ABSTRACT

This article focuses on failures involving dry-type transformers in offshore applications. It addresses the most common causes of failures and the modes of failure. Recommendations are provided for use by specification engineers and end-users to reduce the possibility of failures, including preparation of a suitable specification, siting concerns, operation and maintenance guidelines and procedures needed to be performed after a failure in order to minimize the resulting disruption.

KEYWORDS:

cast coil, cast resin transformers, dry-type transformers, offshore applications, VPI transformer

Failures in dry-type transformers for offshore applications

The consequences of transformer failures in offshore applications can be far more serious than similar failures in industrial and commercial applications

1. Introduction

The consequences of transformer failures in offshore applications can be much more serious than similar failures in industrial and commercial applications. Failures may result in significant costs associated with lost production and transformer repair or replacement costs. Additionally, such failures will involve serious safety issues, such as the possibility of fire, explosion, smoke emission and toxic fume emission.

Due to concerns regarding leaks from liquid-filled transformers and the need to contain the leaking liquid in order to prevent pollution and minimize the risk of fire - a major concern for offshore applications - dry-type transformers, either VPI (vacuum pressure impregnated) or cast coil (cast resin) are the preferred option for offshore applications.

This article will examine the possible causes of failure, describe the modes of failure and provide recommendations to specifiers and end-users for reducing the occurrence of failures.

2. Causes of failure

Below is a selection of common causes of failure, specific to offshore and marine applications.

2.1 Environmental

- Salt - Offshore equipment spends its life operating in a salt-laden atmosphere. This can cause corrosion of the copper or aluminium used for the conductors of the winding and the terminals, and also of the silicon steel core and the carbon steel used for the clamping structure.
- Moisture - Moisture is the enemy of any electrical equipment, and the effects of moisture are obviously a much greater threat in offshore applications.

Offshore transformers located outdoors or even in ventilated rooms that draw cooling air from outside are especially vulnerable to the environmental effects

Due to the inherent vibrations present in drilling rigs and ships, precautions must be taken to prevent the vibration from causing damage to the transformer

Moisture reduces the dielectric properties of the insulation, which is especially problematic for the transformer coils. Surface moisture can lead to tracking over insulation surfaces, particularly in the case of medium voltage transformers.

- Chemical contamination - Many different chemicals are in use on drilling rigs and ships, and these chemicals can be damaging to the transformer insulation and conductors. For example, exhaust gases from engine-driven generators may enter the transformer enclosure, where they can leave carbon deposits on coils which will lead to tracking and eventual damage to the transformer insulation system.

Transformers located outdoors or even in ventilated rooms that draw cooling air from outside are especially vulnerable to the environmental effects listed above, as well as other forms of contamination, such as dust, which can result in a surface prone to tracking.

2.2 Vibration

Since there is inherent vibration in drilling rigs and ships, precautions must be taken to prevent the vibration from causing damage to the transformer. The vibration can be of low frequency, as low as 1–2 Hz and can adversely affect both electrical and mechanical connections. Loose electrical connections can lead to overheating or failure of these connections and possibly also of the transformer. Loose clamping bolts can result in the core laminations becoming loose and in coil displacement, either of which can result in mechanical damage to the structure of the transformer and cause the transformer to become noisy and eventually lead to failure.

Failure of any part of the insulation system will result in damage or catastrophic failure of a transformer coil

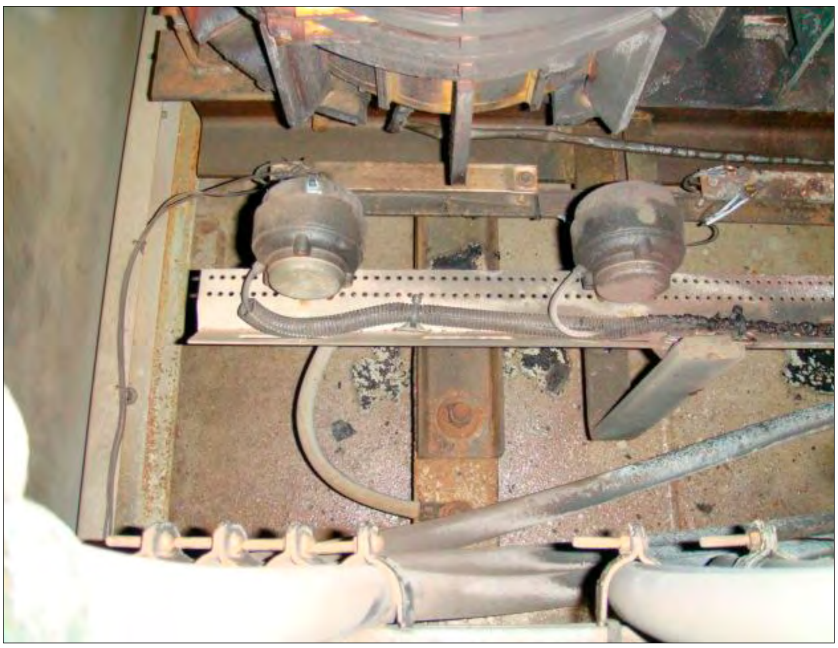

Figure 1. The results of salt laden air being drawn into the transformer enclosure

2.3 Poor ventilation

Space is at a premium on drilling rigs and ships, so transformer rooms are often very small. This can lead to poor ventilation, which in turn can result in overheating of the transformer, causing damage and loss of life expectancy to the insulation system. Transformer rooms need to be provided with sufficient air at the correct ambient temperature, typically 45–50 °C in offshore equipment. This requirement is aggravated by the need to exclude the salt-laden atmosphere from the transformer room. If only air from the outside is used, it is inevitable that this air will contain substances that are potentially damaging to transformers.

Other causes of failure, not specific to offshore and marine applications, such as overloading, incorrect installation, manufacturing or material defects, are also possible.

3. Modes of failure

Modes of failure usually fall into one or more of the following categories:

- insulation system failure,
- conductor failure,
- mechanical damage.

Any of these modes of failure can result from the earlier listed causes of failure. Let us now examine each of these failure modes in more detail.

3.1 Insulation system failure

The construction and insulation of the coils may be regarded as the most critical item in a transformer. Failure of any part of the insulation system will result in damage or catastrophic failure of a transformer coil. Transformer coil insulation takes several forms:

- turn-to-turn,
- layer-to-layer,
- section-to-section,
- winding-to-winding,
- winding to ground.

3.2 Conductor failure

Failure of electrical conductors inside the coils is usually the result of a failure of the insulation system, which permits arcing between the turns or layers of a transformer winding or even between windings. Less common is a failure due to overheating of the conductors resulting from an overload condition. Electrical conductors external to the coil can also fail for similar reasons, but an additional risk is failure due to connection problems, i.e., local heating at a bolted busbar joint or a crimped connection. This type of failure can be the result of vibration, so it is essential that precautions are taken to reduce the possibility of vibration being transmitted to electrical connections. The necessary precautions will be discussed later.

3.3 Mechanical damage

Vibration can also result in the failure of mechanical components such as the supports and clamping structures of the transformer.

4. How to reduce the possibility of failure

The above modes of failure may contribute individually or in combination with one another, and in many cases, it is very difficult to determine which is the direct cause of the failure during investigations after the event. There are several precautions transformer users can take to reduce the possibility of failures, for example, provide a better environment for the transformer, such as an air-conditioned room, and share as much information as possible with the transformer manufacturer during the procurement process. Below are some specific recommendations which transformer users should consider in order to reduce the possibility of transformer failures in offshore applications. These recommendations are the result of observations and successful application in offshore equipment. *However, it is essential to specify the most suitable transformer when ALL factors have been considered.*

4.1 Coil conductor material – copper or aluminium

Copper is capable of carrying a larger current per square inch of cross-section than aluminium. Transformers wound with copper, therefore, have smaller coils than transformers wound with aluminium for an equivalent transformer kVA rating and temperature rise. A smaller core is therefore required to accommodate the smaller coils.

Conductor failure can be the result of vibration, so it is essential that precautions are taken to reduce the possibility of vibration being transmitted to electrical connections

Transformers with copper windings provide two big advantages in offshore applications. They require less ventilation since the load losses generated in copper windings and the no-load losses generated in the core can be less than those in transformers with aluminium windings. They also save space - which is always at a premium in offshore applications - since the transformer is physically smaller. Furthermore, any cost and weight saving achieved by the use of aluminium windings are partly offset by the additional costs of a larger core and more insulation.

Copper is less susceptible to corrosion than aluminium. In fact, aluminium is not permitted by some certifying authorities for offshore applications unless it is coated.

4.2 Transformer technology – VPI or cast resin

First, let us briefly explain the differences between the two transformer technologies commonly employed in dry-type transformers, i.e., VPI transformers and cast-coil transformers.

Vacuum pressure impregnated (VPI) - polyester resin or epoxy resin technology

These transformers are generally referred to as open wound dry-type transformers and use sheet insulation material, such as Nomex, between winding layers. Turn-to-turn insulation is provided either by a polyester coating on the wire used for the winding, or a tape

There are several precautions transformer users can take to reduce the possibility of failures, and it is essential to specify the most suitable transformer when all factors have been considered

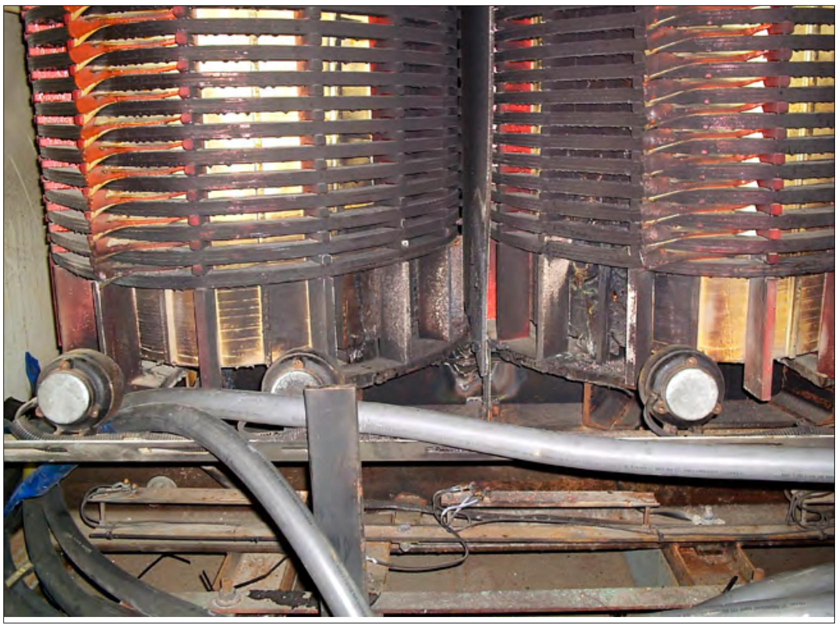

Figure 2. Insulation system failure due to contamination

Copper windings are a better choice than aluminium ones for offshore application, in fact, aluminium is not permitted by some certifying authorities for offshore applications unless it is coated

fabricated from sheet material such as Nomex.

The coils are vacuum pressure impregnated in an epoxy or polyester resin, which is then oven cured. The completed transformer is often dipped in the same resin and oven cured.

Cast resin (cast coil)

The winding method for cast coils is similar to that for VPI coils, but the coils are placed in a mould after winding and resin is introduced under vacuum, after which the coil is placed in an oven for several hours for the resin to cure. The mould is then removed, leaving a coil with a smooth, hard resin surface. The resin thickness is generally greater than the resin on a VPI coil.

Two different technologies are used in the construction of cast-coil transformers, depending upon the manufacturer. These are referred to as the "filled resin system" and "unfilled resin system". The "filled resin system" uses a combination of resin and quartz powder, while the "unfilled resin system" uses only pure resin.

Advantages of cast-coil construction:

- Impervious to moisture - since the casting process results in a completely encapsulated and sealed winding, this renders the winding impervious to moisture, unlike a VPI transformer, where harsh environments can cause the thinner coating of resin to deteriorate, allowing moisture to enter the insulation system.
- Mechanically stronger - the construction and materials of a cast-coil transformer result in greater mechanical strength and resistance to the effects of long-term vibration due to the glass-fibre reinforcement used in the coil, which in combination with the epoxy resin which provides a coil of very solid construction. In addition, the coil support blocks of most cast-coil transformers are provided with shock-absorbing pads or springs, which effectively isolate the coils from the clamping structure to reduce the possibility of vibration being transmitted into the coil, a feature not often found on VPI transformers.
- These construction features also result in increased short-circuit withstand capability.
- Easy to clean – the coils of cast-coil transformers have a smooth surface that may be easily wiped clean with a dry cloth to remove any dust or dirt, which can provide a tracking path.
- Partial discharge – in open-wound, VPI, medium voltage transformers, partial discharge resulting from small air voids in the windings can result in premature aging of the insulation system. The electrical discharges in the air voids eat away at the insulation and can result in the failure of the transformer in a matter of weeks or months. The complete resin impregnation of all parts of the windings on the cast-coil transformers renders them much less vulnerable to partial discharge.

A partial discharge test performed on the coils after manufacture will confirm that the level of partial discharge is less than that permitted by IEEE or IEC Standards. Currently, in IEEE standards, the maximum acceptable level of partial discharge for cast-coil windings is 10 picocoulombs, while the maximum acceptable level of partial discharge for VPI coils is 50 picocoulombs. In cast-coil transformers, the risk of air voids in the winding still exists, but since for these transformers, the partial discharge test is a routine test, the presence of voids will almost always be detected at the fac-

In cast-coil transformers, the risk of air voids in the winding still exists, but since for these transformers, the partial discharge test is a routine test, the presence of voids will almost always be detected at the factory

Figure 3. Cast resin transformer – Sunten Electric

tory. For VPI transformers, the partial discharge test is an "other test", so it will only be performed when requested by the customer.

Cast-coil transformers are typically a little larger and heavier than VPI transformers of the same power rating, and the initial cost is greater. However, they operate at a lower maximum temperature, which can result in reduced load losses, and therefore reduced operating costs. So, it is important to consider the total cost of ownership, i.e., first cost, plus operating cost over the predicted lifetime of the transformer.

4.3 Specify high quality core steel

The use of a low loss grade of silicon steel, such as grade M3, together with "step lap" construction for the core, results in reduced no-load losses and reduced core weight. The reduced no-load losses, in turn, reduce the amount of heat generated.

4.4 Specify appropriate enclosure

Specify the correct degree of enclosure protection, at least NEMA 3R [1], for most offshore applications.

4.5 Specify accessories - vibration dampers, fans, heaters, filters

Specify vibration damping, which will usually be in the form of rubber or cork pads. Determine if such pads are sufficient and suitable for the application, the use of spring dampers may be necessary for applications where vibration is a problem.

Ventilation fans can provide at least a 33% increase in kVA rating of a dry-type transformer, and as stated earlier, this can provide an overload capability.

Transformers that are continuously energized, even with no load connected, generate heat in the silicon steel core, which is often sufficient to prevent moisture build-up. However, heaters installed inside the transformer enclosure will provide heat at times when the transformer is de-energized.

In very dusty environments, the use of filters on enclosure ventilation grilles should be considered.

Offshore applications are subject to the requirements of certification bodies, whose standards generally require the transformers to be suitable for use at a tilt angle of 22.5 degrees, which requires additional mechanical support

4.5 Specify mechanically strong construction to withstand vibration and tilt requirement

Transformers for offshore applications are subject to the requirements of certification bodies such as ABS, DNV, Lloyds, etc., whose standards generally require the transformers to be suitable for use at a tilt angle of 22.5 degrees. This often requires the use of additional support bracing for the transformer, especially for larger transformers.

5. Operation of transformers

It is essential to operate the transformer at all times within its nameplate ratings and to provide sufficient cooling air to maintain the ambient temperature at the maximum permitted value – usually 45 or 50 °C.

5.1 Regular maintenance

Read the manufacturers manual together with IEEE Standard C57.94 [2], for recommendations regarding maintenance.

Keeping the transformer coils clean is of utmost importance. Dust, dirt and other forms of contamination result in a reduction in the dielectric strength of the transformer and may lead to tracking or arcing. Dust should preferably be removed with the use of a vacuum cleaner to suck the dust out, instead of blowing, which can drive the dust into the insulation of the coils instead of removing it. All nuts and bolts should be regularly checked for tightness, and if tightening is required, the manufacturers' recommendations regarding torque values should be observed. This is particularly important for bolted electrical connections in order to prevent overheating of the connections.

The period of time between maintenance procedures will vary, depending upon site conditions. Generally, every twelve months is usually sufficient, but it is recommended that the transformer be inspected every three months during the first year of operation in order to determine the appropriate interval between maintenance procedures.

5.2 Reduce the possibility of contamination into the transformer

When transformers are installed in ventilated enclosures, the ventilation grilles should be kept free of dust and other obstructions. If filters are used, they should be cleaned or replaced at regular intervals, and when filters are installed after the transformer has been placed in service, the manufacturer should be consulted for recommendations regarding cooling since the filters reduce airflow through the enclosure.

The transformer should be protected from exhaust fumes being emitted by other equipment, such as engine-driven generators. These fumes should be prevented from entering the enclosure. The coil surfaces can quickly become contaminated by carbon deposits from these fumes, which will lead to tracking or arcing.

Keeping the transformer coils clean is of utmost importance since the dust, dirt, and other forms of contamination result in a reduction in the dielectric strength of the transformer and may lead to tracking or arcing

If the transformer is out of service for any time, heaters inside the enclosure should be energized to prevent moisture build-up on the coils.

6. After a failure

The failure of a transformer should automatically trigger the protective devices, which will disconnect power from the transformer. If there is a fire resulting from the failure, this will usually stop soon after power has been disconnected since the materials used in the construction of transformers are generally self-extinguishing.

There is often more than one transformer in a transformer room, so any other transformers nearby should be inspected for damage, either secondary fire damage or the presence of powder used to extinguish any fire in the failed transformer. This powder should be removed with a vacuum cleaner, not blown with compressed air. The failed transformer should be inspected and the cause of failure determined in order to avoid further failures after repair or replacement of the failed transformer. Before re-energizing any other transformers on the same power supply or in the same area, it is recommended that these transformers be subjected to basic tests, as detailed in IEEE Standard C57.94, *Recommended Practice for Installation, Application, Operation, and Maintenance of Dry-Type Distribution and Power Transformers.*

7. Conclusions

Dry-type transformers are the preferred option for offshore and marine applications, but there are several factors to take into account during the specification process to ensure that the most suitable transformer has been selected. Careful specification and regular inspections and maintenance will much reduce the possibility of failures, which can be disruptive and very costly.

Bibliography

[1] ANSI/NEMA 250-2020 Enclosures for Electrical Equipment (1,000 Volts Maximum)

[2] IEEE C57.94-2015 IEEE Recommended Practice for Installation, Application, Operation, and Maintenance of Dry-Type Distribution and Power Transformers

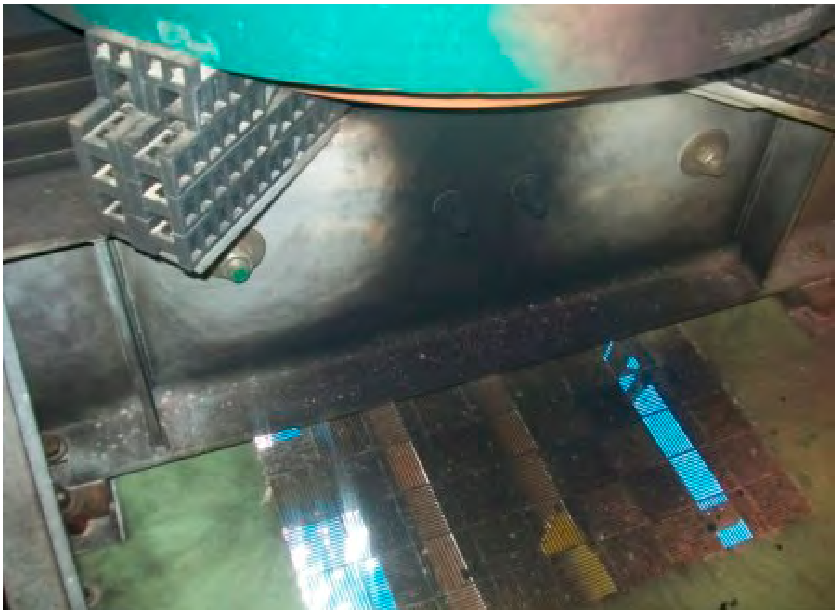

Figure 4. The effect of generator exhaust gases entering the transformer enclosure from the deck below on a drilling rig

In the case of failure, especially if there is fire, if there is more than one transformer in a transformer room, other transformers nearby should be inspected for damage

Author

Derek Foster was born and educated in England. He entered the transformer industry in 1974 and has had extensive experience in the design, manufacture and application of specialty transformers and inductors. In 1994, Derek relocated to the Chicago area, as Engineering Manager for a dry-type transformer manufacturer.

From 2007 to 2009, he worked in China, involved in the setting up of a state of the art transformer manufacturing facility for a US company. His experience includes detailed design of transformers and inductors, transformer and inductor testing, failure analysis, preparation of specifications etc., for transformers for general electrical distribution systems, railway traction substations, marine applications (shipboard), offshore drilling, etc.

Mr Foster is an active member of the IEEE Transformers Committee and from 2003-2017 served as Chairman of the working group for IEEE Standard C57.12.91, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers. In addition to being a member of several other working groups within the IEEE Transformers Committee, he is also a member of the IEEE Traction Power Substation Committee.

Mr. Foster is currently President of Magnetics Design, LLC, providing consultancy services to manufacturers and end-users and providing dry-type transformers, including cast coil and dry-type and water-cooled inductors.