Experiment 2: Single-Phase Transformers

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***Abstract*—The following experiment aquainted us with the single-phase transformer. We observed the transformer while disassembled, noting the geometry of the coil and core. Then, after reassembly, we noted the behavior of the transformer when exciting the primary coil with a sweep of voltages. From this we explain the humming from the transformer, and the results of a open-circuit and short-circuit test.**

I. Transformer Humming

During the experiment, whenever we applied our AC voltage to the primary coil of the transformer, the transformer made a low-pitch humming noise. So, by exciting the device, some of the electrical energy is spent mechanically vibrating it.

The cause is *magnetostriction*, where changing magnetic fields cause particles in a ferromagnetic material to move and change in size [1]. Since the particles are continually being excited by the 60Hz source, we get a vibrating magnetic device.

For a DC source, the frequency is zero, so any ferromagnetic particles will move once and reach an equilibrium, so no continual vibrations can cause humming.

II. Dislodging the Transformer Yoke

Before performing the open-circuit test on the transformer, we applied an input voltage while the yoke (top of core) was loosened.

When we rotate the yoke from its normal position, the cross-sectional area that it makes at the corners of the magnetic core decreases. Remembering the formula for reluctance:

$$\mathcal{R} = \frac{l}{\mu A} \tag{1}$$

Here it's easy to see that a decreasing cross-sectional area A causes a increase in core reluctance $\mathcal{R}$.

We also noted that the source current to the transformer increased when we dislodged the yoke, but this is a direct cause of our increasing core reluctance. From the formula for magnetomotive force (mmf):

$$Ni = \Phi\mathcal{R} \tag{2}$$

Since the coil turns and flux are unchanged, we can see that increasing core reluctance will cause increasing coil current as $i \propto \mathcal{R}$.

III. Open-Circuit and Short-Circuit Tests

Source Voltage (V)	Source Current (A)	Source Power (W)	Secondary Coil Voltage (V)
30	0.085	0.0	65.5
60	0.180	1.0	133.2
90	0.290	2.1	196.7
115	0.435	5.1	251.1
120	0.490	6.5	261.6
125	0.500	8.3	276.5

TABLE I: Open-Circuit Test Data

A. Magnetic Flux Density and Magnetic Field Intensity of Core

From Table 3.1, we can calculate the maximum magnetic flux density $B_{\max}$ and maximum magnetic field intensity $H_{\max}$ using the following equations in [2].

$$B_{\max} = \frac{\sqrt{2}V_{\text{rms}}}{N_1 A_c \omega} \tag{3}$$

$$H_{\max} = \frac{\sqrt{2}N_1 I_0}{l_{\text{eff}}} \tag{4}$$

Using the dimensions of the transformer core, we find that $l_{\text{eff}} = 0.3048\text{m}$ and $A_c = 0.00242\text{m}^2$. On the primary side of the transformer, the number of turns is labelled $N_1 = 230\text{T}$. The angular frequency is $\omega = 2\pi(60\text{Hz})$. With these values, we get the following table:

$B_{\max}$	$H_{\max}$
0.202	90.7
0.404	192.1
0.607	309.5
0.775	464.2
0.809	522.9
0.842	533.6

TABLE II: Calculated Values for $B_{\max}$ & $H_{\max}$

Plotting this data:

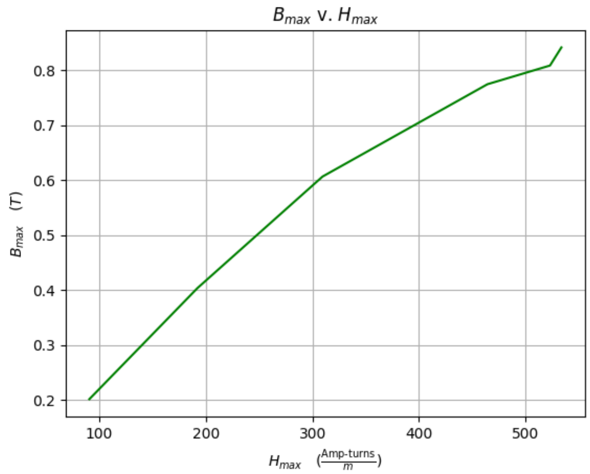

Fig. 1: Magnetization curve for 1ϕ transformer

Also, plotting the excitation current and excitation voltage, we get Fig. 2:

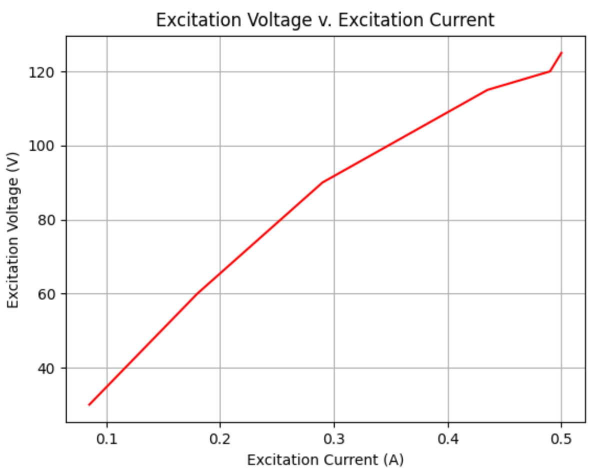

Fig. 2: Excitation Voltage v. Excitation Current

As we can see both plots have the exact same curvature, and they're just scaled versions of each other given the equations for $B_{\max}$ & $H_{\max}$. But, we can see both curves saturate as we approach 120V applied to the primary coil. This tells us that as we approach 120V, we start reaching the magnetization limits of the magnetic material that constructs the core of the transformer.

If we reflect Fig. 1 into the third quadrant, and interpolate the data for $H \in (-H_{\max}, H_{\max})$, we get Fig. 3. This plot representing the top half of a completed hysteris loop.

B. Computation of Magnetizing Branch Elements at 115*V*

Using the data from Table 1, we can calculate R_c and X_m. Since, these are quanities in parallel with the transformer, it is easiest to calculate their reciprocal quanities (conductance G and susceptance B) [2], these are Eq. 5 and Eq. 6.

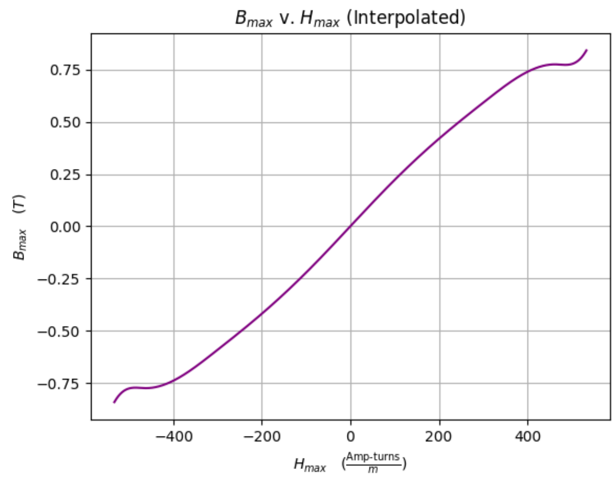

Fig. 3: Interpolated magnetization curve for 1ϕ transformer

$$\frac{1}{R_c} = G_c = \frac{I_{\text{OC}}}{V_{\text{OC}}} \cos\theta_{\text{OC}} \tag{5}$$
$$\frac{1}{X_m} = B_m = \frac{I_{\text{OC}}}{V_{\text{OC}}} \sin\theta_{\text{OC}} \tag{6}$$

We need our power factor,

$$\cos\theta_{\text{OC}} = \frac{5.1\text{W}}{(115\text{V})(0.435\text{A})} = 0.102$$

Which means $\theta_{\text{OC}} = 84.1°$. Now, we can calculate conductance and susceptance,

$$G_c = \frac{0.435}{115}(0.102) = 0.389 \times 10^{-3}$$
$$B_m = \frac{0.435}{115} \sin 84.1° = 3.76 \times 10^{-3}$$

Inverting these to get core resistance and magnetizing reactance,

$$R_c = 2572\Omega$$
$$X_m = 265.8\Omega$$

We also briefly conducted a short-circuit test on the transformer, obtaining the following results,

$$V_{\text{SC}} = 4.000\text{V}$$
$$I_{\text{SC}} = 1.505\text{A}$$
$$P_{\text{SC}} = 4.000\text{W}$$

We can calculate power factor the same as before and get that $\cos\theta_{\text{SC}} = 0.664$, which means $\theta_{\text{SC}} = 48.4°$. Calculating for the leakage resistance and reactance,

$$R_{\text{eq}} = \frac{V_{\text{SC}}}{I_{\text{SC}}} \cos\theta_{\text{SC}} = 1.76\Omega \tag{7}$$

$$X_{\text{eq}} = \frac{V_{\text{SC}}}{I_{\text{SC}}} \sin\theta_{\text{SC}} = 1.99\Omega \tag{8}$$

So, attributing to copper losses in the transformer, $Z_{\text{eq}} = 1.76 + j1.99\Omega$.

C. Core Reluctance at 115V

We can calculate the core reluctance at 115V ($I_1 = 0.435$A) since, $N_1 I_1 = \Phi \mathcal{R}_c = BA_c\mathcal{R}_c$.

$$\mathcal{R}_c = \frac{N_1 I_1}{BA_c} = \frac{(230)(0.435)}{(.775)(0.00242)} = 53.3\text{k}\frac{\text{A-t}}{\text{Wb}}$$

D. Magnetizing Current v. Excitation Voltage

Using $X_m = 265.8\Omega$, we can calculate the magnetizing current I_m for $V_1 = 115, 120, 125\text{V}_{\text{rms}}$, since we know that $I_m = V_1/X_m$.

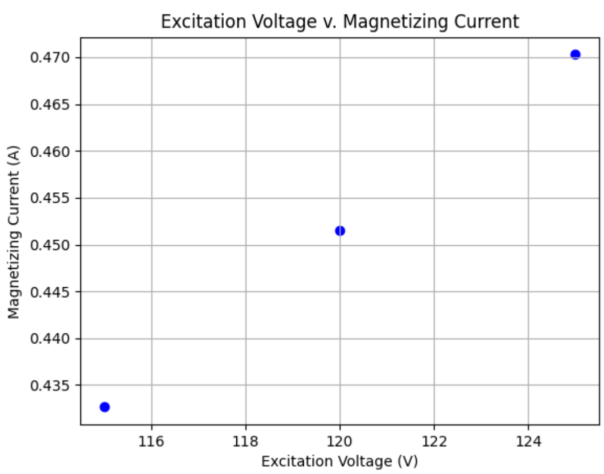

Fig. 4: I_m for 115V, 120V, 125V

E. Equivalent Circuits

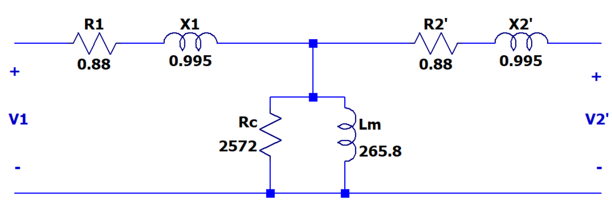

Fig. 5: Primary Coil Equivalent Circuit

Using the approximation in [2],

$$R_1 = R_2' = 0.88\Omega$$
$$X_1 = X_2' = j0.995\Omega$$

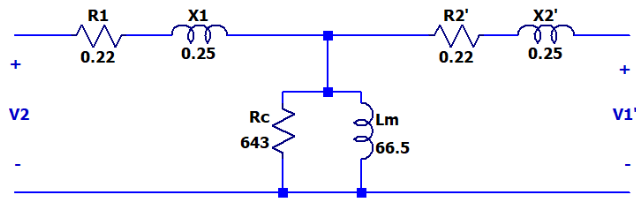

Fig. 6: Secondary Coil Equivalent Circuit

This gives the transformer equivalent circuit in Fig. 5. Which only applies for $V_1 \leq 120$V as the left side of the circuit is the primary coil, which is the 230 turn side. Similarly, Fig. 6 applies for $V_2 \leq 240$V as that is the rated voltage for the 460 turns side.

REFERENCES

[1] B. Forghani, "Magnetostriction, a source of noise in transformers," Siemens Blog, April 2021, accessed: 09-12-2024.

[2] B. Lamichhane, "Lab instruction sheet - session 3," Published to D2L, September 2024, accessed: 09-12-2024.