

Core and frame insulation of power transformers

Part I: History, past and present issues

ABSTRACT

This paper reviews the evolution of core and frame (clamp) insulation failures in power transformers and examines representative fault cases attributable to manufacturing defects, transportation-related displacement of the active part, and in-service malfunctions. Drawing on historical experience and recent field evidence, it shows how dominant failure mechanisms have shifted over time, from degraded insulation of bolted core assemblies to increasingly consequential core-ground and multipoint-grounding faults that can drive circulating currents, localized overheating, and abnormal gas generation. The study un-

derscores the need for continued, systematic, and comparable data collection on core damage to strengthen root-cause attribution and improve prevention strategies. To reduce recurrence and enhance diagnosability, the authors recommend standardizing a robust, monitorable grounding design for transformer cores and frames, particularly for units rated 10 MVA and above.

KEYWORDS:

circulating currents, core and frame insulation, core-ground, multipoint grounding, DGA, earthling, failure, grounding, power transformer



The core and frame (or clamp) insulation are an integral component of the active part (AP) of a power transformer

1. Introduction

This article explores the historical progression and underlying causes of failures in the core and magnetic circuits of transformers, spanning from the late 19th century to the present. During the first half of the 20th century, the primary contributor to transformer failures was damage to the insulating tubes surrounding bolts (tie studs). The partial elimination of these bolts during the 1950s–1970s significantly contributed to a decline in failure incidents. However, the 1970s witnessed a rise in failures predominantly attributed to transportation-related issues, which were successfully mitigated through a combination of technical advancements and organizational improvements.

In the late 1980s and early 1990s, to reduce iron loss, bolts (tie rods) were completely replaced by fiberglass ring ties (tie rods) or metal ties (half ties) with insulated inserts. While this technological innovation addressed earlier challenges, it also revealed previously undetected core ground faults, a latent issue that became increasingly significant. The severity of this issue escalated between 2015 and 2025, with run-in failures being particularly evident in newly manufactured transformers. This trend is explained by the expansion of production activities at new manufacturing plants.

The core and frame (or clamp) insulation are an integral component of the active part (AP) of a power transformer. The term “active part” refers specifically to the core, frame, windings, insulations, and oil necessary for the transformer’s operation. All other components are classified as auxiliary and are beyond the scope of this study. The insulation system of the active part consists of the following sections: core ↔ tank, frame ↔ tank, core ↔ frame.

NOTE 1. In technical literature, the less rigorous term “core” is often used instead of “active part” for the purposes of this study.

The CIGRE 2015 Transformer Reliability Review highlights that failures in the core and magnetic circuits of transformers (operating at ≥ 69 to < 700 kV) contribute to 2–11.1% of total transformer failures (Table 30 in [1]). Core faults include problems such as core insulation degradation (over time, the insulation between the laminations can deteriorate, leading to increased eddy currents and energy losses); core looseness (mechanical stresses and vibrations can cause the core laminations to loosen, resulting in increased noise and potential core damage); core-ground fault; corrosion, etc. In contrast to the 20th century (as discussed in paragraph 2 below), the main failure type today is ground faults, and we will focus on this issue below.

As a reminder, the transformer core laminations, exposed to the electromagnetic field of alternating current, are insulated from each other by a very thin layer of oxide coating, ensuring very small spacing and very high capacitance between them. The large surface area of the laminations also contributes to increased capacitance. This very high capacitance ensures negligible capacitive reactance. Therefore, all laminations remain at virtually the same potential, requiring only one section to be grounded. In addition to this deliberate grounding at one point, the core is completely isolated from the tank.

The core clamping structure is also in close proximity to the electromagnetic field and must be insulated from the core and also grounded to prevent capacitive voltages and discharges on the core.

NOTE 2. *Earthing or Grounding.* Earthing and grounding mean the same thing. The standard you’re working with determines which one you use. If you’re working to an IEC or any national standard harmonised to IEC, then it’s defined as *earthing* in both examples. If you’re working to the

North American (US) standards, then it’s defined as *grounding*. The article prefers the term “grounding” because it is more widely used in the transformer literature.

An additional unintended short circuit to the core ground can disrupt the magnetic field balance, causing heightened losses and localized overheating within the core. This may also result in vibrations, unusual noise, harmonic distortions, overvoltages in the windings, and potentially trigger the operation of protective relays.

To outline solutions to the modern core-ground fault problem, it is useful to first review the experience and methods of combating core defects in the 20th century.

Early on, insulating tubes made of bakelite or cardboard, later replaced by fiberglass, were utilized to isolate bolts from other metallic components of the transformer

2. History

Since the invention of transformers in the late 19th century, core assemblies have traditionally been constructed using bolted cages to secure the laminations. These bolts (tie rods) ensured pressing of core rods and yokes and connection rigidity of the core with frame (yoke beams). Early on, insulating tubes made of bakelite or cardboard, later replaced by fiberglass, were utilized to isolate bolts from other metallic components of the transformer. However, if such an insulating tube degraded (e.g., due to poor quality or cracks), it would compromise insulation. This could result in a short circuit between the yoke laminations and the bolt, leading to overheating and, in some cases, damage or melting of

the laminations. During the 1950s to 1970s, including for reasons of reducing iron losses, design advancements eliminated bolts from core rods, significantly lowering failure rates and addressing some of these issues. In the 1970s, there was an increase in transformer core failures, primarily due to the increasing problem of handling transformers during transportation. To address this, manufacturers introduced shock recorders to monitor handling impacts, standardized acceptable shock levels, and implemented stricter initial inspections. Part of these procedures involved checks for intentional ground faults and ensuring no unintentional ground faults were present. Over time, with practical insights—largely from Doble—the standard for core-to-ground insulation resistance (IEEE Std 62TM-1995) was established.

By the late 1980s and early 1990s, bolts were almost completely eliminated from transformer core designs. Engineers began using fiberglass ring ties or metal ties with insulated inserts to maintain lamination integrity.

While the bolt problem disappeared, it revealed the previously hidden problem of core ground faults, especially multipoint ones. Multiple ground faults in core-tank, frame-tank, or core-frame insulation systems often result in the

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formation of closed electrical loops (e.g., Fig. 1). These circuits interact with the alternating magnetic flux, inducing voltage and creating circulating short-circuit currents between the core and ground. The intensity of these circulating currents is inversely proportional to the circuit's resistance. If left uncorrected, such faults can seriously impair transformer operation and lead to catastrophic consequences. Conversely, an ungrounded (floating) core can build up voltage relative to the ground as a result of electromagnetic coupling with the HV and LV windings, which can similarly disrupt the proper functioning of the transformer.

Starting in the mid-1970s, a notable advancement in transformer design involved the implementation of insulators to extend the core ground from within the tank to its exterior. This design allows for monitoring the condition of the transformer core insulation during manufacturing, installation (after transportation from the factory to the installation site), commissioning, and operation. Separate bushings or a special grounding terminal box are most often used to ground the core and frame to the outer surface of the tank. These bushings are usually connected to the wall or cover of the tank near the hatch inside the tank. The diagram and design of this grounding system are shown in Figs 2 and 3.

The primary causes of core failures can be attributed to various factors involving the design, manufacturing, transportation, and operation of transformers

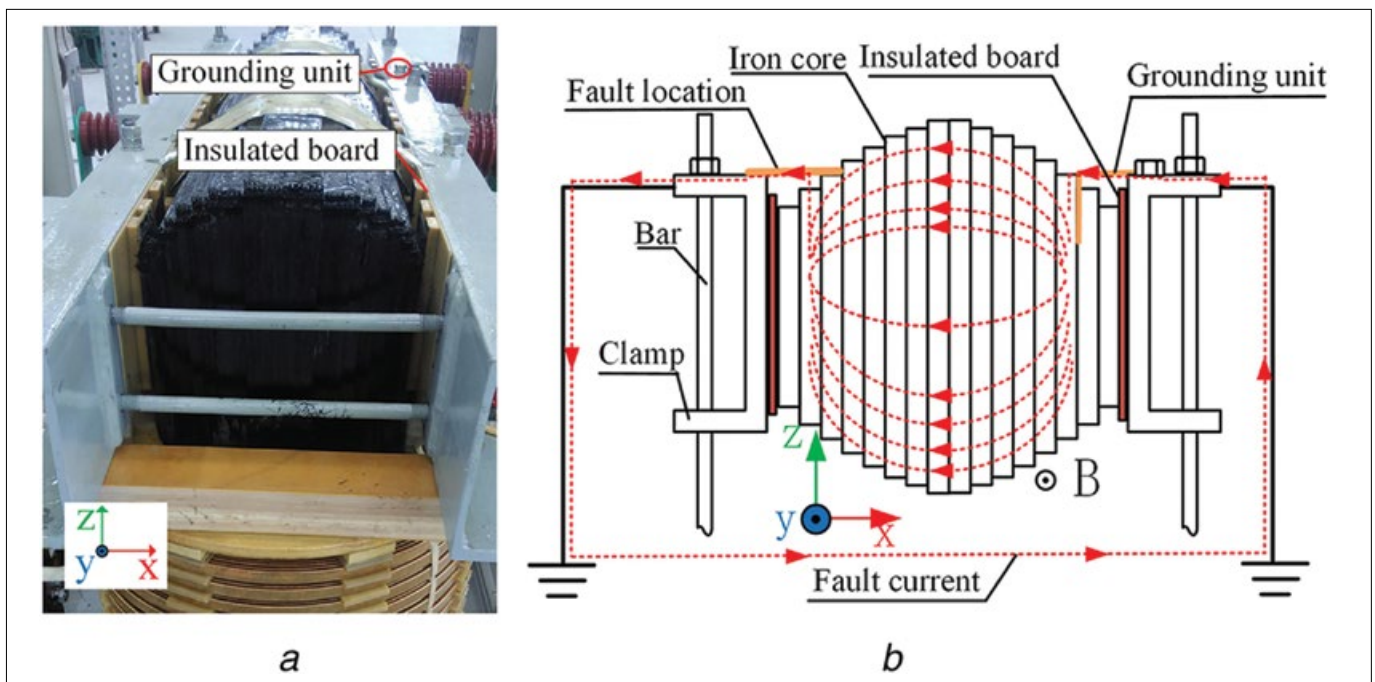


Figure 1. Side view of core grounding (a) and multipoint grounding diagram (b) [2]

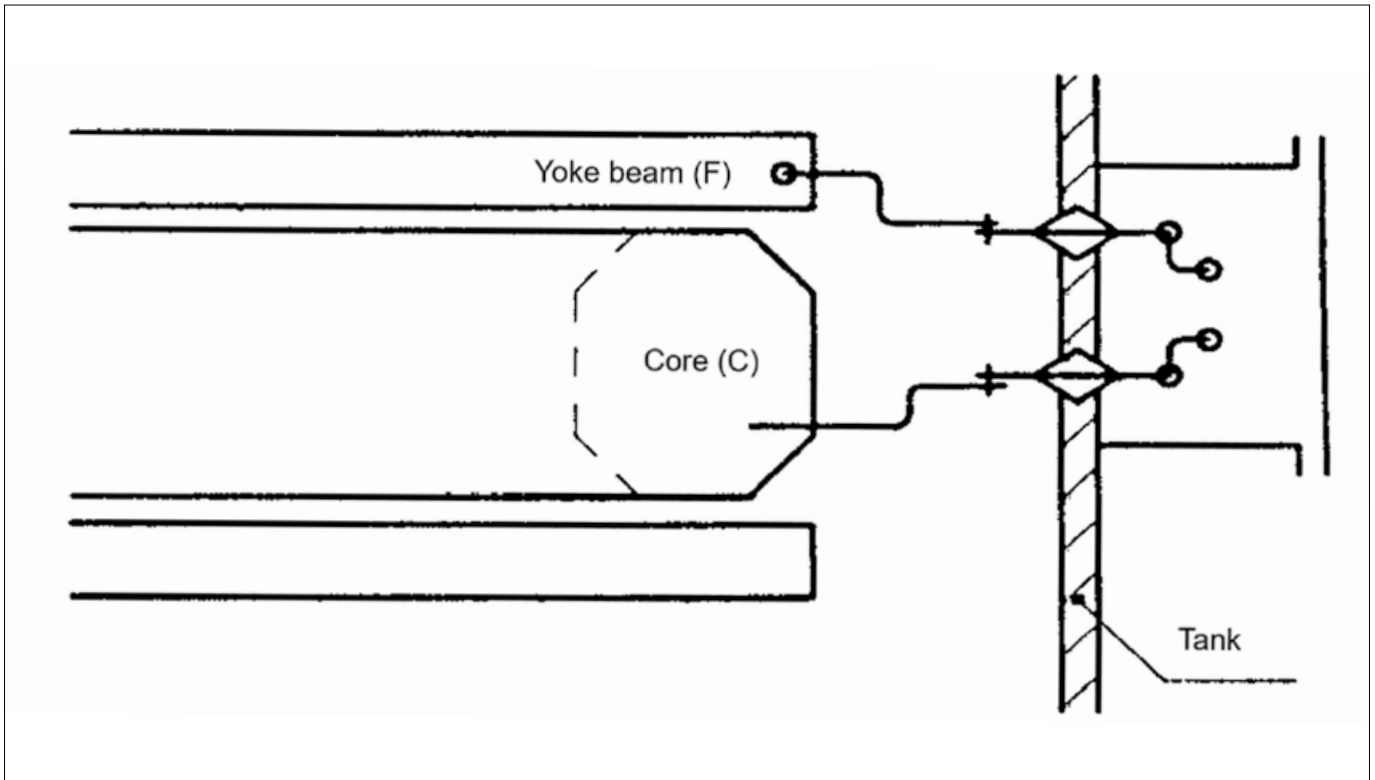


Figure 2. Parallel circuit of core and frame ground terminals to the outside of the tank.



Figure 3. Grounding output unit core and frame (view from inside the tank and on the tank cover)

In the last decade, especially in the Eastern Hemisphere, there has been a resurgence of transformer core grounding issues [2, 3, 4, etc.]. The IEEE Transformers Committee established a task force on Core Ground & Winding Insulation Resistance for the Dielectric Testing Subcommittee (DTSC), which was discontinued due to insufficient information to justify changes to the standards. We will examine some of these cases in more detail and hope that our article will help partially fill this gap.

3. Cases of faults in transformers

The primary causes of core failures can be attributed to various factors involving the design, manufacturing, transportation, and operation of transformers.

A Chinese manufacturer [4] points to the following reasons for core-ground

The insulation of the iron core is affected by moisture or damage, such as sedimentation of mud and moisture, which leads to a decrease in insulation resistance

faults of the transformers it produces: short circuits caused by poor construction technology and design of grounding strips; Multiple grounding points caused by attachments and external factors; grounding faults caused by metal foreign objects left inside the main transformer and rough iron core processes such as burrs, rust, welding slag, etc. There are six common types of iron core faults in transformers:

1) When installing, the iron core comes into contact with the shell or clamp. This situation is caused by negligence or inversion of the stabilizing pin used for

transportation on the fuel tank cover during disassembly, resulting in contact between the iron core and the shell. Other types include iron core clamps that come into contact with iron core columns, silicon steel sheet curled contact clamps, paper detachment between the lower clamp foot of the iron core and the iron yoke, and temperature gauge seat sleeves that are too long and come into contact with clamps, iron yokes, or iron core columns.

2) The steel seat sleeve of the through bolt is too long, causing a short circuit in the silicon steel sheet.



One of the bolts was installed on a beam surface that was not cleaned of paint, leading to micro discharges occurring at this location, causing paint and oil to burn

3) There is a foreign object inside the fuel tank, causing a local short circuit in the silicon steel sheet. For example, a screwdriver was found between the clamp and the iron yoke of a 31.5 MVA/110 kV power transformer at a power plant in Shanxi, and a 120 mm long copper wire was found during the hood inspection of

a 60 MVA/220 kV power transformer at another substation.

4) The insulation of the iron core is affected by moisture or damage, such as sedimentation of mud and moisture, which leads to a decrease in insulation resistance. The insulation of clamps, iron pads,

and iron boxes (paper or wooden blocks) may become damp or damaged, which can also form high-resistance multipoint grounding points inside the iron core.

5) The pump shaft bearing is worn, and metal powder enters the oil tank, accumulating at the bottom. Under the action of electromagnetic force, a bridge circuit is formed, which connects the lower rail with the pad or the bottom of the oil tank, resulting in multipoint grounding.

6) Poor operation and maintenance, failure to conduct regular inspections as planned.

The manufacturer [4], in section 3) refers to two instances of defects. However, other sections lack a detailed breakdown of the types of faults. As a result, we will attribute three faults to factory issues, one to transportation errors, and three to operational problems with the transformers.

Shkolnik from Israel graciously brought to our attention six instances of core grounding issues, some of which he has detailed in his publications [5, 6]. These cases will be examined in more detail below.

The authors also provide examples from their practice.

3.1 Manufacturing defects

CASE STUDY 1 (No. 1 by Shkolnik)

An insulated small wire with a tip was connected to the bottom metal core band. Due to poor crimping of the tip, the wire broke free from the tip. At the moment of rupture, a brief arc occurred, leading to the formation of C_2H_2 and other flammable gases. After a few days, the gas concentration in the operating transformer stabilized.

Method of detection: Comparing the measurement results with previously obtained values.

CASE STUDY 2 (No. 2 by Shkolnik)

The core was grounded to the internal grounding busbar with an uninsulated small wire. When the wire sagged, it touched the upper yoke of the core (Fig. 5). This resulted in a short circuit between the core sheets and the burning



Figure 4. The breakage of the grounding wire from the tip attached to the frame of the core [5]



Figure 5. The touch of no insulated wire to the core [5]

Table 1

Sampling date/Gas	H ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	CO	CO ₂
April 18, 2012	166	837	493	18	0	361	3626

of a portion of the wire (an open circuit in the grounding circuit).

Method of detection: DGA, PD measurement, capacitance measurement between the inner coil and the tank, and screening of other windings.

CASE STUDY 3 (No. 3 by Shkolnik)

During the FAT, the insulation resistance between the core and frame was measured. The factory manual specified 50 MOhm. Despite the lower measured value, the transformer was shipped to the customer. During the SAT, approximately 40 MOhm was measured in the morning and approximately 20 MOhm in the afternoon. A temperature dependence of the insulation resistance was evident. After requesting core drawings, a rubber plate was discovered between the core and frame. The factory installed a resistor inside the tank to limit the current and connected it to the ends of the grounding wires.

CASE STUDY 4 (No. 5 by Shkolnik)

Support legs riveted to the bottom of the frame with bolts. One of the bolts was installed on a beam surface that was not cleaned of paint. Micro discharges occurred at this location, causing paint and oil to burn, resulting in the formation of flammable gases.

A change in the active part’s position in the tank after transportation, in most cases, leads to a complete ground fault; less frequently, the frame-to-tank insulation resistance remains significantly reduced

CASE STUDY 5

The 26.67 MVA, 500 kV reactor manufactured by ABB SpA, Italy, with serial number 32976, installed at the Resistencia substation in Argentina, exhibited dissolved gas concentrations as detailed in Table 1.

One of the hot spots in the core, and the relative dissolved gas levels are shown in Figure 6.

The formation of localized hotspots was attributed to insufficient cooling channels within the core.

3.2 Displacement of the core during transportation

CASE STUDY 6 (No. 4 by Shkolnik)

During transportation of the transformer, sudden braking caused the active part to

shift, resulting in a short circuit between the insulated parts of the core. This was discovered during a visual inspection.

CASE STUDY 7 (No. 6 by Shkolnik)

One of the Frame support legs, with holes for the cylindrical bottom guides, touched each other due to the active part being displaced. The support legs were insulated from the tank bottom with cardboard spacers. Overheating occurred at the contact point, resulting in the formation of flammable gases.

CASE STUDY 8

Fig. 6 shows the inside view of two ZTZ autotransformers after transportation by three modes of transport (rail, river, and road), November 2012, Gorodskaya substation, Yakutia. Frame-to-tank insulation was zero megohms.

As ZTZ’s experience shows, a change in the active part’s position in the tank after

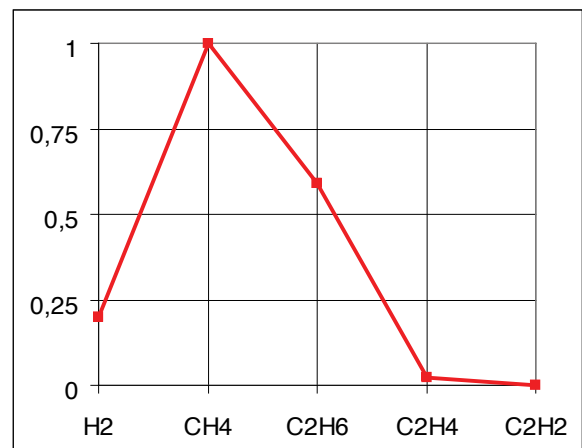
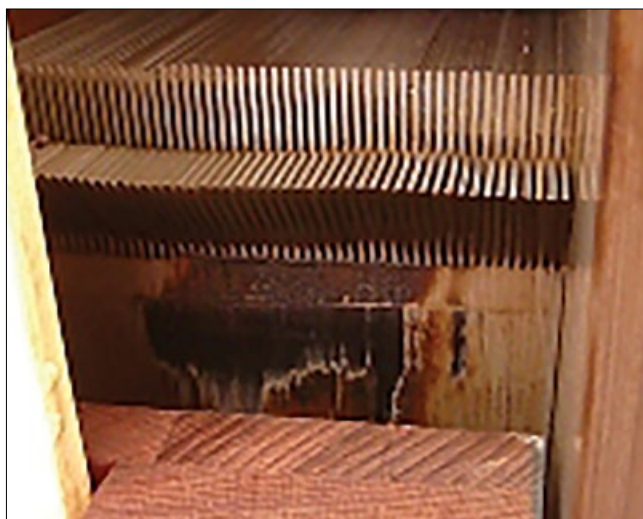


Figure 6. Hot spots in the core and relative dissolved gas levels in reactor 26.67 MVA

A retrospective review of the transformer's operational history suggested that the grounding bolt had likely loosened over time due to operational vibrations and eventually detached from its position

transportation in most cases leads to a complete ground fault; less frequently, the frame-to-tank insulation resistance remains significantly reduced. However, core-to-tank and core-to-frame insulation is generally maintained.

3.3 Failures during operation

CASE STUDY 9

This study examines unstable additional grounding faults detected in May 1992 in a 180 MVA, 220/110/6 kV ZTZ autotransformer used at the Abdurakhmanovo substation in Tatarstan. The study was

prompted by elevated DGA levels. The investigation, which included online and offline tests, revealed that the oil pumps bearings had worn out and metal powder had accumulated at the bottom of the tank. Under the influence of electromagnetic force, bridges formed connecting the lower surface of the magnetic circuit to the bottom of the tank, leading to multipoint unstable grounding. Sparking from the destruction of these bridges caused partial discharges with an intensity of 3-10 nC, detected by an acoustic partial discharge sensor at the bottom of the tank along the axis of the magnetic circuit.

CASE STUDY 10

In June 2000, one of the authors investigated a ground fault in the core of a 250 MVA, 400/110/31.5 kV autotransformer, manufactured by TRO, Berlin, and operating at the Tsarevets substation in Bulgaria. Six months earlier, periodic offline Dissolved Gas Analysis (DGA) tests had detected excessive gas emissions that surpassed previous records and were 2-3 times higher than standard limits. Monthly follow-up tests showed a progressive but non-critical rise in gas levels. The transformer was of the free-breathing type with an open conservator. To determine the cause of the DGA irregularity, several electrical tests were carried out. These included measurements of no-load losses at low voltage (as per GOST), winding impedance, TTR, insulation resistance, DC winding resistance, and capacitance and dissipation factor (C and tg δ). All results were within acceptable limits, except for a significant decrease in the internal winding's capacitance relative to ground



Figure 7. Active part displacement of 63 MVA, 220/110 kV autotransformers cover

Table 2. Dissolved gases in oil and trend of gas generation by [3]

Sample	H ₂	O ₂	N ₂	CH ₄	C ₂ H ₄	C ₂ H ₆	C ₂ H ₂	CO ₂	CO	Remarks
Sept 2008	2	6683	16906	32	1	19	nil	3052	260	
August 2010	3	2962	24617	42	2	30	nil	3102	235	
June 2011	25	3452	25542	44	24	31	2	2938	92	
July 2013	152	4492	15712	605	1000	130	2	1192	80	Unit taken out from service
Sept 2013	157	4029	14831	609	1001	131	2	1199	88	
March 2014	5	4506	12832	5	7	1	0	62	4	Degassing after internal inspection
April 2014	41	5685	18721	178	225	31	0	249	28	
May 2014	41	4496	19637	156	233	34	1	247	32	

compared to previous measurements. This deviation was a clear indication that the core was not short-circuited to ground. The oil was drained, and a person entered the transformer tank. Unfortunately, he was unable to reach the core grounding point. A temporary grounding connection was established at the top of the tank, after which all subsequent measurement values normalized. This temporary grounding solution was later made permanent. A month of monitoring post-repair showed DGA values stabilizing at nearly zero, with no further increases. The transformer continued operating without any additional issues. A retrospective review of the transformer's operational history suggested that the grounding bolt had likely loosened over time due to operational vibrations

and eventually detached from its position. It is possible that previous strong short circuits in the system contributed to this.

CASE STUDY 11

In [3], an example is provided illustrating a multiple grounding issue in a single-phase autotransformer (AT) with a capacity of 167 MVA and specifications of 400/√3/220/√3/33. This problem was

identified using DGA. Initially, starting in 1992, the AT served as a backup unit and was only rarely loaded. Subsequently, gas was emitted from the transformer, as detailed in Table 2.

The AT was sent to the repair center, and during the lifting of the core, several areas of significant overheating were identified, some of which are visible in Fig. 7.

After careful analysis, it was concluded that a break in the core-to-ground circuit was the primary cause of the transformer failure

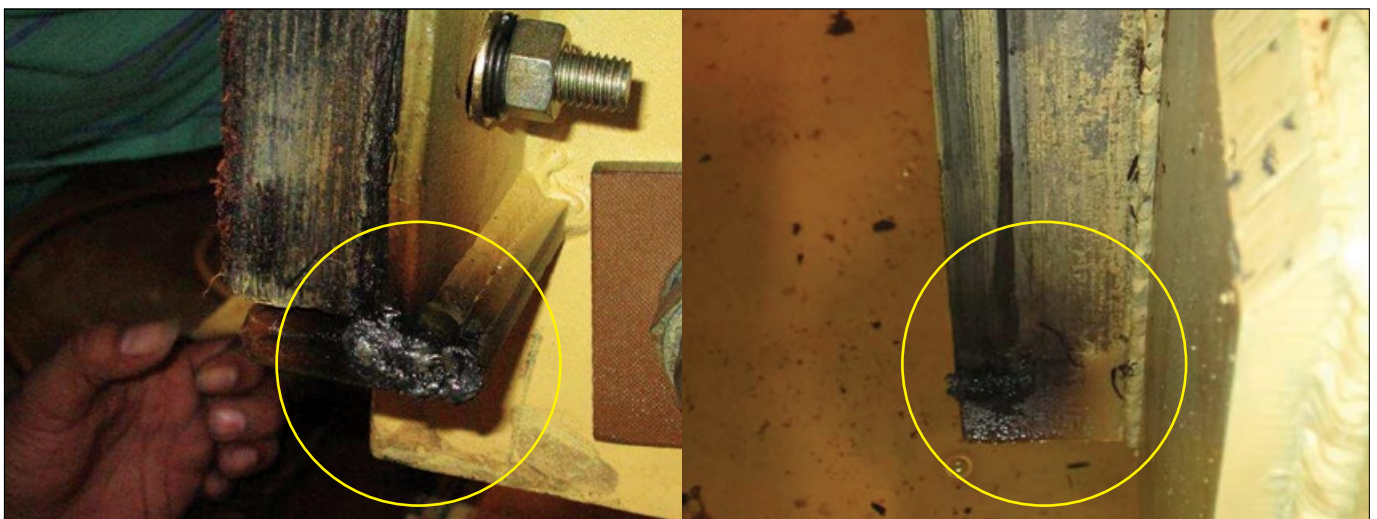


Figure 8. Overheating was observed in the core frame and locking plate of the 167 MVA autotransformer [3].

Of the 17 core failures examined, 12 were identified as run-in failures associated with newly manufactured transformers originating from an expanding number of emerging production facility

CASE STUDY 12 [7]

In a 15.75 kV/400 kV, (3x94) MVA, three-phase GSU transformer used at the MS Hydro Power Plant, Iran (commissioned in 2002), the DGA exceeded the threshold values of flammable gases, established by IEEE C57.104 – 2019. Therefore, power factor, excitation current, transformer turns ratio (TTR), DC winding resistance, and DFR tests were performed. All results, with the exception of the DFR test, yielded no observable remarks.

The oil was drained, and the transformer was disassembled. A comprehensive vi-

sual inspection revealed several defects: light arcing marks were present on the end portion of the core laminations, near the bottom of the transformer; the core's contact with the grounding element was unreliable, with signs of severe oxidation, as shown in Fig. 8. After careful analysis, it was concluded that a break in the core-to-ground circuit was the primary cause of the transformer failure.

CASE STUDY 13: «Fire» in Steel

A ZTZ 120 MVA, 330/110/35 autotransformer, serial number 72258, produced in 1967, and worked at the Sumy-330

substation in Ukraine, showed a notable rise in dissolved gas concentrations, as outlined in Table 3. The relative dissolved gas levels are illustrated in Fig. 10.

Upon disassembly, severe overheating was discovered at the ends of the upper and lower yokes of the core, evident from the black discoloration and traces of oil decomposition products.

Subsequent parts of the article will provide a more in-depth analysis of approaches for identifying core defects, the criteria for their rejection, and strategies for their remediation, while also discussing ZTZ's expertise in these areas. At this stage, however, several preliminary conclusions can be outlined.

Conclusions

1. An analysis of failure cases shows that manufacturers use various core grounding designs, each with varying

Table 3.

Sampling date/ Gas	H ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂
May 5, 2005	Отс.	14	10	15	None.
October 19, 2007	230	490	200	900	5



Figure 9. Severe oxidation on the core-ground connection, resulting in poor contact by [7].

reliability. It is strongly recommended to develop a standardized core grounding design for transformers, especially for transformers rated at 10 MVA and above, within the IEC standard. In our opinion, the best option is to locate the core and flame leads in a separate box on the tank cover.

2. Of the 17 core failures examined, 12 were identified as run-in failures associated with newly manufactured transformers originating from an expanding number of emerging production facility.

3. Active part displacement within the tank during transportation often leads to frame-to-ground faults. Despite this, the insulation between the core and tank, as well as between the core and frame, generally remains unaffected.

4. Additional research on transformer core damage is advised, with an emphasis on enlarging the existing dataset.

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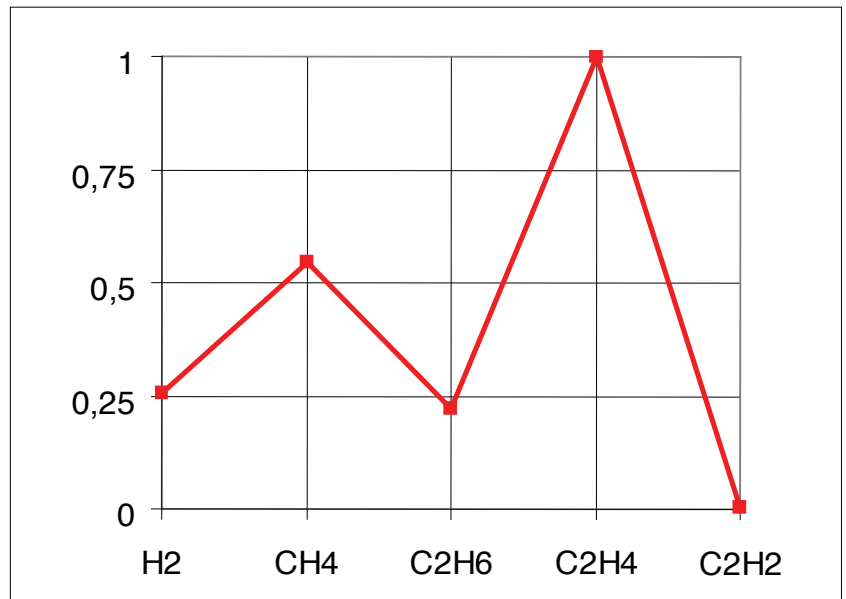


Figure 10. Relative level of dissolved gases in AT 120 MVA

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Authors



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Oleg Svrydenko, with over 24 years of expertise in the transformer industry, previously led the field repair and damage investigation department at the Zaporizhzhya Transformer Plant in Ukraine. He is now part of the service department at the International BEZ Group, which oversees transformer plants in several countries: ETD Transformers (Power Transformers) in Plzeň, Czech Republic; BEZ Transformers (Distribution Transformers) in Bratislava, Slovakia; and Elprom Heavy Industries (Power Transformers and Tap Changers) in Sofia, Bulgaria. Oleg possesses extensive international experience in installation, complex field repairs, diagnostics, and investigations into the causes of damage to power transformers up to 765 kV.