CIGRE-346
2020 CIGRE Canada Conference
Toronto, Ontario, October 19-22, 2020

Advanced Power Transformer Diagnostics – Detection of Core-Ground Issues

ALI NADERIAN JAHROMI[1], PRANAV PATTABI[1], JAFAR MOHAMMADI[1], MOHSEN TANGSIRI[2]
[1]METSCO Energy Solutions, Canada
[2]MS Hydro Power Plant, Iran

SUMMARY

The typical construction of a power transformer results in a high potential being induced in the core, due to the electromagnetic coupling that exists between the core and winding assembly. The transformer core is normally grounded at a single point, to safely divert this induced voltage to the local ground. The core-ground connection also provides a low-resistance path under a short circuit scenario between the transformer winding and core. This allows for the reliable operation of the associated transformer protection relay unit.

The isolation of core from ground forms an integral part of the transformer's insulation system. The core-ground connection must be accessible and further removable for testing. Any issue with the transformer core-ground connection can result in improper grounding, the presence of multiple ground paths, unintentional core-grounds, and a floated core. Multiple core-grounds are created when the core comes into direct contact with the grounded internal metallic structure of a power transformer. Based on the value of the core-to-ground resistance, sustained heating effects can be caused by circulating currents that can eventually result in the melting of the transformer core.

This paper outlines the use of diagnostic procedures such as Dissolved Gas Analysis (DGA) and Duval's Pentagon, Dielectric Frequency Response (DFR) testing, and core-to-ground resistance testing for identifying core-ground defects in power transformers. In this regard, it presents two practical scenarios observed in (i) a 15.75/400 kV, three single-phase (3x94) MVA generating station step-up (GSU) power transformer, and (ii) a 450/600/750 MVA, 500/240/28 kV, 3-phase autotransformer. A practical guideline is also developed for utilities, to identify and proactively respond to core-ground issues in power transformers. Timely intervention through proper diagnostics helps in the early detection of core-ground issues, thereby avoiding the catastrophic failure of transformers and translating to significant savings for utilities.

KEYWORDS

Power transformers, core-ground, dielectric frequency response (DFR), dissolved gas analysis (DGA), circulating currents, transformer grounding, transformer diagnostics, condition assessment.

[1] ali.naderian@metsco.ca

INTRODUCTION

The power transformer core is a critical component that ensures the proper linkage of magnetic flux between the transformer's primary and secondary windings. Transformer cores are typically designated as shell-form or core-form types [1]. The core is electrically isolated from metallic surfaces such as the transformer tank. The operation of a power transformer results in a significant induced potential on the core assembly. Therefore, power transformers are typically provided with a single-point ground from the core, which is essential for ensuring the integrity of the transformer's insulation system.

Though the core/winding assembly is insulated from the rest of the transformer, certain situations can lead to the core coming in direct contact with the transformer tank. This leads to the creation of an additional unintentional core-ground, which is undesirable. The additional unintentional core-ground creates a closed-loop path for circulating currents to be produced within the transformer core [2]. Depending on the condition, such circulating currents can create extreme heating effects within the core, generating dissolved gases, and resulting in the burning of the insulation or melting of the metallic component [2].

Core-ground issues are often difficult to detect and can be easily masked by other defects associated with transformers. There is also a lack of an established industry guideline or emphasis on this topic. In this background, this paper is aimed at developing a practical framework for identifying the presence of a core-ground defect in power transformers. Accordingly, two case studies are presented to highlight the relevant diagnostic tests that can be used, alongside guidance on the interpretation of the corresponding results.

AC SYSTEM GROUNDING

The process of grounding AC systems generally involves connecting the neutral to the ground through a grounding device. Source transformers and generators with Y-connected windings provide a readily available neutral connection in three-phase AC systems. Different types of impedances can be used as the grounding device to connect the system neutral to the ground. The ultimate choice of the grounding medium falls under five main categories: ungrounded, solidly grounded, resistance grounded, reactance grounded, and resonant grounded systems [3]-[5].

In an ungrounded system, the conductors are intentionally not connected to the ground. However, any ungrounded system is in fact capacitance grounded due to the presence of stray capacitances. The use of an ungrounded system is not recommended due to the excessive transient overvoltages under line-to-ground (LG) faults which can result in transformer failure, due to the breakdown of the insulation system [3]-[5]. In a solidly grounded system, the neutral, which can be obtained from a generator, power transformer, or grounding transformer, is grounded without an intentionally inserted impedance [3]-[5].

In resistance and reactance grounded systems, the neutral is grounded by a resistor or a reactor respectively. These can be either high or low resistance/reactance grounded, based on the corresponding LG fault current ratio [3]-[5]. A low resistance/reactance grounded system limits the LG fault current ratio to less than 25 %, typically with a magnitude in the range of 100 A to 1000 A [3]-[5]. In a resonant grounded system, the reactor is specially designed to resonate with the system stray capacitance, so that the LG fault current is negligent and in-phase with the LG voltage [3]-[5].

In the absence of Y-connected windings, a neutral point can be obtained using a grounding transformer, e.g., zigzag, and Y-Δ type transformers [3]-[5]. The characteristics, system impacts, and applications of different AC system grounding strategies are comprehensively reviewed in [6]. One common issue observed in transformers is the defective or poor contact between the neutral bushing and ground due to corrosion on pads or bolts, loose connections, oxidation, and a change in impedance. Aside from the neutral grounding, transformers require a reliable grounding of the tank, bushing, core, and other accessories, for ensuring a safe operating condition.

CORE-GROUND ISSUE: RELEVANT DIAGNOSTIC TESTS

The presence of an additional unintentional core-ground in power transformers can be detected through the Dissolved Gas Analysis (DGA). An increasing trend of hot metal gases – ethane (C_2H_6), ethylene (C_2H_4), and methane (CH_4) is indicative of a possible core-ground issue, resulting in the overheating of the transformer core [7]. It is also useful to verify the concentration of carbon oxides (CO_2 and CO), to determine if the core overheating involves the solid insulation of the transformer. Based on the combustible gas levels obtained from the DGA, it is recommended to use the Duval's Pentagon to identify the relevant fault zone. A thorough inspection of the transformer in subsequent stages can help localize the fault type associated with the relevant fault zone identified (e.g. sparking from core to ground associated with zone D1 (Discharges of Low Energy) of the Duval's Pentagon) [8].

Dielectric Frequency Response (DFR) testing is an advanced diagnostic technique to determine the condition of a transformer's insulation system, based on wide-band frequency sweep. The primary application of this procedure is to determine the moisture content in the transformer's solid insulation [9], [10]. However, it has been established in [10] that DFR can be used to detect a variety of non-moisture related issues in power transformers. The DFR test can be used to identify the high core-grounding resistance issues in power transformers. High dissipation factor values can be caused by the presence of a significant resistance between the transformer core and the grounding strap [11].

The most common test to perform upon suspecting a core-ground issue is a core-to-ground test. This is an offline test that involves disconnecting the intentional core-ground connection [7]. The disconnection process is convenient in situations where the core-ground is brought outside through insulated bushings, but more challenging when located inside the transformer [7]. A 500 V DC megohmmeter is used to apply a DC voltage between the transformer tank that acts as the ground and the core (usually the top of the core or the core-ground lead), and the resultant insulation resistance is measured [7]. A core-to-ground resistance value of less than 100 MΩ is indicative of core-ground issues in service-aged power transformers [7].

CASE STUDY 1

The first case study deals with the neutral-ground and core-ground issues identified in a 15.75 kV/400 kV, three single-phase (3x94) MVA generating station step-up (GSU) power transformer used in a hydroelectric power plant. Periodic offline DGA testing revealed excessive hot metal gases being generated in the transformer compared to the thresholds defined by the IEEE Std. C57.104 - 2019, as shown in Figure 1. Also, hydrogen (H_2) and acetylene (C_2H_2) gases were found to be quite high.

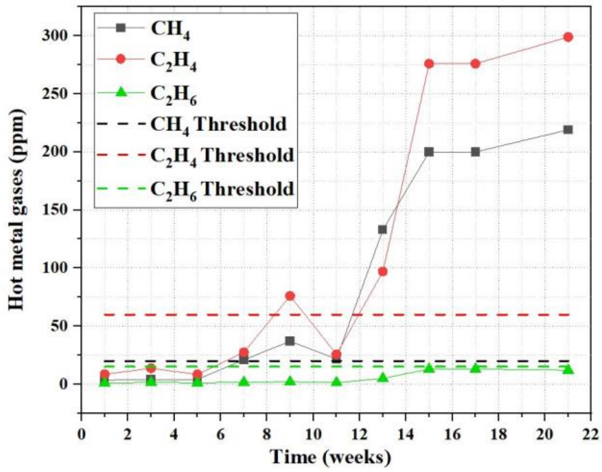

Figure 1: Concentration of hot metal gases generated over 22 weeks

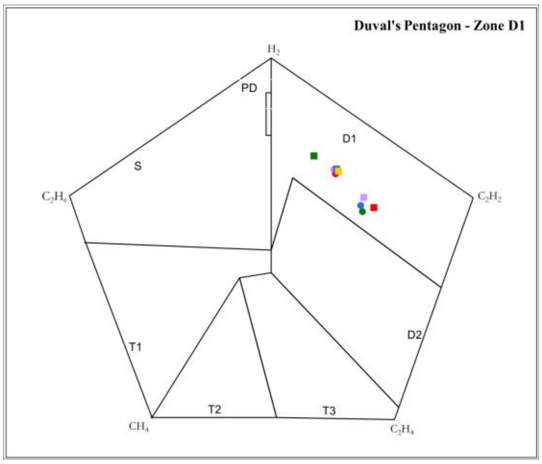

Figure 2: Low energy discharges predicted by the Duval's Pentagon over the 22-week period

Figure 2 shows the Duval's Pentagon developed for this scenario, indicating the presence of low energy discharges within the transformer (Zone D1). With potential overheating indicated by the DGA, several electrical tests such as power factor, excitation current, transformer turns ratio (TTR), and DC winding resistance were carried out and the results were found to be acceptable.

DFR testing was also carried out on the transformer. The DFR test result indicated a spike in the dissipation factor values at higher frequencies (100 Hz - 1000 Hz), as can be seen in Figure 3. The subsequent analysis also yielded the bulk moisture content to be 0.3 %, eliminating the insulation moisture content as a potential root cause.

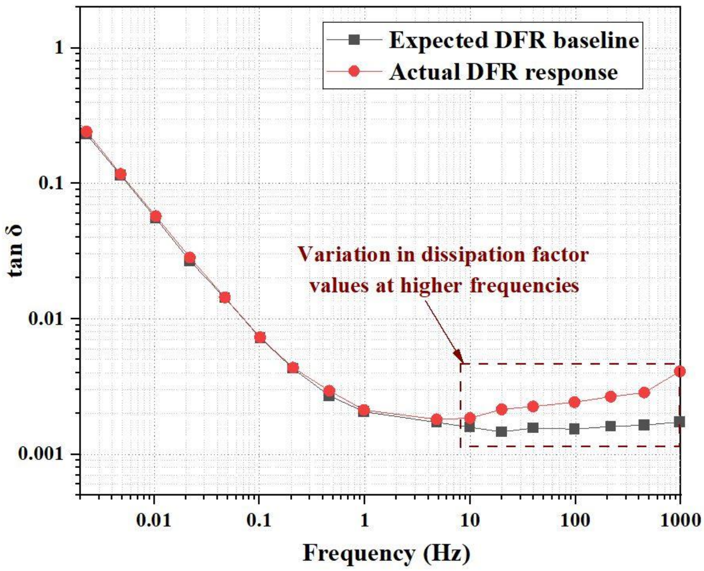

Figure 3: DFR test result, indicating increased dissipation factor values at higher frequencies

The DGA and DFR results indicated some serious overheating issue, involving the core-ground. The core was brought as a separate bushing in this transformer. With the extensive production of combustible gases, the oil was drained out, the transformer disassembled, and a comprehensive visual inspection was performed in the problematic phase of the transformer bank.

Several defects were identified during the visual inspection process. It was observed that the tip of the core sheets towards the bottom of the transformer had light arc stains. Upon inspecting the core-ground connection, the contact was found to be insufficient with signs of severe oxidation, as shown in Figure 4.

Figure 4: Severe oxidation on the core-ground connection, resulting in poor contact

A drop in the concentration of elemental sulfur in transformer oil can result in the formation of corrosive sulfur. Corrosive sulfur dissolves copper in oil at high temperatures and oil-soluble copper molecules can cause the insulating transformer oil to become conductive. The effects of this phenomenon were visible on the paper insulation and in some parts of the high voltage (HV) winding of the isolated phase of the disassembled transformer unit, as shown in Figure 5.

Black deposits on the insulation supports | Signs of PD between discs | Black deposits of Corrosive Sulfur

Figure 5: Presence of corrosive sulfur in the solid insulation and HV windings of the problematic phase

Based on the observations, it was concluded that the discontinuity of the core-ground circuit, with the corresponding oxidation of copper and the presence of corrosive sulfur, were the major reasons behind the overheating and formation of hot metal gases in the transformer.

CASE STUDY 2

In transformers, a core-ground resistor can be added in series with the core-grounding strap to limit the overall current flow through the core-ground [12]. If this resistor is not shorted during the DFR testing, it can result in high dissipation factor values being measured, specifically at higher frequencies [11]. The second case study deals with the use of DFR testing for insulation condition assessment in a 450/600/750 MVA, 500/240/28 kV, 3-phase autotransformer.

Figure 6 shows the DFR test result obtained from the transformer under two scenarios, with the core-ground resistor being shorted and not shorted. Upon analyzing the DFR response, it can be concluded that the effect of the core-ground resistor is discernible at higher frequencies (including the power frequency) while being non-existent at the lower frequencies.

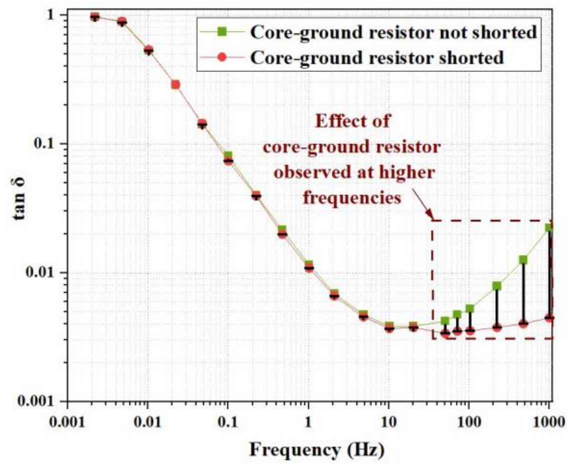

Figure 6: DFR test result, indicating the effect of a core-ground resistor at higher frequencies

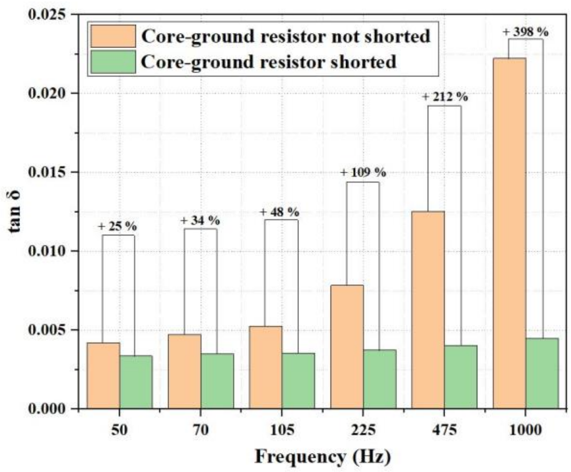

Figure 7: Difference in the dissipation factor values observed at higher frequencies

From Figure 7 it can be seen that the difference in the dissipation factor values measured under the two scenarios varies from 25 % (at 50 Hz) to almost 400 % (at 1000 Hz). This relative change is quite significant and the increased dissipation factor values obtained during DFR testing can be easily misinterpreted because of high insulation moisture content if the core-ground resistor is not shorted prior to the test. The misdiagnosis can have severe implications since it might result in an unnecessary drying of a transformer in an actual good condition.

DISCUSSIONS

One of the major outcomes of this paper is to highlight the importance of grounding in power transformers, including the integrity of the core-ground connection. Utilities typically perform periodic routine maintenance testing every year, including the core-to-ground insulation resistance test by applying 500 V/1 min between the core to ground. The frequency of this testing can be increased if DGA and DFR tests suggest possible core-ground defects.

Ideally, the core-to-ground resistance measured during the core-to-ground test must be high. The recommended core-to-ground resistance value of a service-aged power transformer is above 200 MΩ. However, due to the aging of the core insulation supports, the core-to-ground resistance value can be found to be lower. Table 1 shows the proposed recommendations for service-aged power transformers, based on the corresponding core-to-ground resistance value measured.

Table 1: Proposed recommendations for service-aged power transformers using the core-to-ground resistance test results, based on [2],[7]

Core-to-ground resistance – R_{CG} (MΩ)	Recommendation
$R_{CG}>200$	Acceptable
$100 \leq R_{CG} \leq 200$	Probable core-ground. Additional investigation advised
$10 < R_{CG} < 100$	Definite additional core-ground. Timely intervention required
$0 \leq R_{CG} \leq 10$	Severe core-ground issue. Immediate intervention required

When the measured core-to-ground resistance falls within 100 MΩ, it is indicative of high impedance (additional core-ground) that must be cleared. The process of locating the additional unintentional core-ground can be extremely difficult and requires utmost care and expertise if an inspection is to be carried out. This process is also very expensive and cumbersome as it requires the transformer oil to be completely drained out.

Specific to the core-ground issue, it is important to monitor the trend of dissolved gases in oil, specifically ethane, ethylene, and methane. An increasing trend of these hot metal gases is a flag, and a DFR test must be performed on the transformer. From the DFR test result, it is necessary to check if increased dissipation factor values are observed at higher frequencies when compared to the baseline DFR curve obtained during factory acceptance testing (FAT). It is equally important to consider the nature of the intentional core-ground present in the transformer, and the value of insulation moisture content determined, to avoid any misdiagnosis. Aside from the insulation moisture content, several other issues such as poor oil quality, contamination, and corrosive sulfur can affect the DFR test result. Therefore, a comprehensive analysis is required by combining different diagnostic test results, towards identifying the root cause behind the abnormal gassing observed.

There are a few action items that can be implemented in response to core-ground issues in power transformers, depending on the situation. However, these require a thorough understanding of the possible source of the unintentional core-ground observed in the transformer. In cases where an additional core-ground is suspected to be created due to any form of mechanical disturbance, it is recommended to move the existing intentional core-ground to a new location [2]. When a severe core-ground issue is detected ($0\ M\Omega \leq R_{CG} \leq 10\ M\Omega$), one remedial action is to install a resistor between the transformer core and the tank, to reduce the flow of circulating currents within the transformer [2]. As a final option, the unintentional core-ground can be eliminated by impressing around 40 – 50 A, using an AC or a DC current source, upon careful consultation with the manufacturer [7].

CONCLUSIONS

The transformer core-ground is crucial in preventing any undesirable potential rise within the transformer. The normal practice is to maintain a single point of grounding the transformer core, called the intentional core-ground. Mechanical disturbances to the transformer core assembly can result in the creation of unintentional core-grounds. A disconnect in the core-ground circuit due to oxidation of the connection can also create core-ground issues in transformers, as revealed in case study 1 of this paper.

Some useful diagnostic procedures help identify core-ground defects in power transformers. The core-to-ground insulation resistance test is the major indicator of a possible core-ground issue. DGA can confirm this issue if hot metal gases are generated in excess. Duval's Pentagon helps identify the nature of the fault within the transformer, based on the relative proportion of the combustible gases formed. DFR is another useful technique that can be used to detect internal core-ground issues, based on the dielectric frequency response observed at higher frequencies.

This paper offers practical examples for utilities towards identifying core-ground defects in power transformers. The core-to-ground resistance value can be used to implement a relevant response plan, as shown in Table 1. The relevant course of action is also contingent on the relative magnitude, the trend of combustible gases generated, and the nature of the core-ground issue suspected. In the case of unintentional core-grounds, it is advisable to consult with the transformer manufacturer before implementing a potential solution.

Periodic maintenance testing is of immense importance since it reveals any imminent threats to the expected useful life of a power transformer. Utilities typically perform the core-to-ground resistance test and DGA periodically. Besides, it is highly recommended that utilities perform DFR as a routine maintenance test to detect the presence of high moisture, contamination, corrosive sulfur, as well as internal core-to-ground defects in transformers. In certain critical transformer units, it is very beneficial to install online DGA monitors.

The relative success of a maintenance program is governed by the record-keeping practice of utilities, which is important for future trending and condition assessment. Maintaining a comprehensive database ensures the continued reliable operation of in-service transformers and the timely identification of serious defects such as core-ground issues.

BIBLIOGRAPHY

[1] "IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors," IEEE Std C57.152-2013, pp.1-121, 2013.

[2] J.White, "TRANSFORMER CORE GROUNDS A different path to maintaining insulation systems, " in Electricity Today, vol. 26, no. 6, July-August 2013.

[3] "Recommended practice for grounding of industrial and commercial power systems, " IEEE Std. 142-2007 (Revision of IEEE Std. 142-1991), pp.1-225, 2007.

[4] "Guide for the application of neutral grounding electrical utility systems-part I: Introduction, " IEEE Std. C62.92.1-2016 (Revision of IEEE Std.C62.92.1-2000), pp.1-38, 2017.

[5] "Guide for the application of neutral grounding electrical utility systems-part IV: Distribution, " IEEE Std. C62.92.4-2014 (Revision of IEEE Std. C62.92.4-1991), pp.1-44, 2015.

[6] J. Mohammadi, F. B. Ajaei and G. Stevens, "AC microgrid grounding strategies," IEEE/IAS 54th Industrial and Commercial Power Systems Technical Conference (I&CPS), Niagara Falls, ON, Canada, 2018, pp. 1-7, 2018.

[7] "Transformer Maintenance, " FIST 3-30, United States Department of the Interior Bureau of Reclamation, Oct. 2000.

[8] M. Duval and A. dePabla, "Interpretation of gas-in-oil analysis using new IEC publication 60599 and IEC TC 10 databases," in IEEE Electrical Insulation Magazine, vol. 17, no. 2, pp. 31-41, March-April 2001.

[9] G. Frimpong, U. Gafvert, M. Perkins and A. Fazlagic, " Estimation of Moisture in Cellulose and Oil Quality of Transformer Insulation Using Dielectric Response Measurements," in Proc. of the International Conference of Doble Clients, sec. 8-10, 2001.

[10] "IEEE Guide for Dielectric Frequency Response Test, " IEEE Std. C57.161, 2018.

[11] M. Perkins, A. Fazlagic and G. Frimpong, "Dielectric frequency response measurement as a tool for troubleshooting insulation power factor problems," Conference Record of the 2002 IEEE International Symposium on Electrical Insulation (Cat. No.02CH37316), Boston, MA, USA, pp. 162-165, 2002.

[12] N.W. Hansen, "Power Factor and Capacitance Measurement of Transformer Core Insulation," in Proc. of the 61st Annual International Conference of Doble Clients sec. 8-7, 1994.