RECOMMENDATIONS FOR A SUCCESSFUL INTERNAL INSPECTION OR REPAIR

Michael D. Wolf
Tri-State Generation and Transmission Association, Inc.

ABSTRACT

This paper provides recommendations for a transformer owner to use to increase the likelihood of a successful internal inspection or repair in a transformer main tank or load tap changer (LTC). It details various considerations needed to make the decision as to when to perform an internal inspection, testing recommendations, and process-type recommendations on the internal inspection.

INTRODUCTION

When online test results indicate an issue in a transformer, at some point there will need to be a decision made to take the unit out of service for testing and inspection. The decision to take a unit out for testing and (if warranted) an internal inspection needs to be based on a balance of acceptable risk, time and resource constraints, and the severity of the observed defective condition. An internal inspection before the defect has had the opportunity to evolve to a state where it's not capable of being discovered during a field internal inspection should be avoided. By evaluating the drivers that go into that balance of risk, time and resources, and defect severity, the owner can choose to perform the inspection when the defect is likely to be found. A planned and systemic approach to the internal inspection increases the likelihood of discovering the defect.

DEFINITIONS

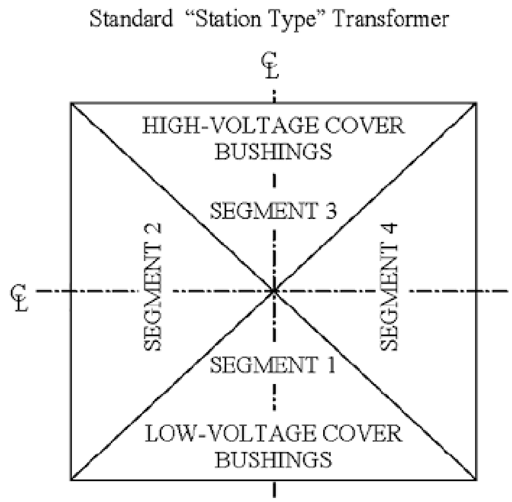
It is useful when discussing internal inspections and repairs to define tasks and transformer components so everyone involved can understand and use the same terminology. This should be done during the planning stage of an internal inspection. Useful definitions are:

Internal inspection
- o An inspection inside a normally oil-filled tank

- Inspection with windings under oil
  - o An inspection that occurs with a lowered oil level, but not with the oil completely removed. The windings must stay submerged in oil so the insulation is not exposed to ambient air.

- LTC internal inspection
  - o Visual assessment of the contacts, detailed measurements and checks inside a drained LTC tank.

It is also important for the inspecting team to refer to locations in the transformer in a consistent manner. Experience shows that using Segment Definitions is a consistent and easily understandable method. A segment map is shown as Figure 1.



Setup for Testing a Single Surge Arrester
Figure 1

Other definitions are helpful to review with the inspecting team but are not necessary to cover in this paper. Reviewing the following terms with the inspection team can prove useful, particularly for those inexperienced with transformer internal construction.

- Core
- Frame
- Windings
- Phase barriers
- Winding wraps
- Leads

When preparing to perform an LTC inspection, terms for the same component can vary by manufacturer. It is important to read and understand the instruction book for the specific LTC so that the same terminology can be used consistently. The following terms can be useful to review with the inspecting team:

- Phase unit
- Selector switch
- Reversing switch
- Diverter/transfer switch
- Vacuum interrupter
- Collector rings
- Slip contacts
- Barrier board

More terms may be required based on the information contained in the manufacturer's instruction book.

WHEN IS THE TIME RIGHT?

Determining when to take a unit out of service for electrical testing and possibly an internal inspection is a challenging task, and it requires the transformer owner to have intimate knowledge concerning his/her fleet, acceptable levels of assumed risk, ease of outage, and how likely the suspected defect is to be found by electrical testing or visual inspection. More than likely the question "when is the right time" will be presented to the owner in one of two instances – unexpected online assessment or unacceptable test results during routine maintenance.

Driven by Online Assessments

If questionable dissolved gas analysis (DGA) is discovered during a routine sample, the first task for the owner should always be to get a follow-up sample analyzed. This helps to limit over-reaction due to a sample error, paperwork/clerical error, cross contamination, or potential issues coinciding with recent service work (for example, maintenance on a vacuum LTC where oil handling equipment had been previously used for an arcing-in-oil LTC).

Once the poor results are confirmed, the owner needs to assess whether the suspected defect is at a point where offline testing and an internal inspection would have the highest likelihood of identifying the defect. This decision must also balance with the owner not assuming an unacceptable amount of risk. For low levels of gassing, the defect severity may need to evolve to a state in which it will be discoverable. Gassing limits should be set based on experience and acceptable risk, with more frequent DGA sampling or online monitoring helping to drive the decision. A consistent gassing trend that suddenly increases dramatically could be an indication that the risk may be getting too great, and the defect may be at a point where the likelihood of discovery is high.

The owner must also recognize the financial and resource burdens of taking a transformer out of service prematurely. If mobile substations are required for an outage on the suspect transformer or other similarly complicated outage requirements exist, the owner needs to be as confident as possible that they are putting the maintenance crew in the best position to find the defect during testing, inspection, and assessment. Other owner-specific considerations to include in the decision are:

- Equipment costs, time, and resources
- Asset criticality
- Spare availability
- Contingency response

Ultimately a balance must be achieved in the decision to remove a transformer from service for testing and potentially a possible internal inspection. Time may be needed for the defect fault to progress to be at a discoverable severity by offline assessment, but one cannot wait so long that the defect severity escalates to an unacceptable state. With the other intangible drivers noted previously, this decision should not be taken lightly.

OFFLINE TESTING

Once the decision has been made to remove the equipment from service, the owner should make provisions for a full set of offline diagnostic tests. It is recommended that a full set of electrical and physical tests be performed, since the suspected defect may have impacted other systems within the transformer. Recommended tests include, but are not necessarily limited to:

- Overall power factor and capacitance
- Bushing power factor and capacitance
- Surge Arrester current and watts loss
- Exciting current and loss (full 16L to 16R if LTC)
- Turns Ratio (full 16L to 16R if LTC)
- Sweep Frequency Response Analysis (SFRA)
- Leakage reactance and loss
- Core ground insulation resistance
- Winding DC resistance

In addition to electrical testing, the functionality of all ancillary transformer components and accessories should be confirmed. This includes checking all alarms and gauges, fans, and pumps. Pumps often have their motors in the same oil as the transformer, so motor winding defects (thermal or discharge) could be mistaken for gassing occurring in the active part of the transformer. It is important to operate the pumps and note any unusual sounds or activity of the flow indicator. Pump motors can be tested minimally for resistance and insulation.

Once all offline evaluation has been completed, the data needs to be evaluated to attempt to find commonality between the offline testing and the suspected defect from the online DGA and other assessments. If the electrical and physical tests don't agree with the suspected fault conditions suggested by the DGA, that inconsistency should be evaluated further. Other possibilities should be considered along with different levels of severity of the suspected defect. Alternative options should always be sought out and considered.

DEVELOP A PLAN

Using the available data, a narrative should be created that links together the test results and condition into a hypothesis. Perhaps the unit does not need an internal inspection or repairs, but it will in the future as the defect becomes more severe, when the test results point more strongly to the defect being discovered. Multiple hypotheses should be devised, based, and ranked. This methodology will be helpful if the results of the internal inspection (if necessary) are not as expected.

If warranted, the internal inspection should focus first on the most likely areas based on the most logical hypothesis gleaned from the data. The owner should find common points inside the transformer and link the test results together by reviewing the conditions and observations from the DGA and testing. Those areas should be noted and inspected first if possible.

For LTCs, while developing a plan, the asset owner should perform a desktop exercise in which the instruction book and nameplate are reviewed and understood. Having a sound understanding of the LTC's sequence of operation is crucial, as is the understanding of the electrical identity of the contacts – where they go and what they do inside the transformer. In service infrared scans can be particularly helpful in identifying LTC problems, so those should be evaluated for any components of concern.

NECESSARY MATERIALS

Having the necessary materials available ahead of time for an internal inspection will help save time and resources so the crew efforts can focus on the inspection. Suggested safety equipment includes but is not limited to:

- Confined space entry materials
- Rescue davit arm or hoist, including non-metallic cable if acceptable
- All applicable company safety documentation should be on-site and followed

Strong, wide beam lighting can make an internal inspection significantly easier. It is recommended that inspecting crews have strong and capable lighting available beyond what is expected to be required. More lighting is always better. Recommended lighting equipment includes:

- All lighting should be battery powered with common, consistent battery systems/sizes
- 2x area lights – either light bars or lanterns
- 2x focus lights – either pistol style or box style
- Spare sets of charged batteries for all lights
- Appropriate chargers plugged in and ready
- All lighting must be tethered and secured while in the transformer. Pull tape and appropriate knots allow flexibility to tie off tethers to inspection personnel, points inside the transformer, or exterior tie-off points

It can be helpful to have mirrors on-site of various sizes to help inspect areas inside the transformer. Various sizes should be available, as should long-reach illuminated articulating mirrors. These items are commonly used for under-vehicle inspections.

Tools should also be made available to the inspectors, all tethered off and accounted for. The following tools may be helpful during an internal inspection:

- Long reach needle nose pliers
- Machinist's rulers in 3-inch, 6-inch, and 24-inch sizes
- Zip lock bags for sample storage
- Permanent marker
- Magnifying glass
- Wooden or rubber mallet
- Brass pick set
- Soft flexible solid copper wire can be useful for probing or reaching
- Minor insulation repair kit
    - Kraft paper, cloth tape, glyptal, and pressboard
- Full set of mechanic's hand tools

SAFETY

Safety during an internal inspection is the most important aspect of the job. All confined space entries should be coordinated following company-specific safety rules and procedures. Local fire department or EMS should be alerted and given the address or coordinates, and all confined space duties shall be assigned prior to entry. The air should be monitored regularly following company guidelines for breathability. A plan should be developed to rotate duties if prolonged high or low temperature exposures are anticipated based on the suspected defect. All employees should be qualified for their assigned duties.

A pre-job briefing should always take place with specific scenarios and planned responses, that should be submitted, along with any necessary permit or paperwork, based on company procedures and guidelines.

Throughout the inspection, a supply of breathable dry air should be on site to assist in maintaining a safe and breathable atmosphere and comfort for the inspectors. Internal atmospheric conditions should be monitored, logged, and shared with the entrants. If the transformer remains partially oil-filled, the team should review the engulfment hazards that will be encountered and agree on mitigation and response plans prior to entry.

INTERNAL INSPECTION

Once the decision has been made to perform an internal inspection, the first consideration should be the maximum oil level inside the transformer during the procedure. Determine if the transformer will be drained fully or if a partial drain will be adequate. This may vary based on company procedures/guidelines. For suspected high-resistance connection issues, it can be useful to first drain the oil to the top of the windings so that the bushing terminals inside the tank can be inspected. There can be value in first lowering the oil level to the top of the windings initially for all suspected defects in the event that the repair does not require further oil to be removed, and the defect is accessible while standing or lying prone atop the frame.

Prior to any entry, the inspectors should be aware of potential combustible atmospheric concerns. Based on the most recent DGA, the combustibility of the air space can be calculated from a spreadsheet provided by Doble. If needed, purge the air space thoroughly with dry air prior to entry to mitigate a combustible environment.

Prior to entry, the pressure between the tank and the ambient atmosphere needs to be equalized. This can be done a variety of ways based on the transformer design. All tools, rags, buckets, and hardware should be positioned as distant as possible from any open hatch flanges. The entrants must remove all items from their pockets and on their person, including jewelry, watches, rings, hair clips or pins, belts or any other personal items. PPE, clothing, and footwear should be cleaned prior to entry.

General Recommendations

Once the primary access hatch has been opened, it can be allowed to vent the transformer for a period of time prior to performing atmospheric monitoring and logging. A tool, fastener, or component log should be on a clipboard atop the transformer that the attendant fills out as appropriate. The atmosphere should be monitored regularly, and a supply of breathable dry air should be available. This can help increase the comfort of the inspectors and it can also help regulate the breathability of the air based on monitoring results.

Once safe, the inspector should look inside for obvious, easy-to-reach defects within arm's reach of the access hatch. If needed, they can then look inside the access hatch and evaluate potential foot placement locations. Once confident in foot placement, the inspector should position their legs into the access hatch and use arm strength to lower their feet down onto the first foothold.

It is critically important for the inspector to employ a "test-then-go" concept for weight distribution while inside the transformer. This means that weight is slowly applied to the potential support prior to committing all of one's weight onto it. If any movement, cracking, or deflection is sensed, the limb should be immediately stopped and withdrawn. Good supports for body weight include the frame of the transformer and any painted steel surfaces. Some wooden members may be suitable for weight distribution, but they must be visually considered, and only used after a test-then-go approach has been implemented.

The inspector must think two steps ahead of his/her movement prior to moving arms or legs. It is easy to get bent into challenging positions that do not have a good exit strategy. Moving or pulling lumps roughly against winding or lead insulation should be avoided at all times as to not skin or damage the insulation.

In very tight areas, the inspector can consider the following movement strategies:

- Lie prone and "wiggle"
- Lie on one's back and shrug up or down with shoulders while aiding with legs
- In either of the two positions above, one can also put hands-over-head and pull.

It can also be helpful for the topside attendants to monitor body placement and be in communication with the inspector – often they can see the placement of the inspector's feet better than the inspector, and a quick "what is my right foot pushing against?" type of question from the inspector can easily remove uncertainty.

Mobile transformers or smaller MVA units may not have readily accessible areas, and the inspector must accept these limitations. In this instance, long reach mirrors and lights can provide visual assessment into otherwise unreachable areas. Other access hatches on the sidewalls of the transformer may provide better visual assessment than an internal inspection.

Initial Inspection Details

It is imperative that the internal inspection is performed in a planned and deliberate manner. From a cardinal direction (tank wall referenced by a point on a compass, example: East side tank wall) or physical location (example: Segment 2) the inspection can begin one phase at a time from atop the frame with strong flashlights. Starting at the bushing bottom terminal or the highest visible point of the draw lead, the leads can be followed down into the windings visually. This inspection path may include the DETC, LTC, or in-tank LTC outer drum and connections. The adjacent tank walls can be quickly inspected, and, if possible, down to the tank floor at their bases. The adjacent areas of the top cover can also be inspected for evidence of fault activity. The top of the core and frame can be inspected from this position, as can the wooden cleat and lead structures. This procedure is then repeated for the next two phases.

If damage is discovered during the top of the frame inspection, the various hypotheses of decreasing likelihood should be reviewed. Does this finding agree and resolve the most likely hypotheses? If yes or no, the defect should be documented fully with pictures, a voice description transcribed in detail by the topside attendant, and a measurement of the defect size and location relative to major identifiable transformer components.

The next consideration is with the repairability of the defect. Does the utility have the knowledge and capability to identify the severity of the defect and execute a repair? If not, calls should be made to get further on-site support or technical consulting.

The author's organization has implemented an effective manner of excluding the inadvertent introduction of foreign material in which the oil was only partially removed is to place sheets of bubble wrap under the impacted area where repairs will take place. Bubble wrap will float on the oil and has enough strength to catch accidentally dropped hardware, debris, or small tools. Other buoyant materials can also be considered.

If no defects are found, proceed to the detailed inspection in the next section. Consider a detailed inspection regardless of the outcome of the initial inspection. The additional time and resources required for the full detailed inspection may not be that more than is already on site. The exception to this is if the defect was found while the transformer was only partially oil-filled with the windings submerged. The extra information found during the detailed inspection may help justify replacement if the defect goes undiscovered or additional defects are found.

DETAILED INSPECTION

Main Tank

If oil was only partially removed for the initial inspection, it is necessary to completely drain the transformer for the detailed inspection. Similar to the initial inspection, a cardinal direction or physical location (example: East tank wall, or Segment 2) needs to be defined at the initiation of the inspection. Starting from that point, adjacent H bushing will be inspected below the flange down to the draw lead or bottom connection. Following the lead, the inspection will follow into the DETC and into the H windings. Observations of discoloration, visible damage, damaged insulation, evidence of overheating of dielectric material or metal, or debris should be documented.

From the windings, identify the X leads as they exit the winding and follow them to the barrier board or up to the X bushing terminals. The X bushings can then be inspected below the flange similar to the inspection of the H bushings. Any other adjacent and accessible winding leads should also be inspected. This process is then repeated for the other two phases.

Once the lead inspections are completed, starting from the same cardinal or physical location, the core, frame, clamping, and blocking should be inspected for movement, discoloration, overheating, evidence of arcing or discharge activity, and loose or missing hardware. Each bolt or connection should be checked for secureness. Other solid insulation on top of the frame can then be inspected, as can other components atop the frame or core such as the core ground insert/lead. If the transformer is equipped with a tap board or links, confirm torque on the fastening hardware and visually assess the connections and insulation. Once all adjacent components have been reviewed, the inspector can then move away from the starting location until all core and frame components are similarly inspected.

Lastly from the top of the frame, the underside of the top cover can be inspected. Take note of any damage, discoloration, evidence of arcing or overheating, or debris on the bushing CTs and their supports, conduit and wiring, and tank accessories such as the sudden pressure relay (SPR) or pressure relief device (PRD). Each tank wall should be visually inspected, paying attention to tank welds for any cracks. Accessories mounted to the tank walls can be reviewed at this time, such as temperature probe wells, gauges, oil level floats, and radiator penetrations. These can be inspected in a methodical manner starting with a defined segment or cardinal location and moving around the unit. Once back to the cardinal direction or physical location starting point, assess the best way to climb down the side of the transformer as practical based on the constraints of the specific transformer. If a lower access hatch exists, evaluate if entering from there makes more sense than climbing down.

If climbing down, inspect the windings on the way down if they are visible. Pay close attention to key spacer and blocking alignment, shorted turns or crossover defects, as well as wider winding deformation. Identify and inspect adjacent phase barriers or winding wraps and inspect the leads that were previously inspected from above from below as proceeding to the tank floor. If possible, repeat this same process on the other two phases alternating progression – upwards on the next phase, downwards on the following phase. This may not be possible due to tank size and/or construction.

From the tank base, inspect the frame, core, clamping, and blocking, similarly to the inspection at the top of the unit. Start from the same cardinal direction or physical location and work around the bottom of the frame in the same manner as above. Note any missing or dislodged blocking, discoloration, or physical damage. If possible, inspect at the ends of the frame as well.

Before leaving the tank base, inspect for any debris, contamination, evidence of arcing or discharge activity, or discoloration. If possible, inspect the lower radiator penetrations and the frame's connection to the tank.

LTC

All LTC internal inspections qualify as detailed inspections due to the similar setup and requirements they share with transformer internal inspections. Before starting, relate the specific tap positions of concern (either from online DGA position relationship or offline test results) to the specific contact combinations by reading and understanding the nameplate. Once the tank door(s) are opened, document the as-found condition of the LTC compartment with as many photographs as possible prior to performing the inspection or any cleaning or corrective maintenance activity. By documenting the as-found condition, evidence indicating the existence of defect or problem may be realized that would otherwise be missed by removing coking, carbon, or other indicating materials. Recommended as-found photographs include, but are not necessarily limited to:

- Reversing switch
- Driveline
- Selector stationary contacts
- Selector moveable contacts
- Vacuum bottles (if equipped)
- Diverter or arcing switch (if present)
- Barrier board

Starting from the left phase unit, inspect the driveline over to the next phase or motor drive. Inspect the reversing switch moveable and stationary contacts and connections. The vacuum bottles can then be inspected, if equipped, or the diverter/arcing switch stationary and moveable contacts and connections. Then begin the process of inspecting each of the selector switch stationary contacts, and finally the selector switch moveable contacts. Next, inspect the collector ring(s) and slip contacts, along with the phase supports or moldings. Working back to the barrier board, other bus work or bolted connections can be visually inspected, ending at the barrier board where a visual inspection of each stud and connection is performed. Lastly, inspect the tank, inside the top cover, tank walls, and tank floor. This process is repeated on the other two phases.

If an anomaly or any contamination is found, clean the LTC with fresh oil and rags. Document the issue with photos and a written description. It can be helpful to identify the size and measure the approximate location of the anomaly to major components.

If no problems are found, clean the LTC with fresh oil and rags and repeat the same inspection process after a thorough cleaning.

After cleaning out the LTC, inspect other minor LTC components in the tank. Gauge interior tank connections, the SPR and PRD connections, and other spring/driveline/mechanical components should be inspected. Document any findings.

If the LTC has vacuum bottles, it likely also has a vacuum interrupter monitoring (VIM) board, fiber connections, and optical CTs. These should be inspected as well, and any findings documented. It is not uncommon to see plastic retaining clips for fiber lead conduits cracked and broken under normal service conditions.

Hand crank the LTC following the procedure contained in the instruction book. Confirm that the oil is either at or above the minimum recommended oil level in the tank such that the springs or other drive components are completely immersed, as stated in the instruction book. Take a video recording of an operation for each phase that shows the reversing switch operating, the selector switch moving, and the diverter/arcing contacts or vacuum bottles. This can help to understand future concerns on other similar LTCs. As needed based on the test results and suspicions, hand crank the LTC through the areas of interest. Finally, push against the phase moldings, barriers, and other structural components by hand. Check for any looseness and document any findings.

POST-INSPECTION CONSIDERATIONS AND PLANNING

After the transformer has been appropriately processed and vacuum filled, the same full set of electrical tests should be performed as was done before the oil was removed. If the fault condition was discovered and repaired, the electrical tests should show that improvement. Whether the problem was resolved or not, an expected response in the test results that can be evaluated should exist.

If the internal inspection concluded with no findings, the condition needs to become more severe, as reflected in the test results, prior to a subsequent inspection. An initial target of a doubling increase in the measurement may be justification for a scheduled repeat of the electrical tests and inspection, with tripling of results being a reasonable limit for immediately removing the unit from service and performing subsequent testing and inspection(s).

It is recommended that the owner document all findings and the path forward in a simple report with photos. The report should have clear action points for future reference, knowing that the next action may be many years away with different responsible staff.

CONCLUSIONS

When choosing to take a piece of equipment out of service for testing and inspection, it is important that the concerning problem can be found. It is important to observe the defect through DGA of increasing frequency and making preparations to take the equipment out of service when the likelihood of discovering the defect is highest. This is an individual calculation for transformer owners as they balance out their acceptable risk, time and resource restrictions, and defect severity. Previous experience based on the owner's unique fleet is the most valuable tool to know when the balance of those drivers has been met.

Once the equipment is out of service, offline test results can be evaluated against the in-service DGA to create multiple hypotheses of decreasing likelihood before entering the tank. If warranted by the test data, an internal inspection can be considered. If the test results suggest that an internal inspection has a likelihood of success. To increase the likelihood of success once inside the tank, the components need to be inspected in a planned and deliberate manner. Rushing an internal inspection is not advisable and can be misleading. Use the information obtained from the internal inspection to identify the most likely cause based on the previously determined hypotheses.

BIOGRAPHY

Michael D. Wolf, PE is a Principal Engineer of Substation Maintenance at Tri-State Generation and Transmission Association, a G&T cooperative in Colorado, Wyoming, New Mexico, and Nebraska. Mike has been working with the operation, maintenance, testing, and commissioning of substation power equipment since 2008. He has a Bachelor's Degree in Electrical Engineering from Clarkson University, a Master's Degree in Power Engineering from Worcester Polytechnic Institute, and is a licensed electrical engineer in five states.