Transport, installation and commissioning of power transformers

ABSTRACT

Whilst much attention is quite rightly given to power transformer design, manufacturing and factory acceptance testing, the final stages of the supply chain are equally important, namely transport, installation and commissioning. The health of the transformer is critically dependent on safe and careful handling during transport and unloading where sudden impacts or shocks can lead to damage of critical components. Of equal importance are the processes and practices used at site during assembly, vacuum processing and addition of the insulating fluid. Commissioning tests ensure that the transformer has not been damaged during handling, that active component connections are correct and that the transformer protection and monitoring systems are operational. This paper will address these issues and provide guidance on world's best practices to ensure a positive outcome for the supplier and the end customer.

KEYWORDS

power transformers, transport, installation, commissioning

How to ensure a safe delivery of a transformer?

1. Introduction

The primary consideration for transport, installation and commissioning of power transformers is to ensure that all activities can be undertaken with minimal risk to people, equipment and the environment. These considerations are more easily managed at the place of transformer manufacture, where activities are undertaken in a controlled environment and those who work with and are in the vicinity of the transformer are appropriately experienced and trained. However, as soon as the transformer leaves the factory, it will enter spaces and locations that are open to the public such as roads, or are under the control of others such as substations which may be in service, under construction or a combination of both. It is essential then that considerable time and effort is given to planning and preparation of detailed and job-specific safe work method statements, site safety management plans and other related documentation. Whilst

A 66 MVA 132/11/11 kV transformer for transport through the streets of London. Note how items have been removed to meet transport dimensions.

this paper will focus on the technical aspects of transformer delivery and installation, the safety and environmental aspects are certainly paramount at all times.

2. Guides

An excellent guide on transport is provided by IEEEC57.150 – 2012, *Guide for the Transportation of Transformers and Reactors Rated 10,000 kVA or Higher* [1]. Other useful information is also found in CIGRE Technical Brochure 520, *Guide for Conducting Factory Capability Assessment for Power Transformers* [2]. The latter document highlights an issue which is often overlooked in assessing the capabilities of transformer manufacturers, and highlights the importance of the manufacturing also demonstrating that it has a high level of experience and competence in transport, assembly and commissioning.

For installation, including transport, refer to IEEE C57.93 – 2007, *Guide of Installation and Maintenance of Liquid-immersed Power Transformers* [3].

It is essential that considerable time and effort is given to planning and preparation of detailed and job-specific safe work method statements, site safety management plans and other related documentation

3. Transport and delivery

3.1 Delivery terms

Delivery terms for transformers will range from ex-works with the buyer being responsible for all costs and risks from that point forward, to the seller being responsible for all aspects of transport, unloading, and placement into position. Reference will need to be made to the contract commercial conditions and the associated International Commercial Terms (INCOTERMS) which determine the responsibilities and costs for the seller and the buyer. These are divided into four groups:

1. Group C: supplier is responsible for arranging and paying for transport and delivery of goods to a nominated destination or port but local transport and unloading may be arranged by the buyer.
2. Group D: generally used where the supplier is responsible for delivery and unloading to the final location with associated installation and commissioning within the scope of works. This approach is highly recommended as it clearly defines the point of handover and ensuing responsibility for any warranty claims.
3. Group E: This is generally used in ex-works contracts where the buyer is responsible for all transport and unloading arrangements. The seller is usually responsible for loading the transformer onto the designated transport vehicle.
4. Group F: This is when the buyer wishes to arrange for main transport separate from the seller, with the seller generally transporting to a main shipping location such as a port.

3.2 Method of transport

In Australia, most transport of power transformers is conducted using road vehicles, although ships are also used for longer journeys or for deliveries to Tasmania and overseas locations. Due to the high cost of transformers, extensive lead times for repair or replacement and the cost of delays to final commissioning, it is very important to select providers that have a proven record of handling heavy equipment and who are proficient with the safe use of heavy haulage equipment and methodologies.

3.3 Preparing for transport

The issue of whether to include fluid in the transport of transformers is often decided by environmental risk management policies as larger transformers can contain tens of thousands of litres of fluid and any spills or leaks in transit can result in costly fines

Smaller transformers, such as this 3 MVA 66/22-11 kV, can be transported fully assembled.

and clean-up operations, as well as presenting a hazard to other road users.

Transformers are now usually fitted with electronic shock recorders that are GPS enabled to record the time, date, location and magnitude of unusual shock events that may occur during transport and unloading. If an event is logged it may be necessary to undertake a thorough external and internal inspection of the transformer as well as diagnostic testing to determine if the event has resulted in any damage to the transformer, especially the active part and other critical elements such as an in-tank on-load tap changer.

There are three general modes of transport for power transformers, with the final configuration usually dependent on the transport weight and dimensions.

3.3.1 Fully assembled and full of fluid

Smaller power transformers are often transported fully assembled and full of insulating fluid. In this case, exposed parts such as bushings, oil temperature gauges etc. must be protected from transport damage. Measures must also be taken to prevent the overflow of fluid from breather pipes due to temperature changes or fluid movement during transport, and to prevent the release of pressure management devices that may release oil if pressure builds up inside the transformer due to increases in ambient temperature.

> **Prior to dispatch, the transformer should be checked for leaks by a combination of pressure and vacuum leak rate tests**

3.3.2 Partially assembled and either partially full or empty

Depending on the physical layout and voltage ratings of a transformer, the most common items to be removed for transport are the bushings, the conservator and the cooler assemblies and associated pipework. Removed items must be carefully identified and packed to prevent damage and moisture ingress during handling, transport, trans-shipping and storage. This requires the preparation of comprehensive packing lists and supervision of loading and unloading.

When the fluid is either partially or fully removed, the remaining space must be pressurised with dry gas to protect the transformer active part and other items, such as leads, current transformers etc., from moisture ingress. Dry nitrogen has been the traditional gas of choice, with a dew point of less than -40 °C, but due to safety issues, it is now more common to use zero grade dry air, which not only presents no health risk to workers but also has a dew point of less than 60 °C.

Prior to dispatch, the transformer should be checked for leaks by a combination of pressure and vacuum leak rate tests. For more discussion on these tests, see pressure tests (chapter 4.2) and vacuum and vacuum leak rate testing (chapter 4.3).

The transformer is usually pressurised to 20 kPa and a gas bottle with a regulating kit attached, which prevents over-pressurisation due to temperature changes by the use of a one-way relief valve, the bottle then maintaining the supply.

3.3.3 Completely disassembled and empty of fluid.

This method is a further variation of the above with the almost all accessories removed and the main tank pressurized with zero grade dry air.

3.4 Route selection and permits

Route selection will involve relevant traffic and road authorities who will select the route and the time of day for transport based on the load limits of roads, bridges and rail crossings and height limits associated with overhead structures and tunnels. For road transport, load limits are generally based on weight per axle and therefore may require trans-shipping the transformer to allow for special trailer configurations to meet specific challenges. In some remote locations, for example hydro-electric power stations, the buyer will specify transformers in three single-phase banks due to the restrictions placed by roads and bridges with limited load bearing capacity. Other utilities and services will also need to be consulted as it may be necessary to temporarily raise overhead power lines and other cable as well as consider over-hanging structures and vegetation.

Obtaining transport permits, especially when travelling through different jurisdictions as is the case for interstate or international deliveries, is often a lengthy process with permits usually having

> **High moisture content may necessitate special processing at site or the return of the transformer to the manufacturer for re-drying**

expiry dates, meaning that any delays in transport may result in the need for re-submission of permit applications and lengthy delays.

3.5 Audit of delivery site

It is essential to undertake a pre-delivery audit of the site where the transformer is to be located to determine access conditions and decide on the method of unloading. Issues to consider include:

- mode of entry (forward or reverse)
- the need for traffic management and/or road closures
- space available for set up of unloading equipment such as cranes, vertical jacks or skating equipment
- load rating and condition of road surfaces at the delivery point
- proximity of overhead structures, bus-bars and lines and whether they will be energised or disconnected
- structures under the road way such as cable pits, tunnels, chambers etc. and associated load limits
- other works in progress that may impact on delivery such as civil works etc.

From this audit, an unloading plan and safe work method statement will need to be developed and approved by relevant authorities and all stakeholders prior to the date and time of delivery.

3.6 Unloading and placement

On arrival, the transformer is checked for any signs of physical damage or shifting during transport, either of which should initiate discussions with the transport provider and the manufacturer. The gas pressure should also be checked to ensure that it is still positive. If not, then the source of the loss must be located and repaired and gas re-applied. It will also be necessary to check for moisture ingress through dewpoint testing and/or some other suitable diagnostic tool such as polarisation/depolarisation current and frequency domain spectroscopy. High moisture content may necessitate special processing at site or the return of the transformer to the manufacturer for re-drying. The moisture should ideally be no more than the ex-works level, which should be at 0.5 %.

The buyer is usually responsible for ensuring that a plinth of appropriate rating has been prepared for the transformer and the location points are clearly defined. Anti-vibration pads are then laid out in accordance with the manufacturers requirements. The transformer's centre of gravity and lifting or jacking locations must be clearly identified and the transformer protected from mechanical damage by slings, chains and other equipment. The transformer can then be unloaded and located in accordance with the pre-approved unloading plan. Wherever possible, the preferred method of unloading is by the use of cranes which are generally favoured for reasons of time duration and safety. The use of cranes, however, may be prohibited due to site restrictions, such as surface suitability, available space and overhead lines and structures, or the availability of suitably rated cranes at the destination site. In this case, other methods are used, such as jack and skate methodology which employs the use of lifting jacks, rails and hydraulic rams.

> **Poor measurement results can be the result of movement of or damage to the transformer active part during transport**

3.7 Insulation resistance testing

Prior to removing the transformer from the transport vehicle, insulation resistance measurements should be undertaken between the transformer core and frame, frame and tank and tank and frame. This is a DC test undertaken at a minimum of 1,000 V. Resultant measurements need to be checked against the original equipment manufacturer's (OEM) design standards and factory test results. Poor readings can be the result of movement of or damage to the transformer active part during transport. These tests are then repeated once the transformer has been unloaded and placed in its final position. If the resultant measurements are unacceptable, the OEM must be consulted.

3.8 Checking of shock logger

After unloading and positioning have been completed, the shock logger is removed and interrogated to determine if any shock events have been recorded. The following table from IEEE C57.93, 2007 [4] gives values that, if recorded, should result in discussions with the manufacturer as to the possibility of internal damage and the need for further investigation or diagnostic testing.

Table 1: Acceleration values that should initiate discussion

Type of impact	Levels for discussion
Longitudinal	3g
Vertical	2g
Transverse	2g

4. Installation and assembly

The installation and assembly of transformers must be undertaken by experienced personnel with suitable equipment that is capable of meeting the high standards for processing required to ensure that the integrity of the transformer is maintained. Relevant quality documentation is also an essential component, including checklists, inspection and test plans and recording of actions and critical information.

The process commences with the careful identification and checking of all parts and accessories to ensure there has been no loss, damage or moisture ingress during transport and handling.

Other key steps to ensure a quality outcome include:

4.1 Gaskets

Anti-seizing lubricant should be applied to bolts before fitting. All disturbed gaskets must be replaced with the new. All connections and flanges that incorporate a gasket must be tensioned using a calibrated torque wrench. Failure to use such a tool can result in over or under tensioning of the gasket which will cause leaks and costly repairs. An example of typical torque settings are shown in the table below:

Table 2: Torque settings for common pipes with galvanised nuts and bolts

Pipe size	Bolt head size	Bolt size	Torque
25 mm NB	18 mm	M12	46 Nm
50 mm NB	24 mm	M16	113 Nm
80 mm NB	24 mm	M16	113 Nm

4.2 Pressure tests

Pressure tests are undertaken with the transformer empty and repeated after filling. Pressure is applied using zero grade dry air or dry nitrogen at 20 kPa using a regulating kit, ensuring that the pressure is equalised across all components of the transformer, including the main tank conservator (and hence the main tank), air bag (if fitted) and OLTC conservator. All valves should be in their in-service position. The same test is repeated after oil filling.

4.3 Vacuum and vacuum leak rate test

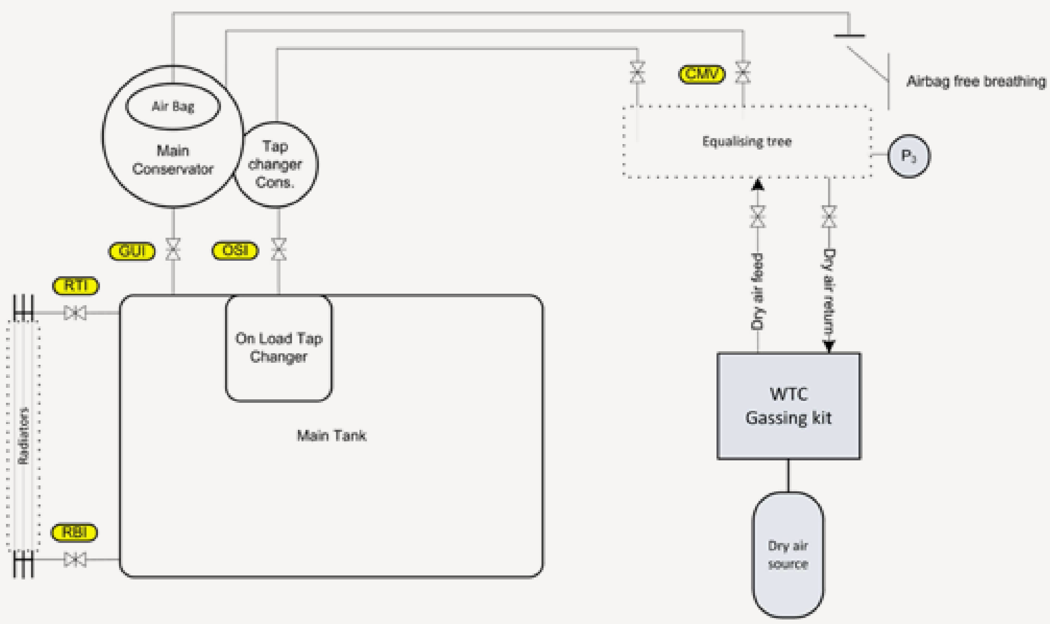
The application of fine vacuum is a critical process in transformer assembly. The correct vacuum can only be achieved if the transformer has been adequately sealed.

Vacuum hoses should be a minimum of 80 mm in diameter and the integrity of the vacuum system checked before they are attached to the transformer. A minimum requirement for a transformer that will be filled from empty is a two stage system rated at 2,000 m3/hour and capable of achieving 0.1 mbar of vacuum or less. The vacuum plant should also include a data logger so that the process can be recorded and reviewed during and after the work has been completed.

It is essential that the vacuum measurement is taken at the transformer tank. It is also critical to verify the vacuum by a leak rate test as an efficient vacuum processing system may be coping with a leak and therefore not give an indication that there is a problem. The vacuum leak rate test should be used before filling an empty or partially filled transformer to determine if the leakage rate is acceptable. The leak-rate will be affected by poor mechanical connections such as leaking valves, gaskets, flanges etc. Note that this test can only be undertaken on transformers that are appropriately rated for application of vacuum.

Care must be taken to ensure that pressures are equalised across various compartments within a transformer such as the main tank, OLTC compartment and a conservator oil preservation system. Reference should be made to OEM recommendations which may vary for different transformer designs.

It is critical to verify the vacuum by a leak rate test as an efficient vacuum processing system may be coping with a leak and therefore not give an indication that there is a problem



Schematic diagram showing the connections for the over-pressure testing of transformers empty of fluid. Note the importance of ensuring that there is equal pressure across different compartments of the transformer.

> The correct processing of insulating fluid is critical to the health of the transformer

An acceptable leak rate is dependent on the transformer volume with recommended levels shown in the table below:

Table 3: Maximum acceptable leak rates for power transformers after one hour (adaption of IEEE C57.93, 2007)

Transformer MVA	Leak Rate (mbar.L/s)
0 < MVA ≤ 30	15
30 < MVA ≤ 100	20
100 < MVA	25

The leak rate, which is measured in mbar.L/s, can be calculated as follows:

$$Leak\ Rate = \frac{(Final\ Pressure - Start\ Pressure)\ x\ (\ Total\ Oil\ Volume\ (L)}{Time\ (sec)}$$

Vacuum levels and hold times will vary depending on the transformer voltage rating. The Table 4 below provides recommended levels for vacuum and hold times for different voltage ratings for new transformers that have been impregnated with insulating fluid such as mineral oil and are considered "dry", i.e. moisture in insulation is <1%.

4.4 Insulating fluid processing

The correct processing of insulating fluid is critical to the health of the transformer. Mishandling can result in contamination of the active part of the transformer and lead to failure. The fluid is an integral part of the insulation and cooling system and therefore must adhere to very strict quality requirements. The two most commonly used fluids are mineral oil and natural ester fluids. Each has their own specific quality requirements for use in electrical equipment, so the associated standards and guides must be consulted and followed.

IEC 60422, 2013, *Mineral insulating oils in electrical equipment – Supervision and maintenance guidance* [5], provides limits for mineral insulating oils after filling in new electrical equipment. It should be noted that once the oil has filtered through a vacuum/degassing filter plant and thence into a transformer, it is no longer classified as "unused." For ester fluids, consult IEEE C57.147, 2008, *Guide for acceptance and maintenance of natural ester fluids in transformers* [6]. It is important to note that these standards are minimum requirements. Customer or manufacturer requirements may be more stringent.

Therefore, it is essential that the fluid is treated prior to entering the transformer. The accepted practice is to use a vacuum degassing/filter plant that utilises filters, heat and vacuum to remove contaminants from the fluid prior to it entering the transformer.

4.5 Physical inspection and repair of damage surface protection systems

The final step in the assembly of the transformer is to inspect all components for signs of damage, rust, water ingress etc. Damage to the paint system will require careful attention to undertake a thorough repair that will prevent future corrosion issues.

5. Pre-commissioning tests

The purpose of electrical tests at site is to:
- verify factory test reports
- check for any changes related to transport and installation
- meet customer specifications
- protect warranty
- ensure that the transformer is fit to be placed into service
- provide a reference for future testing

The amount of testing required will often be specified by the customer but can generally be divided into routine and special tests, although some of those which used to be regarded as special tests are now much more routinely used.

5.1 Routine tests and checks include:

- DC winding resistance through taps
- voltage ratio and phase angle through taps
- insulation resistance of windings
- functional checks or protection and alarm devices such as Buchholz relays and pressure relief devices

Table 4: Vacuum hold times for liquid-impregnated transformers with moisture in insulation <1% (adaption of IEEE C57.93, 2007)

Highest System Voltage: kV	Absolute Pressure (P_A)	Hold Times (hours)		
		Empty	Partial	Top Up
0 < kV ≤ 36	≤ 1.0 mbar	≥ 4 @ P_A + fill time	≥ 4 @ P_A + fill time	-
36 < kV ≤ 72.5	≤ 1.0 mbar	≥ 4 @ P_A + fill time	≥ 4 @ P_A + fill time	-
72.5 < kV ≤ 145	≤ 1.0 mbar	≥ 8 @ P_A + fill time	≥ 8 @ P_A + fill time	≥ 1 @ ≤ 6.0 mbar + fill time
145 < kV ≤ 362	≤ 0.7 mbar	≥ 12 @ P_A + fill time	≥ 12 @ P_A + fill time	≥ 1 @ ≤ 6.0 mbar + fill time

- A minimum diameter of 80 mm pipe shall be used when applying vacuum to an empty transformer.
- A minimum diameter of 50 mm pipe shall be used when applying vacuum for a partial or top up fill.
- If absolute pressure > 10 mbar, then the transformer shall be drained for the process to restart.
- Liquid Filling shall be controlled so that the pressure level is maintained or lower than P_A.

- operation of fans and pumps
- operation of off-circuit and on-load tap changers
- calibration of oil temperature and winding temperature indicators
- CT testing – insulation resistance, ratio, polarity, excitation curve and burden
- insulation resistance of wiring
- checking all wiring circuits for correctness and firm termination
- fluid samples from the transformer main tank and OLTC. Tests should include PCB, DGA, particle count, moisture, dielectric breakdown voltage, acidity, interfacial tension, colour, dielectric dissipation factor and oxidation inhibitor content. Transformer fluid is also tested for furanic compounds.

5.2 Special tests include:

- dielectric loss angle (DLA) of windings and bushings with a capacitive tap
- sweep frequency response analysis (SFRA)
- polarisation/depolarisation current and frequency domain spectroscopy
- magnetising current
- short circuit impedance
- applied and induced voltage

> **Prior to handing over the transformer for service, it is important that the supplier undertakes a formal practical completion audit process in conjunction with the customer**

Site acceptance testing is a critical requirement for ensuring the transformer's condition and preparedness for service.

Table 5: Typical problems detected by electrical tests and DGA [8]

	Diagnostic Technique	Winding Turn to Turn Insulation	Winding/Bushing Insulation	Winding/Bushing/OLTC Continuity	Winding Geometry	Magnetic Circuit Insulation	Magnetic Circuit Integrity
Basic Electrical	Winding Ratio	•					
	Winding Resistance			•			
	Magnetisation current	•					•
	Capacitance and DF/PF		•		•	•	•
	Leakage Reactance				•		
	Insulation Resistance		•			•	
	Core Ground Test					•	
Advanced Electrical	Frequency Response of Stray Losses			•	•		
	Frequency Response Analysis	•			•	•	•
	Polarisation/Depolarisation		•				
	Frequency Domain Spectroscopy		•				
	Recovery Voltage Method		•				
	Electrical Detection of PD	•	•				
	Acoustical Detection of PD	•	•				
	UHF Detection of PD	•	•				
	Dissolved Gas Analysis	•	•	•		•	•

The table above from CIGRE Technical Brochure 445, 2011, *Guide for transformer maintenance* [7] provides a concise summary of the typical problems that may be detected by electrical tests and DGA testing of fluid samples. A more detailed description of key tests and their role is provided in the following pages of this same CIGRE technical brochure.

6. Practical completion and handover

Prior to handing over the transformer for service, it is important that the supplier undertakes a formal practical completion audit process in conjunction with the customer and/or end-user to ensure that all aspects of the scope of works have been completed satisfactorily.

Items to check include:

- surface protection damage
- cleanliness – absence of metal swath from drilling
- signs of rust
- gasket leaks
- weld leaks
- valve leaks
- bleed plugs sealed and not leaking
- bushings – clean, undamaged, not leaking
- rating and diagram plate fitted
- all valves labelled and in correct "in-service" position
- fluid levels – main tank and OLTC
- control cubicles:
  - signs of moisture ingress or rust
  - door seals
  - doors operate correctly
  - no free or loose wiring or components
- review of quality documentation
- provision of manual(s)
- provision of site test reports including fluid tests
- all debris such as packing material etc. removed from site

The supplier and customer should then sign a practical completion form stating that the scope of works has been completed, noting any non-critical tasks outstanding, and that the transformer is at an in-service condition at the time of handover.

Conclusion

This overview of the tasks associated with the transport, installation and commissioning of power transformers highlights that this involves a number of complex tasks which, if not undertaken with due care and diligence, could lead to irreversible damage or loss of service life, or even failure. It is important for users of such services to ensure that the supplier has proven quality, safety and environmental management systems in place and a track record for success in this field.

References

[1] *IEEE Guide for the Transportation of Transformers and Reactors Rated 10,000 kVA or Higher*, IEEE Standard C57.150 – 2012, February 2013

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