Electrical Power Transformer Modeling and Simulation for the Implementation of a Predictive Maintenance Approach

Hamza Ayar, Hasna Nhaila and M El Khaili

May 24, 2022

Electrical Power Transformer Modeling and Simulation for the Implementation of a Predictive Maintenance Approach

Hamza Ayar
IESI Laboratory
ENSET Mohammedia Hassan 2nd
University of Casablanca, Morocco
ayarhamza.ha@gmail.com

Hasna Nhaila
IESI Laboratory
ENSET Mohammedia Hassan 2nd
University of Casablanca, Morocco
hasnaa.nhaila@gmail.com

Mohamed El Khaili
IESI Laboratory
ENSET Mohammedia Hassan 2nd
University of Casablanca, Morocco
elkhailimed@gmail.com

Abstract— **Transformer stations are key components of the electrical power transmission and distribution systems. Their failures are very costly, mainly because of the unavailability of electrical service they cause. Rapid and accurate identification of internal transformer faults is therefore a key function for efficient and safe operation.**

Fault diagnosis of power transformers and related components is a vast field, requiring the correlation of various types of information such as oil analysis, electrical tests, protection tripping, etc. Such a diagnosis is usually established by a human expert from electrical or chemical test results, protection tripping or the history of the device. [13]

In this paper, we present the difference between a dry-type transformer and an oil transformer, in terms of several criteria. Then, we describe the failure modes and the diagnostic techniques, in order to give later an equivalent mathematical model of a single-phase transformer, to visualize the impact of the faults on the exploitable electrical components.

Keywords — Power transformer, Faults, Diagnosis, Transformer maintenance, Failure modes.

I. Introduction

In this paper, we discuss in a general way the possible failure mode for a transformer station, in order to be able to set up a predictive maintenance. The technical characteristics of power transformers and the failure modes are also described.

Power transformers are among the most expensive and critical units in a power system, especially when it comes to 24/7 operation. The normal life span of a power transformer is about 40 years, and the percentage of transformers operating for more than 30 years is increasing due to investments after the 1970s. As a result, the failure rate of transformers is expected to increase significantly in the coming years.

Transformer failures can be catastrophic and almost always involve irreversible internal damage. All major power transformers in a power system must be closely and continuously monitored [1] to ensure their maximum uptime. Our transformer station, which is the subject of this study, has information gathering equipment, but it is not connected to a central processing unit.

In general, there are four main aspects of transformer condition monitoring and evaluation including thermal dynamics, dissolved gases, partial discharge and winding deformation, which must be monitored to determine the condition of the transformer.

The present paper consists of four parts. The first part presents the previous work. The second part describes the diagnostic techniques. The third part illustrates the mathematical modeling of a power transformer. The simulation of the normal operation as well as the injection of some faults are treated in the fourth part.

II. Previous Work

Before starting this section, it is necessary to recall that the power transformer is an equipment that allows to transfer energy from a source to a load, while changing the value of the voltage. The voltage can be either raised or lowered depending on the intended use. The change from one voltage level to another is done by the effect of a magnetic field. A transformer is defined, on the one hand, by its electrical characteristics and, on the other hand, by characteristics related to its technology and conditions of use.

A. Types of power transformer

There are two main families of power transformers depending on the cooling medium: "oil" and "air". Both types have iron-based magnetic circuits and windings made of conductive material for the electrical circuits.

B. History of transformer maintenance

In terms of output value and metering, the voltage level of the dry-type transformer is only 35 kV and the capacity is lower than that of the oil transformer, which is about 2500 kVA. In addition, the production process of the dry-type transformer is relatively complicated compared to the oil-type transformer with the same voltage level and capacity. The cost is also high.

After World War II, the rebuilding of the industry began. A much more competitive market developed, forcing manufacturers to increase production. Overworked electrical machines led to increased downtime and higher transformer repair costs. This increase in production required better maintenance practices, which led to the development of preventive and corrective maintenance.

Before the year 2000, the maintenance method used on power transformers was systematic maintenance on all switchgear. After 2000, we started to use the optimization of maintenance by reliability (OMF), it is a maintenance with variable periodicity according to the importance of the switching blocks, based on:

- A failure mode analysis by criticality
- A classification of structures according to the stakes of the electric system

With the following retained principles:

- Reinforced" or "Nominal" maintenance plans per structure
- Frequencies per maintenance operation
- A detailed description of each operation [2]

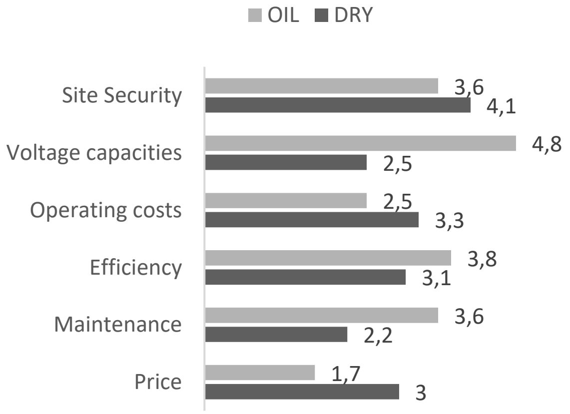

Fig. 1. Comparison between dry and oil-filled transformer types

III. Diagnostic Techniques For Transformer Stations

During commissioning and operation, it is essential that the power transformer is in good condition. Various factors can influence the durability of a transformer throughout its life cycle.
Diagnostic testing and monitoring help us determine the condition of the transformer and select the appropriate corrective measures to ensure reliable operation and extend its life.

A. Failure Modes

There are three main failure modes [3][4] in a power transformer. The first is the dielectric failure mode, which is mainly due to the following phenomena:

- The variation of the internal magnetic field
- The impact of lightning on the transmission system
- The shocks of maneuvers
- Partial discharge
- Dielectric breakdown

The second mode is the thermal failure mode. This failure mode is due to an abnormal rise in temperature of a transformer element. These thermal disturbances have for origins: a lack of cooling, or an increase of the Joule effect.
The third mode is the mechanical failure mode, this failure mode involves the windings and the magnetic circuit, and manifests itself in two forms: electrodynamic and mechanical. [9]
It is electrodynamic in origin and results from the high mechanical forces applied to the winding during a short circuit. The presence of a magnetic field and currents generates Laplace forces on each element of the winding dl given by the following equation:

$$d\vec{F} = I\, d\vec{l} \wedge \vec{B} \quad (1)$$

The second source of this failure mode is mechanical; it results from structural movements during transformer transport operations. In addition to sealing and integrity problems, structural alteration causes displacements between the active parts, insulation damage, and torsional stresses to the magnetic circuit.

B. Diagnostic Techniques

The four major families of transformer diagnostics and their common abbreviations are as follows [4]:

- Dissolved gas analysis (DGA),
- Frequency analysis (FA),
- Partial discharges (PD),
- Methods involving polarization/relaxation mechanisms (PM).

Each of these major families has distinct functions [5] that are complementary to the others:

(DGA): The oil analysis is a method that allows to detect the presence of partial discharges, electrical discharges or overheating in the transformer by evaluating the proportions of the different gases dissolved in the oil. It is carried out by taking spot samples of oil on the transformers, or by an on-line monitoring system which then carries out the analysis on a regular basis.
The furan analysis that can be associated with it consists in looking for the presence of furan in the oil, testifying to a degradation of the insulation and especially the degree of polymerization of the cellulose, a value below 150 is considered critical for the transformer. [10]
(FA): On power transformers, measurements are made on the main insulation between the windings (C_{HL}) and on the insulation between the windings and the tank (C_H, C_L). The terminals are short-circuited and the test voltage is applied to one of the windings while the current through the insulation is measured on the opposite winding or on the tank.

On the feedthroughs, the voltage is applied to the main conductor while the current is measured at the measuring point.
The dissipation factor is calculated via the tangent of the angle between the measured current and the ideal current that would exist in the absence of losses. [11]

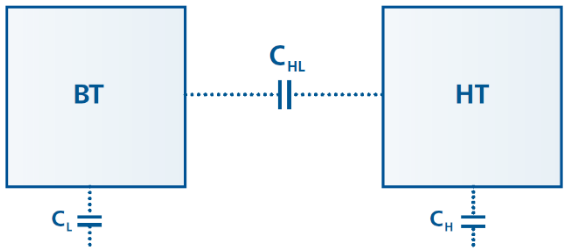

Fig. 2. Capacity measurement and power factor - dissipation factor

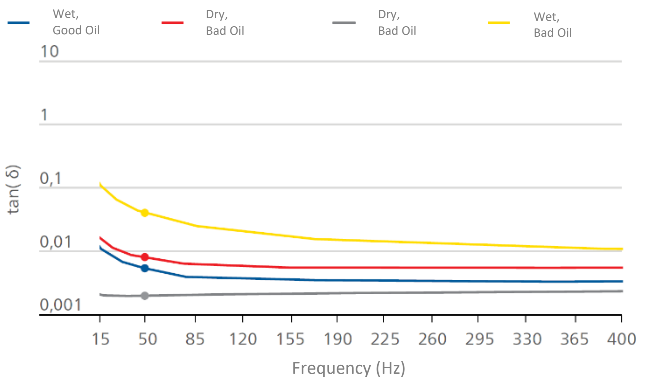

Fig. 3. The tan(φ) of four different transformers below and above the 50 Hz grid frequency

Using frequencies other than the network frequency increases the sensitivity of the measurement since some phenomena are more dominant at frequencies higher or lower than the network frequency. [11] Modern test equipment can perform voltage and frequency sweeps automatically.

(PD): PD measurement is a reliable, non-destructive method of diagnosing the condition of a power transformer's insulation system. It is performed during factory acceptance testing, field commissioning and routine maintenance to detect critical defects and assess risk. PDs are measured in µV (in accordance with IEEE standards) or pC (in accordance with IEC 60270). Advanced noise suppression techniques are commonly applied in environments exposed to high interference to limit irrelevant data. [6][7]

The diagram 3PARD (3-Phase Amplitude Relation Diagram) separates the PD sources from the noise as shown in the following figure:

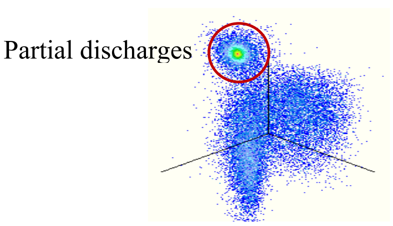

Fig. 4. The separation of PD from noise

(PM): The methods involving polarization and depolarization currents consist in polarizing and then depolarizing the insulation in order to deduce its humidity. Indeed, the latter influences the charging and discharging time constants in the case where polarization phenomena are assimilated to charges and discharges of a capacitor (RC circuit).

The state of an insulator (or the degradation of its state) can be characterized by evaluating the polarization index. This index is defined as the ratio between the current measured after one minute and after 10 minutes [8]:

$$i_p = \frac{I_{t=1}}{I_{t=10}} \quad (2)$$

Insulation is considered as:

$i_p \geq 4 : Good$

$1{,}5 < i_p < 4 : Doubtful$

$i_p \leq 1{,}5 : Bad$

IV. Mathematical Modeling Of A Transformer

In this section, we model a power transformer based on the equivalent model and using the Laplace transform.

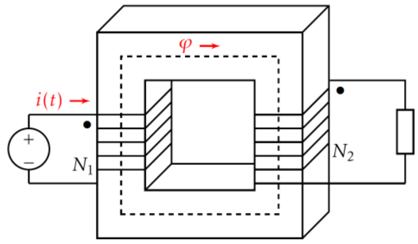

Fig. 5. Internal circuit of a transformer

The transformer consists of at least two windings coupled to a magnetic core (see Figure 5).

The source side is called the primary, and has N1 wire windings. The load side is called the secondary and has N2 windings.

The flux ϕ is the mutual flux. The "●" indicates the polarity of the voltages. By convention, a current flowing into a "●" indicates a positive flux. [8]

A. Equivalent Model

The equivalent circuit diagram of a transformer is a simplified circuit in which the impedance, resistance and leakage reactance of the transformer can be more easily calculated.

Resistances and reactances of transformer, which are described above, can be imagined separately from the windings (as shown in the figure below). Hence, the function of windings, thereafter, will only be the transforming the voltage.

The no load current $\boldsymbol{I_0}$ is divided into, pure inductance $\boldsymbol{X_0}$ and non-induction resistance $\boldsymbol{R_0}$, which are connected into parallel across the primary.

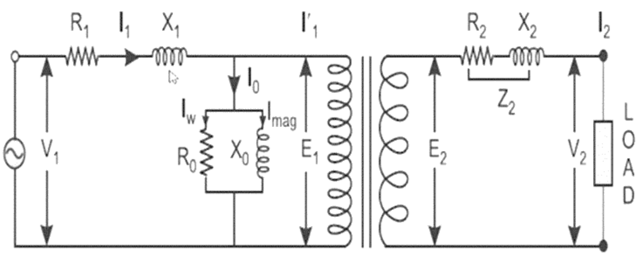

Fig. 6. Equivalent model of a single-phase transformer

$$K = \frac{N_2}{N_1} = \frac{E_2}{E_1} = \frac{I_1}{I_2} \quad (3.a)$$

$$N_1 I_1 + N_2 I_2 \quad (3.b)$$

$$Z_1 = R_1 + jX_1 \quad (4)$$

$$V_1 = E_1 + I_1(R_1 + jX_1) \quad (5)$$

$$I_1 = I'_1 + I_0 \quad (6)$$
$$I_0 = E_1 Y_0 \quad (7)$$
$$Y_0 = \frac{1}{R_0} + \frac{1}{jX_2} \quad (8)$$
$$Z_2 = R_2 + jX_2 \quad (9)$$
$$V_2 = E_2 - I_2(R_2 + jX_2) \quad (10)$$
$$Z_c = R_c + jX_c \quad (11)$$
$$V_2 = I_2(R_c + jX_c) \quad (12)$$

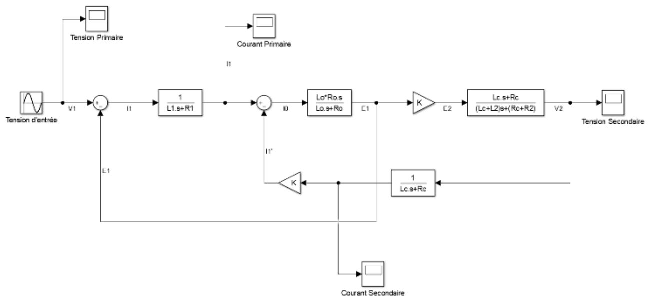

Fig. 7. Block diagram of a transformer model

The parameter values used in the simulation are given in the following table:

TABLE I. PARAMETERS AND VALUES OF OUR SYSTEM

Parameter	Value	Parameter	Value
V_2	$\sqrt{2} \times 1555$ V	L_2	0.084225 H
R_1	4.3218 Ω	R_c	2 Ω
L_1	0.45856 H	L_c	0.005 H
R_0	1080500 Ω	K	0.018
L_0	2866 H	Freq	50 Hz
R_2	7.938 Ω		

B. *Simulations*

We tested our model on Matlab by simulating three aspects: a normal behavior, a fault related to an overload and a leakage current fault of the magnetic circuit.
Figures 8 and 9: Normal operation of the transformer results in voltage and current signals at the secondary that closely follow the electrical signals at the input. This is the operation in the linear zone.

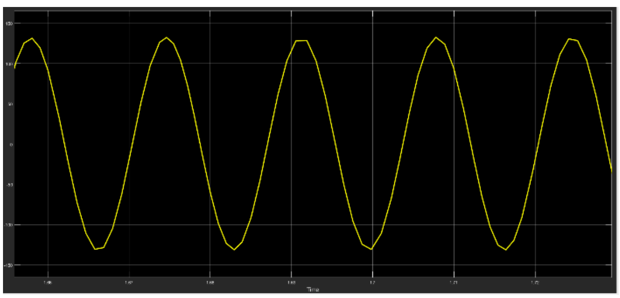

Fig. 8. Secondary current in normal state 130A

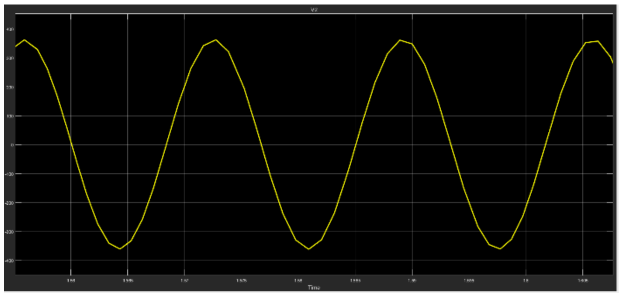

Fig. 9. Secondary voltage in normal state 370V

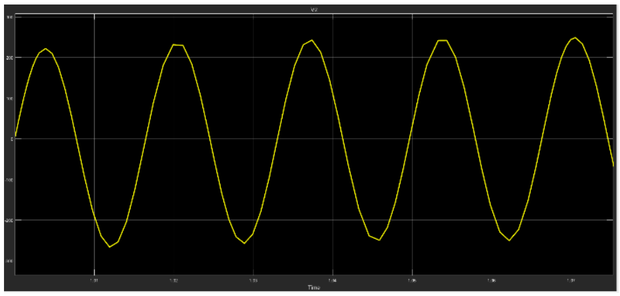

Fig. 10. Secondary voltage in case of overload 215V

Figure 10: The application of an overload is realized through the strong decrease of the load resistance of the receiving circuit.
It can be seen that the transformer has lost its normal operation. The output voltage has become 215V instead of the expected 370V.
In this case, an overload relay trips. **[12]**

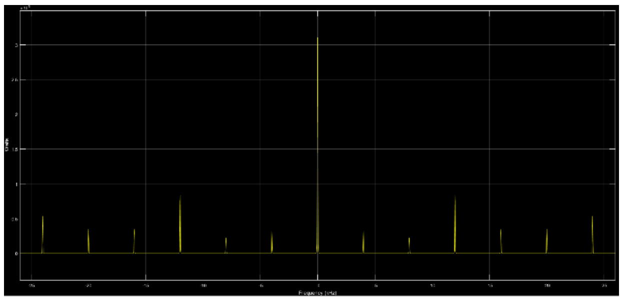

Fig. 11. Harmonic distortion of the output voltage

We notice that the existence of one or more faults in a transformer generates a malfunction of the equipment, and disrupts the expected function of the system, in our case the lowering of a voltage applied to the input of the transformer.
To avoid these problems, we set up protection and signaling devices. These devices carry out a permanent analysis work while guaranteeing the thresholds to be respected.
Several international standards define the functionality of protective relays. The EN60617-7 standard indicates the symbols related to these functions. The American standard ANSI C37-2 uses numbers to indicate the functionality of the protection relay for example: F50, F50N and F64. **[11]**

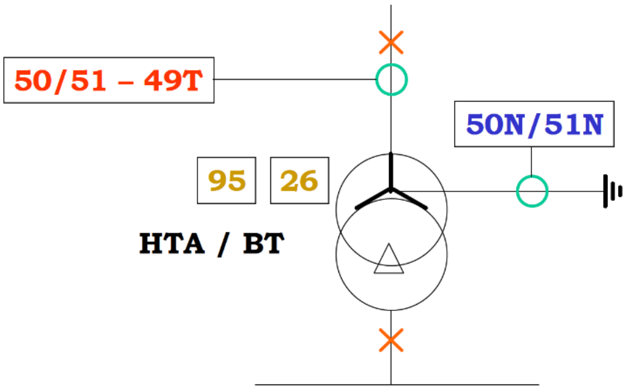

Fig. 12. Example of usual functions of the protection relays

V. Conclusion

The availability of electrical energy depends on the ability to operate without failure in transmission and distribution. During their operation, transformers are subjected to stresses that often lead to the occurrence of faults. The knowledge of the mechanisms of these faults is an important step in the maintenance process. This paper presents the fundamental knowledge about transformers, the different faults that can occur and the assessment of their health status and the mathematical modeling of a transformer via Matlab/Simulink.

The diagnostic techniques shown are related to oil transformers, since these are the most used, and our transformer object of the study is part of the oil category.

The mathematical modeling has been carried out, in order to see the impact of some faults caused on the different electrical components. The implementation of these electrical field tests can be more or less technical and require specialized personnel accordingly.

Finally, measurement data of a transformer are rarely available. The interpretation of most tests is therefore done by comparing the results of the phases. The main difficulty of any diagnostic process is to be able to correctly interpret these different measurements, which according to their results, and their synthesis with other information, can lead to very heavy or risky technical operations.

References

[1] "IEE Colloquium on 'Condition Monitoring and Remanent Life Assessment in Power Transformers' (Digest No.1994/075)," Date of Conference: March 1994, IEE Colloquium on Condition Monitoring and Remanent Life Assessment in Power Transformers, 1994, pp. 0_1-.

[2] B. D. Malpure and K. Baburao, "Failure analysis & diagnostics of power transformer using dielectric dissipation factor," 2008 International Conference on Condition Monitoring and Diagnosis, 2008, pp. 497-501.

[3] C. Chou and C. Chen, "Measurement and analysis of partial discharge of high and medium voltage power equipment," 2018 7th International Symposium on Next Generation Electronics (ISNE), 2018, pp. 1-4.

[4] D. Korenciak, M. Gutten, V. Cefer, M. Sebok and N. Valko, "Diagnostics of Difference Parameters of Transformer Winding in Time and Frequency Domain," 2020 International Conference on Diagnostics in Electrical Engineering (Diagnostika), 2020, pp. 1-4.

[5] E. A. Mackenzie, J. Crossey, A. dePablo and W. Ferguson, "On-line monitoring and diagnostics for power transformers," 2010 IEEE International Symposium on Electrical Insulation, 2010, pp. 1-5.

[6] H. Ji, J. Zhang, Z. Liu, G. Liang and H. Zhao, "Optimal Maintenance Decision of Power Transformers," 2010 International Conference on Electrical and Control Engineering, 2010, pp. 3941-3944.

[7] B. Richardson, "Diagnostics and monitoring of power transformers," IEE Colloquium on Condition Monitoring of Large Machines and Power Transformers (Digest No: 1997/086), 1997, pp. 6/1-6/2.

[8] W. Lair, R. Ziani, S. Mercier and M. Roussignol, "Modeling and quantification of aging systems for maintenance optimization," 2010 Proceedings - Annual Reliability and Maintainability Symposium (RAMS), 2010, pp. 1-6.

[9] R. Phadungthin and J. Haema, "Development of risk optimization model for high voltage substation transformer maintenance," 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2015, pp. 1-5.

[10] M. F. Al Hamdani, R. Azis Prasojo, Suwarno and A. Abu-Siada, "Power Transformer Degradation Condition and Insulation Index Estimation Based on Historical Oil Dat," 2019 2nd International Conference on High Voltage Engineering and Power Systems (ICHVEPS), 2019, pp. 1-5.

[11] OMICRON « Tests de diagnostic et surveillance des transformateurs de puissance » ; OMICRON L4247, 02 2022

[12] C. Antoun, "High Voltage Circuit Breaker and Power Transformer Failure Modes and Their Detection," 2018 Condition Monitoring and Diagnosis (CMD), 2018, pp. 1-6.

[13] D. J. Allan and A. White, "A manufacturers contribution to life management of transformers," International Conference on Life Management of Power Plants 1994, 1994, pp. 74-79.