Confirmatory Test on a Single–Phase Transformer

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Abstract — **Once a transformer is manufactured, there is a need to perform performance parameters such as open-circuit, short-circuit and full-load test. This paper investigates a single-phase transformer through experimental tests, equivalent circuit modelling, and MATLAB Simulink simulation. Tests on an 1150VA 230/115V transformer included open-circuit, short-circuit, and full-load examinations, with a focus on hysteresis effects. Equivalent circuit parameters were derived and validated through simulations, showing agreement in open-circuit and short-circuit scenarios. This paper presented the reason why a confirmatory test needs to be performed on a transformer before usage or after a prolonged outage or disconnection from the circuit as the rated high voltage was confirmed to be 220V instead of 230V on the nameplate.**

Keywords — *transformer, open-circuit, short-circuit, modelling, simulation, test.*

I. INTRODUCTION

Transformers are stationary electrical machines that transform AC voltage from one level to another with the same frequency through the principle of electromagnetic induction with the changing flux, the two levels (input/output or high/low voltage) are electrically isolated [1]. To reduce leakage flux and the effect of hysteresis, grain-oriented ferromagnetic materials with high permeability are used for transformer cores which are laminated to reduce eddy current losses. Single-phase transformers have two windings on their respective cores with the right proportion to achieve the desired transformation ratio (fixed or variable) [1].

This paper discusses the parameters of a single-phase transformer both experimental and MATLAB simulation: open circuit test, short circuit test, full load test and hysteresis loop were carried out on an 1150VA 230/115V transformer.

This paper is written in sections where Section II discusses the experimental tests, Section III discusses the equivalent circuit modelling of the transformer based on laboratory results, and Section IV is based on the Simulink simulation and verification of the effectiveness of the circuit model.

II. EXPERIMENTAL TESTS

The workbench, Figure 1 was set up and proper connection of each stage of the experiment was connected according to the circuit diagram for the respective tests as explained in the subsections below with the following components.

- Autotransformer
- 1150VA 230/115V single-phase transformer
- Digital Wattmeter
- Digital Multimeter
- Clamp-on Current Probe
- Oscilloscope
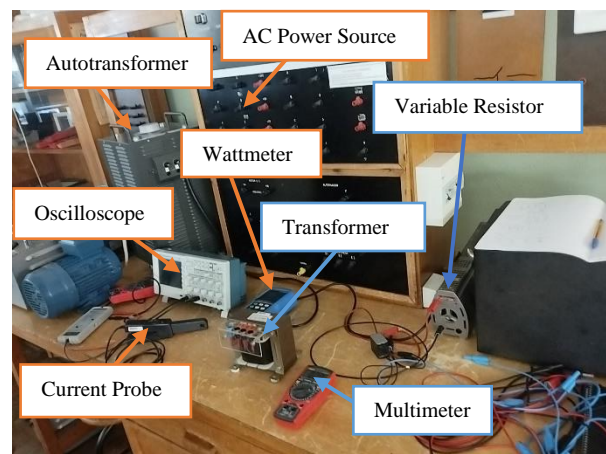- Variable Resistor
- High Resistance Load

Figure 1: DEE Workbench - Electrical Machines Lab

A. Hysteresis Cycle

To view the hysteresis effects, the circuit is connected as shown in Figure 2, A 2.5kΩ resistor and 10µF capacitor were connected in series to the HV side of the transformer and an autotransformer was connected to the LV side while the Oscilloscope was connected as shown.
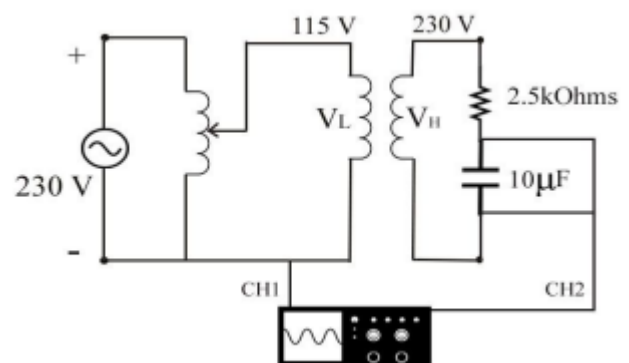

Figure 2: Circuit Diagram for the Hysteresis Cycle

The input voltage was carefully adjusted until the hysteresis loop formed, just before that, the distortion was visible on the input current Figure 3 before resulting in the hysteresis loop shown in Figure 4.
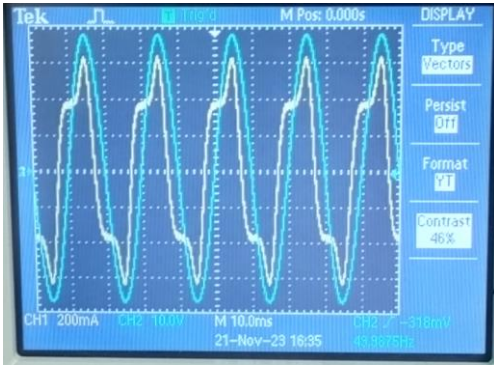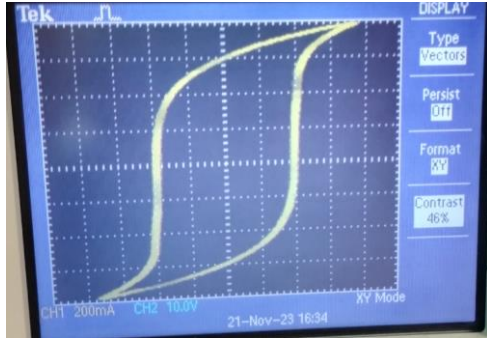
Figure 3: Input Voltage and Current Waveforms

Figure 4: Hysteresis Loop

B. Open – Circuit Test

An open-circuit test was conducted on the HV side. A wattmeter to measure V, P, pf, Q and S, and an autotransformer were connected to the LV side while a voltmeter was connected to the HV side as shown in the circuit diagram in Figure 5. The input voltage from the autotransformer was increased in step until the rated LV side voltage was 115.1V with the corresponding HV side 221V as shown in Figure 6. The measured open circuit test parameters are shown in Table 1.
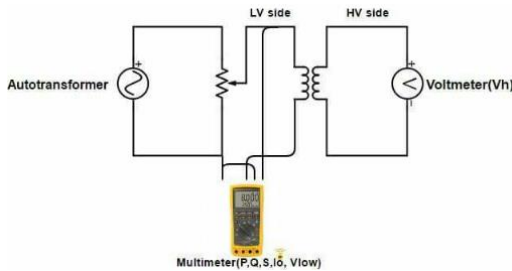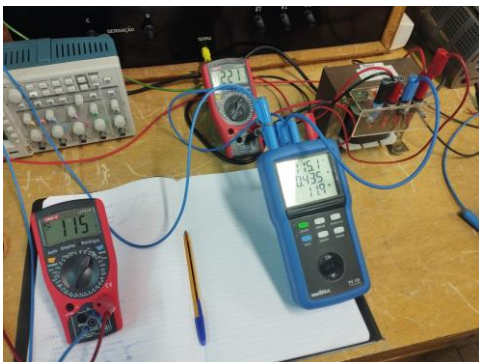

Figure 5: Open-Circuit Test Circuit Diagram

Figure 6: Open-Circuit Test Implementation

Table 1: Open-Circuit Measured Parameters

V_{OC} (V)	I_{OC} (A)	P_{OC} (W)	PF	V_H (V)	Q_{OC} (Var)
115.1	0.435	11.9	0.24	221	48.7

C. Short – Circuit Test

Similar to the open-circuit test in B, the circuit diagram (Figure 7) for this test was implemented. The autotransformer and Wattmeter were connected to the HV side while the LV side was short-circuited with an ammeter, Figure 8. The input voltage was carefully adjusted as $V_{SC} \ll V_R$ until the rated current of the transformer was achieved at 5A, 13.4V.
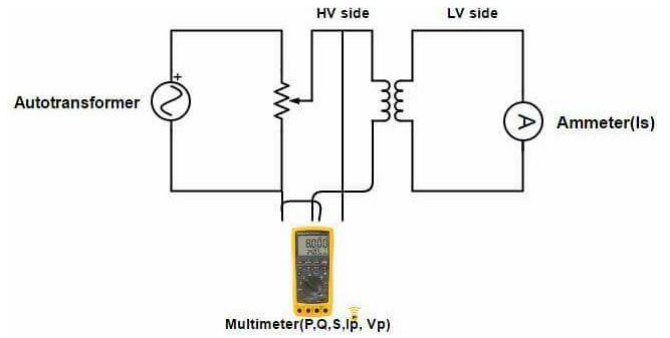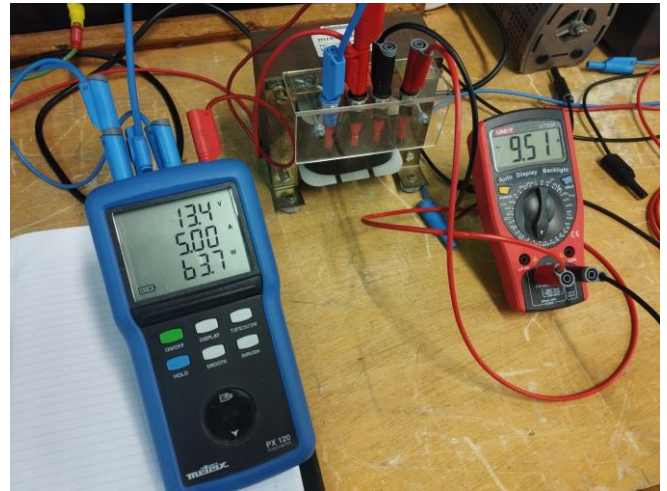

Figure 7: Short-Circuit Test Circuit Diagram

Figure 8: Short-Circuit Test Implementation

The SC test parameters were measured as shown in Table 2.

Table 2: Short-Circuit Test Parameters

V_{SC} (V)	I_{SC} (A)	P_{SC} (W)	PF	I_L (A)	Q_{SC} (Var)
13.4	5	63.7	0.24	9.51	21.9

D. Full – Load Test

The full-load circuit is the same as that of the SC test, however, the LV side is replaced with a highly resistive load bank. The input voltage from the autotransformer was increased until the rated current of 5.01A was achieved at 246V on the HV side of the testing system, Figure 9. The full-load test measured parameters were recorded as shown in Table 3.
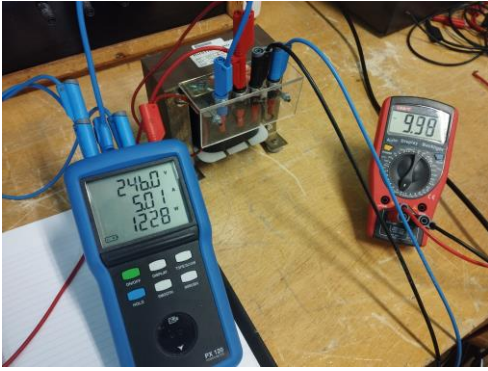
Figure 9: Full-Load Test Implementation

Table 3: Full-Load Test Parameters

V_H (V)	I_H (A)	P_{FL} (W)	PF	I_L (A)	Q_{FL} (Var)
246	5.01	1228	1	9.98	110.7

The output power on the LV side is calculated in equation (1) with the unity power factor. The power loss is shown in equation (2) while the efficiency of this transformer is calculated in equation (3).

$$P_{0ut} = V_L I_L \cos\theta = 121 \times 9.98 = 1207.58W \ldots \ldots (1)$$

$$P_{loss} = P_{FL} - P_{out} = 1228 - 1207.58 = 20.42W \ldots \ldots (2)$$

$$\eta = \frac{P_{out}}{P_{FL}} \times 100\% = \frac{1207.58}{1228} = 98.34\% \ldots \ldots (3)$$

III. EQUIVALENT CIRCUIT MODELLING

This section discusses the modelling of the single-phase transformer to model the same on the MATLAB Simulink with the result obtained from the Lab results in section II. The equivalent circuit a transformer referred to the primary side [1] [2] is shown in Figure 10.
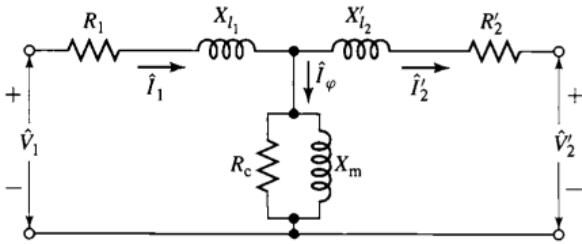

Figure 10: Equivalent Circuit of a Transformer

To obtain the transformer parameters such as magnetizing current, shunt/core resistance, shunt reactance, equivalent impedance etc. the open-circuit and short-circuit parameters measured in the lab were used to calculate these according to their respective equivalent circuits. Figure 11 is the cantilever equivalent circuit of the open-circuit transformer, and the circuit parameters were calculated from equations 4 to 9 [2] using Table 1 details.
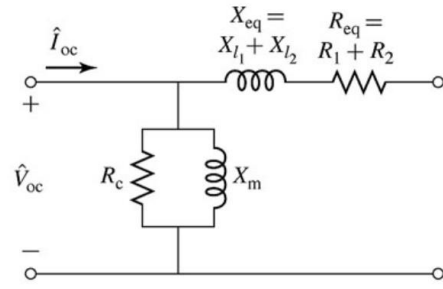

Figure 11: Open-Circuit Equivalent Circuit

$$R_c = \frac{V_{oc}^2}{P_{oc}} = \frac{115.1^2}{11.9} = 1113.28\Omega \ldots \ldots (4)$$

$$I_c = \frac{V_{oc}}{R_c} = \frac{115.1}{1113.28} = 0.1034A \ldots \ldots (5)$$

$$I_m = \sqrt{I_{oc}^2 - I_c^2} = \sqrt{0.435^2 - 0.1034^2} = 0.4225A \ldots \ldots (6)$$

$$Z_{oc} = \frac{V_{oc}}{I_{oc}} = \frac{115.1}{0.435} = 264.6\Omega \ldots \ldots (7)$$

$$X_m = \frac{1}{\sqrt{\left(1/Z_{oc}\right)^2 - \left(1/R_c\right)^2}} = 272.4\Omega \ldots \ldots (8)$$

$$L_m = \frac{X_{m1}}{\omega} = \frac{272.4}{2\pi \times 50} = 0.8671H \ldots \ldots (9)$$

From the open-circuit test result, it can be seen that the input voltage, V_{OC} is 115.1V which produces 221V on the HV side rather than the 230V rated voltage. This is known as transformation derating. Hence, this current value of both LV and HV voltage is used for the transformation ratio (equation 10) [2]. The shunt magnetization impedance is then referred to the HV side as calculated in equations 11 and 12 [2].

$$\alpha = \frac{V_{HV}}{V_{LV}} = \frac{221}{115.1} = 1.92 \ldots \ldots (10)$$

$$R_{cHV} = \alpha^2 R_c = 1.92^2 \times 1113.28 = 4104.29\Omega \ldots \ldots (11)$$

$$L_{mHV} = \alpha^2 L_m = 1.92^2 \times 0.8671 = 3.19671H \ldots \ldots (12)$$

To obtain the series impedance, the short-circuit analysis was performed using the data obtained in Table 2. The equivalent circuit as referred to the HV side is shown in Figure 12 [2].
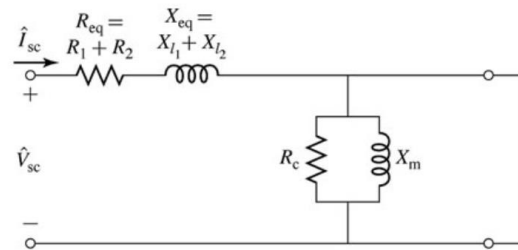

Figure 12: Short-Circuit Test Equivalent Circuit

The equivalent resistance R_{eq} is calculated using equation 15 while equivalent reactance X_{eq} is calculated using equation 16 [1].

$$R_{eq} = R_1 + \alpha^2 R_2 \ldots \ldots (13)$$

$$X_{eq} = X_1 + \alpha^2 X_2 \ldots \ldots (14)$$

$$R_{eq} = \frac{P_{sc}}{I_{sc}^2} = \frac{63.7}{5^2} = 2.548\Omega \ldots \ldots (15)$$

$$X_{eq} = \sqrt{\left(\frac{V_{sc}}{I_{sc}}\right)^2 - R_{eq}^2} = 0.8307\Omega \ldots \ldots (16)$$

According to [1] in page 78, it can be assumed that $R_1 = R_2 = 0.5R_{eq}$ and $X_1 = X_2 = 0.5X_{eq}$ when all the impedances have been referred to the same side. Then the series resistances, reactances and inductances are calculated from equations 17 to 22.

$$R_1 = 0.5R_{eq} = 1.274\Omega \ldots \ldots (17)$$

$$R_2 = \frac{1.274}{\alpha^2} = 0.3456\Omega \ldots \ldots (18)$$

$$X_1 = 0.5X_{eq} = 0.4154\Omega \ldots \ldots (19)$$

$$X_2 = \frac{0.4154}{\alpha^2} 0.1127\Omega \ldots \ldots (20)$$

$$L_1 = \frac{X_1}{\omega} = \frac{0.4154}{2\pi \times 50} = 1.322mH \ldots \ldots (21)$$

$$L_2 = \frac{X_2}{\omega} = \frac{0.1127}{2\pi \times 50} = 0.3587mH \ldots \ldots (22)$$

IV. MATLAB SIMULINK SIMULATION

A. Open – Circuit Test

The circuit diagram in Figure 5 was implemented on MATLAB Simulink with the transformer parameters obtained in section III and input voltage 115.1V is applied to the LV side while HV remained open-circuited. The simulation environment and the results are shown in Figure 13.
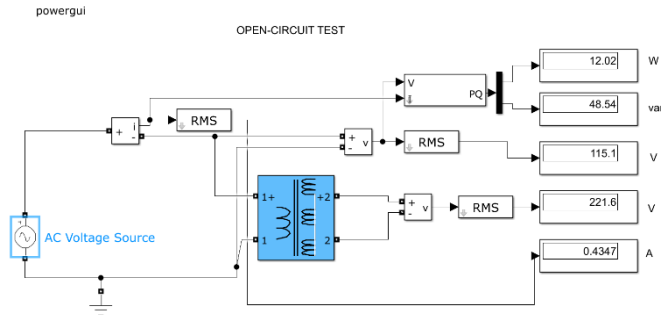

Figure 13: Simulink Open-Circuit Test

B. Short–Circuit Test

Similarly, the circuit in Figure 7 was implemented on a Simulink environment with the LV side short-circuited while a 13.4V was applied to the HV side. The simulation environment and results are shown in Figure 14.

C. Full-Load Test

A high resistance load was connected to the LV output terminal of the circuit in Figure 14. The resistance was gradually reduced until the rated current of 5A was achieved on the HV side of the circuit. Figure 15 presents the results and the Simulink circuit environment of this test.
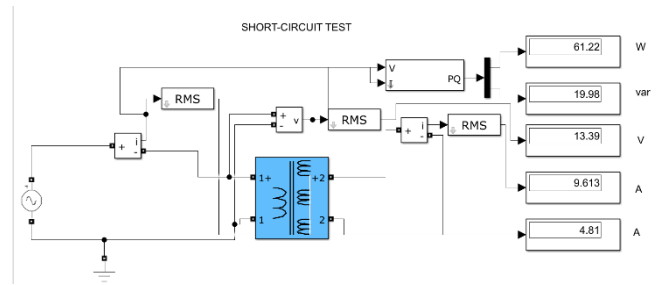

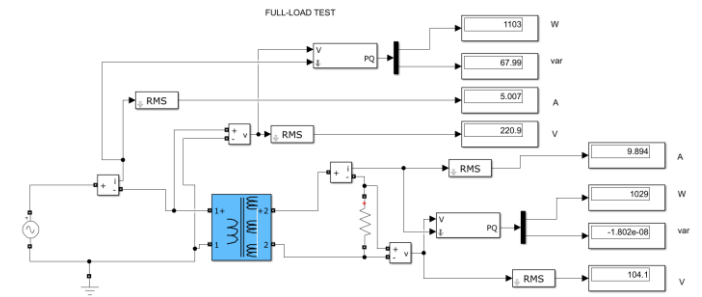*Figure 14: Short-Circuit Test on Simulink*

Figure 15: Full-Load Test on Simulink

The efficiency of the transformer is calculated from equations 23 to 24.

$$P_{loss} = P_{HV} - P_{LV} = 1103 - 1029 = 74W \ldots \ldots (2)$$

$$\eta = \frac{P_{LV}}{P_{HV}} \times 100\% = \frac{1103}{1029} = 93.29\% \ldots \ldots (3)$$

D. Simulink Simulation vs Lab Experiment

Table 4 (last page) Simulink presented the measured parameters from both the experimental and simulation results. Both OC and SC tests present negligible errors between the simulated results and experimental results. However, there is a noticeable error in voltage and power of the Full-Load test, this can be attributed to the type of load to achieve full load for this system. To achieve full load on the experiment, the input voltage was adjusted to 246V while 220.9V was enough to achieve full load current on Simulink.

V. CONCLUSION

In summary, this paper conducted a thorough analysis of a single-phase transformer, encompassing experimental tests, equivalent circuit modelling, and MATLAB Simulink simulation. The open-circuit and short-circuit tests demonstrated good agreement between simulation and experimental results, validating the derived equivalent circuit parameters. Discrepancies observed in the full-load test were attributed to load variations. Overall, the transformer exhibited satisfactory performance, emphasizing the significance of accurate equivalent circuit representation for simulations.

VI. REFERENCES

[1] A. E. Fitzgerald, C. Kingsley and S. D. Umans, Electric Machinery, McGraw-Hill, 2003.

[2] P. Pereirinha, Writer, *Lecture Notes - Electrical Machines.* [Performance]. Instituto Superior de Engenharia de Coimbra, 2023.

Table 4: Experimental Results vs Simulated Results

TEST	Open-Circuit Test			Short-Circuit Test			Full Load Test		
MODE	Experiment	Simulink	%Error	Experiment	Simulink	%Error	Experiment	Simulink	%Error
V_{LV} (V)	115.1	115.1	0%	0	0	0%	121	104.1	14%
I_{LV} (A)	0.435	0.433	0%	9.51	9.609	-1%	9.98	9.894	1%
V_{HV} (V)	221	221.3	0%	13.4	13.4	0%	246	220.9	10%
I_{HV} (A)	0	0	0%	5	4.809	4%	5.01	5.007	0%
P (W)	11.9	12.14	-2%	63.7	61.18	4%	1228	1103	10%
Q (Var)	48.7	48.33	1%	21.9	20.08	8%	110.7	67.99	39%