage (EHV) Transmission Lines:** Lines rated and operated at and above 230 kV, but less than 1000 kV AC (alternating current)
- **Federal Energy Regulatory Commission (FERC):** A U.S. government agency that regulates the interstate transmission and wholesale sale of natural gas, oil and electricity
- **Generator Cranking:** Starting of an auxiliary load of a non-blackstart generator
- **Generator Operator (GOP):** An entity that operates generating facilities and performs the functions of supplying energy and auxiliary services
- **High Voltage Direct Current (HVDC) Transmission Lines:** Lines rated and operated generally in the 100 kV to 1,500 kV DC range
- **High Voltage (HV) Transmission Lines:** Lines rated and operated generally at 69 kV and above, but less than 230 kV AC (alternating current)

- **Independent Electricity System Operator (IESO):** An entity responsible for operating the electricity market and directing the operation of the bulk electrical system in the province of Ontario, Canada. It has been approved by NERC as a Reliability Coordinator (Prior to January 2005, IESO was known as Independent Electricity Market Operator (IMO).)
- **Inter-Control Center Communication Protocol (ICCP):** Protocol used to exchange real-time and historical power system data among transmission control centers
- **Midcontinent Independent System Operator (MISO):** An entity that operates power system across all or parts of 15 U.S. states and the Canadian province of Manitoba. It has been approved by NERC as a Reliability Coordinator
- **North American Electric Reliability Corporation (NERC):** A nonprofit regulatory authority whose mission is to assure the effective and efficient reduction of risks to the reliability and security of the North American electric power grid
- **Northeast Power Coordinating Council (NPCC):** One of the eight Regional Entities responsible for promoting and enhancing the reliability of the international, interconnected bulk power system in Northeastern North America
- **PJM or PJM Interconnection:** A regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of 13 U.S. states and the District of Columbia. It has been approved by NERC as a Reliability Coordinator
- **Regional Entities:** Eight (8) entities that have been approved by FERC and delegated by NERC to monitor and enforce compliance to the NERC-developed reliability standards
- **Reliability Coordinator (RC):** The entity that is the highest level of authority who is responsible for the reliable operation of the bulk power system, has the wide area view of the bulk power system, and has the operating tools, processes and procedures, including the authority to prevent or mitigate emergency operating situations in both next-day analysis and real-time operations
- **Supervisory Control and Data Acquisition (SCADA):** A system of remote control and telemetry used to monitor and control the transmission system
- **Transmission Operator (TOP):** The entity responsible for the reliability of its "local" transmission system, and that operates or directs the operations of the transmission facilities
- **Transmission Owner (TO):** The entity that owns and maintains transmission facilities

2
ELEMENTS OF A POWER SYSTEM RESTORATION PLAN

2.1 Background

Power system restoration is the process of returning generators and transmission system elements to service and restoring load following an outage of the electric system [2]. Around the world, restoration is treated as a critical aspect of power system operations and planning. Authorized entities have put in place mandatory reliability standards and grid codes that range in scope from the development of restoration plans to periodic review/testing/revision of these plans to implementation of these plans following a blackout [3-6]. Compliance is monitored by the authorized entities through reviews of submitted restoration plan materials and onsite audits. Key facilities included in a restoration plan --- for example, blackstart generators --- are classified as part of a critical and confidential facility database and are considered Critical Energy/Electric Infrastructure Information (CEII) defined by the U.S. Federal Energy Regulatory Commission (FERC) [7].

In North America, NERC, functioning as the Electric Reliability Organization, has developed reliability standards that define the reliability requirements on various issues related to planning and operating the North American bulk power system. These standards include details on applicability (i.e. entities responsible to comply), requirements, measures and compliance [3]. The NERC standards on power system restoration include EOP-005-3 and EOP-006-3, which specify the following restoration aspects [3]:

- Identification of blackstart resources;
- Identification of cranking paths from blackstart resources to the non-blackstart generators;
- Identification of load restoration to stabilize frequency and control voltages;
- Annual review and revision of restoration plan;
- Annual testing of blackstart resources;
- Periodic plan verification and testing for steady-state and dynamics performance; Compliance requires power flow and transient stability studies;
- Periodic restoration training.

The roles and responsibilities of various entities involved in the power system restoration process are outlined in Figure 2-1. (The details of restoration process are presented in the remainder of this chapter.) For the definitions of entities shown in Figure 2-1, please refer to the Glossary in Chapter 1.

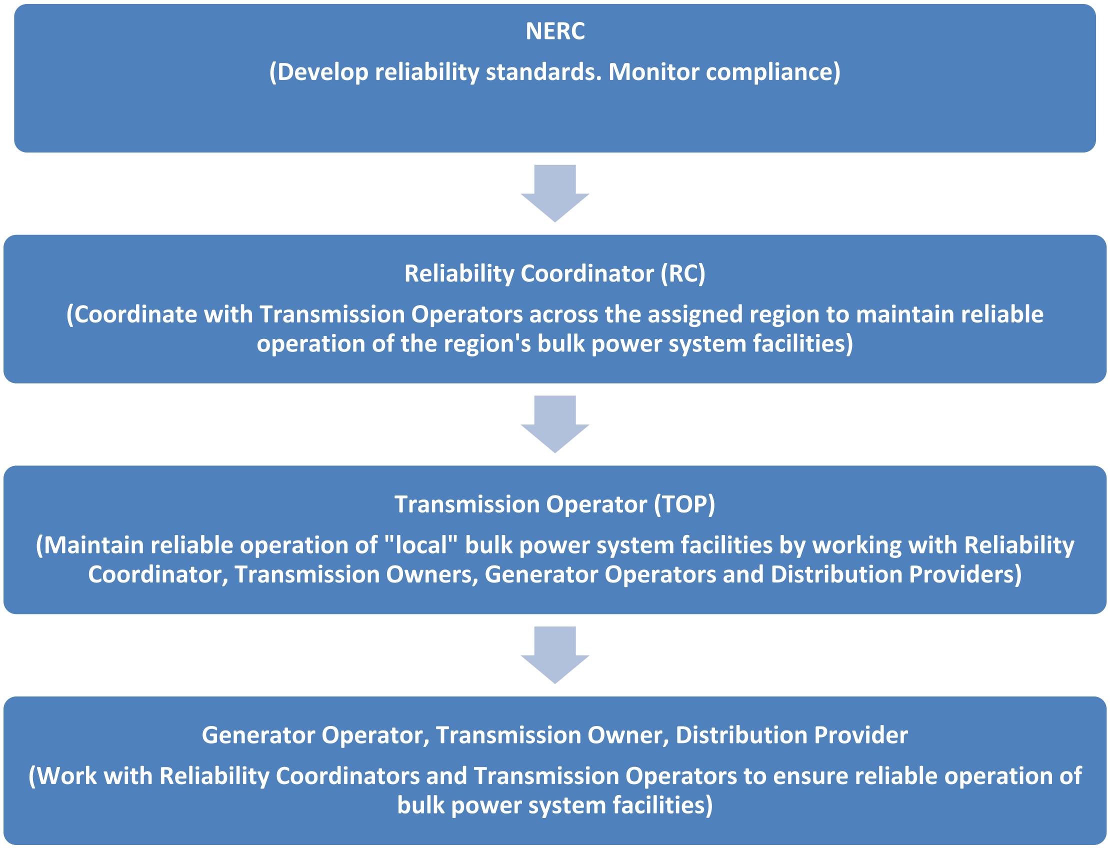

Figure 2-1
Entities Involved in Power System Restoration Process

The timeline of a restoration plan starts when a blackout (or a widespread outage) is recognized and ends when the power system reaches a normal operating state. The normal operating state is assumed to be reached when the next load to be restored is not driven by the need to control frequency or voltage [3]. The focus during restoration is on reestablishing stable operation of the power system with sufficient skeleton so that resources and supply to end-use customers can be restored as expeditiously as possible to minimize interruptions to social life and the economy [8].

A restoration plan covers a wide range of elements that include staffing, monitoring, communication, documentation, testing/validation and system-specific facility energization procedures for generators, transmission lines, transformers and loads. Some of these restoration plan elements are defined and implemented by a Reliability Coordinator (RC) that has wide area coordination responsibilities. Other elements are defined and implemented by transmission operators (TOPs) that have local transmission system responsibilities. These various restoration plan elements are discussed below beginning with Section 2.2.

Before discussing the details of a typical restoration plan, the following two reviews of global restoration processes are worth noting.

2.1.1 CIGRE – December 2017 [8]

A survey of 18 operators (i.e. RCs and TOPs) was conducted in key areas of restoration. These operators were from 12 European countries, Australia, Brazil, U.S., Canada, Japan and South

Korea. It was concluded that most operators adopt common approaches in various restoration aspects that range from developing system-specific plans to providing training to conducting drills to communicating with other operators. Also, most operators have put into place: well-structured restoration plans, communication facilities, communication protocols with other operating entities and with public entities, and adequate training and preparedness. It was observed that an overarching objective of restoration is to focus on reestablishing stable operation of the power system with sufficient skeleton so that resources and supply to end-use customers can be restored as expeditiously as possible in order to minimize interruptions to social life and businesses. Suggestions for improvement included reviews and revisions in the following areas:

- loss of SCADA/EMS/ICCP functionality;
- backup supply for data (e.g. sequence of events, relay targets, etc.) just after a blackout;
- use of HVDC transmission lines; and
- the role of renewable and distributed energy resources.

2.1.2 Joint FERC-NERC Review – January 2016 [2]

The objective of the joint FERC-NERC review [2] was to assess and verify the electric utility industry's recovery and restoration planning, and to test the efficacy of related standards. Restoration plans of nine operators (TOPs and RCs) were reviewed. It was concluded that for the most part, the plans were thorough and highly detailed. These plans required identification and testing of blackstart resources, identification of primary and alternate cranking paths, and periodic training and drills. The plans included cyber security response and recovery details for critical cyber assets. Each operator had full-time personnel dedicated to the roles and responsibilities defined in the restoration plan. Suggestions for improvement included reviews and revisions in the following areas:

- loss of SCADA/EMS/ICCP functionality;
- requirements to update a restoration plan and verification/testing of an updated plan;
- operator training;
- availability of blackstart resources and blackstart resource testing; and
- cyber incident response and recovery plans.

Various elements of a restoration plan are described next.

2.2 Restoration Strategies

As part of restoration planning by an operator (either an RC or a TOP), a worst-case total blackout scenario is assumed, with no external system help available except by a pre-arranged agreement. An operator develops its restoration plan based on electrical characteristics of its power system. An example of system characteristics is the makeup of the transmission network, in terms of dominance of HV or EHV lines and the geographic spread of these lines across the network. Another example is the makeup of generation, in terms of blackstart versus non-blackstart generators, fuel types and geographic locations.

Some operators utilize a “bottom-up” (or “core-island”) approach [9], which starts with one or more blackstart generators to develop a transmission backbone, typically made up of HV lines. Use of HV lines is preferred during the early restoration stage because the lower line charging (i.e. capacitive component of a transmission line) requirements of HV lines pose less difficulty in controlling voltages as compared with the charging of EHV lines. The transmission backbone is utilized to form cranking paths to start the area non-blackstart generators. Next, an island is formed by securing a balance between the available area generation and load.

Conversely, some operators use a “top-down” (or “backbone-island”) approach [9] that takes advantage of EHV lines and the associated generation, with islands formed by balancing available generation and load. For example, NYISO restoration procedures are based on energization of the 345 kV (EHV) transmission backbone [10], a top-down approach. Often, operators utilize a combination of both (bottom-up and top-down) approaches to take advantage of differing characteristics in various parts of their systems.

Irrespective of the approach, a restoration plan calls for the creation of multiple islands that are synchronized together after being stabilized independently. This incremental approach has advantages that include: parallel and simultaneous restoration of different transmission/ generation/load facilities; and avoiding problems in one island affecting another island.

During the restoration planning phase, a restoration strategy typically assumes that all the transmission/generation/load facilities are available to restore the power system, although some operators plan for unavailability of certain transmission facilities. As discussed later in Section 2.6.2, during an actual restoration event, the strategy is reviewed and revised based on the known availability of key facilities included in the restoration plan and of neighboring system facilities.

Following a HEMP event, communications and controls may be damaged and unavailable which could affect recovery efforts. The industry is currently developing measures to harden communications and control equipment. However, until these hardening options are implemented, it is prudent to assume widespread unavailability of, and perhaps damage to, this equipment following a HEMP event.

2.3 Staffing and Responsibilities

Power system restoration is a joint responsibility between a transmission operator (TOP) and its Reliability Coordinator (RC). A restoration plan includes:

- an RC restoration plan that defines wide area system-level restoration requirements, principles, strategies and guidelines developed by the RC; and
- TOP restoration plans that provide system-specific details developed by the member TOPs.

Each RC’s restoration plan clearly identifies roles and responsibilities of the RC and its member TOPs. The RC coordinates the restoration plans of all its TOPs and coordinates its plan with the neighboring RCs. According to the FERC January 2016 report [2], the restoration plans reviewed by FERC were generally clear and sufficient in defining the roles and responsibilities among entities. This FERC review also concluded that each operator had full-time personnel dedicated to the roles and responsibilities defined in their respective response and recovery plans [2].

From the HEMP perspective, some or all the damaged communications and control equipment may need to be repaired or replaced; thus, requiring additional technical staff and spare equipment. Such factors should be considered when developing a restoration plan to be prepared for a HEMP event.

2.4 Communication Protocols and Facilities

An RC restoration plan includes communication protocols and procedures between itself and its TOPs, with its neighboring RCs, and with the regulatory entities, government agencies, public and the media. A TOP plan includes communication protocols between itself and its RC, with the neighboring TOPs, with the generator operators, with distribution entities, regulatory entities, government agencies, the public and the media. For these various communication categories, dedicated personnel are assigned, and their responsibilities are defined. For example, NYISO's Emergency Operations Manual describes in detail its communication procedures for government and public relations notification, and for interactions with its TOPs and neighboring RCs through its Emergency Hot Line System [11].

Restoration plans also emphasize the role of various types of communication means such as voice, print (fax, email), SCADA and ICCP [9]. It is recognized that remote terminal unit (RTU) failures at substations due to HEMP (or otherwise) may result in questionable integrity of SCADA/ICCP data. Backup communication equipment and facilities are also planned for by the operators. Periodic testing of primary and backup communication equipment and training for communication personnel are often included in restoration plans.

CIGRE and FERC reports [2,8] concluded that availability of SCADA and ICCP data is critical during system restoration. Therefore, additional efforts on personnel training and exploring ways to deal with loss of SCADA/ICCP data would be helpful [2,8].

From the HEMP perspective, as mentioned above, efforts to harden the communications equipment are essential and must continue. Meanwhile, from a restoration planning perspective, it may be prudent to assume widespread damage to, and unavailability of, communications equipment following a HEMP event. Preparations could include full redundancy, sparing and hardening of all data and communication sources and equipment. In addition, field personnel can be made available for manual monitoring of key electrical quantities (perhaps using clamp-on portable analog meters) at the transmission and generating stations located along the cranking paths. Also, power flow simulations can be performed to derive or estimate electrical quantities for unmanned stations using the data received from the manually monitored stations.

To support electrical infrastructure resiliency, EPRI is investigating the impact of, and mitigation for, the loss of SCADA/ICCP/EMS data and data communications to/from a control center [12]. The outcome of this investigation can be adopted in restoration plans to improve restoration response following a HEMP-induced blackout.

2.5 RC Restoration Plans

An RC restoration plan defines wide area system-level restoration requirements, principles, strategies and guidelines for its own system-level coordination function as well as for the member TOPs' facility restoration function. A typical RC plan consists of following components:

- Applicable reliability standards or grid codes and compliance
- Restoration philosophy and strategy
- Restoration stages, process and steps
- Staffing and responsibilities
- Communications procedures/protocols/equipment considerations
- Guidelines to energize various facilities (such as transmission lines, transformers and shunt devices), to synchronize and load generators, and to restore loads
- Guidelines for power system performance monitoring and adherence (Note: Voltage and frequency performance is critical during restoration.)
- Power system protection and coordination considerations
- Island synchronization guidelines
- Guidelines for interconnection with neighboring TOPs
- Testing and validation of restoration plans and blackstart resources
- Training and drills
- Market interactions during the restoration process

Some RCs cite the assumptions they used in developing their restoration plans. Examples of such assumptions are as follows [9]:

- All generation and transmission facilities are available for service and are undamaged.
- All communication resources are functional.
- Emergency energy supply systems are operational.
- Fuel inventories are adequate.
- Substation batteries are adequate.
- All circuit breakers are operational.
- Manpower requirements can be met with available manpower.
- Additional manpower is available through existing manpower procurement procedures.

As discussed earlier, from the HEMP perspective, the assumption of availability of all facilities may not be appropriate following a HEMP-induced blackout since communication and protection and control equipment may be inoperable and perhaps damaged. Such a potential scenario should be factored in when developing restoration plans to be prepared for a HEMP-induced blackout.

2.6 Restoration Steps

The granularity of the restoration process and steps varies among RCs. For example, one RC has its high-level process broken down as Analyze, Stabilize, Restore and Return to Normal [13]. Based on a review of multiple RC restoration processes and steps documented in [10-11, 13-21], illustrative restoration steps are shown in Figure 2-2 and described below.

Figure 2-2
Illustrative Restoration Steps

2.6.1 Step 1: System Status Assessment

An immediate assessment of system conditions, including the available transmission and generation resources, is an essential first step. The SCADA and ICCP data can help with the assessment, which is dependent upon the availability of RTUs, EMS equipment and associated infrastructure. Communicating with member TOPs and neighboring RCs is also essential, which is dependent upon the availability of communication equipment and dedicated personnel. While some data may be missing due to facilities being out of service and/or damage to equipment, it is essential to review all the available data to come up with a reasonable picture of the resources that are available to initiate restoration.

2.6.2 Step 2: Determine and Implement Restoration Strategy

Based on Step 1, the restoration strategy needs to be revisited and revised by the RC to take into consideration the existing system conditions and availability of key transmission and generation facilities. This can help in coming up with a high-level restoration sequence. This revised strategy must be then communicated by the RC to the affected entities such as the TOPs and neighboring RCs.

Following a HEMP-induced blackout, Steps 1 and 2 will take on an added meaning because of the possibility of widespread loss of communications and equipment damage. It will become essential to review all the available data and to predict the unavailable data, in order to reasonably assess system status. Depending upon the confidence level for system status assessment, strategy selection (Step 2) could become challenging.

2.6.3 Step 3: Implement Restoration Procedures

TOPs can start restoring the transmission, generation and load facilities, while maintaining satisfactory voltage and frequency performance. This step also includes synchronizing islands after they have been stabilized. For this implementation step, the TOP can use the guidelines documented in its RC's restoration plan.

During the early stage of restoration, voltage and frequency performance is an extremely critical factor. Accordingly, all RCs provide guidelines on voltage and frequency performance monitoring and adherence. This involves issues such as Ferranti voltage rise, switching shunt devices, balancing generation and load, adding load following a transmission line energization, etc. For example, one RC provides the following guidelines [14]:

- In an islanded mode, during initial restoration stage, select one unit to run in isochronous mode. (Note: Isochronous governor control refers to a governor droop setting of 0%. This mode of operation results in the governor attempting to control frequency solely in accordance with the governor's frequency target value. When operating isochronously, the governor attempts to fully recover the frequency to its target value.)
- Auto MW and automatic voltage regulator (AVR) controls of generators on.
- For cranking a non-blackstart generator, the load pick-up capability of available online generation needs to be at least 10 times the HP rating of the largest motor of the non-blackstart generator auxiliaries (e.g. induced draft (ID) fan or forced draft (FD) fan of a steam generator in a coal fired plant).

2.6.4 Step 4: Interconnection with Other TOPs

When appropriate, using tie lines to connect with neighboring TOPs can expedite the restoration process at the interconnection level. Assisting a neighboring TOP is encouraged as long as it does not cause an adverse impact to the restoration process [15]. It is worth noting that according to some RC guidelines, after a TOP has been able to stabilize its subsystem or island, supplying cranking power to a neighboring system is of higher priority than supplying additional load in its own system [14,21].

2.7 TOP Restoration Plans

A typical TOP restoration plan consists of similar aspects as an RC plan, except it is specifically focused on its own transmission system. These aspects include:

- applicable reliability standards or grid codes and compliance;
- staffing and responsibilities;
- communication procedures, protocols, and equipment considerations;
- specific guidelines for power system performance monitoring and adherence;
- island synchronization guidelines;
- testing and validation of restoration plans and blackstart resources;
- verification of protection settings on cranking paths; and
- training and drills.

The most noteworthy aspect of a TOP restoration plan consists of system-specific step-by-step procedures to energize various facilities (such as transmission lines, transformers and shunt devices), to reconnect and load generators, and to restore loads. These procedures are essential for Step 3 (Implement Restoration Procedures) of the 4-step restoration process mentioned above. Figure 2-3 gives an overview of TOP restoration procedures.

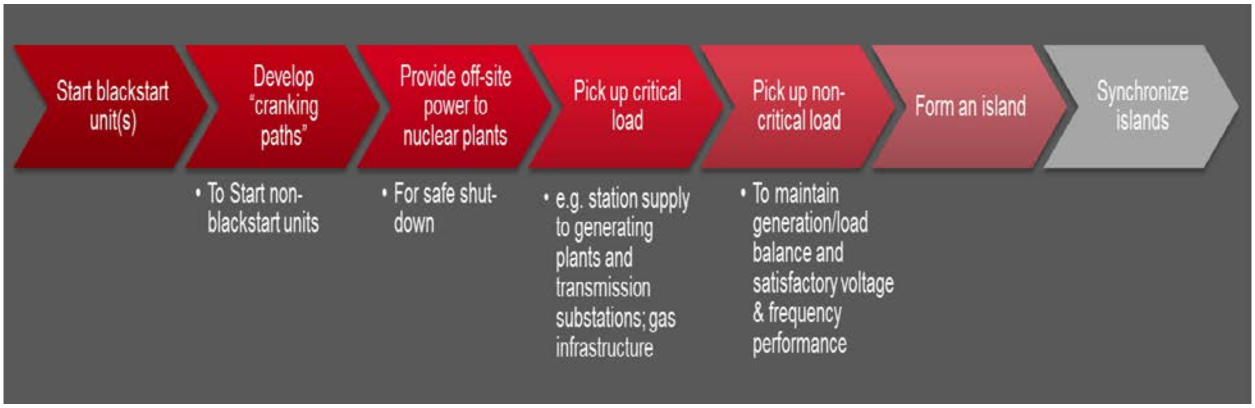

Figure 2-3
An Overview of TOP Restoration Procedures

As shown in Figure 2-3, blackstart resources initiate the restoration process. Strategically placed blackstart generators are key for efficiently restoring a power system. Periodic testing of these resources is required to ensure their continued effectiveness. Many TOP plans include blackstart generators with dual fuel (gas and oil) capabilities and onsite fuel available to run 2-3 days or more. If necessary, environmental waivers to run generators are sought during restoration.

In May 2018, FERC, NERC and the Regional Entities issued a report summarizing their review of blackstart resources of nine (9) North American operators [22]. The review specifically focused on availability and testing of blackstart resources. The review concluded that these operators have sufficient blackstart resources in their restoration plans, and they also have comprehensive strategies for mitigating against loss of any additional blackstart resources going forward [22]. The review also found that these operators have performed expanded testing of blackstart capability and gained valuable knowledge that was used to verify and improve their restoration plans [22].

Other key aspects of a TOP step-by-step facility energization procedures are as follows:

- Each TOP is responsible to restore its own system. Help from an external system is to be avoided/minimized, except for pre-arranged external blackstart resources. However, when implementing a plan during an actual restoration process, seeking help from, or providing help to, a neighboring system is encouraged when feasible.
- The TOP may adopt a "bottom-up" or a "top-down" or a combination approach, depending upon restoration objectives, company philosophy, and more importantly, its system characteristics such as the makeup of its transmission network and generation resources.
- Cranking paths that connect blackstart resources to non-blackstart generation resources must be identified and analyzed to ensure satisfactory steady-state and dynamics performance. Cranking path are developed with the aim to pick up as much generation as possible to speed up the restoration process. Periodic simulation-based analysis of these cranking paths is required to ensure their continued effectiveness [3,8,10,14,15,18,21].
- Providing safe shutdown (offsite) power to nuclear plants is of high priority.
- After stabilization of a subsystem, supplying cranking power to a neighboring system is of higher priority than supplying additional load within the subsystem or island [14,21].

- In developing its restoration plan, a TOP divides its system into multiple islands (or subsystems or zones). Each island typically consists of one blackstart generator. Each island is carefully selected based on factors such as available blackstart resources, generation-load balance, station switching layouts, etc. The TOP develops cranking paths for each island. These islands are then synchronized with each other at selected synchro-scope locations. (Note: The points of natural synchronization between islands should be identified so that synchroscopes can be pre-installed to insure phase angle between islands do not create equipment failure when tying the islands during restoration.) This incremental approach for system restoration works well during the time when generation and transmission resources may be scant, as would be the case following a blackout. Restoring multiple islands in parallel is likely to speed up restoration. Also, any problem during restoration confines to the island only and does not affect the neighboring islands of the system.
- Load pickup during restoration requires a deliberate approach. The priority is given to restore critical loads that consist of: cranking power to all units with a hot start time of 4 hours or less, safe shutdown of nuclear plants and critical natural gas infrastructure [21]. Priority loads also include: pumping stations for oil pipelines, military installations, flood water control installations, hospitals and other emergency operations [2].
- While the goal during initial restoration is to restore the above critical loads, the process emphasizes the voltage/frequency performance needs of the power system. Initial load restoration is focused on: providing load to online generators, damping of voltage transients, and consuming excess reactive power (Mvar). The loads that are restored are selected based on size, ability to be quickly energized, and their location within the energized system. Higher priority customer loads are energized only after system conditions have stabilized to accommodate these loads, to avoid any regression. In some instances, even higher priority customer loads cannot be energized until sufficient resources are connected to ensure that fault currents are high enough to operate protection systems. As the restoration process progresses, additional loads are picked up based on their relative priority. As more substations are energized, more blocks of load can be safely picked-up by online generating units. Then, a gradual transition occurs from picking up load based on voltage/frequency performance needs to picking up load based on load priority. In some cases, there may be a need to remove some of the load from heavily loaded feeders before they can be restored to service.

Following a HEMP-induced blackout, the pre-defined TOP step-by-step facility energization procedures may not be practical to implement due to the possibility of widespread inoperable/ unavailable/damaged equipment. Therefore, as mentioned in Section 2.6.2 (Step 2), the restoration strategy may need to be revised by focusing on another less damaged portion of the system. When considering alternative cranking paths based on available generation, transmission, distribution and load resources, analytical tools and simulation studies may be helpful to establish technical feasibility of these paths.

When implementing step-by-step facility energization procedures in real-time following a blackout, the power system behavior is quite different compared to its behavior during normal operation. The system being restored is weak, which can produce large and unacceptable deviations in voltage and frequency; thus, causing potential regression. Therefore, the standard operating practices for normal power system may not be appropriate. Some of the technical issues that warrant special considerations are discussed below.

2.8 Voltage Performance Issues During Restoration

The following describes potential voltage performance issues that can occur during restoration.

2.8.1 Stead-State Voltage Performance

Energizing a transmission line can cause excessive voltage at the receiving end of the line due to a phenomena referred to as Ferranti voltage rise, and is due to line charging. The online generation must have adequate under-excited capability be able to absorb the additional reactive power generated by the open circuited transmission line. Shunt reactors can also be used to control voltages. Otherwise, an elevated open-end voltage can cause personnel safety issues and equipment damage. Under an extreme scenario, if the reactive power absorption capability of all online generators is fully utilized, generator self-excitation condition may occur, which could lead to a runaway voltage situation [23, 24].

Therefore, voltage control during restoration calls for multiple approaches such as careful energization of lines, use of shunt devices (reactors, SVCs, etc.), use of synchronous condensers, load pickup following line energization, removal of shunt capacitors, etc.

Generators are the primary voltage control tool during a restoration condition. During the initial stages of restoration, when few generators are online, absorbing the reactive power generated from transmission open circuited or lightly-loaded lines is a critical issue to manage. The online generators must not be forced to absorb so much reactive power that they become under excited and trip via loss of field (LOF) relays [23] or exhibit oscillatory instability. A generator trip under highly stressed restoration conditions could cause regression to a previous recovery state.

System loading also plays a part in the control of voltage. For example, the addition of some customer load at the open-end of a transmission line may dramatically reduce the overvoltage due to Ferranti rise. Energizing load with a low lagging power factor would be helpful since the load absorbs the excess reactive power from the energized transmission lines. Thus, successive energization of a line followed by a load, when feasible, could be an effective approach during power system restoration.

Another approach is to delay the energization of transmission lines with high line charging until the system is strong enough to accommodate the increased reactive power injection. For example, PJM's restoration plan calls for delaying the energization of 500 kV lines until after a certain level of generation is online [21]. Often, during the early stage of restoration, TOPs rely on their HV transmission network, instead of EHV network, to develop the transmission backbone for cranking paths.

To ensure satisfactory voltage performance, it is essential for a TOP to perform power flow studies of its step-by-step facility energization procedures. Such studies are required as part of compliance to restoration standards/codes [3,15]. Additionally, for the scenarios involving startup of relatively large induction motors of non-blackstart generators (e.g., forced draft or induced draft fans), time-domain simulations are necessary for compliance purposes [3].

2.8.2 Switching Surges and Transient Overvoltages (TOVs) [23]

When a transmission line is energized, a transient overvoltage (TOV) occurs because of travelling wave switching surge phenomenon. In general, the higher the steady-state operating voltage and the weaker the system, the higher the TOV. Therefore, the power system may be exposed to relatively high TOVs during restoration. High TOVs can cause equipment damage and/or operation of protective devices; thus, risking regression.

A system's exposure to TOV-related damage during restoration conditions should be identified and evaluated by conducting a switching surge or electromagnetic transients (EMT) study of the intended restoration approach. The system restoration plan should reflect the results of EMT studies and include guidelines to avoid high TOV magnitudes.

2.9 Frequency Performance Concerns During System Restoration

During restoration conditions, frequency control requires a system operator's careful attention to energizing additional load because only a few generators may be online. An energization of even a relatively lightly loaded distribution feeder can have a significant impact on system frequency in the early stages of restoration. If the system frequency deviation is too large, equipment damage or trip-out can result, which may lead to regression. Although it is desirable to pick up only small blocks of load in the early stages of restoration, the power system configuration may not allow splitting a load into sufficiently small blocks.

Some industry guidelines with respect to frequency control and load restoration are as follows:

- Some operators open up all load feeders before initiating the restoration process, in order to control the amount of load pick up.
- Frequency should normally be held within a range of 59.75 to 61 Hz with an attempt to regulate toward 60 Hz. A system operator may want to raise the frequency higher (e.g. 61 Hz) if a large load block is about to be restored.
- Avoid energizing load blocks that are greater than 5% of the restored area's total synchronized generation [25-27]. This conservative rule is designed to avoid activating under-frequency relays or generator volts/Hz relays.
- Consider the possible problems that could result from the undesirable shedding of load via automatic under-frequency load shedding (UFLS) schemes.
- Consider the possible problems that could result from the undesirable automatic pick-up of load via automatic load restoration schemes.
- If the frequency regulation burden is too great for any one generator, two or more generators, preferably located at the same generating station to facilitate coordination, should share frequency regulation.
- When two or more systems are synchronized together to form a larger system, only one system should control the frequency. If two systems attempt to simultaneously regulate the frequency, an undesired competition between the two systems could result. In general, one system (the one with the best responding generation) should control frequency while the other systems assist when asked for help. Also, when multiple units are going to be operating in an island, before synchronizing them, isochronous governor control should be reverted back to droop control mode.
- MISO's guidelines suggest that when cranking an off-line generator, the online generation needs to be 10 times the HP rating of the largest motor of the off-line generator [14].

3
SUMMARY

High-altitude electromagnetic pulse (HEMP) refers to an electromagnetic pulse created by the detonation of a nuclear weapon in space. HEMP has the potential to damage power grid assets over a wide area; thus, interrupting power delivery and adversely impacting bulk power system reliability [1]. Because of these potential impacts, HEMP poses unique challenges to existing restoration processes. EPRI is engaged in a multi-year R&D effort to investigate potential HEMP threat by providing technically based research results to inform system assessments and inform decisions regarding mitigation. The industry is still in the early stages of identifying the potential impacts of a HEMP event on the bulk power system and mitigating those impacts. Until assessment and hardening efforts are complete, it is prudent to consider the potential consequences of a HEMP attack and evaluate existing restoration plans in that context. The potential impacts of HEMP on the restoration process and possible considerations for improving preparedness are provided below.

3.1 Potential Impacts of a HEMP-Induced Blackout on Restoration Process

A HEMP-induced blackout could pose restoration challenges in the following three main categories:

1. unavailable/inoperable/damaged equipment (including generation/transmission/load facilities) along the cranking paths;
2. impaired levels of situational awareness (including observability and controllability); and
3. inability or difficulty to notify response personnel.

Thus, recovering from a HEMP-induced blackout can present challenges that may not be experienced following the blackouts due to other causes. These challenges are identified in Chapter 2 in the description of various aspects of a restoration process. Table 3-1 provides a summary of potential impacts of a HEMP-induced blackout on restoration process.

Table 3-1
Potential Impacts of a HEMP-Induced Blackout on Restoration Process

Restoration Step (Refer to Figure 2-2)		Potential Impacts of a HEMP Event
1	System Status Assessment	Damage to communication equipment may cause partial to total loss of SCADA/ ICCP/EMS data, and therefore, impaired levels of situational awareness.
2	Determine and Implement Restoration Strategy	Identifying a practical restoration strategy could be challenging due to impaired situational awareness mentioned above and because of the possibility of widespread inoperable/unavailable/ damaged equipment. The restoration strategy may need to be revised by focusing on another less damaged portion of the system.
3	Implement Restoration Procedures	The pre-defined TOP step-by-step facility energization procedures may not be practical to implement due to the possibility of widespread inoperable/unavailable/damaged equipment. If a revised strategy (Step 2) calls for alternative cranking paths based on available generation, transmission, distribution and load resources, analytical tools and simulation studies may be helpful to establish technical feasibility of these paths.
4	Interconnection with Other TOPs	Impacts will be similar to those mentioned for the above 3 steps.

3.2 Suggestions to Be Prepared for Restoration following a HEMP-Induced Blackout

Suggestions to help the industry to be prepared for restoration following a HEMP-induced blackout are listed in Table 3-2. For each of the thirteen (13) suggestions of Table 3-2, further discussion is presented following the table. Industry efforts are already underway to address many of these suggestions. (Note: For completeness, the reader is encouraged to read Appendix B, which presents a comprehensive set of suggestions to cover broader aspects of power system restoration beyond HEMP.)

Table 3-2
Suggestions for Preparedness

Suggestions		Summary
1	Equipment Redundancy/Sparing	Deploy additional backup/sparing for key protection & control and communication equipment at key transmission and generating stations.
2	Reduction in Magnitude/Duration of HEMP Impact Through Mitigation and Hardening	Employ investigative efforts to find ways to reduce HEMP impact on power system.
3	Dispatching Field Personnel (including notification of personnel to respond)	During restoration, dispatch field personnel to check damage to key & vulnerable equipment along the cranking paths.
4	Equipment Repair	Make personnel available to repair damaged equipment along the cranking paths.
5	Communication Equipment	Employ investigative efforts to assess HEMP impact on communication equipment and data transmission.
6	Transmission-Distribution Coordination	Improve coordination between transmission and distribution operators.

Table 3-2 (continued)
Suggestions for Preparedness

Suggestions		Summary
7	Manual Monitoring	During restoration, dispatch field personnel for manual monitoring of key electrical quantities along the cranking paths.
8	Simulation Studies and Tools	During restoration, perform simulations to support operations (e.g. to evaluate technical feasibility of alternate cranking paths).
9	Loss of SCADA/ICCP/EMS Data	Employ investigative efforts to assess impact of loss of data on operational (EMS) tools and processes and to find mitigation measures.
10	Restoration Plan: Assumptions	Revise assumptions to account for potential unavailability of critical equipment along the established cranking paths. (Also, identify natural points of synchronization of islands for synchroscope placement.)
11	Restoration Plan: Restoration Strategy	Devise an alternate strategy, assuming unavailability of vulnerable equipment along the established cranking paths.
12	Restoration Plan: TOP Facility Energization Procedures	Devise alternate cranking paths, assuming unavailability of vulnerable equipment along the established cranking paths.
13	Training	Revise the training to account for above mentioned revisions in restoration plans and restoration processes.

Suggestions 1 and 2 (Table 3-2): The electric power industry has been investigating the ways to be prepared for HILF events. (Note: HILF events include a HEMP event, as well as natural phenomena (e.g. hurricanes, tornadoes, earthquakes, geomagnetic disturbances, etc.) and physical/cyber terrorist attacks.) The major theme for industry preparedness revolves around improving system resiliency, the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from, such an event [28]. Industry preparations for resiliency span across both near-term (or operational) time horizon and long-term (or planning) time horizon. The related solutions are as follows:

- Redundancy of certain key protection and control devices by providing an additional layer of backup devices
- Hardening of vulnerable power system equipment.
  - Note: The industry is developing the ways to harden the communication equipment and IEDs. However, until these hardening efforts are implemented, it is prudent to assume widespread unavailability of, and perhaps damage to, this equipment following a HEMP event.
- Keeping a spare inventory of critical equipment.
- In reference [29], CIGRE proposed the following suggestions to be prepared for a HILF event, such as a HEMP event.
  - Reducing the magnitude of immediate impact by installation of emergency control schemes.
  - Reducing the duration of impact by: 1) Proactive mobilization of key technical personnel and 2) implementing ways and tools to foretell potential impact (to direct the restoration efforts accordingly).

- Provision of sustained auxiliary supplies (e.g. diesel generators at generating plants, batteries at transmission substations, etc.).
- Improved coordination and communication with distribution system operators.
- Provision of local emergency supplies (maybe in the form of microgrids) at critical facilities such as gas infrastructure facilities, hospitals, etc.

Suggestions 3 and 4 (Table 3-2): As mentioned above, one of the challenges following a HEMP-induced blackout may be unavailable/inoperable/damaged equipment (including generation/transmission/load facilities) along the cranking paths. The related solutions are as follows:

- Dispatching field personnel to check potential damage to vulnerable equipment. This would likely require auxiliary power for testing relays and circuit breakers and for running compressors. Station batteries will likely survive an EMP event and can be used for initial power supplies. One potential solution is to install diesel generators at transmission substations.
- Repairing/replacing key damaged equipment. This will require additional technical staff, which should be factored in when developing a restoration plan to be prepared for a HEMP event.
- With a HEMP event, dispatch capabilities of personnel not actively working will likely be compromised. Personnel training must occur to direct blackstart generation personnel and field switching personnel on need to self-dispatch and where they should assemble. Use of the National Emergency Broadcast System should be considered as an option to aid the notification of response personnel until secure EMP hardened communication systems exist for utilities.

Suggestion 5 (Table 3-2): Investigate the impact of loss of communications equipment and data. For example, the EPRI Black Sky project evaluated emergency communication requirements for a HILF event and concluded that high frequency radio, satellite phone systems and hardened inter-utility private fiber networks can provide effective communication means during a HILF event [30]. Also, we may need to anticipate that a HEMP attack will be coincident with a Cyber-attack, which will make this more difficult.

Suggestion 6: Close coordination between transmission and distribution system operators will be essential for the TOP to be aware of HEMP-induced damage to loads so that generation/load balance can be achieved. Also, it will be prudent for TOPs to develop their restoration plans in coordination with their respective distribution system operators to maximize leverage from distribution resources such as DERs and micro-grids.

Suggestions 7, 8 and 9: As stated previously, one of the challenges following a HEMP-induced blackout may be impaired levels of situational awareness (including observability and controllability). The related three (3) suggestions are as follows:

- Making field personnel available for manual monitoring of key electrical quantities (perhaps using clamp-on portable analog meters) at the transmission and generating stations located along the cranking paths.

- Performing simulation studies: 1) to derive or estimate electrical quantities for unmanned stations using the data received from the manually monitored stations; and 2) to find or validate (from the technical feasibility viewpoint) alternate cranking paths in case of damaged equipment along the established cranking paths.
- Investigating impact/mitigation of loss of SCADA/ICCP/EMS data. To support electrical infrastructure resiliency, EPRI is investigating the impact of, and mitigation for, the loss of SCADA/ICCP/EMS data and data communications to/from a control center [12]. The outcome of this investigation can be adopted in restoration plans to enhance preparation for a HEMP-induced blackout.

Suggestions 10, 11 and 12: System restoration plans may need to be revised to effectively restore power system following a HEMP-induced blackout. The related suggestions are as follows.

- Revisiting restoration plan assumptions. In a restoration plan, the assumption of availability of all facilities may not be appropriate since communication and protection equipment may be inoperable and perhaps damaged. Such a potential scenario could be factored in when developing restoration plans to enhance preparedness for a HEMP-induced blackout.
- Planning for an alternate restoration strategy. Following a HEMP-induced blackout, Step 1 (System Status Assessment) and Step 2 (Determine and Implement Restoration Strategy), described in Section 2.6, will take on an added meaning because of the possibility of widespread communications loss and equipment damage. It will become essential to review all the available data and to predict the unavailable data, in order to reasonably assess system status. Depending upon the confidence level for system status assessment, the strategy selection step could become challenging. Having an alternate restoration strategy in place will be helpful, in case the established strategy cannot be implemented.
- Planning for alternate TOP facility energization procedures. Following a HEMP-induced blackout, the pre-defined TOP step-by-step facility energization procedures (i.e. Step 3: Implement Restoration Procedures in Section 2.6) may not be practical to implement due to the possibility of widespread inoperable/unavailable/damaged equipment. Therefore, alternative cranking paths may need to be identified, based on available generation, transmission, distribution and load resources. This will require analytical tools and simulation studies to find alternate cranking paths and to establish technical feasibility of these paths. Having an alternate set of facility energization procedures in place will be helpful, in case the established procedures strategy cannot be implemented.
- The existing and alternate cranking paths should be analyzed through simulations to understand if sufficient system protection exists for weak network conditions. This may require the use of a Real Time Digital Simulator.

Suggestion 13 (Training): Additional restoration-related training in the context of a HEMP-induced blackout will be needed to provide information on potential impacts and some of the new approaches (such as manual field measurements) mentioned above.

3.3 Summary

The potential impact of HEMP can be summarized as follows:

- unavailable/inoperable/damaged equipment (including generation/transmission/load facilities) along the cranking paths;
- impaired levels of situational awareness (including observability and controllability); and
- inability of difficulty to notify response personnel.

Recovering from a HEMP-induced blackout can present challenges that may not be experienced following the blackouts due to other causes. These challenges can be summarized as follows:

- Identifying a practical restoration strategy could be challenging due to impaired situational awareness and because of the possibility of widespread inoperable/unavailable/ damaged equipment. The restoration strategy may need to be revised by focusing on another less damaged portion of the system.
- The pre-defined TOP step-by-step facility energization procedures may not be practical to implement due to the possibility of widespread inoperable/unavailable/damaged equipment. If a revised strategy calls for alternative cranking paths based on available generation, transmission, distribution and load resources, analytical tools and simulation studies may be helpful to establish technical feasibility of these paths.

To be prepared for restoration following a HEMP-induced blackout, the efforts needed by the industry are summarized in Table 3-2. These efforts include:

- Preparations for equipment redundancy/sparing/hardening
- Making field personnel available for system monitoring and equipment repair during restoration
- Enhanced coordination between transmission and distribution operators when preparing restoration plans as well as during restoration
- Development of enhanced restoration plans
- Performing simulation studies of existing and alternate cranking paths in advance as well as during restoration
- Training.

4
REFERENCES

1. *High-Altitude Electromagnetic Pulse Effect on Bulk-Power Systems: State of Knowledge and Research Needs*. EPRI, Palo Alto, CA: 2016. 3002008999.
2. Federal Energy Regulatory Commission, FERC-NERC-Regional Entity Joint Review of Restoration and Recovery Plans, January 2016.
3. NERC, Reliability Standards for the Bulk Electric Systems of North America, Updated February 15, 2018.
4. European Union (ENTSO-E), Establishing a Network Code on Electricity Emergency and Restoration, 24 November 2017.
5. Australian Energy Market Operator, Power System Security Guidelines, 25 January 2018.
6. National Grid – Saudi Arabia, The Saudi Arabian Grid Code, October 2016.
7. Federal Energy Regulatory Commission, Critical Energy/Electric Infrastructure Information; Recent Highlight, November 17, 2016, https://www.ferc.gov/legal/ceii-foia/ceii.asp
8. CIGRE, System Restoration Procedure and Practices, December 2017.
9. PJM, System Restoration Workshop – Part 1, July 11, 2012.
10. NYISO, System Restoration Manual (Manual 20), April 2017.
11. NYISO, Emergency Operations Manual (Manual 15), July 2017.
12. *Assessment of Extreme Contingencies Affecting Energy Management System (Control Center Functionalities (Supplemental Project Notice)*. EPRI, Palo Alto, CA: 2017. 3002010084.
13. Peak Reliability, Reliability Coordinator Area Restoration Plan, Version 6.0, June 1, 2017.
14. MISO, Power System Restoration Plan, Version 11, August 4, 2017.
15. European Union Commission, Regulation 2017/2196, Establishing a Network Code on Electricity Emergency and Restoration, 24 November 2017.
16. ENTSO-E, Supporting Document for the Network Code on Emergency and Restoration, 25 March 2015.
17. National Grid, Black Start Strategy, August 2017.
18. Independent Electricity System Operator (IEOC), Ontario Power System Restoration Plan, December 15, 2017.
19. ISO New England, Master/LLC Procedure No. 18 – System Restoration Plan, September 22, 2017.
20. ERCOT, ERCOT Nodal Operating Guides – Section 4: Emergency Operations, July 1, 2017.
21. PJM, Manual 36, System Restoration, Revision 24, June 9, 2017.
22. FERC, NERC and Regional Entities, Report on the FERC-NERC-Regional Entity Joint Review of Restoration and Recovery Plans – Recommended Study: Blackstart Resources Availability (BRAv), May 2018.
23. *EPRI Power System Dynamics Tutorial*, EPRI, Palo Alto, CA: 2009. 1016042.

24. J.W. Feltes, et al, Some Considerations in the Development of Restoration Plans for Electric Utilities Serving Large Metropolitan Areas, IEEE Transactions on Power Systems, Vol. 21, No. 2, May 2006, pp. 909-915.
25. M.M. Adibi, et al, The Impacts of FACTS and other New Technologies on Power System Restoration Dynamics, IEEE Paper Compendium PES-TPC1, July 2014, pp. 132-139.
26. R. Podmore, Smart Grid Restoration Concepts, IEEE Paper Compendium PES-TPC1, July 2014, pp. 304-314.
27. F. Levesque, et al, Restoration Plan – The Hydro-Quebec Experience, IEEE Paper Compendium PES-TPC1, July 2014, pp. 159-167
28. The Definition and Qualification of Resilience, Technical Report PES-TR65, IEEE Power and Energy Society, April 2018.
29. CIGRE, Lessons Learnt from Recent Emergencies and Blackout Incidents, January 2015.
30. *Black Sky Communications Evaluation*. EPRI, Palo Alto, CA: 2018. 3002013919.
31. FERC/NERC, Arizona-Southern California Outages of September 8, 2011 – Causes and Recommendations, April 2012.
32. NPCC, Restoration of the NPCC Areas Following the Power System Collapse of August 14, 2003
33. ECAR Bulk Power Restoration after Blackout of August 14, 2003
34. Molly Lempriere, Power Technology, Turning the lights back on after Hurricane Harvey, November 7, 2017. https://www.power-technology.com/features/turning-lights-back-hurricane-harvey/
35. NYISO, Final-Report_2003Aug14-Blackout_Feb2005
36. FRCC Event Analysis Team, Final Report of FRCC 2/26/2008 Event, October 30, 2008
37. *System Restoration and Black Start with HVDC and Renewables*. EPRI, Palo Alto, CA: 2017. 3002010724.
38. M. El-Zonkoly, "Renewable energy sources for complete optimal power system black-start restoration," in IET Generation, Transmission & Distribution, vol. 9, no. 6, pp. 531-539, 4 20 2015
39. J. Sprooten, T. Gunst, C. Mestdag, O. Bronckart, *Elia Group, Belgium*. “Power System Restoration with high penetration level of renewable generation - New challenges and strategies,” Saudi Arabia Smart Grid Conference, December 2014. J. Sprooten, T. Gunst, C. Mestdag, O. Bronckart, Elia Group, Belgium. “Power System Restoration with high penetration level of renewable generation - New challenges and strategies”
40. H. Zhu and Y. Liu, "Aspects of power system restoration considering wind farms," International Conference on Sustainable Power Generation and Supply (SUPERGEN 2012), Hangzhou, 2012, pp. 1-5.
41. L. Seca, H. Costa, C. L. Moreira, J. A. Peças Lopes “An Innovative Strategy for Power System Restoration using Utility Scale Wind Parks”. 2013 IREP Symposium-Bulk Power System Dynamics and Control –IX (IREP), August 25-30, 2013, Rethymnon, Greece
42. T. T. H. Pham, Y. Besanger and N. Hadjsaid, "New Challenges in Power System Restoration with Large Scale of Dispersed Generation Insertion," in IEEE Transactions on Power Systems, vol. 24, no. 1, pp. 398-406, Feb. 200910.1049/cp.2012.1788.

A

RESTORATION EXPERIENCES FOLLOWING MAJOR GLOBAL BLACKOUTS

The restoration principles, practices and plans presented in Chapter 2 provide a foundation for the bulk power system operators to be prepared to restore a power system following a blackout. Over the past few decades, some operators have already utilized these restoration plan elements when restoring their systems after blackouts. A review of how effective the then-existing restoration plans were is presented with the goal of identifying the lessons learned.

A.1 Observations from Global Restoration Experience

These observations are focused on effectiveness of restoration principles, practices and plans, when TOPs and RCs restored their power systems following major blackouts [29,31-35].

A.1.1 Overall Effectiveness of Restoration Process

In its January 2015 report, CIGRE summarized its review of restoration experience following eighteen (18) global blackouts shown in Table A-1 [29]. CIGRE concluded that operators' performance and response procedures in restoring their power systems appeared to meet general expectations [29]. A similar observation, supporting the overall effectiveness of power system restoration process, was also made by several operators that restored their systems following blackouts [31,32,36].

Table A-1
Summary of Blackouts Analyzed by CIGRE [29]

Event	Area Affected	Customers Affected	Main Causes	Restoration Time
UCTE System Disturbances on 04 November 2006	3.4 M km²	15 M	Design/App error. Com. Failure Operator error	90 min
Large Disturbance in TEPCO, Japan 16 July 2007	N/A	None	Natural phenomena	N/A
Inadequate Reserve Margin, S. Africa 26 February 2008	Entire country	All	Inadequate investment	N/A
Large Disturbance in Florida, USA 26 February 2008	Good part of Florida	Not a/v	Errors in Maintenance	Not available
Frequency Excursion Great Britain 27 May 2008	Not a/v	600,000	Lack of coordination between transmission and distribution grid codes on generator ride through requirements	40 min
Klaus Cyclone Hitting France/Spain, 24 January 2009	380,000 km²	2 M	Natural phenomena	Up to 5 days

Table A-1 (continued)
Summary of Blackouts Analyzed by CIGRE [29]

Event	Area Affected	Customers Affected	Main Causes	Restoration Time
Brazilian System Blackout, 10 November 2009	3.1 M km²	40 M	Natural phenomena	Up to 237 min
Storm in Portugal, 23 December 2009	2807 km²	350,000	Natural phenomena	Up to 132 hours
Snow/Ice Storm in N. Ireland, 30/31 March 2010	13,843 km²	138,000	Natural phenomena	Up to 18 hours
Brazilian System Disturbance on 21 January 2002	3.1 M km²	40 M	Design/App error	Up to 270 min
Northeastern USA/Canada Blackout, 14 August 2003	Multiple states in US and Province of Ontario in Canada	50 M	Design/App error. Primary equip. failure. Secondary equipment failure. Com. failure. Operator error. Inadequate diagnostic support	30 hours. for the majority of the affected load
Downtown Toronto Canada Blackout, 15 March 2010	Not a/v	240,000	Primary equip. failure	Up to 215 min
Australian bush fire disturbance, 28 January – 5 February 2009 (Multiple executions of load shedding)	500,000 km²	Up to 1 M	Natural phenomena. Operator error. Lack of load forecast for extreme weather. Lack of organizing work in control room during extreme events.	From less than 1 hour to up to 4 hours
Brazilian NE Blackout on 04 February 2011	1.2 M km²	40 M	Design/App error. Secondary equip. failure	Average 194 min
System Oscillations in Central Europe, 19/24 February 2011	N/A	N/A	Not identified	System was intact; oscillations lasted 15 min
Southwest USA on 08 September 2011	Not a/v	2.7 M	Com. Failure. Operator error. Inadequate Investment	Up to 900 min
Blackout in Argentina Western Area, 04 April 2012	250,000 km²	6.5 M	Natural phenomena	Ave 1.5 hours, up to 14 days
Large Disturbance in East Japan, 11 March 2011	Not a/v	4 M	Natural phenomena	UFLS operations, plus rolling blackouts for 10 out of next 17 days

A.1.2 Preparations (Restoration Plans, Tools and Training)

While the elements of the restoration plans described in Chapter 2 reflect the latest developments, many of these elements, in some form or another, have been in place for decades. These elements provide opportunities for the TOPs and RCs to be prepared for restoration. The following preparations were helpful to the operators in restoring their power systems following major blackouts.

- Tools and training: The CIGRE review mentioned above concluded that operators' tools and training appeared to be adequate [29].
- Documentation: Based on restoration experience following the August 14, 2003 U.S./Canada Power Outage, IESO quoted the following [32]: "We confirmed that maintaining a well-documented restoration plan, supported by training and rehearsals involving the [IESO], was and will continue to be a key investment."
- Process/Training: Similarly, in summarizing restoration experience following the August 14, 2003 U.S./Canada Power Outage, NPCC credited its effective and successful restoration process to well-trained operators, and to mandatory requirements for restoration plans and testing of key facilities [32].

A.1.3 Staffing, Roles and Responsibilities and Coordination

In some instances, power system restoration was hampered by the lack of clarity of roles and responsibilities among various entities such as the TOPs, RCs, distribution system operators (DSOs), etc. For example, during the U.S. Southwest Outage of September 2011, some delays were encountered because of lack of clarity of responsibilities and coordination among the TOPs and the RC [31]. The CIGRE review mentioned that a better level of coordination between TOPs and DSOs could have improved response and restoration time [29].

Based on restoration experience following the August 14, 2003 U.S./Canada Outage, ECAR reported that significant additional staffing may be required during restoration that follows a widespread blackout [33].

A.1.4 Communication

ECAR reported that during restoration following the August 14, 2003 U.S./Canada Outage, some level of failure occurred in the public telephone system and cell phones, when the available multiple voice communication facilities provided backup [33]. During restoration following the February 2008 FRCC event, some TOP and RC staffs did not consistently identify themselves and their affiliations, which led to minor confusion [36].

A.1.5 Situational Awareness

The CIGRE review noted a lack of adequate situational awareness during restoration following several blackouts [29]. This supports the concern reported in Chapter 2 about loss of SCADA/EMS/ICCP functionality during a blackout that could hamper situational awareness during restoration [2,8].

A.1.6 Coordination with Distribution System

During power system restoration following Hurricane Harvey in Texas in November 2017, it was reported that smart meters installed by CenterPoint in the Houston area helped the utility in identifying the outages [34]. The key observation here is that smart metering can help in identifying the location of the outages so that field personnel can be efficiently dispatched to support power system restoration efforts.

It was also reported that during Hurricane Harvey, a number of microgrids protected hospitals and gas stations from outages [34]. For example, in Houston, 21 shops and gas stations were able to stay operational because of an Enchanted Rock natural gas microgrid system. Also, due to a thermal microgrid system, the Texas Medical Center was able to continue providing medical care throughout Harvey, while the same medical center was crippled in 2001 due to less severe flooding. Thus, microgrids can help in power system restoration by keeping some of the load energized through an outage or a blackout. This can help the bulk power system restoration efforts through proper coordination between transmission system operators and distribution system operators.

Increasing penetration of distributed energy resources (DERs) provides another opportunity and reason to coordinate with the distribution system operator. If DERs are designed to continue to serve local load, it should be reflected in how a transmission operator achieves load/generation balance during restoration.

A.2 Lessons Learned

The restoration principles, practices and plans of Chapter 2 should be reviewed, and revised if necessary, to incorporate the following lessons learned.

A.2.1 Overall Effectiveness of Restoration Process

Based on restoration experience following the August 14, 2003 U.S./Canada Power Outage, NPCC suggested the following [32]: "Rigorous and enforceable criteria and well-defined authority must be retained." In this regard, the following excerpt from Section 2.1 that describes today's state is worth repeating: "Around the world, restoration is treated as a critical aspect of power system planning and operations. Authorized entities have put in place mandatory reliability standards and grid codes that range in scope from development of restoration plans to periodic review/testing/ revision of these plans to implementation of these plans following a blackout. Compliance is monitored by the authorized entities through review of submitted restoration plan materials and onsite audits."

A.2.2 Preparations (Restoration Plans, Tools and Training)

Based on restoration experience following the August 14, 2003 U.S./Canada Power Outage, NPCC recommended the following [32]:

- Procedures and Training for Island Synchronization, Island Stabilization, Load Shedding, Roles & Responsibilities, and Inter-Area Restoration Training Drills; and
- Improvements in tools for Alarm Management and Wide Area View.

Based on restoration experience following the August 14, 2003 U.S./Canada Power Outage, NYISO recommended the following [35]:

- A need to expand the scope of training that relates to the TOP restoration plans; and
- Coordination of restoration efforts between all parties involved.

Based on restoration experience following the FRCC System Disturbance of February 26, 2008, FRCC recommended the following [36]:

- Review/develop procedures/guidelines for notification and system operation documentation, when protection systems are removed from service for protection system and/or equipment maintenance activities.

The CIGRE review proposes a novel perspective on preparations, which does not directly relate to improvements in restoration plan elements, but focuses on reducing the impact of any disturbance, including a high-impact low-frequency (HILF) event that could potentially cause a blackout [29]. The suggestions include [29]:

- Reducing the magnitude of immediate impact by installation of emergency control schemes; and
- Reducing the duration of impact by: a) proactive staff mobilization (e.g. in anticipation of a weather storm); b) implementing ways and tools to foretell potential impact (to direct the restoration efforts accordingly); c) provision of sustained auxiliary supplies (e.g. diesel generators at generating plants, batteries at transmission substations, etc.); d) improved coordination and communication with distribution system operators; and e) provision of local emergency supplies (maybe in the form of microgrids) at critical facilities such as gas infrastructure facilities, hospitals, etc.

A.2.3 Staffing, Roles and Responsibilities and Coordination

Based on their restoration experience, several operators emphasized the need to clearly define roles and responsibilities, as well as staffing requirements, during restoration activities [31, 35, 36].

A.2.4 Communication

Operators' restoration experiences have suggested a review of the adequacy of voice communication procedures and equipment [32, 33, 36]. Based on restoration experience following the August 14, 2003 U.S./Canada Power Outage, NYISO recommended establishing a "command post" location at each transmission control center [32, 35]. Based on restoration experience following the August 14, 2003 U.S./Canada Power Outage, ECAR reported that public appeals can be a helpful tool for load reduction [33].

A.2.5 Situational Awareness

The CIGRE review notes a lack of adequate situational awareness during restoration following several blackouts [28]. In this regard, investigating the ways to deal with loss of EMS/SCADA/ICCP data will be helpful to the industry [2, 8].

A.2.6 Coordination with Distribution System

Coordination with distribution system operators needs to be given high priority because of continuing increased penetration of microgrids and DERs. Also, such a coordination can help in identifying the specific outages, load loss and equipment damage, which could possibly provide an indication of extent and duration of load recovery.

B
SUGGESTIONS FOR FUTURE WORK

Based on discussions presented in Chapters 2, Appendix A and literature search, suggestions for future work on power system restoration are presented in this chapter. Note that these suggestions are more in the context of improving the restoration process in general, and are not specific for improving recovery following a HEMP-induced blackout.

B.1 Suggestions to Improve Effectiveness of Current Restoration Processes and Practices

The following suggestions provide added emphasis on several specific aspects of current restoration processes and practices. These suggestions are aimed at enhancing the effectiveness of the restoration plans described in Chapter 2. (As mentioned in Section A.2.1, these plans have been found to meet general expectations, so these suggestions are not intended to address any deficiencies.) The TOPs and RCs can address these suggestions in their restoration plans that are generally issued annually. Some of these suggestions may already have been addressed by the operators in their latest restoration plans.

B.1.1 Preparations (Restoration Plans, Tools and Training)

- Understand the implications of the changing generation mix --- such as retirement of fossil-fuel generation and increasing penetration of renewable generation --- on future availability of adequate blackstart resources [2].
- Investigate the feasibility/practicality of expanding the scope of testing performed to confirm the viability of blackstart resources to energize the facilities included in a restoration plan [2,22]. For example, such testing could involve using a blackstart generator to crank the auxiliary load of a non-blackstart generator, provided such testing could be meaningful in validating the cranking path without jeopardizing an interruption of any customer load that may have been picked up.
- Clarify the power system changes and events that require an update to a restoration plan. Also, clarify the verification and testing needed for an updated plan [2].
- Emphasize the training or drills related to the transfer of responsibility from a TOP to an RC when an island has been stabilized by the TOP [2].
- Consider using HVDC lines during the early restoration stage, instead of waiting to energize them during the late restoration stage [2,8]. Such a strategy can expedite the restoration process, especially if the HVDC lines transport generation from remote areas that can help with voltage control and load-generation balance. In this regard, reference [37] can provide guidance because it compares, from the restoration perspective, the AC, the line commutated converter HVDC (LCC-HVDC) and the voltage source converter HVDC (VSC-HVDC) lines [37]. The VSC-HVDC is especially well-suited to provide support during the early restoration stage [37].
- Specify the types of cyber security incidents that would trigger response and recovery plans. Develop details on cyber security response and recovery plans needed for critical cyber assets [2].

- Consider drills to ensure the robustness of the developed cyber security response and recovery plans [2]. Analyze cyber security events and develop learnings for incorporating in the response and recovery plans [2].
- Expand the use of cyber security expertise and tools for restoration purpose [2].
- Develop guidelines and tools to aid operators during an island synchronization process [8].
- Develop guidelines and tools to aid operators to improve the effectiveness of improving voltage and frequency performance [8].
- Make a provision for backup supply for key data --- such as sequence of events, relay targets, etc. --- just after a blackout [8]. Also, store the data captured for event analysis.
- Mitigate the risks associated with reliance on a single fuel for blackstart resources [22].
- Verify modeling data used in performing dynamic simulations to crank auxiliary load of a generating unit [22].
- Make sure to develop procedures and training for island synchronization, island stabilization, load shedding, roles & responsibilities, and inter-area restoration training drills [32].
- Improve the tools for Alarm Management and Wide Area View [32].

B.1.2 Staffing, Roles and Responsibilities and Coordination

- Clearly define roles and responsibilities, as well as staffing requirements, during restoration activities [31, 35, 36].

B.1.3 Communication

- Review the adequacy of voice communication procedures and equipment [32, 33, 36].
- Improve communication capabilities by adding private phone lines and satellite phones [8].
- Consider having alternate communication methods (e.g. hand-held radios), in case typical methods are not available.
- Establish a "command post" location during restoration at each transmission control center [32, 35].
- Public appeals during restoration can be a helpful tool for load reduction [33].

B.1.4 Situational Awareness

- Improve situational awareness tools by incorporating advanced SCADA and EMS functionalities, wide-area monitoring and control capabilities, and advanced analytical tools such as dynamic security analysis (DSA) [8].

B.1.5 Coordination with Distribution System

- Coordination with distribution system needs to be given high priority because of continuing increased penetration of microgrids and DERs. Also, such a coordination can help in identifying the specific outages, load loss and equipment damage, which could possibly provide an indication of extent and duration of load recovery. A TOP's restoration plan should reflect the specific aspects (e.g. DERs, microgrids, etc.) of coordination with the applicable distribution system operators.

B.2 Suggestions to Investigate New Restoration Approaches

Investigative efforts are recommended to find new restoration approaches to address the following aspects.

B.2.1 Loss of SCADA/EMS/ICCP Data/Functionality

FERC/NERC and CIGRE reviews [2,8,29] suggested to plan for loss of SCADA/ICCP/EMS data following a blackout. Such planning could involve full redundancy, as well as hardening, of all data and communication sources and equipment. In addition, field personnel can be made available for manual monitoring of key electrical quantities (perhaps using clamp-on portable analog meters) at the transmission and generating stations located along the cranking paths. Also, power flow simulations can be performed to derive or estimate electrical quantities for unmanned stations using the data received from the manually monitored stations.

To support electrical infrastructure resiliency, EPRI is investigating the impact of, and mitigation for, the loss of SCADA/ICCP/EMS data and data communications to/from a control center [12]. The outcome of this investigation should be adopted, including any associated training, in restoration plans.

B.2.2 Role of Renewable Generation

Currently, renewable generation resources are kept disconnected during the early restoration stage and are connected only after a majority of the system is restored and stabilized [37]. Using renewables as a blackstart resource is a major challenge because multiple wind turbines at multiple wind farms must be coordinated with the available load [37]. Another concern is the variability of the renewable resources, which translates to uncertainty of the amount of available generation at any given time during restoration [37]. However, investigations have been underway to understand the challenges and to find solutions for using renewables during the early restoration stage [38-41]. Specific aspects that require focused R&D efforts and field testing include: accurate forecasting of renewable resources; integrity of communication system associated with renewables; ability to connect renewable resources step-by-step, while coordinating with load pickup; ability to control and de-rate renewable resource power output for frequency control during restoration; and ability to connect in weak grid scenarios [37].

B.2.3 Role of Distributed Energy Resources (DERs)

A TOP’s restoration plan could potentially include the role of DERs, in coordination with the associated distribution system operator (DSO). The TOP’s restoration procedures would then include working with the DSO to reenergize the DERs at appropriate timing to help transmission network restoration. If the DERs remain connected during a blackout, the TOP can work with the DSO to manage the generation/load balance using the DERs. For such procedures to work, in addition to the TOP-DSO coordination, the TOP will need to have observability, and perhaps controllability, of the DERs.

Reference [42] suggests a restoration procedure that uses DERs to blackstart islanded areas on the distribution network. The idea is that the transmission system restoration progresses as predefined in the existing plan. At the same time, at the distribution network level, DERs with blackstart capability would be operated in island mode to re-energize the distribution grid, creating micro grids, which might speed up the entire restoration process. Similar to restoration at transmission level, wind and solar coordination of control and communication need to be available at this point [42].

B.2.4 Role of Microgrids

As mentioned in Section A.1.6, a series of microgrids protected hospitals and gas stations from outages during Hurricane Harvey [34]. Thus, microgrids may help in power system restoration by keeping some of the load energized through an outage or a blackout. This may help the bulk power system restoration efforts through proper coordination between transmission system operators and distribution system operators.

Similar to the role of DERs mentioned in Section B.2.3, a TOP's restoration plan could potentially include the role of microgrids, in coordination with the associated DSO. If the microgrids remain connected during a blackout, the TOP can work with the DSO to manage the generation/load balance using the microgrids. For such procedures to work, in addition to the TOP-DSO coordination, the TOP will need to have observability of the microgrids.

B.2.5 Coordination with Distribution System

Coordination with distribution system operator needs to be given high priority because of continuing increased penetration of microgrids and DERs, and installation of smart meters. In addition, such a coordination can help in identifying the specific outages monitored by a DSO using smart meters, load loss and equipment damage, which could possibly provide an indication of extent of outage and duration of load recovery. A Transmission Operator's restoration plans must spell out details regarding specific coordination required with the associated DSO.

B.2.6 Restoration Following High Impact Low Frequency (HILF) Events

The electric power industry has been investigating the ways to be prepared for HILF events such as natural phenomena (e.g. hurricanes, tornadoes, earthquakes, geomagnetic disturbances, etc.) and high-altitude electromagnetic pulse (HEMP), terrorist (physical) and cyber attacks. The major theme for industry preparedness revolves around improving system *resiliency, the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate absorb and adapt to, and/or rapidly recover from, such an event* [28]. Preparations span across both near-term (or operational) time horizon and long-term (or planning) time horizon. Some of the aspects being investigated include: hardening of vulnerable power system equipment; keeping a spare inventory of critical equipment; and investigating the impact of loss of key equipment, communications and situational awareness data/information, and the ways to mitigate the impact. For example, the EPRI Black Sky project evaluated emergency communication requirements for a HILF event and concluded that high frequency radio, satellite phone systems and hardened inter-utility private fiber networks can provide effective communication means during a HILF event [30].

CIGRE proposed the following suggestions to be prepared for a HILF event [29] from the long-term (planning) perspective. These ideas do not directly relate to improvements in restoration plan elements, but focus on reducing the impact of any disturbance, including a high-impact low-frequency (HILF) event, that could potentially cause a blackout [29]. The suggestions include [29]:

- Reducing the magnitude of immediate impact by installation of emergency control schemes; and
- Reducing the duration of impact by:
  - proactive staff mobilization (e.g. in anticipation of a weather storm);
  - implementing ways and tools to foretell potential impact (to direct the restoration efforts accordingly);
  - provision of sustained auxiliary supplies (e.g. diesel generators at generating plants, batteries at transmission substations, etc.);
  - improved coordination and communication with distribution system operators; and
  - provision of local emergency supplies (maybe in the form of microgrids) at critical facilities such as gas infrastructure facilities, hospitals, etc.

HEMP presents a unique threat to electric power grid resiliency, and EPRI is engaged in a multi-year R&D effort to investigate potential HEMP threat by providing technically based research results to inform system assessments and inform decisions regarding mitigation. The learning from this project will provide TOs with the guidance necessary to harden the bulk power system against the potential impacts of HEMP, and; thereby, improve the restoration process.

Export Control Restrictions

Access to and use of this EPRI product is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or U.S. permanent resident is permitted access under applicable U.S. and foreign export laws and regulations.

In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI product, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case by case basis an informal assessment of the applicable U.S. export classification for specific EPRI products, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes.

Your obligations regarding U.S. export control requirements apply during and after you and your company's engagement with EPRI. To be clear, the obligations continue after your retirement or other departure from your company, and include any knowledge retained after gaining access to EPRI products.

You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of this EPRI product hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

3002014579

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com