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Assessment of Techniques for Diagnostic Tests and Maintenance of Power Transformers

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Abstract

Power transformers play an essential role in the transmission, distribution and utilization of electrical energy. Ensuring their correct operation and extending their life span is of paramount importance for distribution and transmission system operators. This paper presents an assessment of techniques for diagnostic tests and maintenance in power transformers. The main components, accessories and protections of transformers are explained. Also, the main maintenance activities as well as diagnostic tests and their acceptance criteria are explained and detailed according to international standards.

Keywords: Power transformers, diagnostic tests, maintenance

1 Introduction

Power transformers are mainly used as a link between generation and transmission systems, as well as transmission and distribution networks to finally reach final electricity consumers. In transmission systems, the main function of a transformer consists on increasing voltage magnitudes in order to transport electricity over long distances. This is possible due to the reduction of current magnitudes on transmission lines, which also reduces power losses [1]. In distribution systems, power transformers are commonly used to decrease voltage magnitudes up to operational levels suitable for electric devices in industries.

Transformers can also be used for improving power quality [2], controlling phase angles [3] starting motors [4] and filtering harmonics [5].
The core of a transformer is responsible for conducting the magnetic flux connecting the primary and secondary winding. This is built from steel sheets in silicon with thicknesses between 0.28 and 0.35 mm. The grain is oriented in the direction of magnetization to avoid losses by magnetization currents; this material has estimated losses between 0.4 to 0.6 W/kg. Figure 1 depicts the assembly process of a core.

Figure 1. Ferromagnetic core lamination.

The core of the transformer comprises the electric circuit and permits the circulation of the current which generates the magnetic flux in the primary and the secondary current that flows towards the load. The coils are made of wire or a strip of copper or aluminum. In distribution and low power transformers, insulated conductors are used in dielectric enamels and varnishes and in power transformers copper plates are insulated with thermo stabilized Kraft paper. Figure 2 shows the process of making a coil. The Presspan fibers and the stringers are the main elements of the insulation system.
The active part of the transformer is submerged in dielectric oil in a tank and it is complemented by accessories and their own protectors to guard against overpressure, high temperatures, turbulent flows or air in the oil. Figure 3 depicts the active part of a typical power transformer.

Figure. 2. Coil construction

Figure 3. Transformer active part

The main accessories of a transformer include:

- Expansion tank: permits volume changes due to temperature variations.
- On Load Tap Changer (OLTC): permits on load voltage regulation. Tap changers are usually installed in the high voltage winding.
- Bushings: permit the connection of the coils to the outside.
- Radiators or heat exchangers: permit natural cooling.
- Fans: Increase cooling by forcing air through the radiators.

Figure 4 shows a typical power transformer in Colombia, during routine testing. Due to the large number of transformers installed in the electrical power system, most companies are interested in knowing the actual state of these transformers by evaluating the condition of their insulation, coils and dielectric oil, to define when to perform maintenance and to therefore extend their useful life and maximize their in-service time.

Figure 4. Typical power transformer 115 / 13.8 kV

There are different ways transformers can deteriorate and this depends largely on the operating conditions to which they are exposed during use. This includes electrical and mechanical overloads associated with the frequency of current failure, and surges caused by testing or atmospheric discharges. For these reasons, it is important to thoroughly evaluate the condition of the transformer, by periodically carrying out electrical tests such as physicochemical analysis of the liquid insulation to assess the progress of the deterioration in the equipment. This paper describes the main maintenance activities that must be carried out in power transformers as well as the diagnostic tests and their acceptance criteria.

2 Maintenance activities

There are several maintenance activities that must be carried out to guarantee the proper operation of power transformers. These are described as follows.

2.1 Visual inspection

Consists of a thorough inspection to check if there are any faults in the equipment. These include: oil leaks, misaligned parts, damaged paint, corrosion or defects in supporting structures, also the condition of the insulator bells and the oil level in capacitive bushings. The correct functioning of the cooling system (fans and pumps) and the ventilation system must also be checked.
In addition, some readings are taken such as temperature records using thermal imaging and the oil thermometer to verify that the transformer has not suffered any significant temperature increase.

2.2 Thermographic inspection

Permits detecting of hot spots, loose connections, currents circulating through the tank, defects in the cooling system (counter rotating pumps, fans rotating in reverse, etc.) and short circuits in magnetic shields in the walls of some transformers. It is also possible to detect low oil levels in oil-insulated bushings when they lose their tightness and oil flows into the tank.

2.3 Oil analysis

The dielectric oil isolates electrically the windings, dissipates the heat and prevents corrosion of the metal parts. In general, the oil characteristics are:

- High dielectric strength to resist electrical stresses, and extinguish arches and discharges in their interior.
- Low viscosity to circulate and dissipate heat.
- Aging resistance that guarantee long life.

Oil degradation is caused by operational conditions such as operation at high temperatures, contact with air, water, metal parts in iron such as core presses, screws and contact with copper present in terminals and conductors. The main symptoms of oil degradation are darkening, generation of polar substances, acid formation, sludge precipitation and reduction of the dielectric properties.

Physicochemical analysis: To determine the state oil state, physicochemical analyzes should be done at least once a year. These analyzes allow the evaluation of some variables associated with the oil condition such as moisture content, acidity, surface tension, concentration of furanic compounds (by-products of paper degradation), dielectric strength and oil power factor. Table 1 shows the basic acceptance criteria and the normal state for the physicochemical analyzes in dielectric oil.

Table 1. Physicochemical analysis standards

Test	Standards	Acceptance Criterion
Dielectric Strength	ASTMD 1816-04 NTC 3218 - 1991 ASTM-D 877 - 00	> 40 kV
Power Factor	ASTMD 924-99e1	< 0.05 New < 0.08 Used
Colorimeter Index	ASTMD 1500-98	> 0.5 y <3
Interfacial Voltage	ASTMD 971-99a ASTMD-2285-99	> 22
Neutralization number	ASTMD 974-01	< 0.11
Moisture Content	ASTMD 1533-00	< 25
PCB’s	ASTM D- 4059	< 50 ppm
Corrosive Sulfur	ASTMD 1275	Less than 2b

Dissolved gas analysis (DGA): This is carried out in a certified laboratory using the methodology of analysis of gases dissolved by chromatography. Such procedure permits the detection of internal arcs, bad electrical contacts, hot spots, partial discharges and overheating of conductors.
These gases must be analyzed over time, since the older the transformer, the more gases are present; however if there is an over increment of gases this indicates an incipient fault in the transformer. Table 2 shows the regulations for the analysis of dissolved gases by gas chromatography and the acceptable values for power transformers [6], [7].

Table 2. Acceptance criteria of gas chromatography

GAS		**Acceptance criteria, concentration [ppm]**			
		BBC	**DORN**	**CEGB**	**DOBLE**
Hydrogen	H_2	200	200	100	100
Methane	CH_4	100	50	120	100
Carbon Monoxide	CO	500	500	350	250
Ethylene	C_2H_4	150	80	30	100
Ethane	C_2H_6	100	35	65	60
Acetylene	C_2H_2	15	5	35	5
Carbon Bioxide	CO_2	5000	6000	-	-

Table 3 shows the key gases to help diagnose the condition of the transformer. Because the gases can increase in different proportions, the international standard [7] classifies the transformer in four conditions as indicated in Table 4. Table 5 shows each condition and its definition.

Table 3. Key gases in gas chromatography

Key Gas Condition	**Condition**
Acetylene	Arching - failure
Hydrogen	Corona effect - Low energy electrical discharge
Ethylene	Superheated oil
Monoxide and Carbon dioxide	Superheated cellulose (paper insulation)

Table 4. Conditions of gases according to international standard

Cond	**H_2**	**CH_4**	**C_2H_4**	**C_2H_2**	**C_2H_6**	**CO**	**CO_2**	**TDCG**
1	0-100	0-120	0-35	0-50	0-65	0-350	0-2500	720
2	101-700	121-400	36-50	51-100	66-100	351-570	2500-4000	791-1920
3	701-1800	401-1000	51-80	101-200	101-150	571-1400	4001-10000	1921-4630
4	>1800	>1000	>80	>200	>150	>1400	>10000	>4630

Table 5. Considerations according to different power transformer conditions

Condition	**Sample**	**Consideration**
1	Annual	Continue in normal operation
2	Quarterly	Analyze for individual gases to determine the load trend
3	Monthly	Analyze for individual gases to determine the load trend. Stoppage plan
4	Weekly - Daily	Stoppage Plan to and to put out of service

3 Diagnostic tests

Diagnostic tests are a fundamental tool for determining incipient faults in power transformers. They allow an early intervention to avoid major damage or unexpected outputs that otherwise would affect service quality indexes, causing economic losses for companies. The main field tests performed on transformers are [7], [8]:

- Transformation relation
- SFRA frequency response analysis
- Measurement of the power factor
- Power factor of Capacitive bushing
- Excitation current
- Dispersion Reactance

- Windings resistance
- Insulation resistance

These tests must be carried out under the guidelines of international standards, guaranteeing their repeatability and the obtaining of accurate and reliable results. To diagnose a fault as many tests as possible must be performed, in this way the results can be correlated and their historical behavior can be verified.
Table 6, shows the typical failures detected by each test and the acceptance criteria according to international standards [7]-[15].

Table 6. Tests on power transformers immersed in oil

Test	Criteria	Identify
Transformer ratio	+/- 0,5 %	Short, open or poor turns of the exchanger
Response analysis in SFRA frequency	Reference traces and measurements should be the same	Mechanical and geometrical deformations in core and coils
Thermography	Difference in temperature	Hot spots, loose connections
Measuring Factor power	< 1,0 en 115 kV < 0,5 en 230 kV	Pollution, wear, humidity and degradation of insulation
Excitation current	5 %	Short between turns, and deformations in the core
Dispersion reactance	5% Three-phase equivalent 2% Single-phase equivalent	Mechanical and geometrical deformations in core and coils
Power factor at Bushings	< 1,0	Pollution, wear, humidity and degradation of insulation
Measurement of resistance of Windings	+/- 5%	Short or partially open spirals, tap changer contacts
Measurement of resistance of insulation	Values in GΩ, IP > 1,5	Pollution, wear, humidity and degradation of insulation
Core press Insulation Resistance	> 500 MΩ	Leakage currents from the magnetic circuit to earth

5 Conclusions

This paper describes and identifies the main techniques used by maintenance personnel for diagnosing the condition of power transformers. These diagnostics involve a large number of variables, which are evaluated not only in a single period but also as a trend over time.

The dynamics of different mechanisms that might cause failures inside transformers must be taken into account in the definition of the maintenance frequency. Some techniques such as reliability centered maintenance can help to define this frequency taking into account particular aspects such as load, voltage level, fault history, etc.

Finally, it should be emphasized that the failure risk management of transformers must consider, in addition to an adequate maintenance strategy, the possibility of having spare units that allow reducing the impact in case of failure occurrence in this equipment.

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References

[1] M. A. Elsaharty, J. I. Candela, P. Rodriguez, Custom Power Active Transformer for Flexible Operation of Power Systems, *IEEE Trans. Power Electronics*, **33** (2018), no. 7, 5773-5783. https://doi.org/10.1109/tpel.2017.2740360

[2] K. A. Tavares and K. M. Silva, Evaluation of Power Transformer Differential Protection Using the ATP Software, *IEEE Lat. Am. Trans.*, **12** (2014), no. 2, 161-168. https://doi.org/10.1109/tla.2014.6749533

[3] T. Ding, R. Bo, Z. Bie, X. Wang, Optimal Selection of Phase Shifting Transformer Adjustment in Optimal Power Flow, *IEEE Trans. Power Syst.*, **32** (2017), no. 3, 2464-2465. https://doi.org/10.1109/tpwrs.2016.2600098

[4] W. Huan, S. Xiangrui, J. Guangzhe, The study of switch transformer medium voltage asynchronous motor soft-start device, *Proceedings of The 7th International Power Electronics and Motion Control Conference (IPEMC)*, (2012), 1-6. https://doi.org/10.1109/ipemc.2012.6259235

[5] H. Jou, K. Wu, J. Wu, W. Chiang, A Three-Phase Four-Wire Power Filter Comprising a Three-Phase Three-Wire Active Power Filter and a Zig–Zag Transformer, *IEEE Trans. Power Electronics*, **23** (2008), no. 1, 252-259. https://doi.org/10.1109/tpel.2007.911779

[6] Schweiz, Zürich, Testing of Power Transformer. Routine, Type test and Special test, First Edition., vol. 1. ABB.

[7] IEEE Std C57.104-1991, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.

[8] IEEE Std C57.106-1991, IEEE Guide for Acceptance and Maintenance of Insulating oil in Equipment. https://doi.org/10.1109/ieeestd.1992.101092

[10] IEEE Std 62-1995, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus Part 1: Oil Filled Power Transformers, Regulators, and Reactors. https://doi.org/10.1109/ieeestd.1995.122640

[11] NSI/IEEE C57.12.90-1999, Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformer.

[12]ANSI/IEEE C57.12.00-2000, IEE Standard General Requirements for Liquid-Immersed Distribution, Power and Regulating Transformers. https://doi.org/10.1109/ieeestd.2000.91813

[13] ANSI/IEEE C57.12.91-1999, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers.

[14] ASTM D1816-04 Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Using VDE Electrodes.

[15] IEEE Std C57.19.100-1995, IEEE Guide for Application of Power Apparatus Bushing. https://doi.org/10.1109/ieeestd.1995.79071

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