Exploring Transformer Basics

Understanding Transformers: Part 1

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Abstract: The purpose of this application note is to provide a brief introduction about the operation of transformers and to explore how the transformer parameters are measured, including magnetizing inductance, leakage inductance and turn ratio.

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Terminology

Primary Voltage
The voltage that is fed to the primary windings of a transformer

Secondary Voltage
The voltage that is induced at the secondary windings of a transformer

Magnetizing (Primary) Inductance
The ability of the primary windings to induce a magnetic flux that links through the iron core with the secondary windings and contribute to the induction of the secondary voltage

Leakage Inductance
The parasitic characteristic of the primary windings to generate a leakage magnetic flux that does not contribute with the main magnetic flux in the induction of the secondary voltage

Turn Ratio
The ratio of the number of turns in the primary windings to the number of turns in the secondary windings

Introduction to Transformers

A transformer, in its simplest, structure is a two-terminal device that increases or decreases the voltage level of an AC input voltage. As illustrated in Figure 1, a transformer consists of three main components: primary windings, secondary windings and Iron Core.

When an AC voltage is applied to the primary windings, a magnetic flux is generated, as described by Faraday's law of induction:

$$V_p = N_p \frac{d\Phi_1}{dt}$$

Equation 1

Whereas:
V_p = Voltage applied at the primary
N_p = Number of turns of the primary windings
$\frac{d\Phi_1}{dt}$ = Rate of change of the generated magnetic flux with respect to time

The induced alternating magnetic field permeates through the iron core to the secondary windings and induces a voltage at the secondary, as indicated by Faraday's law of induction:

$$V_s = N_s \frac{d\Phi_2}{dt}$$

Equation 2

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Whereas:
V_s= Voltage induced at the secondary
N_s= Number of turns in the secondary windings
$\frac{d\Phi_2}{dt}$=Rate of change of the magnetic flux that permeates the secondary windings with respect to time

Ideally, all the changing magnetic flux generated by the primary is used to induce voltage at the secondary. Therefore:

$$\frac{d\Phi_1}{dt} = \frac{d\Phi_2}{dt}$$

Equation 3

By dividing Equation 1 by 2 and from Equation 3:

$$\frac{Vp}{Vs} = \frac{Np}{Ns} = n$$

Equation 4

Whereas:
n = Turn ratio

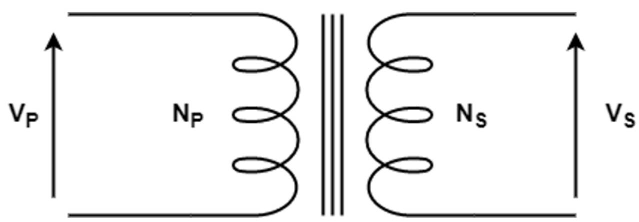

Figure 1: Ideal Transformer

From Equation 4 above, the primary voltage is related to the secondary voltage through the turn ratio. By choosing a turn ratio for a given input voltage, the secondary voltage can be set to the desired level. [1]

Magnetizing (Primary) Inductance

The relationship between the different currents in the transformer is as shown in Figure 2 and Equation 5 below:

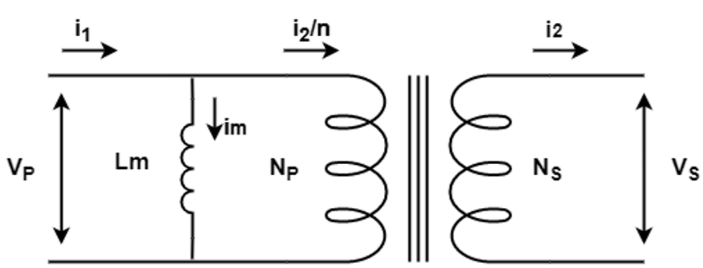

Figure 2: Currents Flowing Through the Transformer

$$\boldsymbol{i_1 = \frac{\Phi R}{N_p} + \frac{N_s}{N_p} i_2 = i_M + \frac{i_2}{n}}$$

Equation 5

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Whereas:
i_1= Primary terminal current
i_2= Secondary terminal current
i_m= Magnetization current
Φ = Induced magnetic flux in the iron core
R = Reluctance of the iron core
N_p= Number of turns in the primary windings
N_s= Number of turns in the secondary windings
n = Turns ratio (N_p/N_s)

When the primary windings are energized in no-load condition, ideally the transformer should represent an infinite impedance, and no current should flow through the primary windings since the secondary current is zero due to open circuit condition (i_2=0). However, in practice, a magnetizing current (i_m) will be running through the primary terminal due to the induced magnetic field in the iron core, as indicated by Equation 5. By utilizing this observation, the magnetizing inductance that is responsible of i_m can be measured as outlined in the following section.

Magnetizing (Primary) Inductance Measurement

1. To measure the magnetization inductance, the secondary windings are left open so that the current running through it becomes zero.
2. When selecting the testing frequencies, it is important to consider the self-resonance frequency (SFR) of the windings. The higher the frequency, the more the parasitic capacitance starts to dominate. Therefore, it is recommended to keep the testing frequency at least 20% less than the SRF of the transformer. [2]
3. The testing current must be set such that the core operates in the linear region of the BH Curve to avoid core saturation.
4. Below are the recommended testing conditions for the anticipated inductance value. [2]

INDUCTANCE RANGE	PREFERRED TEST SIGNAL	
	FREQUENCY	VOLTAGE
100nH → 1uH	300KHz	10mV
1uH → 10uH	100KHz	30mV
10uH → 100uH	30KHz	50mV
100uH → 1mH	10KHz	100mV
1mH → 10mH	1KHz	100mV
10mH → 100mH	100Hz	100mV
100mH → 1H	100Hz	300mV
1H → 10H	50Hz	1V
10H → 100H	50Hz	5V
100H → 1KH	50Hz	5V
1kH → 10KH	20Hz	5V

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5. By connecting the LCR meter probes to the primary terminals, the meter's reading will reflect the total inductance (L_{total})

$$L_{total} = L_m + L_p$$

Equation 6

Whereas:
L_m= Magnetization inductance
L_p= Leakage inductance

6. Since both L_{total} and L_p (refer to "Leakage Inductance Measurement" section) are known, the value of the magnetizing inductance (L_m) can be easily calculated from Equation 6 above.

Leakage Inductance

By nature, not all the of the magnetic flux that is induced by the primary windings interacts with the secondary windings. Some leakage flux will self-link back to the primary coil without contributing to the main flux, as shown in Figure 4. This is represented in the transformer model by a series inducive reactance X_p , as shown in Figure 3 below:

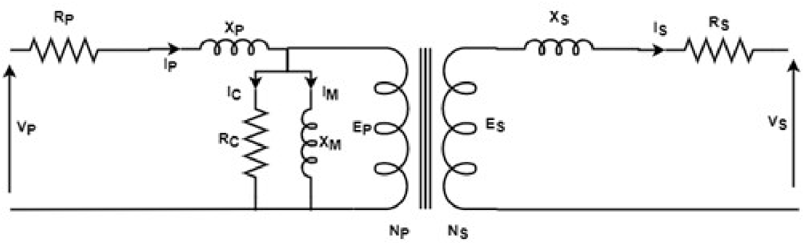

Figure 3: Non-Ideal Model of transformer

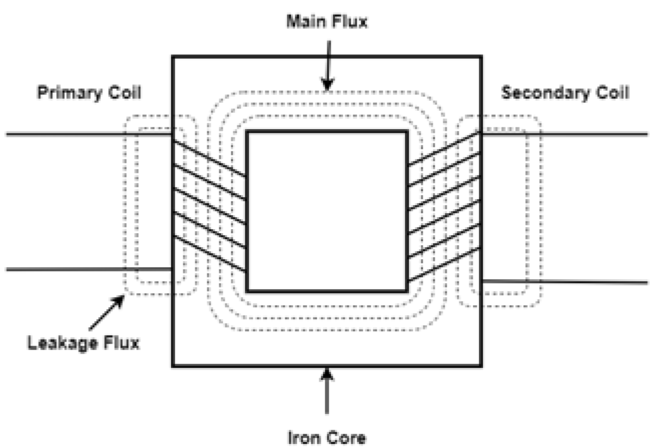

Figure 4

Leakage Inductance Measurement

1. To measure the value of the leakage inductance, the secondary windings are shorted so that the voltage across it becomes almost zero. (While reaching zero is ideal, it is practically impossible to achieve because short circuit resistance cannot be equal to zero.) Therefore, the induced voltage (E_p) of the primary windings becomes almost zero.

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2. By connecting the LCR meter to the primary terminals, the measured inductance value will reflect the leakage inductance.
3. When selecting the testing frequencies, it is important to consider the Self-Resonance Frequency (SFR) of the windings. The higher the frequency the more the parasitic capacitance starts to dominate. Therefore, it is recommended to keep the testing frequency at least 20% less than the SRF of the transformer. [2]
4. The testing current must be set such that the core operates in the linear region of the BH Curve to avoid core saturation.
5. Below are the recommended testing conditions based on the anticipated leakage inductance value. [2]

LEAKAGE INDUCTANCE RANGE	PREFERRED TEST SIGNAL	
	FREQUENCY	CURRENT
100nH → 1uH	300KHz	50mA
1uH → 10uH	100KHz	20mA
10uH → 100uH	30KHz	10mA
100uH → 1mH	10KHz	5mA
1mH → 10mH	1KHz	5mA
10mH → 100mH	100Hz	5mA
100mH → 1H	100Hz	1mA
1H → 10H	50Hz	500µA

Turn Ratio

Turn ratio is defined as the ratio of the number of turns in the primary windings to the number of turns in the secondary windings. This parameter is crucial to determine the secondary voltage for a given primary voltage, as indicated in Equation 4.

Turn Ratio Measurement

One way to measure the turn ratio of a transformer is by using a signal generator and an oscilloscope.

1. A sinusoidal wave is applied at the primary of the transformer, while the output from the secondary terminals is observed using an oscilloscope.
2. Using the value of voltage applied by the signal generator (Vp) and the measured voltage by the oscilloscope (Vs), the turn ratio can be easily calculated using Equation 4.
3. It is important to note that each transformer has gain characteristics that change with frequency. Hence, the output measured by the oscilloscope may not be what is expected at extremely low or high frequencies. The frequency band at which the gain is not attenuated varies from one transformer to another. Therefore, the applied frequency from the signal generator must be adjusted to a range where the amplitude of the voltage seen on the oscilloscope is almost constant.
4. The applied voltage from the signal generator must be selected carefully based on whether the transformer being tested is a step-up or step-down transformer. The voltages and current levels should not exceed the rated values of the oscilloscope input channel and probes as well as the transformer primary windings and secondary windings.
5. If, for example, the turn ratio of a transformer is 1:100, putting 5V at the primary results in 500V across the secondary, which might be beyond the measuring capabilities of the oscilloscope. Therefore, it

is recommended to apply the testing signal to the side with the higher number of turns so that the voltage at the secondary is lower. However, this means the current value is increased and therefore, choosing a low current value (in mA or uA range) is advised.

6. It is not necessary to perform this test at the rated voltage or the intended operation voltage to calculate the turn ratio.

Conclusion

In this application note, the basic operation of the transformer and how some of its parameters are measured has been explored. A measurement of the magnetizing inductance can be performed in the lab by using an LCR meter. The secondary terminals are left open while the inductance is measured at the primary terminals. The meter's reading will correspond to the total inductance and by subtracting the leakage inductance from the total value, L_m the value can be obtained. The leakage inductance can also be measured in the lab by using an LCR meter. In this case, the secondary terminals are shorted while the inductance is measured at the primary terminals. The inductance reading will correspond to the leakage inductance (L_p). The turn ratio of a transformer is calculated by applying a voltage at the primary windings and measuring the voltage at the secondary terminal. By utilizing the relationship between the voltages and the turn ratio, the leakage inductance can be easily calculated.

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[2] Wilde Theodore. Electrical Machines, Drives and Power Systems, sixth. Taramani, Chennai: Pearson India, 2014.

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