

ECE 241L Fundamentals of Electrical Engineering

NAME _____

Experiment 8 A-C Transformer, Magnetization & Hysteresis

PARTNER _____

A. Objectives:

- I. Measure leakage inductance and resistance loss
- II. Measure magnetization inductance and hysteresis loss
- III. Measure turns-ratio

B. Equipment:

Breadboard, wire, 100Ω resistor, 600Ω 1:1 telecomm transformer
Oscilloscope: Tektronix TDS3043 Digital Storage Scope
Function Generator: Tektronix AFG310/320 Arbitrary Function Generator
Digital Volt-Ohm Meter (DVM): Fluke 189 (or equivalent)

C. Introductory Notes:

A-C TRANSFORMER

An a-c transformer consists of two coils of wire wound on the same core. Usually the core is of a special alloy of iron that concentrates the magnetic field. A current in one of the coils induces a magnetic "**flux**" in the iron that passes through both coils. If the current is time varying (a-c) the induced flux is also time varying. From Faraday's Law of induction, a time-varying magnetic field will cause a voltage in a wire immersed in the field. In the case of a transformer, there are two coils immersed in the field. Current in the first coil, called the "primary", induces a voltage in the same coil as a result of the "self-inductance". However, the magnetic flux also passes through the second coil called the "secondary", and induces another voltage due to "mutual inductance". **The ratio of voltage in the two coils is proportional to the number of turns of wire in each coil.** If the number of turns in the primary is n_1 and the number of turns in the secondary is n_2 , the turns ratio is $N:1 = n_1/n_2 = v_1/v_2$. It can also be shown that if a current is allowed to flow in the secondary, it will be inversely proportional to the turns-ratio, multiplied by the current in the primary. An ideal transformer obeys the set of equations

$$N/1 = n_1/n_2 \quad \text{TURNS-RATIO}$$

$$v_1/v_2 = N \quad \text{VOLTAGE RATIO}$$

$$i_1/i_2 = 1/N \quad \text{CURRENT RATIO}$$

In many transformers (e.g. audio output transformers, traditional electronics power supply transformers,) there is a voltage "step-down" from input terminal 1 ("primary") to output terminal 2 ("secondary"). There is a corresponding "step-up" in current for terminal 2. Power is conserved since

$$v_1 \cdot i_1 = v_2 \cdot i_2 \quad \text{CONSERVATION OF POWER}$$

However, a load impedance $Z_2 = v_2/i_2$ connected to the secondary appears as a "reflected impedance" Z_1 in the primary. The reflected impedance is proportional to the **square** of the turns-ratio.

$$Z_1/Z_2 = (N)^2 \quad \text{REFLECTED IMPEDANCE RATIO}$$

For example, an audio transformer can be used to step up the impedance of a loudspeaker from 8 ohms to 1000 ohms in order to make the power amplifier more efficient. Using a transformer allows the load to be "matched" to the Thevenin impedance of the amplifier to provide maximum power transfer. Large power transformers are used to step up the voltage from the power generating station for connection to the long distance power lines. Since the transmission loss in the power lines is proportional to the square of the current, power is transmitted at as high a voltage as can be practically attained, typically thousands of volts. Power lines are mounted high above the ground for safety reasons. At the user end, another transformer is used to step the voltage down to a safe level for residential customers. These step-down transformers are about the size of a trash-can, and can be seen attached to power poles.

An ideal transformer cannot be attained. A practical transformer obeys a set of linear equations.

$$\begin{aligned} v_1 &= Z i_1 + N v_2 && \text{TRANSFORMER EQUATIONS} \\ i_2 &= N i_1 + Y v_2 \end{aligned}$$

v_1 = primary voltage

v_2 = secondary voltage

i_1 = primary current

i_2 = secondary current

Z = primary impedance, "looking forward" with a short circuit secondary

Y = secondary admittance "looking backward", with an open circuit primary

N = turns ratio n_1/n_2

The transformer equations can be described by an equivalent circuit shown in Figure 1

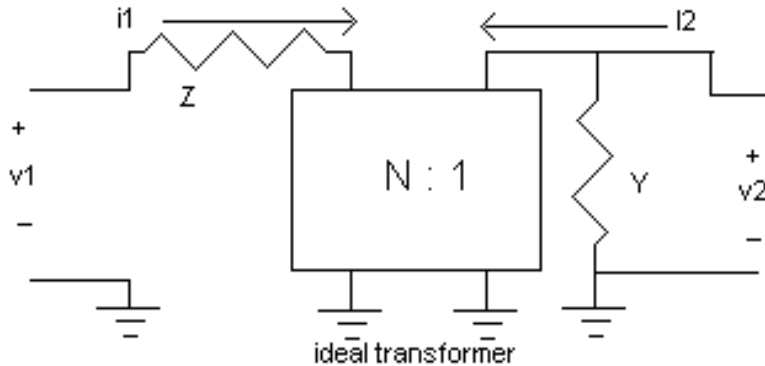


Figure 1 Equivalent circuit of a transformer, showing the parameters.

The constants N , Y , and Z are called the "**parameters**" of the transformer. If these values are measured, the transformer can be used to design a circuit for a given application. Most commercial transformers specify only the primary and secondary rated voltage, and the secondary rated current. From this information, the turns ratio can be calculated, and also the rated power. The remaining parameters must usually be measured by the user, if required. For many applications, the rated values are sufficient.

The primary impedance Z is a combination of "leakage inductance" and "resistance loss". The resistance loss is also called "copper loss".

The secondary admittance Y is a combination of "magnetization inductance" and "hysteresis loss". The hysteresis loss is also called "iron loss".

IDENTIFICATION OF TRANSFORMER PARAMETERS

Z Parameter

Using the first equation, assume that a voltage v_1 is applied "looking forward" into the primary of the transformer, while the secondary of the transformer is connected to a short circuit so that $v_2 = 0$.

Elimination of the second term allows identification of the Z parameter.

$$v_1 = Z i_1 + 0$$

$$Z = v_1/i_1 \quad \text{when } v_2 = 0$$

The impedance "looking in" appears as a resistance due to electrical losses in the coils of wire, plus a small inductance due to "leakage" of magnetic flux that does not link the secondary with the primary. It is conventional to represent the leakage inductance and wire resistance as an impedance $Z = \text{ratio a-c voltage/current}$. Impedance is a *Complex* quantity in which the *Real* part is due to the resistance and the *Imaginary* part is due to the leakage reactance.

$$Z = R_c + jX_k$$

R_c = resistance due to energy loss in the coil wires

jX_k = reactance due to magnetic flux that does not link primary with secondary

$jX_k = j 2\pi f L_k$ L_k = leakage inductance

Y Parameter

Using the second equation, assume that a voltage v_2 is applied "looking backward" into the secondary of the transformer, while the primary of the transformer is connected to an open circuit so that $i_1 = 0$.

Eliminating the first term in the equation allows identification of the Y parameter.

$$i_2 = 0 + Y v_2$$

$$Y = i_2/v_2 \quad \text{when } i_1 = 0$$

The transformer appears as an inductor, with some apparent resistance in parallel. The inductance is the "magnetization inductance" of the transformer, the voltage resulting from the rate of change of a small a-c current in the secondary coil. However, the resistance is not due to conduction in the wires, but is evidence of magnetic "hysteresis" (pronounced HISTER-REE-SIS). Hysteresis is energy lost in the process of reversing the polarity of the magnetic field in the iron core at every cycle of the applied a-c voltage. It is conventional to represent the magnetization inductance and hysteresis resistance as a parallel combination of equivalent circuit elements. The ratio of a-c current/voltage is called "admittance" = Y , the reciprocal of impedance. Admittance is a *Complex* quantity in which the *Real* part is due to the hysteresis resistance and the *Imaginary* part is due to the reactance of the magnetization.

Note: Admittance = current/voltage ratio is the reciprocal of Impedance.

$$Y = 1/R_h + 1/(j X_m)$$

R_h = equivalent resistance due to hysteresis loss

jX_m = reactance due to magnetization = $j2\pi f L_m$

L_m = inductance due to magnetization

N Parameter

The turns ratio can be determined with either equation. In the first equation, connecting an open circuit to the primary $i_1 = 0$ results in eliminating the first term so that the N parameter can be identified.

$$v_1 = 0 + N v_2 \rightarrow N = v_1/v_2 \quad \text{when } i_1 = 0$$

Using the second equation, connecting a short circuit to the secondary $v_2 = 0$ results in eliminating the second term, providing an alternative way of identifying the N parameter.

$$i_2 = N i_1 + 0 \rightarrow N = i_2/i_1 \quad \text{when } v_2 = 0$$

EXPERIMENTAL MEASUREMENT OF PARAMETERS

Short Circuit Test

The short circuit test is made from the primary side, with the secondary short circuited. By inspection of the governing equations, if the secondary is short circuited then $v_2 = 0$ and the impedance Z can be calculated by measuring the ratio voltage/current in the primary. The absolute magnitude $|Z|$ is calculated from the ratio of an applied RMS voltage to the resulting RMS current.

$$|Z| = [v_1]/[i_1]$$

The phase angle $\angle Z$ can be calculated by comparing the voltage wave to the current wave on a dual trace scope. Since the impedance is inductive, the voltage will lead the current and the angle will be positive.

$$\angle Z = \angle v_1 - \angle i_1$$

Converting from polar to rectangular gives the Real and jImaginary parts: $\Re(Z) = R_c$ & $j\Im(Z) = +jX_k$

Open Circuit Test

The open circuit test is made from the secondary side, with the primary open circuited. The admittance parameter Y seen "looking backward" into the secondary can be calculated from the ratio of the current to an applied voltage, $Y = i_2/v_2$. Since Y is a *Complex* quantity, the absolute magnitude $|Y|$ can be calculated from the ratio of the RMS voltage to the RMS current.

$$|Y| = [i_1]/[v_1]$$

The phase angle $\angle Y$ can be calculated by comparing the current wave to the voltage wave on a dual trace scope. Since the admittance Y is inductive, the current will lag the voltage, and the angle will be negative.

$$\angle Y = \angle i_1 - \angle v_1$$

Converting from polar to rectangular form (use the P-->R key on your calculator) gives the *Real* and *jImaginary* parts.

$$\Re(Y) = 1/R_h \quad j\Im(Y) = 1/(jX_m) = -j/X_m \quad \text{since } 1/j = -j$$

By inspection of the governing equations, the turns ratio parameter N can also be calculated by open circuiting the primary, which sets $i_1 = 0$, and hence

$$N = [v_1]/[v_2].$$

D. Procedure:

I. Open Circuit Test

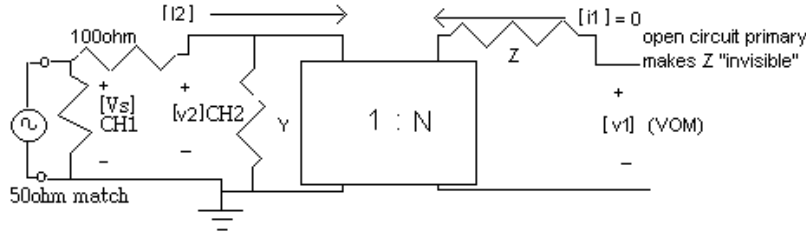


Figure 2 Open Circuit Test, made from the secondary side

The transformer is connected as in Figure 2. Make connections to the transformer using the breadboard. In this part, measurements will be made with the a-c source connected to the secondary side. The secondary side [v2] and the primary side [v1] both have three wires, the center wires are center-tap (CT) connections, and are not used in this experiment.

1. Circuit Connections:

Connect a 100Ω resistor in series with one terminal of the secondary in order to measure the current as $(V_{CH1} - V_{CH2})/100\Omega$. Connect the AC voltmeter to the wires from the transformer primary to measure [v1].

2. Measurements:

Set the input voltage [v2] to the maximum available voltage.

(a) Use VOM to measure [v1] RMS using AC VOLTS [v1] = _____

(b) Measure [v2] RMS on scope CH2 RMS [v2] _____.

Calculate the turns-ratio $N = [v1]/[v2] =$ _____

Compare to the rated turns ratio _____

(c) Measure current [i2] RMS from the voltage [Vr] RMS across the 100 ohm resistor (CH1 –CH2). $[i2] = [Vr]/100 =$ _____

Calculate the absolute magnitude of the admittance $|Y| = [i2]/[v2] =$ _____

(d) In this part you will measure the phase angle between $\sqrt{v2}$ and \sqrt{Vr} . (or $\sqrt{i2}$) Measure the time for one period T of the voltage wave, using the [CURSORS]. Measure the time difference Δt between the points where both waves are at zero going positive. Calculate the phase by the ratio of the times, multiplied by 360 degrees. The phase of the admittance is negative because the current lags the voltage (inductive circuit).

$$\angle Y = \angle i2 - \angle v2 = 360 \Delta t/T = (-) \text{_____ degrees}$$

(e) Convert from polar to rectangular $\Re(Y) =$ _____ $= 1/R_h$ $R_h =$ _____ ohms

$$jIm(Y) = \text{_____} = 1/(jX_m) + jX_m = \text{_____ ohms}$$

II. Short Circuit Test

1. Circuit Connections

The transformer is connected as in Figure 3. (It is not necessary to rebuild the circuit. Just reverse the connections of the transformer to the rest of the circuit). The 100 ohm resistor is now inserted in series with the primary in order to measure the current. The Signal Generator is connected to the primary. A short circuit (jumper wire) is connected to the secondary. The AC VOLT meter is not used in this part.

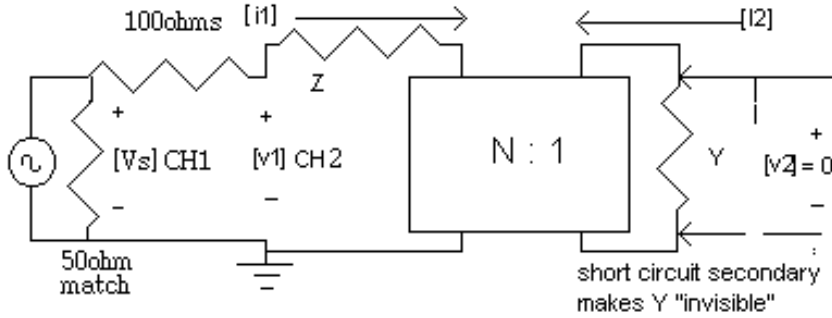


Figure 3 Short Circuit Test, made from the primary side.

2. Measurements

(a) Measure [v1] RMS. [v1] = _____

(b) Measure the voltage across the 100 ohm resistor (CH1-CH2) [Vr] = _____

Calculate [i1] RMS = [Vr]/100 = _____

Calculate |Z| = [v1]/[i1] = _____ ohms

(c) Measure the phase angle between $\angle v_1$ and $\angle V_r$ using the same procedure as in part I. The resistance will dominate so the phase angle will be small.

$\angle Z = \angle v_1 - \angle i_1 = 360 \Delta t/T = (+) \text{ _____ degrees}$

(d) Convert from polar to rectangular $\Re(Z) = \text{_____} = R_c \text{ ohms}$

$j\text{Im}(Z) = \text{_____} = jX_k \text{ ohms}$

Measure the d-c resistance of the secondary with the OHM meter = _____

Measure the d-c resistance of the primary with the OHM meter = _____

Calculate the secondary resistance "reflected" to the primary as $(R_{sec}) \times N^2 = \text{_____}$

Add the reflected secondary resistance d-c to the primary d-c resistance

$R_{sec} \times N^2 + R_{pri} = \text{_____}$

Compare the sum to R_c measured from Z. Theoretically they should be the same.

$R_c = \text{_____}$ Fractional error = _____

There is no D-C resistance corresponding to R_h , because this "resistance" is only present for ac voltages and currents.

E. Summary: (To be completed at the end of lab)

Comment on this experiment. What did you learn?

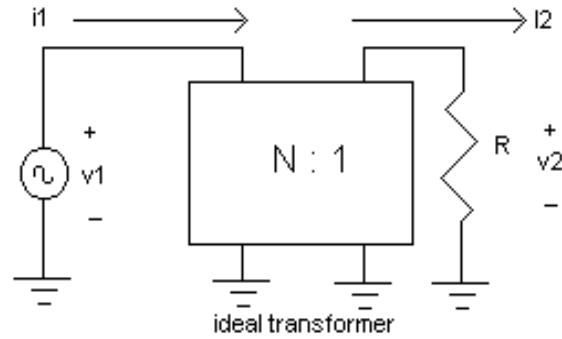
Were there any surprises?

What formulas do you need to remember?

F. Homework:

1. Given an ideal transformer, $N = 12$. A resistance $R = 8$ ohms is connected to the secondary. The voltage on the primary is $v_1 = 14$ volts.

$v_2 =$ _____ volts $v_1/i_1 =$ _____ ohms



2. Given a lossy transformer. The open circuit test is made from the secondary side. The measured value of the input admittance $Y = 1/R_h + 1/jX_m = i_2 / v_2 = 0.12 \angle -30$ degrees.

$R_h =$ _____ ohms $jX_m =$ _____ ohms

