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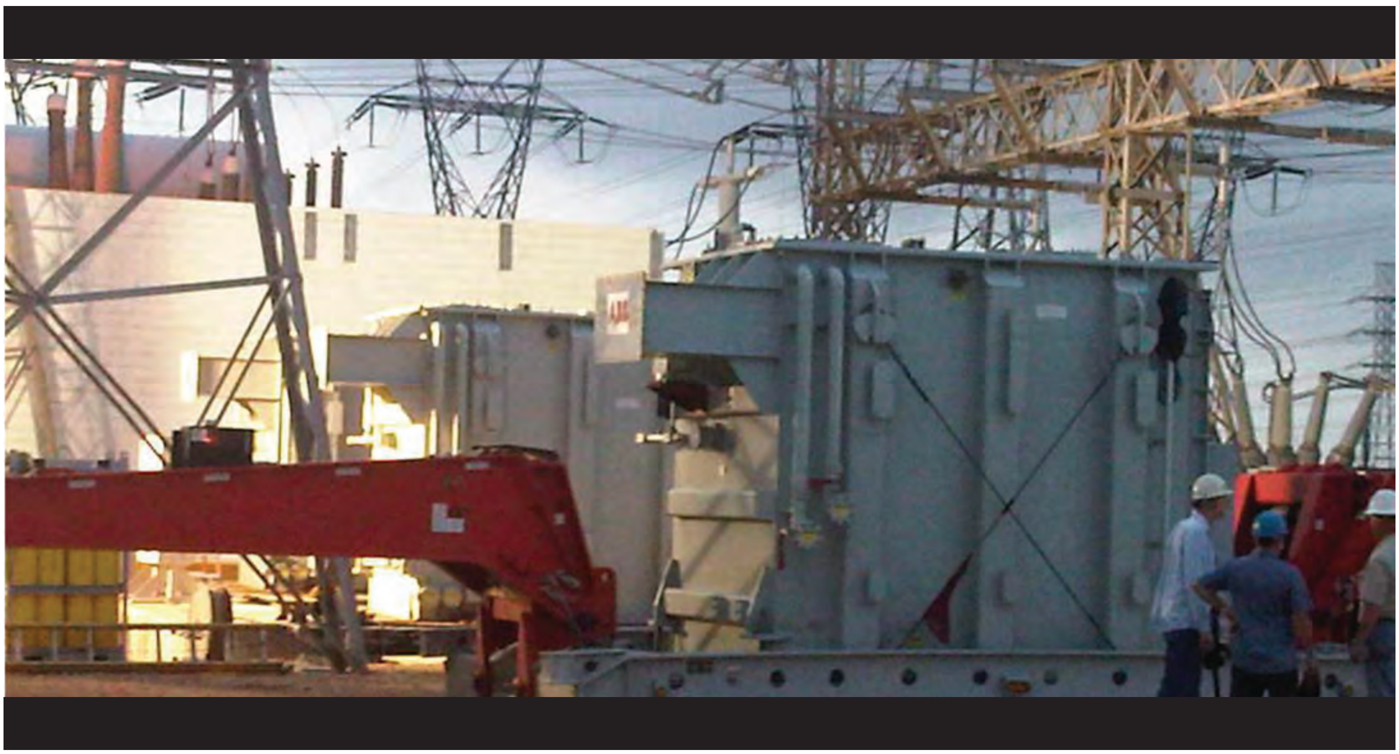
THE ROLE OF RECOVERY TRANSFORMERS IN AN INTEGRATED HILF EVENT STRATEGY



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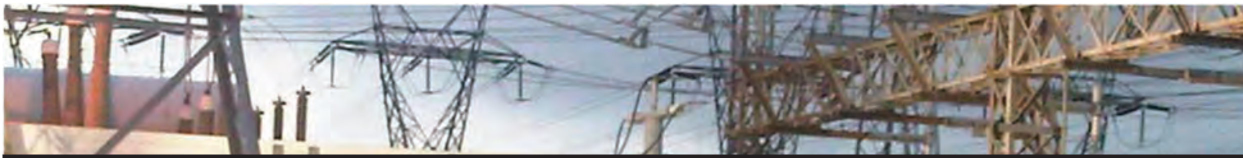

Executive Summary

The U.S. Department of Homeland Security (DHS) and EPRI are engaged in a project that is an important part of an overall strategy to mitigate the potential impacts of high-impact, low-frequency (HILF) events. Working as a complement to power system operational measures, operational risk management, power system equipment hardening, and other approaches, the Recovery Transformer – when fully deployed – can enhance the ability to respond and recover rapidly after a HILF event. This paper describes the Recovery Transformer project, including the recent successful deployment of its prototype in Texas, its role vis-à-vis other mitigation approaches, and next steps for the project.

Background

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 HILFs such as GMD, EMPs/HEMPs, natural disasters, and coordinated attacks. 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 failure, few spares exist, and those that do are not easily installable at other locations besides those originally intended.

The North American power grid, for example, has built-in redundancy to accommodate simultaneous failure of a small handful of high-voltage transformers. The North American Electric Reliability Corporation (NERC) N-1 reliability standard (contingency) is designed such that failure of one high-voltage transformers may strain the power system but not cause a major outage or cascading failure. The concern is that simultaneous failure of a higher number of high-voltage transformers (e.g., as a result of a HILF) could lead to a major failure.

This adds up to a potentially significant vulnerability, and risk, in the power system. One approach is to attempt to retrofit these transformers with devices that harden them against various HILFs. This approach shows promise; various designs have been proposed that block or reduce 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. These same devices have the potential to shield against EMP attack.

However, this may be a challenging approach due to the sheer number of high-voltage transformers, various different designs and sizes, and need to ensure that any retrofits do not adversely affect normal operation. With regard to the number of transformers, according to a 2004 ABB study for the Federal Energy Regulatory Commission (FERC) updated in 2010, there are 1547 high-voltage transformers in the U.S. alone (i.e., high-side voltage of 345-kV and above). With regard to design variation, impedance of most units ranges from 9-15 percent, MVA ratings vary from 150-750 MVA, and other design variations include single-phase versus three-phase; shell form versus core form; three-, five-, or seven-leg models; and others.

Various operational measures, such as reducing load on some high-voltage transformers in advance of the HILF 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 measures may not completely protect all high-voltage transformers from overload, damage, or failure.

Another approach is to make available to other utilities in the event of a HILF the limited number of 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 [1]. The goal of the NERC GMD

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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 would help speed power restoration. NERC's GMD 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 Edison Electric Institute (EEI) Spare Transformer Equipment Program (STEP) or other regional or neighboring utility sharing arrangements [2]. 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. About 50 transmission providers that represent about 70 percent of the U.S. transmission grid currently participate in this program [3].

The spare transformer sharing approach may be limited by the differences in high-voltage transformer designs (listed above), as well as design needs of specific installations (e.g., 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 spare transformers (in locations where they were not originally designed to be installed) a time consuming process in the event of a HILF.

Rapid Response Capability

If a HILF severely damages more than a handful of high-voltage transformers simultaneously, a rapid response capability would be needed. This need would be especially acute if the damaged transformers are in the same geographical area, which would be a likely objective of an intentional, coordinated attack HILF. At the very least, such a rapid response capability would complement other measures in place.

The U.S. Department of Homeland Security (DHS), EPRI, and the U.S. Department of Energy are working together to demonstrate such an approach that, when fully deployed, would provide just such a rapid response capability for high-voltage transformers. The primary objective of this Recovery Transformer, or RecX, project is to enhance resilience to power outages due to natural disasters or deliberate attacks. The project team has successfully designed, tested, and installed a prototype RecX that can be stored in a centralized location and rapidly transported and installed at a remote utility location.

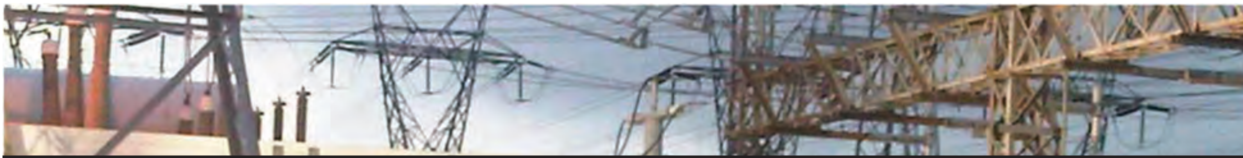
The particular RecX designed in this prototype project – constructed by contractor ABB – is applicable to more than 90 percent of all U.S. 345-kV/138-kV transformers. And this high-side/low-side voltage combination is the most common one in the U.S., representing 689 of the 1547 high-voltage transformers currently installed (see Table 1). Seven of the 13 NERC regions use transformers with this voltage combination, and the 345-kV/138-kV transmission grid covers a significant portion of the U.S. geographically.

Table 1. The most common combination of high-side and low-side voltage for high-voltage transformers in the U.S. is 345-kV/138-kV – the combination selected for the prototype RecX project.

High Side Voltage	**Low Side Voltage - kV**										**Total**
kV	**500**	**345**	**287**	**230**	**161**	**138**	**120**	**115**	**69**	**34**	
765	4	25	0	3	0	11	0	0	0	0	40
500		26	1	225	41	33	0	29	4	0	359
345			0	136	99	689	30	173	17	4	1148

Total	**1547**

Highlights 79% of Transformers
Highlights 12% of Transformers
Total Highlighted is 91%



The three single-phase transformer prototypes were successfully transported to, installed, and energized at a CenterPoint Energy (CNP) substation outside of the Houston area over a five and one-half day period in March 2012 (see Figure 1). The host utility for this project, CNP serves over 5 million customers in the Houston area. The completion of this deployment exercise represents a quantum leap for the electric power industry to rapidly replace high-voltage transformers in emergency situations. A one-year intensive equipment data monitoring program is now underway to verify the performance of the three units.

Figure 1. Installation of the three single-phase prototype high-voltage Recovery Transformers at CenterPoint Energy in March 2012.

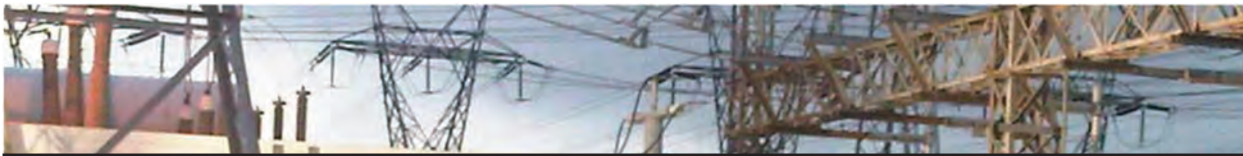
The RecX Program

The crux of the RecX is rapid deployment and broad applicability at a range of utility substations. Under normal circumstances, replacement transformers are typically custom ordered and built, requiring about one year for scheduling, design, and construction, and can take four weeks or more to deliver and install. Typical installations require rail transportation, and a heavy duty crane, along with the associated scheduling. Conversely, RecX transformers are designed to be emergency replacements for the transformers found at utility substations across the U.S. RecX transformers will be deployed rapidly during the recovery time period after transformer major outages (when the transformer cannot be repaired in a few days). At present, high-voltage transmission systems in different regions operate at various voltage levels, making standardized transformer design difficult. The RecX transformer is designed to replace as many high-voltage transformers as practical. The RecX Program advances conventional transformer technology to build a prototype that is small enough and light enough to be easily transported and installed at substations across the country in a few days.

RecX Functional Requirements

The RecX functional requirements that follow are consistent with requirements to mitigate the effects of HILF events (see Figure 2).

- **Applicability:** Because the recovery transformer will need to replace as many transformers as possible, the applicability rate is set at 90 percent or higher for the 345/138-kV voltage class.
- **Manufacturing:** Because the recovery transformer needs to support recovery in acts of war, natural disaster, or other HILFs, independent manufacture in the U.S. is a requirement.
- **Cost to Manufacture:** The RecX cost should be 20 percent less than a conventional equivalent.
- **Storage Functionality:** 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 high-voltage transformer. The RecX requirement is less than one week. The components of the total time to energize are described as follows:
  - **Transportation Time:** A conventional transformer is estimated to take one week to transport to the substation. The goal of the RecX program is to reduce transportation time to 24 hours from the storage site to the substation.
    - **Shipping Size:** A conventional transformer is often too tall and in some cases too wide to pass standard bridges and underpasses. The RecX requirement is for the transformer to be transportable by road and the specific goal is to reduce the size by 25 percent.
    - **Shipping Weight:** A conventional single phase unit weighs 225,000 to 250,000 lbs. The RecX requirement for shipping weight (including trailer) is to be low enough for road transportation on a standard lowboy trailer, which is about 120,000 lbs.
  - **Installation Time Once on Site (includes startup time):** Once on site, a conventional transformer takes about one week to install and energize, including about four days to fill with insulating oil and commission. The RecX requirement is 60 hours or less, including 12 hours or less to fill and commission.
- **Site Preparation Requirements:** For a conventional transformer, there are typically considerable site preparations to build a pad to support the transformer and to build firewalls and oil containment pits to accommodate the oil cooling system. For RecX these preparations are required to be minimal.
- **Installation Requirement for Special Equipment:** A conventional transformer may require special crane or lifting equipment to install as well as special equipment to load gas filled bushings and to pull a vacuum for oil insulation. The RecX requirement is to minimize or eliminate special installation requirements.
- **In-service Factors**
  - **Operational Reliability:** Conventional transformers have an excellent operational record and are proven reliable in service. The RecX requirement is to equal this reliability record.
  - **Overload Capability:** The RecX 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.
  - **Operational Efficiency:** Conventional transformers are highly efficient (99.8 percent). The initial RecX goal was to achieve 99.00 percent efficiency in service. The prototype RecX has an efficiency of 99.78 percent.
  - **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 RecX requirement is to not increase safety risks.

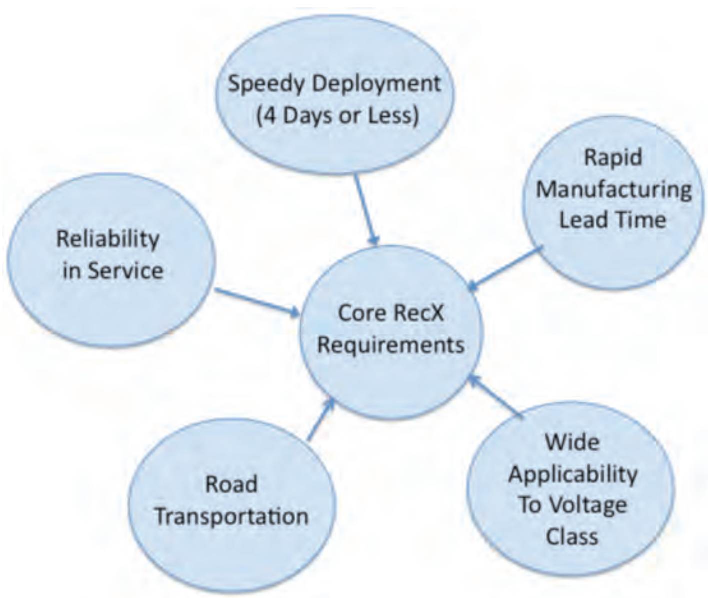
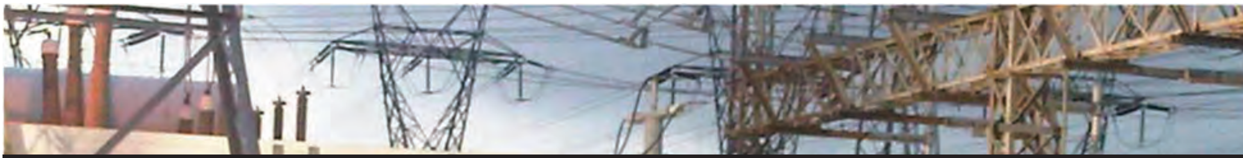


Figure 2. Core RecX requirements are consistent with those of technologies needed for HILF event mitigation.



Phased Approach and Next Steps

DHS and EPRI are conducting the RecX program in two phases. The first phase, currently in progress, demonstrates RecX capability using current state-of-the-art transformer technologies applied to the unique project requirements. This phase includes the one year of equipment data monitoring.

The RecXs at CNP will be monitored closely during a one-year prototype live demonstration. However, successful demonstration of one set of three single-phase transformers does not provide the utility industry sufficient readiness to address a HILF or natural disaster. The second phase addresses the full deployment strategy. Because the above described HIILF event may simultaneously affect multiple critical EHV transformers, a carefully considered risk assessment and strategy for readiness and wide deployment of RecXs is needed. The strategy should consider the myriad technical and policy issues related to RecX deployment continent wide. This effort would provide the industry a blueprint for broad deployment of RecXs in the event of an emergency – a necessary capability given the critical nature of EHV transformers.

The risk assessment strategy would perform an inventory of the high-voltage transformers the RecX can replace, identify risks (including HILFs), assess risk probabilities, review specifications and define criteria and probabilities for transformer replacement. The result will be estimation of how many transformers are at risk per unit time, how quickly spares are needed, and how many spares are needed per unit time to deploy. This strategy will include both urban and rural areas. Based on these vulnerabilities, a risk response would document strategies for transformer storage, deployment, transportation, and installation, as well as workforce requirements and logistical and decision making policy issues.

For More Information

For more information on the Recovery Transformer project and EPRI's HILF research project, contact EPRI Senior Technical Executive Rich Lordan, 650.855.2435, rilordan@epri.com.

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