WHITE PAPER / **ELECTRICAL UPGRADES FOR POWER TRANSFORMERS**

CONSIDERATIONS FOR UPGRADING AND REPLACING TRANSFORMERS AT HYDROELECTRIC GENERATION FACILITIES

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Transformer failures can cause extended facility downtime, lost revenue, and unexpected large capital expenses for the hydroelectric power generation industry. A proactive approach can help in assessing existing transformer condition as well as predicting and planning for impending failures.

According to the U.S. Energy Information Administration, the average age of a hydroelectric power generation facility in the United States is 64 years. With the recent push to decarbonize the power industry, hydropower remains an integral part of our energy future. As a result, many aging hydroelectric facilities will pursue life extension projects in the coming years, including the replacement of large generator step-up and unit auxiliary transformers. This paper outlines the considerations facility owners should make to monitor existing transformers and to execute power transformer replacment projects.

Transformers are a critical part of the power generation infrastructure. The generator step-up transformer converts the generator voltage to a higher voltage for transmission, while auxiliary transformers reduce the generator or transmission system voltage for use by the facility's process equipment. These large power transformers are often made-to-order, and equipment lead times of 12 months or more are fairly common. Failure of any individual transformer could render a facility unusable for an extended period while a replacement transformer is procured and installed. As a result, transformer failures may lead to significant loss in revenue to hydroelectric power generation facility owners. Traditionally, one of the only ways to guard against the severe financial impact of a transformer failure was to have a spare transformer on-site and ready for installation should it be needed.

The probability of a transformer failure depends on many factors. However, in general, if power transformers operate within their design parameters, the chance of failure follows a "bathtub curve." For the first few years of operation, the chance of failure is higher because of potential design defects or manufacturing flaws. After a transformer has been in service for a few years, it enters its period of most reliable operation with the lowest chance of failure. Typically, after 30-40 years, the likelihood of transformer failure rises again as the equipment reaches the end of its design life. Mitigating risks associated with transformers reaching the end of their useful service lives needs to be part of the long-term operation and maintenance plan of a facility.

CONDITION MONITORING OF EXISTING TRANSFORMERS

Identifying appropriate ways to assess the health and longevity of transformers is imperative. There are various means and methods to perform condition monitoring of transformers. The following is a summary of some key types, as well as explanation of the benefits and how various transformer parameters can help in foreseeing and preventing a failure.

DISSOLVED GAS ANALYSIS

A dissolved gas analysis (DGA) is an assessment of the transformer insulating oil used to determine the gas concentrations within the oil. A particular type of gas and its concentration can provide early indication of an imminent transformer failure. While oil samples can be taken manually and sent to a laboratory for analysis, transformers can also be retrofitted with modern online DGA monitors that measure gas composition in real time. Whether it is electrical insulation paper aging, long time overloads or internal arcing, most DGA monitors can trigger an alarm to notify the user of a potential problem, and some of the advanced models can even report the constituent gases and respective quantities. It is a best practice to perform DGA testing of the transformer oil at regular intervals to understand how the equipment's condition is changing over time, as results are most meaningful when compared to baseline measurements.

ELECTRICAL TESTS

Electrical tests including insulation resistance, winding resistance, turns ratio and other tests that may be performed when the transformer is deenergized and properly locked-out and tagged-out, can also provide valuable diagnostic and condition information. Sweep Frequency Response Analysis (SFRA) is a recommended additional test that can provide valuable information about the internal mechanical condition of the transformer. As is the case with DGA testing, it is best to perform electrical tests at regular, although less frequent, intervals to understand how the condition is changing over time. Occasionally there are concerns that certain electrical tests such as insulation resistance may weaken transformers that are nearing their end of life.

ADVANCED WINDING AND OIL TEMPERATURE MONITORING

The per-unit life of a transformer, per Institute of Electrical and Electronics Engineers (IEEE) standard C57.91, is a function of temperature (i.e., loading). Consequently, most large power transformers have various instruments (gauges or relays) to show winding temperature and/or oil temperature, with measurements most commonly derived from a "hot-spot" current transformer and a capillary type thermometer or a resistance temperature detector (RTD) submerged in the transformer oil. New intelligent monitors, installed locally at the transformer, can actively monitor this temperature data to predict life consumption, manage transformer cooling systems, and transmit temperature information back to the facility distributed control system (DCS), or other supervisory control and data acquisition (SCADA) system, for trending and monitoring. Intelligent monitoring and automatic cooling systems can reduce the transformer temperature and prevent premature failure from thermal overload conditions.

BUSHING AND SURGE ARRESTOR POWER FACTOR, CAPACITANCE AND PARTIAL DISCHARGE

Failed bushings and surge arresters are common causes of catastrophic failure in transformers. Transformer bushings and arresters undergo power factor testing in the factory to establish a baseline for insulation health throughout their lives. Typically, transformers have to be deenergized and disconnected to perform the required routine maintenance testing, which can require a facility outage or, in some cases, local blackout conditions. Alternatively, transformers can now be equipped with online bushing power factor and capacitance or partial discharge monitoring systems to detect insulation degradation over time and highlight the need for repair prior to failure.

ON-LOAD TAP CHANGER DIAGNOSTICS

A on-load tap changer controls the output voltage of a transformer by automatically modifying the number of turns in a winding, which changes the voltage ratio of the transformer. Because it is one of the few transformer components with moving parts, it is more prone to failure. A reliability study by Hydro-Quebec noted that on-load tap changers (and bushings) were the cause of two-thirds of its transformer failures. Failures occur in the electrical insulation and in the mechanical portions of the on-load tap changer. Actively monitoring the on-load tap changer motor, position and contact wear — as well as automation of other tap changer preventive maintenance items — can help to lengthen the life of the on-load tap changer and prevent early transformer failures.

CONSIDERATIONS FOR REPLACING TRANSFORMERS

Should a transformer show signs of aging, there are many steps in the replacement process that need to be considered to minimize facility downtime and provide an efficient installation. Without detailed planning, improper transformer physical designs, inadequate ancillary systems and unrecognized site conditions can lead to unanticipated schedule and cost impacts.

CAPITAL COST DEVELOPMENT

When planning a major transformer replacement, it is important to recognize ancillary costs that are in addition to the basic cost of the transformer itself. Even turnkey supplier installations will require additional scope that must be executed by others. Some of the scope items that could represent additional costs include:

- Disposal of the existing transformers and oil.
- Facility owner project management, safety and technician support.
- Fire protection deluge system modifications or upgrades.
- Integration of new advanced transformer monitoring instrumentation into the facility control system.
- Isolated phase bus modifications and/or refurbishment.
- Third-party electrical testing.
- Transformer protection modifications or upgrades due to new transformer characteristics, such as megavolt-ampere (MVA) rating, impedance, etc.

MANUFACTURING LOCATION AND TRANSPORTATION

An important part of the transformer procurement process is identifying where each bidder's transformers are manufactured to evaluate risks associated with shipping logistics. Many high-quality transformers are manufactured both domestically and internationally, but shipping methods and the associated logistics need to be considered early in the procurement cycle. Understanding logistics and planning accordingly can help to maintain delivery schedules and minimize potential outage delays.

PHYSICAL DESIGN

Special care should be taken during the transformer design phase when reviewing physical arrangements submitted by the manufacturer. It is common for many transformers to have fixed primary and/or secondary bushing interfaces, such as isolated phase or nonsegregated bus duct, that can require costly, time-consuming field modifications if new bushing heights or locations do not align with field conditions. Control panel locations might be fixed in situations where auxiliary power and control conduits are embedded in the existing transformer foundation. To minimize potential design errors and mitigate overall risk it is important to perform a detailed 3D scan of the existing transformer area to obtain safe, accurate measurements without deenergizing the transformer. These measurements are critical in performing a proper review of the new transformer's physical design characteristics.

SUPERVISION AND SAFETY

Facility owners should consider requiring the manufacturer to supply on-site supervision for the duration of the installation effort, including project managers and/or superintendents responsible for subcontractor coordination and site safety. Many turnkey solutions provided by manufacturers will require demolition, heavy-haul and electrical subcontractors. This approach provides the owner with a single point of contact for any coordination or issues that may arise and simplifies the installation process.

FACILITY SPACE CONSTRAINTS

While transformer replacements are relatively short in duration, they require the use of a large amount of space during installation, typically in high-traffic areas of the facility. Space will be needed for the following and should be clearly identified on a site plan of the facility outage:

- Crane staging area
- Heavy-haul rig parking for offloading
- Laydown space for transformer accessories (bushings, conservator tank, radiators, etc.)
- Space for oil processing rigs and equipment

For facilities where space is at a premium, such as hydroelectric plants, alternate installation methods may need to be considered. Where a crane cannot be staged in a convenient location and is unable to reach the existing transformer pad, the use of a "jack-and-slide" installation technique may be required, using hydraulic skidding systems to push the transformer into place.

FIRE PROTECTION

Where transformer deluge systems are required, special consideration should be made early in the procurement process regarding whether the existing deluge piping should be reused or replaced. In many cases, new transformer geometries will require a complete redesign and replacement of the deluge piping system to maintain proper spray coverages. At a minimum, the deluge piping will need to be removed in preparation for the installation of the new transformer(s). Additionally, modern firewall requirements should be reviewed and oil containment volumes analyzed if the new transformer oil quantity data differs from the existing to confirm that fire protection measures comply with the latest National Fire Protection Association (NPFA) standards. NPFA 851 provides fire protection recommendations and best practices for large power transformer installations at hydroelectric generating facilities and should be used for guidance through this process.

OTHER CONSIDERATIONS

Many replacement transformers that are larger in capacity due to unit uprates, or of a more robust design, may weigh more than the units being replaced. In this case, a structural evaluation must be performed to determine whether foundation modifications are required. For facilities where sister units must remain online during a transformer replacement outage, the following items may need to be considered as part of constructability review and planning efforts:

- Adjacent, energized transformers and bus ducts
- High-voltage line clearances
- Operations and maintenance pathways

Likewise, if key transformer design parameters, such as base MVA rating, winding voltages/taps, or impedance, change during a replacement, a detailed electrical system study should be completed. The scope of the study should include not only the new transformer, but also the electrical equipment associated with it. Examples of electrical system parameters that may change during a transformer replacement include:

- Arc flash hazards (i.e., incident energy levels)
- Breaker interrupting capabilities
- Bus short circuit withstand levels
- Protective relay settings

COMMISSIONING

Prior to placing a replacement power transformer in service, it is common to perform a no-load "soak" of the unit in which the transformer primary is back fed from a utility source with the secondary disconnected or unloaded. The soak typically occurs for 24 hours and is used to monitor the transformer for any abnormalities — such as high temperature, excessive vibration and liquid leaks — prior to the application of load.

For generator step-up transformers that do not have a low-side generator circuit breaker, extra caution and planning must be performed during this process, as the generator is required to be disconnected from the transformer through removal of flexible links in the isolated phase bus. Additionally, control system and electrical protection system modifications may also be required to allow closure of the high-side generator circuit breaker during the test. For these reasons, it is recommended that a detailed back feed procedure be developed with all stakeholders before transformer installation.

CONCLUSION

Transformers are critical and valuable generating facility assets that have a major impact to facility capacity factors and unit performance. Because there are minimal moving parts, transformers are often neglected as part of routine maintenance cycles. However, with advances in technology, a more proactive maintenance and monitoring approach can extend the life of a power transformer and accurately predict equipment life expectancy. While replacing a transformer at a power generating facility can be a complex effort spanning a year or more, outage durations and unexpected cost overruns can be minimized with careful planning at early project stages.

BIOGRAPHIES

RYAN CARLSON, PE, is a senior electrical engineer at Burns & McDonnell. He has more than 10 years of experience working on industrial and power generation projects, including transformer upgrade and replacement projects. He often leads electrical equipment upgrade and replacement projects to increase system reliability and safety. He is also an active participant in the IEEE Power System Relaying Committee. He has a Bachelor of Science in electrical engineering from the University of Nebraska-Lincoln and a Master of Engineering Management from the University of Kansas.

JOSH HANCOX, PE, is a department manager for the Southeast region at Burns & McDonnell. He has nearly two decades of experience in electrical engineering and construction, encompassing nuclear, fossil and hydropower stations, and pharmaceutical, chemical and manufacturing projects. He specializes in calculation/system studies, relay protection calculations/settings, relay testing, substation (switchyard and plant) automation (utilizing various control and communication protocols) and substation startup. He earned a Bachelor of Science in electrical engineering from Clemson University.

WADE JOHNSON, PE, is a department manager at Burns & McDonnell. He has more than 13 years of experience as an electrical power engineer and project manager in the power generation industry. His experience includes project management, lead engineer, construction/field engineer and system checkout and startup engineer roles for thermal, hydro and renewable energy facilities. Wade specializes in power generation capital upgrade projects, including transformer, switchgear, control system and protection upgrades. He has a Bachelor of Science in electrical engineering from the South Dakota School of Mines and Technology.

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