CONSIDERATIONS FOR A POWER TRANSFORMER EMERGENCY SPARE STRATEGY FOR THE ELECTRIC UTILITY INDUSTRY

Prepared by

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EXECUTIVE SUMMARY

Background and Motivation

Various agencies have emphasized, and recent events have demonstrated, the critical nature of power transformers in the face of possible high-impact, low-frequency (HILF) events. HILF events include intentional malicious events (e.g., physical attacks, cyber-attacks, coordinated attacks, electromagnetic pulse weapons, and others), natural disasters (e.g., hurricanes, earthquakes, severe geomagnetic disturbances, etc.), and non-intentional or accidental events such as nuclear power plant accidents.

An emergency spare transformer program is a key part of preparation for, and rapid recovery from, a HILF event. The Department of Homeland Security (DHS)/Electric Power Research Institute (EPRI) Recovery Transformer is an example of one key component to a successful emergency spares program.[1] This landmark program has resulted in the successful design, manufacture, factory testing, transportation, installation, energization, and field testing of the world's first set of rapid deployment high-powered 345-kV emergency spare transformers. This program was conducted at a single U.S. utility (CenterPoint Energy). However, recovery from HILF events calls for broader implementation of prudent measures related to emergency spare transformers. The first needed step is an assessment of recommended practices and guidance for all utilities when implementing enhanced emergency spare transformer programs.

Conclusions and Recommendations

Over the long-term, as new transformers are designed and manufactured to replace the aging population now in service, there is an opportunity to plot a parallel beneficial path forward. If the new "conventional" transformers that are installed can be designed for more broad applicability across substations in a utility service territory, they can better ameliorate HILF threats along with serving their current purpose (e.g., replacement of transformers that fail in normal service). In other words, a more broadly applicable transformer design has benefits for both HILF events that disable transformers, as well as "blue sky" events such as equipment failures in normal service. Over time, most installed transformers and their spares would be more broadly applicable by design (i.e., a single design would meet transformer needs at multiple substations of similar rating in a utility service territory).

Extending this vision of a future conventional design beyond broader applicability to also include rapid construction, transportation, and installation requires an analysis to determine the relative costs and benefits of such an approach.

[1] The DHS/DOE "Energy Sector Specific Plan"(2010) listed the Recovery Transformer as a key research and development capability requirement in the energy sector.

To begin the path towards realizing this long-term strategy, the industry recommends the following:

- Industry stakeholders can work together to enhance the probabilistic analysis of spares by incorporating hazard function information on HILF threats, beginning with physical security attacks. These analyses can then be run at host utilities in the independent system operator (ISO)/regional transmission organization (RTO) service areas. This work will further strengthen the business case for incorporating emergency spares, including flexible spares, at utilities by providing a methodology for calculating return on investment. This work will also serve to solidify future expanded involvement of ISOs/RTOs in this process.
- Industry stakeholders can work with various transformer original equipment manufacturers (OEMs) to define standardized agreements with OEMs for first more broadly applicable spares, and eventually, more broadly applicable conventional transformers.
- Industry stakeholders can work with transformer OEMs to refine functional specifications for more broadly applicable spares, with an eye towards migrating these design features into "conventional" transformers that are installed as existing units are retired; and ultimately standardizing these designs first within utility service territories, and then within regions where possible.
- Effective collaboration of government (DHS, the U.S. Department of Energy (DOE), and others), EPRI, the Edison Electric Institute (EEI), utilities, private enterprise (OEMs and others), the North American Electric Reliability Corporation (NERC), and regulators is critical for success over the long term. Due to the critical nature of this work, EPRI recommends a forum for exchange of information on this topic between representatives of these stakeholders.
- Communication of the results of the current report, the forum, and subsequent work in various forms to all stakeholders is crucial to success.

This report is intended to encourage industry discussion. This report represents the culmination of six years of collaboration between the DHS and EPRI on the Recovery Transformer.

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CONTENTS

Section 1: Introduction and Background

Background: Recovery Transformer Program

This report represents the culmination of six years of collaboration between the U.S. Department of Homeland Security (DHS) and The Electric Power Research Institute (EPRI) on an emergency spare transformer program called the Recovery Transformer. This landmark program has resulted in the successful design, manufacture, factory testing, transportation, installation, energization, and field testing of the world's first set of rapid deployment high-powered emergency spare transformers. This work is documented in numerous DHS reports, videos, and articles.

On March 17, 2012, engineers at a CenterPoint Energy (CNP) Substation near Houston, Texas energized three single-phase, extra-high-voltage Recovery Transformers. The Recovery Transformer implementation was the result of a 3½-year collaboration between EPRI, CNP, government (DHS), and private industry (the transformer manufacturer, ABB). The three energized, single-phase prototype transformers represent an important milestone in utility risk management. The 345-kV/138-kV transformers were installed and energized in less than six days (106 hours), which included a 25-hour road journey from a temporary storage site at the ABB factory in St. Louis, Missouri where they were designed and manufactured. This unprecedented pace of transport and energization, compared to the 30 days that are typically required (assuming that a compatible transformer is even available), successfully demonstrated the Recovery Transformer concept [1].

The Recovery Transformers at CNP were then monitored closely during a one-year prototype live demonstration. The three transformers operated within design specifications for the duration of the one-year monitoring period. The Recovery Transformer reached its peak load on August 9, 2013 of 330 MVA, which is approximately 55 percent of its design capacity of 600 MVA. Alternate configurations tested during the monitoring period operated successfully. These include a remote cooling system rather than an integrated cooling system, which provides flexibility if the substation poses space constraints, and provision of power to the substation from the tertiary of the transformer itself. These results successfully concluded the official monitoring period of the Recovery Transformers and further demonstrated the viability and usefulness of the Recovery Transformer approach and equipment. The three Recovery Transformers continue to operate on CNP's grid.

Motivation for this Work

Various agencies have emphasized, and recent events have demonstrated, the critical nature of power transformers in the face of high-impact, low-frequency (HILF) events. HILF events include intentional malicious events (e.g., physical attacks, cyber-attacks, coordinated attacks, electromagnetic pulse weapons, and others), natural disasters (e.g., hurricanes, earthquakes, severe geomagnetic disturbances, etc.), and non-intentional or accidental events such as nuclear power plant accidents (see Section 2). An emergency spares program is a key part of preparation for, and rapid recovery from, a HILF event. The Recovery Transformer is one example of a key component of a successful emergency spares program conducted at a single U.S. utility (CenterPoint Energy). However, protection from HILF events calls for broader implementation of prudent measures related to emergency spare transformers. The first needed step is an assessment of recommended practices and guidance for all utilities when implementing enhanced emergency spare transformer programs. This report responds to this need. It is intended to encourage industry discussion on this important topic.

Objectives and Organization of This Report

Building on the success of this Recovery Transformer deployment, this report explores the deeper set of considerations for emergency spare transformer strategies for utilities and the industry.

Objective	Section in This Report
Document existing utility transformer spares strategies	Section 3
Document considerations for utility transformer spares strategies	Section 4
Assess the threats that could lead to the need for transformer replacement	Section 5
Define and analyze various sample scenarios in which emergency spares would be needed, covering threats, storage location, and inventory creation	Sections 5-6
Define the criteria for emergency spare transformers	Section 6
Describe possible paths and tactics that utilities and the industry can implement to enhance spares programs	Section 7
Describe considerations for a long-term emergency spare transformer strategy	Section 8

Approach

To gather the information in this report, the project team synthesized information from the results of the DHS/EPRI Recovery Transformer project described in this section. Additionally, this work was inspired by the extensive work conducted by DHS, the North American Electric Reliability Corporation (NERC), the Edison Electric Institute (EEI), the U.S. Department of Energy (DOE), and other entities exploring HILF events, power system resiliency, and related industry work, which the project team synthesized and applied to the specific area of emergency spare transformers. The team also leveraged project plans from new research initiatives that EPRI is now undertaking, including the transmission resiliency framework and transmission physical security projects described below.

The team supplemented this information with interviews with utilities of various sizes, types, and geographic locations; independent system operators/regional transmission organizations (ISO/RTOs); transformer original equipment manufacturers (OEMs); insurance industry personnel; and others. These interviews also served to solicit feedback on topics to be discussed in this report, including the threat assessment, transformer criteria, and comparison of spares approaches. The team also leveraged the expertise of internal EPRI and DHS personnel. This information was then synthesized and organized into the present report.

For clarity, the project team established terminology for various types of spares discussed in this report. As shown in Figure 1:

- An overall transformer spares program at a utility today typically includes only "conventional spares," which are defined as spares used in the event of ordinary equipment failures (i.e., not as a result of a HILF).
- This report covers "emergency spares," which are defined as spare transformers that are used in the event of a HILF.
- Emergency spares can include repurposed conventional spares and "flexible spares" which are pre-manufactured, rapidly deployable, spare transformers that are sufficiently flexible to serve as spares for multiple substations in a utility's service territory.
- These flexible spares, in turn, can include the DHS/EPRI Recovery Transformer manufactured by ABB, and/or flexible spares from other OEMs.

Relationship to Other EPRI Work

This work is an important part of the broader research effort conducted by EPRI, NERC, DHS, EEI, DOE, utilities, and others to help the industry prepare for and recover from a broad array of HILF events. Emergency spare transformers are an important part of any strategy related to HILF events. EPRI's most recent work on HILF potential impacts, mitigation, and risk management is documented in the 2013 EPRI report 3002001935.

HILF events can also be viewed in the broader context of power system "resiliency." In fact, many define resiliency as the ability to harden the power system against and quickly recover from such events. In 2013, EPRI's advisory members determined that regardless of future industry changes, the power system needs to be more resilient. EPRI is working with various stakeholders to assemble a roadmap and action plan to accelerate science and technology to make the power system more resilient.

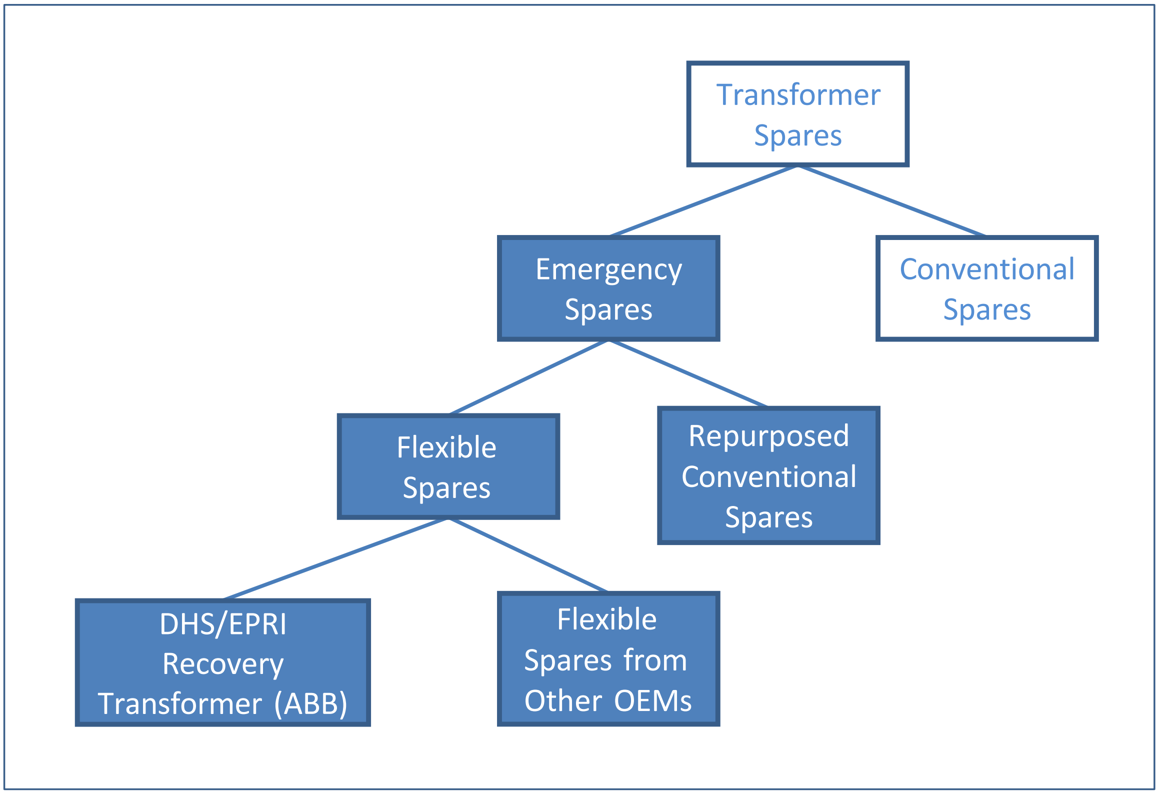

Figure 1. EPRI's Lexicon for use of the term "Spares" in this Product. *Terms in White reference the conventional non-Emergency Spares. Terms in blue reference Emergency Spares options.

Section 2: High-Impact Low-Frequency Events: Recent Research

Overview

Although the North American electricity grid is one of the most reliable power systems in the world, a class of rare, but potentially catastrophic damaging risks is of growing concern in the industry. These so-called HILF events potentially include the following:

- Intentional malicious events, including:
    - Electromagnetic pulse (EMP), high-altitude EMP (HEMP), and/or weaponized intentional electromagnetic interference (IEMI) attacks; and
    - Coordinated cyber, physical, or blended attacks.
- Natural disasters such as:
    - Severe geomagnetic disturbances (GMDs),
    - Hurricanes and consequent flooding,
    - Earthquakes and consequent tsunamis,
    - Severe tornadoes,
    - Severe wildfires,
    - Severe ice storms, and
    - Pandemics.
- Non-intentional or accidental events such as nuclear power plant accidents.

Although some HILF events have never occurred and the probability of their occurrence is difficult to estimate, this does not mean that their probability of occurrence is zero. The potential for long-term damage from HILF events warrants evaluation and enhancement of operational and planning practices to address HILF risks.[2] This requires a cooperative effort between EEI, NERC, FERC, DHS, DOE, and other government entities, utilities, EPRI, and other stakeholders. Industry budgets are constrained, with entities juggling the need to address infrastructure upgrades, smart grid projects, global climate initiatives, and other projects. Maintaining affordable electricity is always a goal of the industry, but HILF risks are part of the current issues that the industry must address.

NERC and DOE have led efforts to address HILF risks to the North American bulk power system. They jointly sponsored a workshop on HILF risks in November 2009. Their initial joint report published in June 2010 presented proposals for action and mitigating options [2].

Building on this report, in November 2010, NERC's technical committees published a Coordinated Action Plan that provided recommended actions to address risks from HILFs including physical attack, coordinated cyber-attack, GMDs, and pandemics [3]. In parallel, NERC released its Critical Infrastructure Strategic

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[2] Note that this report does not attempt to quantify the risk of HILF events. The report assumes the existence of risk and outlines considerations for emergency spare transformers in the presence of undefined HILF risks. The study of risk in the context of emergency spares is a candidate for further study.

Roadmap [4]. These reports provided the strategic priorities and direction needed to understand and address HILF risks. NERC then formed four Task Forces to address three HILF types: coordinated physical attacks, coordinated cyber-attacks, and severe GMDs. In May 2012, the NERC Severe Impact Resilience Task Force examined severe impact scenarios that included coordinated physical attack, coordinated cyber-attack, and GMD, and issued a report that provides recommendations for enhancing power system resilience. One of its recommendations is to "consider the spare equipment critical to bulk power system restoration and ways to improve availability of spares." [5]

EPRI initiated a research project in 2012 to address HILF events from the perspective of a holistic risk management approach. This report consolidates EPRI 2012 work on HILF events in a single technical update, including state-of-the-science information on EMPs/HEMPs, a preliminary integrated risk management approach for HILFs, information on a mitigation approach (Recovery Transformers), and insights presented at EPRI's 2012 webinar on HIL risks [6].

In 2012, the National Research Council published a report on research it conducted at the request of the DHS on terrorism and the electric power system. One of its recommendations is to "fund the research, development, manufacture, and deployment of stocks of compact, easily transported, high-voltage restoration transformers for use in temporary recovery following the loss of several to many regular transformers." The foreword of the report, written at the report's publication, points out that "the report already has helped DHS focus on research aimed at developing a recovery transformer that could be deployed rapidly if many large power transformers were destroyed" [7].

HILF Events in the Context of Power System Resiliency

HILF events can be viewed in the context of transmission, distribution, and end-use resiliency. In the context of the power system, resiliency is the ability to harden the system against—and quickly recover from—HILF events. Enhanced resiliency of the power system is based on three elements: damage prevention, system recovery, and survivability:

- Damage prevention refers to the application of engineering designs and advanced technologies that harden the power system to limit damage.
- System recovery refers to the use of effective tools and techniques to quickly restore service as soon as practicable.
- Survivability refers to the use of innovative technologies to aid consumers, communities, and institutions in continuing some level of normal function without complete access to their normal power sources.

Recent extreme weather events—including the U.S. hurricanes Katrina and Sandy and the Tohoku earthquake and tsunami in Japan—have demonstrated the need for greater resiliency. Other natural HILF events that pose threats to resiliency include large tornadoes, large wildfires, and severe GMDs.

Although recent severe weather events have raised awareness of the need for enhanced resiliency, extreme weather has occurred as long as the power system has existed. Other trends and events in the last decade—with profound pace and scope— have increased the possible risk of HILF events and their potential impact on society, and hence, further shaped the need for enhanced resiliency. A 2013 act of vandalism that damaged several high-voltage transformers in a West Coast substation has focused the industry's attention on the need for enhanced physical security and resiliency against such attacks. Wide deployment of communication nodes in the grid in the past decade raises concerns of possible cyber-related attacks. Coordinated cyber or physical attacks are of growing concern. Increasing dependence on natural gas-fired power generation can pose vulnerabilities if a HILF event disrupts the gas pipeline infrastructure.

At the same time, HILF events pose national security, economic, and social impacts. As described in a DHS fact sheet, " acing threats to our Nation from cyber-attacks that could disrupt our power, water communication and other critical systems, the President issued the Executive Order (EO) 13636 on Improving Critical Infrastructure Cybersecurity and Presidential Policy Directive (PPD) 21 on Critical Infrastructure Security and Resilience." [8]

The Critical Role of Power Transformers during Recovery from HILF Events

In the broader context of HILF events and power system resiliency, this report focuses on the utilization of spare equipment to support more *rapid recovery* from HILF events.

Power transformers play a critical role in the electric power transmission and distribution system—acting as the off-ramps to bring power from the high voltage transmission network down to the distribution level at substations across the country.[3] Hence, power transformers are a critical part of any spares strategy.

High voltage transformers are critical to the continued reliable operation of power systems. More than 90 percent of consumed power passes through high-voltage transformers at some point. These large devices, weighing hundreds of tons each, are potentially vulnerable to the effects of HILF events. This vulnerability is compounded by the fact that many U.S. high-voltage transformers are approaching or exceeding their design lives. Due to their size and complexity, these transformers are expensive and time consuming to replace in the event of failure due to a HILF. In the event of catastrophic or regional attack, insufficient spares may exist, and those that do are not easily installable at other locations besides those originally intended.

The North American power grid has built-in redundancy to accommodate failure of a single high-voltage transformer. The NERC N-1 reliability standard (contingency) is designed such that failure of one high-voltage transformer may strain the power system but not cause a major outage or cascading failure. The concern is that

[3] DOE's report on Large Power Transformers and the U.S. Electric Grid, April 2014, provides more information on these assets.

simultaneous failure of a number of high-voltage transformers could pose a significant vulnerability.

Potential Ways to Address Power Transformer Vulnerability

One approach to addressing this vulnerability is to attempt to retrofit these transformers with devices that harden them against various HILFs. This approach shows promise to harden against GMDs and EMP attack, for example. Various designs have been proposed that block or reduce geomagnetic induced current (GIC) flow in transformers and lines to mitigate GMDs, including series compensation, use of blocking capacitors in the neutral ground, and use of neutral resistors to reduce GIC flow [9].

However, this may be a challenging approach due to the number of high-voltage transformers, the number of different designs and sizes, and the need to ensure that any retrofits do not adversely affect normal operation. With regard to design variation, impedance of most units covers a wide range and MVA ratings vary from 150-750 MVA. Other design variations include single-phase versus three-phase; shell form versus core form; three-, five-, or seven-leg models; and others. Another limitation of this approach is that is does not adequately harden against other types of HILFs, including physical attack.

Various operational measures, such as reducing load on some high-voltage transformers in advance of an impending GMD or severe weather, will certainly help to mitigate transformer damage. However, depending on the severity and character of the HILF (e.g., HILFs with little or no warning such as physical, cyber, or coordinated attacks), such measures may not protect all high-voltage transformers from overload, damage, or failure. After the HILF, traditional recovery measures (e.g., rerouting of power, load shedding, islanding, use of backup generation, and others) would certainly be deployed, but these may be insufficient to restore the power system in a timely fashion, depending on the impact of the HILF.

Section 3: Power Transformer Spares: Existing Strategies

Overview

A strategy for emergency spare transformers can complement transformer hardening approaches and power system operational measures to enhance resilience against HILFs. Information in this section was obtained by interviewing/surveying a number of utilities of various sizes and geographic locations across North America, as well as other stakeholders.

Some utilities have implemented various combinations of the following strategies for spare transformer programs. Hence, a comprehensive emergency spare transformer strategy for a given utility could include some combination of these existing strategies:

- Utility stocking of dedicated, interchangeable spare transformers, typically for reliability purposes (conventional spares), as opposed to purposes of rapid recovery from HILFs.
- Ordering conventional spares early due to approaching end of life.
- Retaining retired conventional transformers for use as spares.
- Formal sharing arrangements such as the EEI Spare Transformer Equipment Program (STEP) program and the NERC Spare Equipment Database (SED) program.
- Informal and formal sharing arrangements with neighboring utilities.
- Utility agreements with transformer OEMs.
- Efforts to establish a standardized transformer design(s) within a utility.
- Some emerging program of rapid delivery and installation of flexible spare transformers specifically designed for this purpose, such as the Recovery Transformers initially deployed and proven in a one-year test in the DHS/EPRI project, or alternative projects (e.g., the approach from a commercial company described later in this section).

Utility Stocking of Interchangeable Spare Transformers

One approach is for individual utilities to stock conventional spares for critical transformers that are equivalent and interchangeable, and then repurpose them as emergency spares as needed. This approach ensures that each spare is completely compatible with the transformer it replaces. Hence, the functional requirements of the spares are identical to those of the transformers to be replaced. However, this approach requires that the utility stock a large number of spares. At least one utility interviewed uses this approach.

One interviewed utility routinely installs four single-phase conventional transformers in each bank at many substations, instead of the needed three transformers, to provide an on-site spare for each bank. Instead of performing an analysis to identify critical substations, this utility installs the fourth transformer as a standard practice. Each spare transformer is filled with oil and is connected to the rest of the bank through a switch, such that the spare can be energized within 24 hours to replace any of the three single-phase transformers without being moved. To some extent, these transformers can be transported to a different substation if a spare is needed, making them repurposed conventional spares, but the utility indicated that this would require 1-2 months. This approach also calls for transformer functional requirements that are almost identical to the transformers that they replace. However, due to location of these spare transformers at the substation next to existing transformers, these spares provide limited protection from physical attack HILFs.

There seems to be a wide range of approaches among utilities with regard to stocking spares. Some do not stock any spares, some stock a few selected spares, some stock spares for almost all transformer banks, and some also are engaged in development of flexible spare transformers of various types (as described below).

Utility Conventional Spares Early Ordering Due to Approaching End of Life

Another approach is to order conventional spares earlier than needed for transformers that are nearing the end of their service lives, especially if they are at critical substations, and then repurpose them as emergency spares as needed. In this way, the utility gains a spare that will certainly be needed eventually. In this approach, the primary planning criterion is the condition and projected remaining life of the transformer. This can be done by assessing the health of each transformer, approximating the probability of failure of each transformer, and using this information to determine risk. This risk can then be correlated to cost and compared to actual cost. Such an analysis may ultimately enable estimation of return on investment for these assets. At least one utility of those interviewed currently has adopted this practice.

Retaining Retired Utility Transformers as Spares

Another approach is to keep retired transformers on hand and then repurpose them as emergency spares as needed. Such transformers that are retired but have not failed may be usable temporarily after a HILF. Using these previously retired transformers in this way can "buy time" until new transformers can be obtained, manufactured, and transported. At least one utility interviewed currently has adopted this practice.

Transformer Sharing Programs

NERC SED and EEI STEP Programs. In the event of a HILF, the SED and STEP programs make available to other participating utilities the limited number of conventional spare transformers that do exist. This approach makes sense and is a key recommended "proposal for action" in NERC's 2010 assessment of HILF risk to the North American bulk power system [2]. The goal of the NERC GMD Spare Equipment Database (SED) program is to provide a means to securely connect entities that need replacement transformers with entities that have such spares available. In the event of a HILF-type event, such as a significant GMD, access to information about available spares to match particular needs at a specific substation location will help speed power restoration. NERC's Spare Equipment Database Task Force (SEDTF) is spearheading this effort. This program is not intended to replace or supersede any existing transformer sharing programs, such as the EEI Spare Transformer Equipment Program (STEP) or other regional or neighboring utility sharing arrangements [10].

EEI's STEP Program, launched in 2006 in response to the 9/11 terrorist attacks, addresses the need to pool resources in response to a terrorist attack. This program only goes into effect when the President of the United States declares an event to be a terrorist attack. About 50 transmission providers that represent about 70 percent of the transmission grid currently participate in this program. Participants sign a Spare Transformer Sharing Agreement, which "carries with it a binding obligation to provide a transformer or transformers if called upon by another STEP participant." The transfer is a sale that is pre-approved by FERC and the participants' respective state commissions [11].

Utility-Specific Spares Programs and Informal Sharing. To complement participation in one or both of the formal sharing arrangements (SED and STEP) or as a preferred alternative to these arrangements, some utilities have adopted internal programs to manufacture and store on-hand conventional spare power transformers for their power system. Some utilities have also entered into informal transformer sharing arrangements with neighboring utilities. These collaborative programs are further discussed in the section on considerations for a utility emergency spare transformer strategy.

ISO/RTO Perspective on Transformer Sharing Programs. ISOs/RTOs have diverse views on involvement in utility spare transformer programs. One interviewed ISO/RTO indicated that it has no involvement in spare transformer strategies, but that the transmission owners (TOs) are responsible for this. Another ISO/RTO interviewed, PJM, directs the purchase of spares by TOs in its operating territory. By virtue of its broad perspective, the ISO/RTO is able to pool data from TOs in its territory and identify the need for spares. This direction is based on a probabilistic risk assessment (PRA) that applies hazard functions to a transmission congestion analysis to assess risk. Today, the hazard function incorporates state data on transformers (based on equipment condition assessments), and hurricane and tornado probabilities (see Figure 2). While this is clearly a strategy for conventional spares, inclusion of severe weather probabilities also makes it a strategy for emergency spares to some extent. To date, the hazard function has not incorporated a physical attack due to insufficient data. However, further work may enable this approach to be extended to physical security attacks and other HILFs [12].

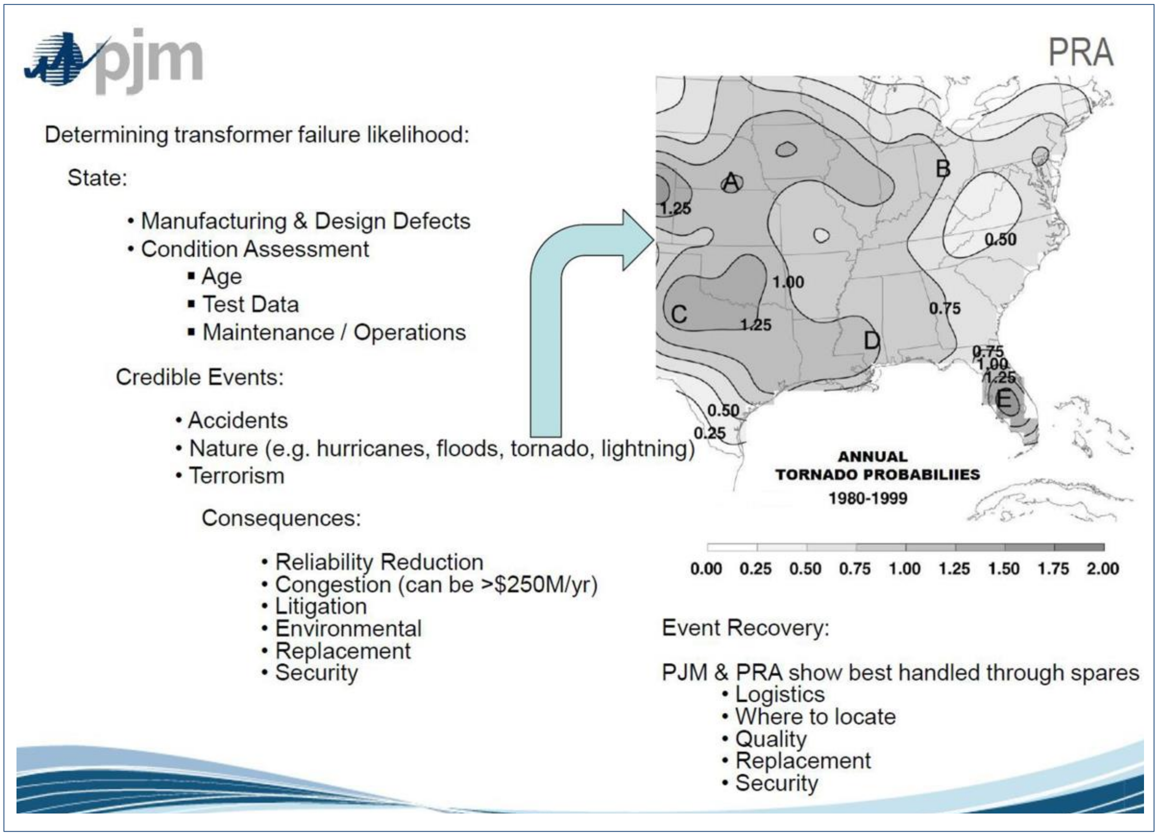

Figure 2. The PJM Probabilistic Risk Assessment for Spare Transformers [12]
Figure credit: PJM

Utility Agreements with Transformer OEMs

Some utilities interviewed either have established or are working to establish functional requirements and designs for conventional spares with at least one leading transformer OEM, and some utilities are working to establish agreements with at least one OEM to expedite manufacturing if needed. This may involve OEM pre-ordering and stocking of long-lead time parts and materials. One utility pointed out that the best way to expedite OEM production in an emergency is to put in place a “master agreement” and transformer design with the OEM in advance. This agreement can include negotiated reduced lead times in an emergency. However, it should be noted that agreements that provide one utility higher priority delivery might increase the lead-time for another utility, due to finite OEM production capability; this may not improve the overall response time to filling all utility transformer orders.

Standardized Transformer Design

Utilities can consider moving toward a standardized[4] transformer design for its service territory. In the May 2012 report of the NERC Severe Impact Resilience Task Force, NERC states that "To promote greater interchangeability of components, increase the standardization of component specifications such as physical size and electrical rating." [5] Such a standardized design would reduce the number of different types of spares that the utility would need to keep on hand. At least one utility interviewed is in each of the following states with regard to standardized transformer design:

- It is already considering such a standardized design;
- It is interested in standardization;
- It has reduced its number of designs; or
- It prefers to stay with transformers that are built to their specific design standards.

An ISO/RTO interviewed described a logistics study it conducted a few years ago that showed that use of a common transformer design plus use of transformer sharing would significantly decrease the number of spares needed and cover more risk. The common design consisted of a small number of standardized transformers that differ primarily in impedance. Some transmission owners vetoed the plan, citing transformer transportation and auxiliary equipment difficulties.

Flexible Spare Transformers

Overview. The conventional spare transformer sharing approach may be limited by the differences in high-voltage transformer designs. Impedance of most units ranges from 9-15 percent and MVA ratings vary from 150-750 MVA. Other design variations include single-phase versus three-phase; shell form versus core form; three-, five-, or seven-leg models; and others. Other design needs of specific installations include tap ratios, cooling system variations, use of gas-filled bushings, and others. These and other complexities would almost certainly make transportation, installation, and energization of conventional spare transformers that are repurposed for emergency purposes (in locations where they were not originally designed to be installed) a time consuming process in the event of a HILF. Replacement conventional transformers are frequently custom ordered and built (requiring a year or more in custom design and scheduling) and can take four weeks or more to transport and install.

An approach that can address this limitation is flexible spare transformers that are specifically designed and manufactured to enable rapid delivery, installation, and energization at utility substations in the event of a HILF. Such flexible spare transformers can be pre-manufactured and stored at a utility's central storage

[4] In this report, a "standardized" transformer design means that the transformer would meet certain defined functional requirements that would enable flexibility, for example. However, the detailed design, materials, manufacturing process, and other decisions as to how to achieve these functional requirements would not be standardized.

facility, for example (or potentially at a central storage facility shared by multiple utilities) for rapid deployment to various substations when needed. This approach can complement other emergency spare transformer strategies. It could reduce recovery time in the event of a HILF. The estimated elapsed time from the call to action until the transformer is energized is four weeks for a conventional three-phase power transformer.[5] The requirement for the Recovery Transformer was one week or less. This may provide an appropriate industry benchmark for all flexible spare transformers. Flexible transformers can incorporate modifications that reduce weight, decrease space requirements, and simplify on-site installation, while matching the reliability and performance of conventional transformers.

Recovery Transformer. One example of a flexible spare transformer is the Recovery Transformer program recently demonstrated by DHS and EPRI. Described in Section 1 of this report, this project successfully demonstrated the design, manufacture, factory testing, transportation, installation, energization, and field testing of the world's first set of rapid deployment high-powered flexible spare transformers.

Other Flexible Spare Transformer Programs. Construction of additional flexible spare transformers like the Recovery Transformer can provide utilities a rapid way to replace high-voltage transformers in the event of a natural disaster, man-made attack, or unexpected failure—without lengthy, costly service outages. Other OEMs are working on designs for flexible spare transformers, but their designs are currently confidential, and hence, cannot be described in this report. However, in 2014, one interviewed utility described a current program to work with a transformer OEM to develop a power transformer that is sufficiently flexible in design to provide a suitable spare for multiple substations. While the MVA rating of the transformer is fixed, external tap changers provide various high-side/low-side voltage combinations. Other functional requirements and design features provide additional flexibility, but are confidential to the particular utility and OEM. The cost impact of these additional features is yet to be determined. The additional cost needs to be weighed against the added ability to replace multiple transformers and replace them more rapidly.

The utility expects these transformers to provide a service life of 5-10 years, rather than the conventional 40-year life. To be stored at the utility's central storage facility or facilities, several of these transformers will be constructed. The utility estimates that such a transformer could be deployed and energized in approximately three days rather than the months required to order a new transformer. Now under development, this transformer will complement the utility's existing set of conventional spare power transformers, enhancing the utility's ability to rapidly restore power in the event of multiple transformer failure. Given the strategic nature of the 345-kV/138-kV transformers in North America (the most prevalent high-voltage transformer), this capability can provide a needed boost to system reliability in the event of these (HILF) events.

[5] EPRI business case document and EEI STEP participants.

Commercial Company Transformer Rental Program. At least one for-profit, commercial company (e.g., WattStock)[6] seeks to fill an industry need for spare transformers. The business model is to rent spare transformers in a range of voltages to utilities across the United States in exchange for some combination of fees.

Participation in such a program could be a small percentage of typical operation and maintenance (O&M) costs. The company would need some minimum number of transformers to make the program financially viable. The transformers could be stored at various customer-dependent sites.

Investor owned utilities (IOU) could use a program like this as a means of balancing capital spending, which some IOUs indicated may be increasingly tightened by public utility commissions, with O&M spending, which is small and can be included in the rate base.

A program like this could provide risk-reduction against "blue sky" failures of transformers as well as failures of transformers due HILF events. The company could maintain an inventory of spares at regional distribution centers close to covered assets that could be rapidly transported and installed at utility sites as needed. The company could provide transformers with multiple high- and low-voltage capability, and modular design for ease of installation. They could provide temporary replacement until a permanent replacement could be constructed, transported, and installed. They could address impedance mismatch issues by allowing efficiencies to decrease or using methods of compensating for the mismatch temporarily until a permanent transformer replacement could be installed.

[6] See www.watt-stock.com.

Section 4: Considerations for a Utility Emergency Spare Transformer Strategy

Information in this section was obtained by interviewing/surveying a number of utilities of various sizes and geographic locations across North America.

When developing new or assessing existing transformer spares strategies for individual utilities or the industry as a whole, the following considerations are relevant:

- Functional requirements and applicability of transformer design and characteristics to multiple substations;
- Power system reliability criteria and planning criteria;
- Spare transformer financial and budgetary considerations, including rate base treatment, capital planning, and business case;
- Emergency spare transformer storage location, logistics of transportation to the substation, and time to energize from call to action;
- Coordination and collaboration with other utilities or industrywide;
- Regulatory drivers; and
- Utility staffing and training.

Functional Requirements and Applicability of Transformer Design and Characteristics to Multiple Substations

Identification of the critical functional requirements for emergency spare transformers is an important consideration for a utility-specific or industry-wide spares strategy.

Functional Requirements to Enable Broader Applicability. To reduce the number of spares needed, individual utilities can identify what functional requirements are necessary to enable a single spare transformer to be applicable to more than one substation if possible. This enables a utility to stock a manageable number of spares that cover most of all of its critical substations. In all cases, the high-side/low-side voltage and MVA rating must match. For some utilities, other electrical characteristics such as voltage regulation provision, fault withstand, or more generally, impedance, must be a close match. These are typically a function of the utilities system and transformer fleet characteristics. For some utilities, the physical size (footprint) of the transformer may be a critical consideration—foundation space limitations at substations may necessitate certain physical sizes and geometries. Functional requirements related to transportation, storage, and time to energize from call to action are addressed separately below.

Flexible Spare Transformer Functional Specifications. The estimated elapsed time from the call to action until the transformer is energized is four weeks for a conventional three-phase power transformer. The flexible spare transformer requirement is one week or less. Although transformers can be transported in various ways from a utility's central storage facility to the substation site (e.g., via road, river, air, or rail), the primary functional requirement is rapid delivery and energization, regardless of transportation means employed. The goal is to rapidly install the flexible spare transformer to restore load without introducing additional safety risks or environmental impacts, compared to conventional transformers.

Recovery Transformer Functional Specifications. EPRI developed more detailed functional requirements for the Recovery Transformer—an example of a flexible spare transformer—including its applicability across the range of North American high-voltage transformers. This program developed and implemented a prototype high-voltage transformer that can replace more than 90 percent of the 345-kV/138-kV voltage class power transformers in the U.S. fleet. This voltage class represents a large portion of the total power transformers in the United States. Appendix B lists the key functional requirements of the DHS/EPRI Recovery Transformer. Appendix C describes impedance considerations for flexible spare transformers in general and the Recovery Transformer specifically.

Power System Reliability Criteria and Planning Criteria

In assessing the need for, and number of, spare transformers needed, individual utilities examine combinations of the following:

- Historical transformer failure rates (internal and compared to industry rates);
- Condition of existing transformers;
- Transformer manufacturing lead times;
- Number of transformers already ordered and in the process of being manufactured;
- The likelihood of transformer failures, unanticipated load growth (including commercial/industrial customers who grow rapidly and require fast installation of transformers), and HILF events; and
- Competing pressure for affordability and reliability, including economic factors such as the cost of energy delivered, outage costs, etc.

These factors are assessed in tabular form in Section 6 of this report.

Contingency Criteria. The base planning criteria may be planning to accommodate N-1 contingencies, but emerging more stringent regulatory requirements and a desire to be prepared for the possibility of multiple simultaneous transformer failures in a HILF event, may motivate utilities to adopt a more stringent criteria. Pending regulation regarding physical security is likely to also influence criteria for spares. For an attack on any single site, at least one interviewed utility plans to be able to restore all customers quickly and then rebuild to an N-2 condition within 2-3 months.

Restoration Times. With regard to the desired timeframe for full restoration from a HILF attack, recovery times from major natural disasters can act as a guide. Major hurricanes have led to recovery periods of a few weeks. Such outages present significant economic impacts and disruptions to interdependent critical infrastructures. (Economic losses from Hurricane Sandy alone are estimated at $30-$50 billion [13].) Emergency spare transformers can help to reduce restoration times.

Federal Government Involvement. The federal government is taking action with regard to significant power outages. Based on DHS discussions with FEMA, FEMA is looking at developing a Power Outage Incident Annex (POIA) to the Federal Interagency Operations Plan (FIOP) for both Response and Recovery. The purpose of the POIA is "to provide hazard-specific supplemental information to the Response and Recovery IOPs." The scope includes terrorism, natural disasters, and accidents. "The POIA will detail how the Federal government delivers core capabilities to respond to and recover from the impacts of a significant power outage incident." FEMA is coordinating with DOE and other federal agencies; state, local, and tribal governments; and the private sector in this effort "to save lives, protect property and the environment, and meet basic human needs when there is a threat or an actual power outage incident." [14]

Substation Criticality Analysis. A key step is to perform internal analyses to identify critical substations, and place a high priority on spares for these facilities, or in the case of at least one utility interviewed, to stock spares for *all* critical facilities. The process of identifying critical substations is specific to each utility. EPRI conducted a recent study to establish criticality rankings for fossil plant systems and components, which can be extended with further research to power transformers [15]. One interviewed utility employs a rigorous approach to identifying critical substation assets to identify needed spares. The utility assesses the consequence of asset failure on customer service, customer reliability, cost, transmission reliability, regulatory considerations, safety, and public perception. The utility uses a methodology that includes assigning criticality scores and categories for each power transformer. For transformers deemed most critical, the utility stocks a spare for each bank type *and* maintains N-2 redundancy. For moderately critical transformers, the utility stocks a spare for each bank type. For less critical transformers, no spares are stocked.

Spare Transformer Financial and Budgetary Considerations, Including Rate Base Treatment, Capital Planning, and Business Case

Spare transformer financial and budgetary considerations include the following:

- The circumstances under which state public utility commissions allow utilities to include spare transformers in the rate base (and hence gain cost recovery from the date purchased) is an important consideration. This may drive decisions as to whether to locate the transformer at the substation or at a central storage facility, and if located at the substation, whether to energize the spare for partial load. Most utilities interviewed indicated that their commission currently allowed it to rate base a transformer as soon as it is received—it need not be energized or at a substation—and that capital for spares need not be itemized separately from the overall investment plan.

- Federal, municipal, and rural electric cooperatives may need to submit their plans to other decision makers, instead of public utility commissions.
- Some utilities are constrained in their capital programs; as a result, they need to incorporate power transformer spares purchases in their overall capital program and prioritize these relative to other equipment purchases.
- Some utilities may be required (either via internal regulations or regulatory requirements) to prepare a business case (or business justification) for purchase of transformer spares. Much of the information in this report can help inform the considerations included in such a business case.

Emergency Spare Transformer Storage Location, Logistics of Transportation to the Substation, and Time to Energize from Call to Action

Storage location and the mode and logistics of transportation of the spare transformer from a storage location (if applicable) to the substation affect the time to energize the transformer. Minimizing this time to energization is crucial to facilitate more rapid recovery from a HILF event.

Emergency Spare Transformer Storage. With regard to storage, utilities may consider storing their spare transformers at various locations, including at the substation or at the utility's central storage facility (see Table 1). If the spare is stored at the substation where it would be energized, time to energization can be minimized because no transportation is necessary (see the top highlighted blocks in Table 1). In addition, confidence in its readiness for operation is high, and ongoing value of the transformer can be derived if it is energized and put into partial use. However, the transformer's location at the substation potentially subjects the transformer to some of the same threats that the spare is intended to address (e.g., physical security threats, GMDs if energized, and EMPs/HEMPs/IEMIs). This approach limits protection from these HILFs and limits its likely availability during recovery. At least one utility interviewed is currently using this option, but plans to consider alternatives in light of the threat of possible physical attacks. In the May 2012 report of the NERC Severe Impact Resilience Task Force, NERC states that "The spare equipment should be readily accessible, but a physical distance from the equipment being replaced [is recommended] to minimize the possibility of damage as a result of collateral or intentional actions." [5]

Alternatively, if the transformer is stored at a utility's central storage facility, no ongoing value can be derived from the transformer until it is energized, time to energization is higher, and confidence in its readiness for operation is lower. However, the transformer's protection from most HILFs is much higher due to its storage in a location remote from the substation (see the lower highlighted blocks in Table 1). Storing the transformer indoors at the central storage location would further increase protection from physical attack. At least one utility interviewed stores power transformers at a central location. The company does not currently protect the transformers from HILFs (e.g., physical barriers) at this central location, but this is likely to be re-evaluated as a result of the NERC CIP-014 Reliability Standard on physical security [16]. This Standard is issued in response to the FERC Order on Reliability Standards for Physical Security Measures [17].

Table 1. Emergency Spare Transformer Storage Scenarios

Storage Location Scenarios (Independent of Inventory Creation Method)	Continual Value Derived from Transformer	Transport and Energization Time	Confidence in Readiness for Operation	Protection from HILFs
Priority (Based on Utility Interviews)	**Low**	**High**	**Moderate**	**High**
Transformer energized on utility site	Yes	None	High	Very limited
Transformer not energized on utility site	No	Short	Moderate	Limited
Transformer stored in utility's central storage facility	No	Moderate	Moderate	High
Transformer stored at central industry site	No	Moderate	Moderate	High
Transformer part of STEP program	No	Moderate	Moderate	High

Another alternative is transformer storage at a central industry facility—an option with similar characteristics as utility central storage.

Appendix D contains lessons learned regarding transformer storage from the DHS/EPRI Recovery Transformer program. Based on experience from this program, the following recommended storage considerations for emergency spare transformers are offered:

- **Store Filled with Oil:** Maintain the transformers filled with transformer insulation oil.
- **Transformer Monitoring:** Incorporate dissolved gas monitoring and some sort of intelligent monitoring system to monitor the condition of the transformer during storage.
- **Covering/Preloading:** Cover ancillary equipment required to complete transformer installation at the host utility site and preload it on flatbeds for rapid transport.
- **Inventory Checklists:** Prepare in advance, maintain, and apply inventory checklists of equipment needed.
- **Spare Parts Kit:** Assemble a spare parts kit that will travel with the deployment. This kit should include gaskets, o-rings, oil pressure relief valves, and other items. Identify a full list of these parts. For larger ancillary equipment, instead of including spares (which is not practical for all components), identify where spares can be located and transported to the site.

- **Bushing Protection:** Store the bushings in a clean and dry place. Provide suitable protection for terminals and mounting hardware to prevent corrosion. Protect any exposed spring assembly at the oil end of the bushing to prevent corrosion. Store a vertically mounted bushing in an upright position. Store a horizontally mounted bushing in a horizontal position.

Emergency Spare Transformer Transportation. Transportation mode and logistics also play an important role. While some utilities with small service territories do not face major transportation limitations, larger utilities can face significant transportation challenges. Emergency spare transformers can be transported from a storage location to the substation by air, rail, barge, or truck, depending on the route needed and service territory. Some utilities interviewed have contracts with transportation companies in place to transport power transformers and/or have good relationships with emergency management offices to obtain transportation waivers and police escorts in emergency conditions.

When devising a transportation plan for an emergency spare transformer, transportation pre-planning is recommended. If possible in advance, route plans, convoy configuration, permit acquisitions, and liability insurance should all be devised or acquired in advance. This includes establishing and obtaining pre-approval for proposed routes from various state permitting agencies and reviewing/updating these approvals periodically as required.

A flexible trailer, such as the MA-65 customer trailer (built by Nelson Manufacturing) used in the Recovery Transformer program, as two advantages over a traditional lowboy trailer (See Figure 3). Firstly, the transformer sits on a sled that can form the base pad for the transformer, avoiding the need for a crane to unload the transformer and avoiding the need to prepare a special surface or lay concrete at the substation prior to deployment. Secondly, the flexible trailer can maneuver the transformer into place through parallel parking. The hydraulics on gooseneck jeeps at either end of the sled allow the transformer to be lifted clearof obstacles and lowered to the ground when in place.

Additional transportation procedures and requirements were developed and executed in the Recovery Transformer Program.

Figure 3. Transportation of the Recovery Transformer on the MA-65 custom trailer avoids the need to prepare a special surface or lay concrete at the substation prior to deployment.

Coordination and Collaboration with Other Utilities or Industrywide

Coordination and collaboration across utilities benefits individual utilities and the industry as a whole. Existing formal sharing arrangements such as EEI STEP and NERC SED, as well as informal sharing arrangements between utilities play an important role in any transformer spares strategy. The broad availability of significant numbers of emergency spare transformers could be an important complement to other sharing programs. Utilities interviewed expressed varying levels of interest and participation in these various collaborative options. Reservations with the collaborative programs noted by some interviewed utilities included concerns about sharing assets that the utility fully finances, the practicality of transporting spares over long distances, impedance mismatching, and information confidentiality.

Consideration of how these collaborative opportunities complement utility specific spares programs for individual utilities and the industry as a whole is a key consideration. One way to examine this area is to examine “tiers” or spares that are a function of the threat impact. For example, the first tier of response after an attack could include utility installation of spares on hand. The second tier of response could tap into collaborative programs if applicable. Depending on the structure of a broadened emergency spare transformer program, these transformers could be transported to needed sites on a priority basis (e.g., as a function of predefined substation criticality).

Regulatory Drivers
Public utility commissions in various jurisdictions may impose the following considerations for utilities seeking to enhance their spares strategy:

- The rules for transformer qualification for rate base treatment;
- Requirements for detailed capital plans, and whether these plans require a separate treatment for power transformer spares;
- The new NERC CIP-14 requirements for physical security of transformers may factor into decisions regarding the location of spare transformers; and
- Planning criteria requirements for power transformers. Some jurisdictions are considering or have implemented more stringent criteria than the traditional N-1 contingency requirements.

Utility Staffing and Training

An important component of any utility transformer spares strategy is utility staffing and training. The planning, transportation, installation, and energization process for spare transformers in response to HILFs can be incorporated into utilities' existing emergency response plans, which typically address major storm preparedness and response. These emergency plans typically define the roles and responsibilities of utility personnel, both before, during, and after major events. When power transformer replacement is needed rapidly, utilities must mobilize a significant team of personnel, which can be defined in these plans. Either these plans or separate policies also cover the conduct of upfront and periodic training, tabletop and field exercises, and drills—some of which often include involvement of local and federal law enforcement officials and other stakeholders. Utilities can modify these plans to accommodate transformer spares strategy and activities.

Section 5: Power Transformer Threat Assessment

Any examination of emergency spare transformer strategies must include an assessment of the possible threats to these transformers. This section describes the type of threat selected for use in this report to assess considerations for a transformer spares strategy, define criteria for needed spare transformers, and describe tactics and a long-term strategy for transformer spares. This threat assessment was performed in collaboration with utility personnel.

Overview

Although some HILF events have never occurred and the probability of their occurrence is difficult to estimate, this does not mean that their probability of occurrence can be assumed to be zero. Hence, preparing to respond to these threats is a prudent step for utilities and in a broader context, for society to take, especially in light of the potentially significant impacts of these events to the electric infrastructure and the infrastructures that it supports.

A comprehensive assessment of the probabilities, impacts, and hence, risks of various combinations of HILFs is beyond the scope of this project and report. However, some threat definition is necessary for assessment purposes. This enables assessment of considerations for a power transformer spares strategy, definition of criteria for needed spare transformers, and description of tactics and a long-term strategy for transformer spares.

Interested stakeholders are encouraged to perform their own analysis with a range of presumed probabilities. This will provide an estimate of probability-weighted cost, along with the sensitivity of the presumed probability cost and mitigation strategy. A current EPRI project to develop a transmission resiliency framework will help enable this capability.

Focus on Physical Security

The recommended approach adopted in this report is to focus on a recent threat that has emerged as a major concern among utility decision makers across North America. This is the threat of physical attacks on power system assets, primarily power transformers. This threat has emerged as a concern based on recent incidents. The primary recent incident is the sniper fire attack using high-powered rifles by unknown assailants that caused a significant equipment outage of several power transformers at a West Coast (Metcalf) substation in April 2013 [18]. This threat can be generalized to include any form of physical attack that causes a significant power transformer outage at a critical substation. This threat is relevant for use in this assessment of power transformer spares strategies for the following reasons:

- It illustrates the potential vulnerability of the power system to this sort of attack. The event actually occurred, was a deliberate act, occurred recently, and hence, is top of mind among industry decision makers.

- It poses a direct threat to power transformers.
- It can occur at any location across North America, and hence, has broad applicability to a diverse set of stakeholders. This can be compared, for example, to GMDs, which primarily affect upper latitudes; or natural disasters such as hurricanes, tornadoes, derechos, earthquakes, and tsunamis, which pose regional impacts.
- It is a threat that has traditionally not been explicitly and thoroughly addressed, and hence, poses some urgency for consideration.

Scenario Definition

A recommended approach is to adopt a plausible variation on the 2013 West Coast attack as a base attack, and to also include plausible extensions of this attack as the basis for transformer spares assessments and subsequent work. The representation of these scenarios is not intended to suggest that they are probable risks. Rather, they were selected because they were plausible and they stimulate thinking about the value, costs, and risks of an emergency spares program. Interested parties can use these scenarios for analysis of their spares strategy, or they can develop their own scenarios.

The actual 2013 attack significantly damaged the ancillary equipment of several power transformers at the substation, rather than the core transformers themselves. The attack also simultaneously severed fiber-optic communication lines in an attempt to cut off utility communication with the substation—a tactic that was only partially successful. The defined base attack recommended for this analysis is a variation on this 2013 event in which assailants are assumed to damage the transformers themselves, rather than ancillary equipment, and are assumed to successfully sever communications between the utility and the substation, preventing emergency switching operations and other necessary response measures. Plausible extensions of this base attack that are broader in scale can then be defined.

A detailed assessment of the potential impacts or probability of any of these threats is beyond the scope of this project and report. However, the level of interest and concern among utility decision makers in the wake of the 2013 event indicates that expanded, simultaneous events like this one would certainly be of greater concern.

While this type of threat is used in this project and this report, it is important to remember that is only one example of myriad HILF events that the industry potentially faces. Stakeholders are encouraged to develop other plausible scenarios of interest that can be used to assess resiliency.

Section 6: Criteria for Emergency Spare Transformers and Comparison of Spares Approaches

This section describes the criteria for effective emergency spare transformers, describes scenarios for spares storage and creation in terms of these criteria, and compares and assesses the criteria/scenarios.

Spare Transformer Storage Locations

Table 2 shows the four storage location scenarios and criteria related to storage location.

Table 2. Emergency Spare Transformer Storage Scenarios, Criteria, and Priorities

Storage Location Scenarios (Independent of Inventory Creation Method)	**Continual Value Derived from Transformer**	**Transport and Energization Time**	**Confidence in Readiness for Operation**	**Protection from HILFs**
Priority (Based on Utility Interviews)	**Low**	**High**	**Moderate**	**High**
Transformer energized on utility site	Yes	None	High	Very limited
Transformer not energized on utility site	No	Short	Moderate	Limited
Transformer stored in utility's central storage facility	No	Moderate	Moderate	High
Transformer stored at central industry site	No	Moderate	Moderate	High
Transformer part of STEP program	No	Moderate	Moderate	High

Table 2 also shows the priority of each of these four criteria, based on utility interviews and EPRI judgment. The primary criterion is the need for protection from HILFs due to:

- Increased attention to physical security threats;
- Selection of physical security as the primary threat for assessment purposes in this report (see section 5); and
- The need to rapidly transport and energize spares.

The desires to derive continual value or ensure confidence in readiness for operation were emphasized less often.

Applying these priorities, Table 2 shows a fundamental trade-off (highlighted boxes) when selecting storage locations. Spare transformers stored at the substation (whether energized or not) enable more rapid energization due to their location on site, but offer little protection from some HILFs (including the physical security threat on which this assessment is based) due to their location on site. Conversely, spare transformers stored centrally offer higher protection from HILFs (due to their remote location from the site of the potential attack), but require significantly more time to energize due to the need to transport the transformers prior to energization. One potential solution to this trade-off is to install physical security protection (e.g., barriers) at the substation to protect against physical attack, but this would not protect against other HILFs such as GMDs and EMPs/HEMPs/IEMIs.

Based solely on storage location, the optimal approach seems to include storage of spares at the utility's central storage facility for protection against HILFs including physical security attacks, with advance plans for expedited transport and energization to minimize recovery time. This approach does not enable utilities to derive continual value from the transformer, but this was not highly emphasized by interviewees. The concern that storage at the utility's central storage facility does not maximize confidence in readiness for operation can be obviated by implementing proper storage recommendations, some of which are listed in Appendix D of this report.

Emergency Spare Transformer Inventory Creation

Table 3 lists seven scenarios for creation of a spare transformer inventory:

- The utility orders conventional spares for transformers (nearing the end of life) earlier than needed.
- The utility orders conventional spares for any critical transformers (regardless of remaining life).
- The utility keeps retired transformers on hand.
- The utility orders rapid manufacture of conventional transformers after an event.
- The utility participates in sharing arrangements (e.g., SED, SEDTF, utility alliances).
- The utility orders emergency spare transformers before the HILF event for their own use only.
- The utility pools resources to order shared spares (emergency spare transformers) before the HILF event.

It also shows the following criteria related to inventory creation:

- Transformer manufacturing cost;
- Transformer reliability and remaining life;
- How long the transformer will be available for HILF protection; and
- The timing of the transformer availability after a HILF event. (Note that this is based on the previous two columns that list manufacture timing and time to manufacture).

Table 3. Emergency Spare Transformer Inventory Creation Scenarios, Criteria, and Priorities

Inventory Creation Scenarios (Independent of Storage Location)	Manufacturing Cost	Manufacture Timing	Time to Manufacture	Availability Timing	Transformer Reliability and Remaining Life	Length of Time Available for HILF Protection
Priority (Based on Utility Interviews)	**Low**	**High**	**Low**	**High**	**Low**	**High**
Utility orders conventional spares for transformers (nearing end of life) earlier than needed	Moderate	Before HILF	Standard	Fast	High	Short
Utility orders conventional spares for any critical transformers (regardless of remaining life)	High	Before HILF	Standard	Fast	High	Long
Utility keeps retired transformers on hand	Low	Before HILF	None	Fast	Low	Short
Utility orders rapid manufacture of conventional transformers after a HILF event	High	After HILF	Less than Standard	Slow	High	Long
Utility participates in sharing arrangements (STEP, SEDTF, utility alliances)	Low	Before HILF	None	Fast	High	Long
Utility orders emergency spare transformers before the HILF event for its own use only	High	Before HILF	Less than Standard	Fast	High	Long
Utilities pool resources to order shared spares (emergency spare transformers) before the HILF event	Moderate	Before HILF	Less than Standard	Fast	High	Long

Table 3 also shows the priority of each of these criteria, based on utility interviews and EPRI subject matter expertise. The primary criteria are the need for rapid availability of spare transformers after the HILF event (e.g., physical security attack, to speed restoration) and the length of time that the transformers will be available for protection against the HILF (physical attack).

Based on these criteria, the optimal approach seems to be:

- The utility orders conventional spares for any critical transformers (regardless of remaining life).
- The utility participates in sharing arrangements (e.g., SED, STEP, utility alliances).
- The utility orders emergency spare transformers before the HILF event for their own use only.
- The utility pools resources to order shared spares (emergency spare transformers) before the HILF event.

Combined with the optimal approach described in the storage section (storage of spares at utility's central storage facility with plans for expedited transport), the optimal combination includes complementing this storage strategy for conventional spares and participation in sharing agreements with construction of emergency spare transformers for individual utility use and/or in shared arrangements.

Section 7: The Path Forward: Business Case Summary and Tactics for Emergency Spare Transformers

Overview

This section summarizes the business case elements for enhanced emergency transformer spares programs, and describes tactics that utilities and the industry can pursue to enhance spares programs.

Business Case

This report in its entirety serves to provide the high-level business case for utilities to enhance their emergency spare transformer strategy by:

- Explaining the motivation for the emergency spares strategy (threats);
- Describing existing strategies for emergency spare transformers;
- Describing considerations for utilities when establishing new or enhanced spare transformer strategies;
- Proposing a sample threat for spares assessment;
- Describing storage scenarios, criteria, and priorities for emergency spares to protect against this threat; and
- Describing inventory creation scenarios, criteria, and priorities for emergency spares to ameliorate this threat.

As EPRI's transmission grid resiliency framework takes shape, utilities will also be able to use the framework to run analyses that support their business case.

Tactics for Individual Utilities: Emergency Spare Transformer Programs

This section describes a possible path forward by describing tactics that individual utilities can pursue to enhance emergency spare transformer programs. Based on the study results, DHS and EPRI recommend that individual utilities take some combination of the following steps, based on their particular needs:

- Utilities should consider creating and implementing a plan for its emergency spare transformers that includes:
    - Storage of conventional spares at its central storage facility within the utility service territory;
    - Participation in sharing arrangements; and
    - Purchase of emergency spare transformers and central storage of these at its facility.

- Utilities that have not implemented a capital program of stocking spare transformers for critical substations should explore this option. Some of the leading practices outlined in this report will aid this process.

- Utilities that are currently stocking their spare transformers at substations should evaluate the costs and benefits of relocating them to their indoor central storage facility. While this would increase their usefulness in protection against HILF events, especially physical security attacks, such relocation may also slow utility response to non-HILF-related outages. Some of the leading practices for central storage in Appendix D of this report will aid this process.
- Utilities that have not engaged in sharing arrangements (SED, STEP, and formal or informal arrangements) should consider such pooling of resources to mutual benefit.
- Utilities should evaluate purchase of flexible spare transformers to supplement their other spares. The information on the EPRI/DHS Recovery Transformer program, as one example of a flexible spare transformer program, in this report can aid this process.

Tactics for the Industry: Emergency Spare Transformer Programs

The remainder of this section describes collaborative actions that the industry can implement to enhance emergency spares programs over the mid-term and long-term.

Opportunities for Cost Recovery. The circumstances under which public utility commissions (or other decision makers in the case of federal, municipal, and rural electric cooperatives) allow utilities to include spare transformers in the rate base (and hence gain cost recovery from the date purchased) is an important consideration. This may drive decisions as to whether to locate the transformer at the substation or at a central storage facility, and if located at the substation, whether to energize the spare for partial load.

Most utilities interviewed indicated that its commission currently allowed it to rate base a transformer as soon as it is received—it need not be energized or at a substation—and that capital for spares need not be itemized separately from the overall investment plan.

However, some utilities are constrained in their capital programs; as a result, they need to incorporate power transformer spares purchases in their overall capital program and prioritize these relative to other equipment purchases. EPRI's transmission resiliency framework project, now underway, will provide utilities a methodology for prioritizing investments, including emergency spare transformers, to maximize resiliency. Utility participation in this initiative is encouraged.

This transmission resiliency framework can also help utilities that are required (either via internal regulations or regulatory requirements) to prepare a business case (or business justification) for purchase of emergency spare transformers. Much of the information in this report can also help inform the considerations included in such a business case.

Cost recovery for emergency spare transformers for the purposes of protecting against physical attacks may be aided by the recent submittal of the NERC CIP-014 Reliability Standard on physical security [16], which was issued in response to the FERC Order on Reliability Standards for Physical Security Measures [17]. The latter directs NERC to "submit for approval one or more Reliability Standards that will require certain registered entities to take steps or demonstrate that they have taken steps to address physical security risks and vulnerabilities related to the reliable operation of the Bulk-Power System. The proposed Reliability Standards may require owners or operators of the Bulk-Power System, as appropriate, to identify facilities on the Bulk-Power System that are critical to the reliable operation of the Bulk-Power System. Then, owners or operators of those identified critical facilities should develop, validate, and implement plans to protect against physical attacks that may compromise the operability or recovery of such facilities." [17]

Utility Agreements with Transformer OEMs. One approach for enhancing the timely provision of emergency spare transformers involves utilities forging upfront agreements with transformer OEMs to more rapidly produce these transformers as needed. Some utilities interviewed have established or are working to establish transformer functional requirements and designs with at least one leading transformer OEM, and some utilities are working to establish agreements with at least one OEM to expedite manufacturing if needed. An approved design (discussed further below) could reduce procurement time by 1-2 months. This may involve OEM pre-ordering and stocking of long-lead time parts and materials. One utility pointed out that the best way to expedite OEM production in an emergency is to put in place a "master agreement" and transformer design with the OEM in advance. This agreement can include negotiated reduced lead times in an emergency. However, it should be noted that agreements that provide one utility higher priority delivery might increase the lead-time for another utility, due to finite OEM production capability; this may not improve the overall response time to filling all utility transformer orders.

One way to take the next step in this area is for the industry to sponsor a workshop for utilities, ISOs/RTOs, and transformer OEMs to share ideas and discuss ways to establish mutually beneficial utility agreements with transformer OEMs. Utilities that have already established such agreements can present their lessons learned, OEMs could discuss the sorts of agreements that are feasible from their perspective, and ISOs/RTOs can discuss the benefits of these agreements from their perspective.

Standardized Transformer Design. Utility agreements with transformer OEMs can be taken one step further by working with OEMs to develop a standardized design for emergency spare transformers in its service territory and then enter into an upfront agreement to rapidly produce these transformers as needed. In the May 2012 report of the NERC Severe Impact Resilience Task Force, NERC states that "To promote greater interchangeability of components, increase the standardization of component specifications such as physical size and electrical rating." [5] Such a standardized design would reduce the number of different types of spares that the utility would need to keep on hand. It would also streamline the ordering of emergency spare transformers after a HILF event. At least one utility interviewed is in each of the following states with regard to standardized transformer design:

- Is already considering such a standardized design;
- Is interested in standardization;
- Has implemented a limited number of designs; and
- Prefers to stay with transformers that are built to their specific design standards.

One way to take the next step in this area is for the industry to sponsor a workshop for utilities, ISOs/RTOs, and transformer OEMs to share ideas and discuss ways to move forward with standardized transformer design. Utilities that have already implemented or at least researched the process of implementing a standardized transformer design can present their lessons learned, and ISOs/RTOs and OEMs can discuss the benefits of these designs from their perspective. The functional requirements for flexible transformers described in this report can help inform this process.

Insurance Industry Point of View.[7] From an insurance perspective, one of the largest utility assets insured today are power transformers because of their high cost in a single location and high failure rates. By contrast, wires, poles, and towers are typically not deemed insurable because they cover such large areas and insurers are usually not able to underwrite and price such exposure.

Utility insurance products that utilities typically purchase consist of property damage coverage, which is offered on an all-risk basis that includes electrical or mechanical failure. This insurance covers first-party property damage only (hard physical assets that the utility owns). It does not cover any indirect impacts due to loss of the assets (e.g., outage costs, customer interruption costs, etc.). This coverage can be extended to include terrorism by virtue of the federal government backstop to insurance companies that is part of the Terrorism Risk Insurance Act (TRIA) established in 2002. The latter provides reinsurance for insurance companies that insure against terrorist acts that have an adverse effect on financial markets. TRIA is eligible for renewal in 2014; U.S. Congress has renewed it twice since 2002. However, if this reinsurance is not renewed, insurance companies are unlikely to continue to offer terrorism insurance; their property damage policies will probably contain a terrorism exclusion, which would effectively eliminate coverage for the type of physical security threat described in this report. The program has generated $40 billion in revenue for the insurance industry since its inception, but has not paid out a claim. Overall, approximately 60 percent of all businesses have purchased the insurance since 2002 [19].

From an insurance industry perspective, the Metcalf event is not categorized as

[7] For more information on insurance and the energy sector, see the 2013 DOE report on "Insurance as a Risk Management Instrument for Energy Infrastructure Security and Resilience."

terrorism, as the insurance industry defines it. This is because the required "triggers" for it to qualify as a terrorist act did not occur. One trigger is that the U.S. Treasury Secretary must designate the event as a terrorist event—a designation that even the Boston Marathon bombing did not receive, for insurance purposes [19].

Some insurance companies offer utilities business interruption insurance, which would cover loss of revenue during an outage caused by the equipment failure. Although some generation owners[8] purchase this type of insurance, few if any utilities do.

The utility insurance situation becomes even clearer by examining the type of financing that utilities use and by comparing the utility situation to the generation owner situation. First, with regard to financing, "nonrecourse financing" means that lenders have an interest in an asset and hence require that the borrower have insurance on its assets. Generation owners are nonrecourse financed, so they must have property damage insurance. However, generation owners do not have the protection of a rate base to cover their business interruption costs in the event of an equipment failure. Hence, generation owners typically purchase property damage insurance *and* business interruption insurance; the latter covers some of their indirect costs. Some insurance companies offer generation owners rate improvement on their policies if they stock spares, in the form of lower cost, broader coverage, or both.

However, utilities are not nonrecourse financed. Instead of passing on the risk of the asset failure to investors, utilities retain the risk. Utilities typically purchase this coverage with a very high deductible. If an unexpected equipment failure occurs, the utility pays the high deductible, purchases new equipment, and places additional costs associated with that equipment in the rate base. If outages result from the equipment failure, end use customers endure the majority of the outage costs.

In summary, physical damage to utility transformers is typically covered by high deductible insurance. Indirect costs, such as those covered by business interruption insurance, are not covered because utilities typically choose not to purchase this insurance, but instead absorb this risk and cost. These indirect costs, as well as societal costs such as outage costs, are absorbed by ratepayers, and in some cases, shareholders. This means that *insurance that utilities typically purchase* tends to not provide a powerful incentive for enhancement of spare transformer programs. Of course, many other drivers for enhanced spare transformer programs exist, which are discussed elsewhere in this report.

ISO/RTO Participation. ISOs/RTOs can play a major role in enhancing utilities' emergency spare transformer programs. ISOs/RTOs bring a broad perspective that cuts across utility service territories but is in a common system operating area. With

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[8] Here, the term "generation owner" means a for-profit owner of generation (e.g., a merchant generator), not a traditional utility that also owns and operates power generation equipment.

this perspective, ISOs/RTOs are able to pool data from transmission owners (TOs) in their service areas and identify the need for spares.

One ISO/RTO interviewed in this study, PJM, directs the purchase of spares by TOs in its operating territory. This direction is based on a probabilistic risk assessment (PRA) that applies hazard functions to a transmission congestion analysis to assess risk. Today, the hazard function incorporates state data on transformers (based on equipment condition assessments), and hurricane and tornado probabilities [12]. Due to insufficient data, the hazard function does not currently incorporate a physical attack. However, a recommended next step is for the industry to work with ISOs/RTOs on a pilot basis to determine this data and incorporate a physical security attack into the PRA. If successful, this process could then be made available to other ISOs/RTOs.

Due to its broad perspective, another potential role for ISO/RTOs is to encourage standardized transformer design in its service area. PJM described a logistics study it conducted a few years ago that showed that use of a common transformer design plus use of transformer sharing would significantly decrease the number of spares needed and cover risk. The common design consisted of a small number of standardized transformers that differ primarily in impedance.

Private Company Participation. The private sector can play a potentially important role in filling the industry need for spare transformers. The for-profit business model of renting spare transformers in a range of voltages to utilities across the United States in exchange for compensation in various forms is promising. DHS supports this concept and encourages the industry to consider exploring this option as one potential method for providing emergency spare transformers.

Section 8: Long-Term Strategy and Recommendations

This report has focused on repurposing conventional spares for emergency spare purposes, and complementing these conventional spares with flexible spares. Section 7 provides tactics that will help individual utilities and the industry move in this direction. Widespread adoption of these measures will significantly increase power system resiliency against a broad array of HILF events.

Over the long-term, as new transformers are designed and manufactured to replace the aging population now in service, there is an opportunity to plot a parallel beneficial path forward. If the new "conventional" transformers that are installed can be designed for more broad applicability across substations in a utility service territory, they can help to ameliorate HILF threats along with serving their current purpose (e.g., replacement of transformers that fail in normal service). In other words, a more broadly applicable transformer design has benefits for both HILF events that disable transformers, as well as "blue sky" events such as equipment failures in normal service. Over time, most installed transformers and their spares would be more broadly applicable by design (i.e., a single design would meet transformer needs at multiple substations of similar rating in a utility service territory).

Extending this vision of a future conventional design beyond broader applicability to also include rapid construction, transportation, and installation requires an analysis to determine the relative costs and benefits of such an approach. This approach would serve to ameliorate failures due to HILF events, but does not as significantly benefit "blue sky" equipment failures. As a result, utilities need to conduct a cost-benefit analysis to determine if this additional attribute should be designed into conventional transformers, or if "flexible transformers" such as the Recovery Transformer will still be needed as a separate class of transformer for HILF recovery.

To realize the vision of a more broadly applicable transformer, OEMs would need to move toward design and manufacture of such a transformer for conventional use and for spares. Utilities and ISOs/RTOs would need to work closely with OEMs to define these designs while meeting all of their functional requirements. This adds new urgency and meaning to some of the tactics described in the previous section, including utility agreements with transformer OEMs, standardized transformer design, and ISO/RTO participation. ISOs/RTOs in particular can play a key role in facilitating this path forward by virtue of their broad regional perspective and relationships with its member transmission owners (TOs). For OEMs, this represents an opportunity to offer a better product to an industry with a pressing need. The regulatory impetus for such a path forward is already taking shape with NERC's recent Reliability Standard response to the FERC physical security order. This path is consistent with the DHS charter to enhance the security and resiliency of the critical electric power infrastructure. EPRI's role is to provide technology guidance to the industry to help optimize the design, based on its experience in the recently completed pilot Recovery Transformer project.

To begin the path towards realizing this long-term strategy, the industry recommends the following:

- Industry stakeholders can work together to enhance the probabilistic analysis of spares by incorporating hazard function information on HILF threats, beginning with physical security attacks. These analyses can then be run at host utilities in the ISOs/RTOs service areas. This work will further strengthen the business case for incorporating emergency spares, including flexible spares, at utilities by providing a methodology for calculating return on investment. This work will also serve to solidify future expanded involvement of ISOs/RTOs in this process.
- Industry stakeholders can work with various OEMs to define standardized agreements with OEMs for first more broadly applicable spares, and eventually, more broadly applicable conventional transformers.
- Industry stakeholders can work with transformer OEMs to refine functional specifications for more broadly applicable spares, with an eye towards migrating these design features into "conventional" transformers that are installed as existing units are retired; and ultimately standardizing these designs first within utility service territories, and then within regions where possible.
- Effective collaboration of government (DHS, DOE, and others), EPRI, EEI, utilities, private enterprise (OEMs and others), NERC, and regulators is critical for success over the long term. Due to the critical nature of this work, EPRI recommends a forum for exchange of information on this topic between representatives of these stakeholders.
- Communication of the results of the current report, the forum, and subsequent work in various forms to all stakeholders is crucial to success.

For More Information

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Appendix A: Acronyms

CNP	CenterPoint Energy
DHS	U.S. Department of Homeland Security
DOE	U.S. Department of Energy
EEI	Edison Electric Institute
EHV	extra high voltage
EMP	electromagnetic pulse
EPRI	Electric Power Research Institute
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
GIC	geomagnetic induced current
GMD	geomagnetic disturbance
HEMP	high altitude electromagnetic pulse
HILF	high-impact, low-frequency
IEMI	intentional electromagnetic interference
IOU	investor-owned utility
ISO	independent system operator
NERC	North American Electric Reliability Corporation
OEM	original equipment manufacturer
PRA	probabilistic risk assessment
R&D	research and development
RTO	regional transmission organization
SED	spare equipment database
STEP	spare transformer equipment program
TO	transmission owner
TRIA	Terrorism Risk Insurance Act

Appendix B: Recovery Transformer Functional Requirements

This appendix lists the key functional requirements for the DHS/EPRI Recovery Transformer.

- **Manufacturing:** Because the recovery transformer needs to support recovery in acts of war or natural disaster, independent manufacture in the United States is a requirement.
- **Cost to Manufacture:** A high manufacturing cost will place downward pressure on the number of spares. The Recovery Transformer cost should be similar to a conventional equivalent.
- **Storage Functionality:** A high storage cost and/or short storage life will adversely impact the long-term program viability. The storage cost should be low, and the life of the transformers and ancillary equipment should be long.
- **Overall Time to Energize from Call to Action:** The estimated elapsed time from the call to action until the transformer is energized is four weeks for a conventional three-phase power transformer.[9] Because power outages affect significant customer numbers, rapid service restoration is crucial. The Recovery Transformer requirement is six days or less.
- **In-service Operational Reliability:** Conventional transformers have an excellent operational record and are proven reliable in service. The Recovery Transformer requirement is to equal this reliability record.
- **In-service Environmental Impact:** Conventional oil insulated transformers present fire and oil leakage risks to the environment. In some instances, noise can be a nuisance. The Recovery Transformer functional requirement is to have environmental impact similar to a conventional transformer.
- **In-Service Voltage Regulation:** Conventional transformers provide voltage regulation via a load tap changer. It is preferred but not required that the Recovery Transformer provide voltage regulation.
- **In-Service Overload Capability:** The Recovery Transformer requirement is to provide overload capability consistent with a conventional transformer, which is two times nameplate capacity. Overload capability can only be sustained for short time periods without reducing the transformer life and risking premature failure.[10]
- **In-Service Operational Efficiency:** Conventional transformers are highly efficient (99.8 percent). The initial Recovery Transformer goal was to achieve 99 percent efficiency in service.

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[9] EPRI business case document and EEI STEP participants.

[10] US Department of the Interior, "Permissible loading of oil-immersed transformers and regulators,"1991, http://www.usbr.gov/power/data/fist/fist1_5/vol1-5.pdf.

- **In-Service Safety:** Conventional transformers exhibit safety risks associated with potential damage from highly pressurized oil escaping as well as the fire risk if the oil escapes the transformer tank. The Recovery Transformer requirement was to not increase safety risks.
- **Operation at Altitude:** Because the Recovery Transformer may be deployed anywhere in the contiguous United States, it must be designed to operate reliably at any altitude between -500 feet and +5500 feet above sea level.[11]
- **Installation:** The Recovery Transformer needs to be designed to be installed on gravel, which adds flexibility to the installation.
- **Noise Levels:** The NEMA standard noise level for a 200-MVA 345/138 kV conventional transformer is 86 dba (source ABB). Noise level limits at some substation locations (for example big cities) are tighter than 86 db. The sound level specification for Recovery Transformers is 72 dB for the transformer only, and 80 dB for the transformer and cooling.

[11] The prototype Recovery Transformer deployed to CenterPoint Energy is designed to operate at the ANSI standard altitude specification of 3,300 feet.

Appendix C: Impedance Considerations for Emergency Spare Transformers

Further examination of impedance illustrates the importance of consideration of transformer electrical characteristics. At the same time, such examination also reveals that utilities have options in addressing impedance mismatch.

Transformer percentage impedance is the voltage drop at full load due to the wind resistance and leakage reactance. Impedance is expressed as a percentage of the rated voltage. Impedance determines the maximum value of current that will flow under fault conditions. A transformer with a lower impedance leads to a higher short-circuit fault current level (and vice versa). Impedance also determines the voltage drop that occurs under load ("regulation"), and affects load sharing when two or more transformers operate in parallel.

The range of transformer impedances is 5-21 percent. The design choice made for the prototype DHS/EPRI Recovery Transformer program, for example, was an impedance of 14 percent or lower. This is a conservative choice because the Recovery Transformer impedance is higher than the existing grid fault protection setup, and the latter will protect against faults without impacting the transformer.

To use an emergency spare transformer to replace a transformer with higher impedance, careful consideration needs to be given to the grid setup at the substation. Use of a higher impedance than the most common impedance also reduces weight because less copper is required. A mismatch in impedance greater than a few percent between the emergency spare transformer and the remaining transformers operating in parallel is unadvisable both because the lower impedance transformers will "hog" the load, and because circulating currents can be created.

If the utility has a transformer with a high impedance of 20 percent, for example, then its breaker coordination fault protection scheme assumes that the transformer has an impedance of 20 percent, which limits the short circuit fault current to a maximum of five times the normal current of the transformer. If this transformer is replaced with an emergency spare transformer with 14 percent impedance, for example, the short circuit fault current increases to seven times the normal current of the transformer. A utility with a protection system assuming a lower maximum fault current may not have breakers that could interrupt the fault. As a result, the breaker system and transformer may be at risk of damage in this arrangement.

However, even in this situation, the utility may still be able to use the 14 percent impedance transformer. For example, if the utility's low-side voltage lines are of limited length and clear of any vegetation or other danger of fault, the risk of a short circuit is low. The utility can balance the low risk of a fault against the value of having an emergency spare transformer in the absence of alternatives. Utilities can also consider employing current limiting reactors in the low-side voltage lines downstream of the emergency spare transformer. The purpose of these reactors is to increase the effective impedance of the transformer. The consequence is an increase in voltage drop for the transformer, but this may also be an acceptable compromise in an emergency.

When an emergency spare transformer with 14 percent impedance is introduced with transformers with a 20 percent impedance, for example, the load sharing between the transformers is not balanced and increases the risk of overload of the lower impedance units. In this case, an analysis should be performed. It may be preferable in this situation to deploy multiple emergency spare transformers and to disable the higher impedance transformer(s).

Appendix D: Recovery Transformer Storage Lessons Learned

Transformer storage lessons learned that were identified in the DHS/EPRI Recovery Transformer program, include the following:

- **Store Filled with Oil:** Maintain the transformers filled with transformer insulation oil.
- **No Load:** Apply no electrical load to the transformers in storage.
- **Storage Configuration:** Store the transformers in a partially assembled state, filled with insulating oil, with an attached Constant Oil Pressure System (COPS). The COPS is an overflow tank that manages transformer oil overflow caused by expansion when temperatures rise.
- **Vacuum Sealing:** Vacuum seal the transformers to prevent exposure of the insulation oil or the internal core and coils to the open air.
- **Transformer Monitoring:** Incorporate dissolved gas monitoring and some sort of intelligent monitoring system to monitor the condition of the transformer during storage.
- **Covering/Preloading:** Cover ancillary equipment required to complete transformer installation at the host utility site and preload it on flatbeds for rapid transport.
- **Keep Equipment Separate for Each Transformer:** Store separate sets of ancillary equipment that are dedicated to a specific transformer. Clearly mark equipment for each transformer unit and its ancillary parts with the transformer nameplate ID.
- **Preloading:** Layout and preload all ancillary equipment for each transformer on two trailers.
- **Inventory Checklists:** Prepare in advance, maintain, and apply inventory checklists of equipment needed.
- **Spare Parts Kit:** Assemble a spare parts kit that will travel with the deployment. This kit should include gaskets, o-rings, oil pressure relief valves, and other items. Identify a full list of these parts. For larger ancillary equipment, instead of including spares (which is not practical for all components), identify where spares can be located and transported to the site.
- **Consider COPS Tank Removal During Storage:** Explore the efficacy of leaving the COPS tank off the transformer during storage. This can be done by using a blanket of nitrogen to protect the oil from exposure to the atmosphere. This would avoid the need to remove the COPS tank during site installation, saving deployment time. One concern is that this alternate approach could lead to gas saturated oil. The processing units at CNP have degassing functionality that does not slow down the process.

Recommended storage facility considerations include the following:

- **Temperature Requirements:** Store the transformers indoors at a temperature of 15 degrees C (59 degrees F).
- **Additional Oil:** Store additional transformer insulation oil (in addition to the oil extracted from the transformers) to fill the external cooling system after installation at the host site.
- **Equipment and Personnel:** Make available a crane, forklifts, pre-stage dry air capability, oil processing rigs, and personnel trained to operate this equipment.
- **Space Requirements:** Provide sufficient space to house the transformers, flatbed trailers, and additional equipment.