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CIGRE US National Committee
2017 Grid of the Future Symposium

Qualitative Evaluation of Technologies for Use in a Spares Strategy for Large Power Transformers

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SUMMARY

The United States of America (US) electric power industry has robust protection and restoration mechanisms in place to maintain and restore continuity of electric power grid in response to major disruptions due to natural disasters or human actions. Historically, electric utilities have relatively quickly restored electric service to the vast majority of users even after major events such as hurricanes, tornadoes, floods, and earthquakes.

A concern remains that severe natural disasters or coordinated, intentional attacks could disrupt the grid to an unprecedented extent, delaying the restoration of electrical service for months or even years, affecting industries, the economy, and security. Large power transformers (LPTs) of 100 MVA or greater, operating at 345 kV or higher voltage, are the hub of the electric transmission system. More than 90% of electric power consumed in the US passes through LPTs . These expensive, large, and heavy transformers are typically custom-designed for specific uses and sites. Typically requiring long lead times (up to 12 months to design and manufacture), these LPTs also require more than one month for transport, assembly, and commissioning. LPTs are potentially vulnerable to physical attack, electromagnetic-induced damage via electromagnetic pulses (EMPs), intentional electromagnetic interference (IEMI), or geomagnetic disturbances (GMDs). These potential vulnerabilities suggest that severe event scenarios may result in simultaneous damage or destruction of many LPTs.

The Electric Power Research Institute (EPRI) with support of transformer subject matter experts conducted a review of transformer technologies that could be used for replacement Large Power Transformers (LPTs) in a spares strategy. The report reviews existing and emerging LPT technologies and qualitatively evaluates them using a defined set of spares planning criteria. The report evaluates the following six transformer technologies, which are in various stages of development or utilization: conventional mineral oil-immersed LPT, fast recovery LPT, SF6 gas-insulated transformer, solid-state transformer, superconducting transformer, and the EPRI transformer of the future.

KEYWORDS

Transformer, Resiliency, Spares, Recovery transformer, Transmission

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This paper reviews six existing and emerging LPT technologies and qualitatively evaluates them using a defined set of spares planning criteria:

1. Conventional mineral oil-immersed LPT – Wide-scale deployment
2. Fast recovery LPT – One operational U.S. pilot demonstration
3. SF_6 gas-insulated transformer – Deployed for certain applications
4. Solid-state transformer – Subsystem validation (in use at distribution level)
5. Superconducting transformer – Early field demonstration
6. EPRI transformer of the future – Exploratory research

These LPT technologies vary in design, construction materials, size and weight, operation, and stage of usage or development. These technologies also vary in terms of measurable criteria of the transformer's value as a potential spares candidate:

- Technology readiness level (TRL)
- Financial:
    - Manufacturing cost
    - Storage/layup cost
    - Ongoing operating and maintenance (O&M) cost for in-service equipment
- Operational:
    - Applicability across voltage class
    - Transportation timing (including time to ready equipment for transportation)
    - Transportation options
    - Installation timing
    - Training and other human resources impacts

1. Conventional Mineral Oil-Immersed LPT

In a conventional oil-immersed LPT, mineral oil immerses the LPT core and coils, which provides a path for heat transfer away from the conductor and provides electrical insulation within the transformer system. Oil circulates through ducts in and around the coil and core assembly. Air-cooled radiators and/or heat exchangers cool the oil. Oil-immersed transformers make up essentially all of the existing LPT fleet in North America. As a result, the entire LPT industry infrastructure in North America is oriented toward the oil-immersed design.

The inherent benefits resulting from this design include a strong and geographically diverse manufacturing base, mature field support network, readily available internal component spares inventories, long life, industry-wide incumbent maintenance and repairs knowledge, and standard maintenance procedures. One drawback of this technology (from the perspective of recovery) is the size and weight of the units. Due to this substantial size and weight, transportation requires considerable planning and specialized equipment. Another drawback is that procurement of a conventional oil-immersed three-phase transformer can take from six months to over a year from detailed design (assuming a new design is required) to manufacture and customer delivery. Oil-immersed transformers in storage can be energized within about four weeks from call to action, depending on the distance and means of transportation.

Conventional oil-immersed LPTs are typically transported by rail and/or barge. To provide a general understanding of the size and weight of these transformers, dimensions and weights of LPTs in four different voltage classes are provided below.

Table 1
Typical LPT dimensions, weights, and costs [2]

Voltage Class	**230/115 kV**	**345/138 kV**	**765/138 kV**	**765/345 kV**
Capability (MVA rating)	300 MVA	500 MVA	750 MVA	500 MVA
Single-Phase/Three-Phase	Three Phase	Three Phase	Three Phase	Single Phase
Approximate Price	US$2 million	US$4 million	US$7.5 million	US$4.5 million
Approximate Width	21 ft (6 m)	45 ft (13 m)	56 ft (17 m)	40 ft (12 m)
Approximate Length	27 ft (8 m)	25 ft (7 m)	40 ft (12 m)	30 ft (9 m)
Approximate Height	25 ft (7 m)	30 ft (9 m)	45 ft (13 m)	40 ft (12 m)
Approximate Weight	170 tons (154 metric tons)	335 tons (304 metric tons)	410 tons (372 metric tons)	235 tons (213 metric tons)

Note: Prices are F.O.B. factory and do not include taxes, transportation, special features and accessories, special testing (short-circuit, etc.), insulating oil, field installation, and optional services. The spare equipment database task force (SEDTF) estimates the installed cost will be about 25-30% higher.

2. Fast Recovery LPT

This subsection describes general attributes of fast recovery transformers, describes the EPRI/DHS/ABB "Recovery Transformer" installed at CenterPoint Energy, and summarizes other fast recovery transformer designs.

The concept of a fast recovery LPT is based on a conventional oil-immersed LPT design that enables more rapid delivery, installation, and energization at a substation site. Fast recovery LPTs have a deployment and energize target of six to seven days. From an operational perspective, the fast recovery LPT should provide similar environmental, voltage regulation (with energized load tap changers for in-service voltage regulation), and overload capacity characteristics to those of a conventional oil-immersed LPT. The primary advantages of fast recovery LPTs are:

- Faster transport and energization
- More flexible applications

Disadvantages of fast recovery LPTs are:

- Slightly higher I^2R losses
- Loss of flexibility to regulate voltage at the substation (if not equipped with external tap changers)
- Larger footprint requirements because they employ three single-phase units in lieu of a three-phase transformer.

A single-phase fast recovery LPT costs about the same as a conventional single-phase transformer of the same voltage and MVA. Three single-phase transformers cost about 50% more than an equivalent three-phase transformer because the phases in a three-phase transformer share the same core, reducing material requirements.

Figure 1
Recovery transformer
Source: EPRI/DHS/CenterPoint Energy

Table 2
Dimensions and weight of fast recovery LPT at 345/138 kV

Voltage Class	345/138 kV
Capability (MVA)	200 MVA
Single Phase/Three Phase	Single Phase
Approximate cost	US$2.5 million
Approximate Width	9.5 ft (2.9 m)
Approximate Length	18 ft (5 m)
Approximate Height	11.5 ft (3.5 m)
Approximate Weight	65 tons (50 metric tons)

There are additional recovery transformers under development. New designs are being considered that will be equipped with de-energized tap changers to provide various high-side and low-side voltage combinations (e.g., combinations of 500 kV or 345 kV on the high side, and/or 230 kV, 138 kV, and 115 kV on the low side), as well as load tap changers for voltage regulation. With these enhancements, fast recovery LPTs could provide suitable spares for multiple substation applications.

Siemens has developed a “mobile resilience transformer” and is delivering six of the units to Con Edison and has delivered three of the units to Westar Energy. Both installations will use a design that can operate on multiple voltage levels, includes pre-installed cooling systems, and incorporates plug-in bushings and connections that reduce installation time.

3. Gas-Insulated Transformer

The construction of a gas-insulated transformer (GIT) is similar to an oil-immersed transformer, with the exception of insulating material and cooling medium. GITs use SF_6 gas for cooling instead of oil, and GITs use PET film or plastics for insulation instead of using oil-impregnated paper and pressboard. The benefits of GITs originate from the properties of the SF_6 cooling gas. During the first 0.2 seconds of an internal fault, a GIT using SF_6 gas achieves a tank pressure increase of less than 5%. During the same internal fault timeframe, an oil-immersed LPT experiences over 100% increase in tank pressure. The non-flammable and non-explosive characteristics are also beneficial in the event of attacks that cause an internal fault. In addition, the non-flammable properties of the SF_6 gas reduce the potential for fire damage to the LPT as well as other nearby structures. The SF_6 gas also eliminates the environmental impacts of oil losses.

The height of the fully assembled GIT transformer is 6 to 8 ft (1.8 to 2.4 m), shorter than a fully assembled oil-immersed LPT because no conservator or pressure relief system is needed for the SF_6 gas. The size and non-flammable properties of the GIT make it useful in densely populated areas, and GITs are heavily utilized in Japan in applications up to 300 MVA. Research revealed no reports of large, gas-insulated LPT implementations in the U.S.

Drawbacks of the GIT technology include:

- Limited manufacturing capability
- Existing capacity limitations (currently less than 275-kV, 300 MVA capacity applications)
- High manufacturing costs (1.5X as compared to oil-immersed LPTs)
- Limited flexibility
- Training expenses associated with field training for gas cooling systems,
- Spares and infrastructure costs associated with cooling equipment (gas blowers and coolers) for SF_6 gas
- SF_6 fault-related byproducts are highly toxic
- Because SF_6 is a potent greenhouse gas, application of GIT imposes additional handling and tracking requirements on the utility. SF_6 is the most potent evaluated greenhouse gas, with a global warming potential of 23,900 times that of carbon dioxide (CO_2) when compared over a 100-year period [4]. Given the relatively low amounts of SF_6 used and released compared to CO_2, its overall contribution to global warming is estimated to be less than 0.2%.

4. Solid-State Transformer

The solid-state transformer design uses semiconductor-based devices to achieve voltage transformation, thereby reducing the volume and weight compared to conventional oil-immersed transformers.

The concept of a solid-state transformer technology [5] provides significant flexibility over conventional LPT functionality. If the technology concept is realized, the transformers could be configured to accommodate any input or output frequency. Therefore, solid-state transformers could take in dc and ac power from wind turbines and solar panels and change the frequency and voltage as needed for the grid. Solid-state LPTs lend themselves to modularity, so utilities could arrange several devices in series or parallel combinations to achieve a desired voltage or MVA capacity. The solid-state transformer can be substantially smaller and lighter. Compared to conventional oil-immersed LPTs, the physical size and weight ratio of a solid-state transformer module is approximately 1:100.

Solid-state transformers are currently limited to distribution applications because high-voltage and high-current throughput capabilities are premature at high voltage and power applications. I^2R losses are higher than conventional transformers, with efficiency in the range of 97%.

Manufacturing costs can be twice as high as conventional transformers due to the initial cost of semiconductor devices. Installation and maintenance require significant specialized training. Long-term reliability of power electronics-based transformers is unproven. As an emerging technology, they have limited application in the immediate term. Although efficiency degradation negatively affects operating costs, benefits in the areas of prospective maintenance, extended lifespan, and power flow control may offset the efficiency losses.

5. Superconducting Transformer

There are two main differences in the design of a superconducting transformer compared to the oil-immersed transformer. A superconducting transformer uses superconducting wires for the transformer coils, and cryogenic coolers are used to cool a liquid nitrogen tank that circulates coolant around the coils at an operating temperature of 70°K (-203°C, -334°F). Significant advantages of the emerging superconducting transformer technology include no I^2R losses (although there are cooling system losses), and reduced footprint (one-third to one-half the size of an oil-immersed transformer (although the cooling system will add to the super-conducting transformer system footprint)). The reduced size of the superconducting transformer would reduce weight, thereby improving transportability.

The current state of superconducting technology is emerging based on development of superconducting wire and the cost of that wire. Superconducting cable projects are being implemented (albeit subsidized) to transfer power at distribution voltages to deliver significant power to congested load pockets in a limited corridor. As wire production increases to serve the transmission and distribution line industry, economies of scale will drive the use of superconductivity to more applications, including LPT transformers. Installation and maintenance require significant training. Because the design of superconducting transformers is evolving, its operational life is unproven.

6. EPRI Transformer of the Future

In contrast to some of the above transformer concepts, EPRI anticipates that the transformer of the future will be an evolutionary enhancement to the conventional oil-immersed transformer. This ongoing effort consists of evaluating each subsystem within the transformer (e.g., dielectric, cooling, insulation, core, bushings, etc.) to optimize performance, as well as identifying improvements needed to achieve that optimal state of performance in a unified set of subsystems. EPRI is executing the project in three phases:

1. Identify and prioritize ideal characteristics of the transformer of the future
2. Develop a full-scale prototype
3. Demonstrate performance in an operational environment

The target timeframe for development of an operational unit is energization in a laboratory setting is five years. Design targets and benefits include:

- Longer lifespan
- Flexible applications
- Graceful failure (e.g., benign environmental impact and non-flammable)
- Lower maintenance expense
- Reduced weight and smaller size
- Improved resiliency to recover the system from a natural or forced outage

Table 3
Spare transformer technology qualitative comparison

Transformer Technology Type	Technology Readiness Level (TRL)	Manufacturing Cost (multiplier)	All Inclusive Storage Cost (multiplier)	Ongoing O&M Cost for In-Service Equipment (multiplier)	Applicability (% of Voltage Class)	Transportation Timing	Transportation Options	Installation Timing	Training and HR Impact (Training, OSHA, Safety Equipment, Compliance Modifications)
Conventional Oil-Immersed (Existing Basis for Comparison)	9	1X	1X	1X	10% of voltage class	30 days	rail, barge, road	14 days	Training for maintenance, transportation, assembly, repairs, and storage are standard across utilities.
Fast Recovery (Flexible Design Focused on Existing Technology and Speed to Energize)	8	1X	1X	1.2X (higher losses)	97% of voltage class	7 days	rail barge road	3 days	Minor training required for existing human resources (HR) base to incorporate specific flexibility based design updates. Utilization of existing skills and experience is feasible with vendor video classes or contractor based training.
SF_6 Gas Insulated	8	1.5X	1.2X	1X (Trade-off of reduced maintenance versus cooling blowers)	10% of voltage class	30 days	rail, barge, road	10 days	Significant training associated with cooler system maintenance and repair, SF_6 gas analysis, limited access to standards and Occupational Safety & Health Administration (OSHA) information, plastic insulation durability.
Solid State	4	2X	0.5X	1.5X (higher losses and component costs)	100% of voltage class, plus other voltage classes	3 days	air, rail, barge, road	3 days	Modular components require functional circuitry based knowledge. Training to test and replace modules will be new paradigm. Contract electricians market could outsource the labor base.
Superconducting	6	1.5X	0.5X	0.8X (longer life span and less I2R losses)	10% of voltage class	21 days	rail, barge, road	3 days	Cryogenics training for cooling technology, limited access to standards and OSHA information, cryo cooler maintenance training.
Transformer of the Future	1	1X-1.5X	0.5X	0.8X (longer life span and less I2R losses)	100% of voltage class	7 days	air, rail, barge, road	3 days	Unknown at this time, but desirability for longer lifespan, graceful failure, and lower maintenance may lead to technologies with minimal training requirements (possibly solid state)

KEY
SUITABLE
NEUTRAL
IMPROVEMENT

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