ECE-385L-001- Electric Machine Lab

Lab Instruction Sheet- Session 4 (Experiment-3)

Experiment #3: Multi-Winding Transformers

The purpose of the experiment is to familiarize students with the multi-winding transformer, the experimental determination of the transformer equivalent circuit and its performance under load.

1. **BACKGROUND**

1.1. Transformers with output and input taps.

The power transformer is used for stepping up or down the supply voltage to match the voltage of the load. Fig. 1(a) shows a two-winding step-down transformer.

It is possible to create multiple secondary outputs for the purpose of supplying loads of different voltage rating by tapping the secondary winding of the transformer at different turn ratios. Fig. 1(b) shows a two- winding transformer where the secondary carries three outputs defined by the turn ratio 25:4:3:1.5. This is the ratio between the turns of the primary winding, the turns of the full secondary winding (a-d), the turns between b-d, and the turns between c-d. The name plate description of the same transformer will read 240-38.4/28.8/14.4 V. A dash "-" separates the primary and secondary voltages; a slash "/" is used to separate the different output voltages. The outputs can all be loaded simultaneously, or only one can be selected through a switch according to the application requirements.

It is also possible to tap the primary winding, as it is in fig 1(c). With reference to that figure, 25:12.5:4 is the ratio between the full primary turns (H1-H3), the primary turns between H2-H3 and the full secondary turns X1-X2. The need for tapping the primary is to allow the transformer to supply the same rms voltage under different supply voltages: in the example of fig 1(c), the transformer will supply 38.4 V to the load, if it is fed either from a 240- or a 120-V supply (e.g. a useful application when traveling across countries with different nominal utility voltage). The practical description of this transformer is 240/120-38.4 V.

Finally fig. 1(d) shows a very common application: the center-tap transformer. Here the center tap is used as a common terminal on the secondary side (often grounded). This transformer provides two equal voltages—note that the voltages have opposite phase. Applications include utility transformers and rectifier transformers.

1.2. Transformers with multiple windings

Multiple outputs can also be obtained using multiple windings (the windings are commonly distinguished by referring to them as primary, secondary, tertiary, and so on). The main reason for using multiple windings rather than tapping the secondary winding multiple times is to obtain galvanic isolation between the outputs. All the windings (primary, secondary, etc.) are wound around the same limb of the magnetic core so they see the same core flux. Only the terminals of one of the windings, namely the primary, are connected to the source; the terminals of the other windings are connected to the loads. Fig. 1(e) shows a three-winding transformer. The ratio 20:4:1 is the turns ratio between windings 1, 2 and 3 respectively. A practical description of this transformer in terms of the nominal voltages will be 120-24$\times$ 6 V.

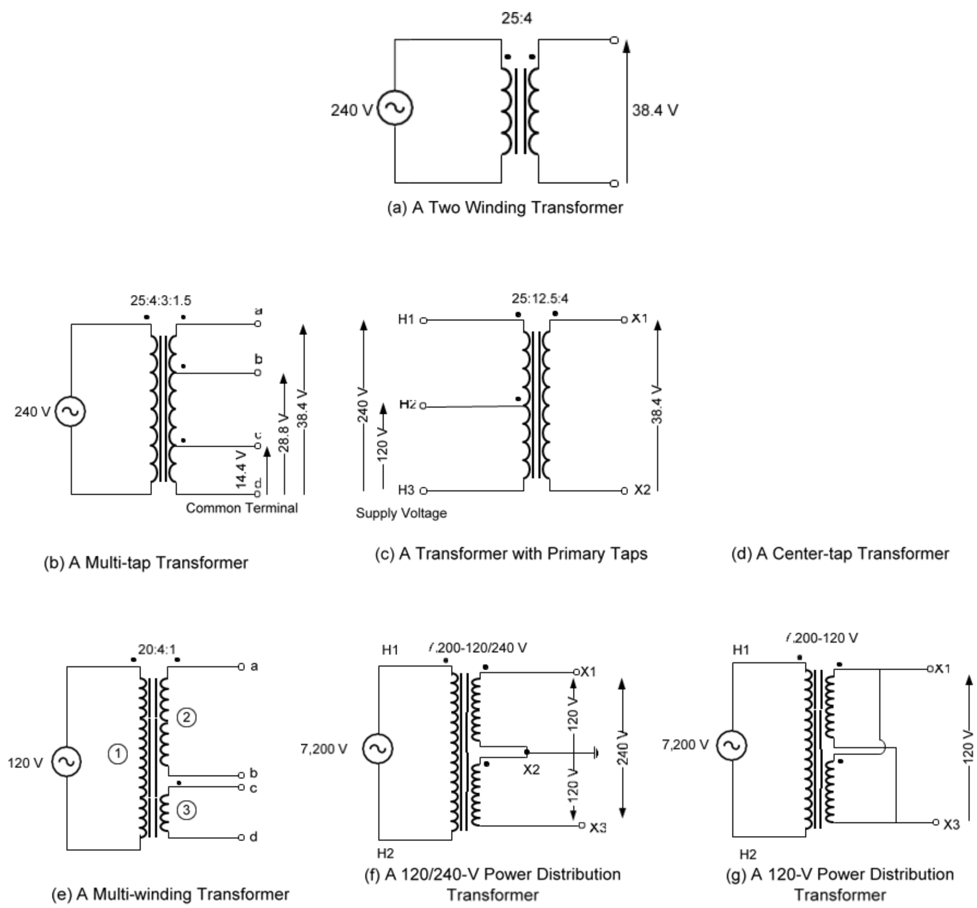

Fig. 1. different Transformer Types and Connections

In certain applications it is possible to connect the two output windings in series to obtain the sum voltage. In fig. 1(e), by connecting the 24-V and 6-V windings in series, a 30-V output is obtained. Transformers that are of general use may have multiple windings and taps to permit different configurations in order to achieve the desired output voltage level.

Fig 1(f) shows an application of the power distribution transformer used in residential power supply. The secondary consists of two equal windings each rated at 120 V. The two secondaries are connected in series to obtain a 120/240-V supply. This is the usual configuration of the distribution transformer: lights, outlets and medium power appliances are connected between either one of the 120-V terminals and the center one (ground); heavy loads such as electric stoves, heaters and driers require a 240-V supply, so they are connected between the two 120-V terminals. On some occasions where the 240-V supply is not needed, the secondaries can be paralleled to create a single 120-V system (i.e., in fig 1(g)). Two parallel secondaries can carry twice as much current. However, when paralleling two windings it must be made certain that they have the same rated voltage.

The primary current of a multiple winding or multiple tap transformer is calculated using Ampère’s law:

$$n_1 I_1 - n_2 I_2 - n_3 I_3 - \ldots = 0, \qquad (1)$$

where, I_1, I_2, I_3, etc. are respectively the current phasors of the primary winding (assumed to enter the dotted terminal) and each of the secondary windings (assumed to exit the dotted terminal), n_1, n_2, n_3, etc. are corresponding members in the transformer turns ratio, $n_1 : n_2 : n_3 \ldots$

1.3 Transformer operation under load

A usual approximation of the transformer equivalent circuit under normal load is to ignore the excitation branch during the solution and to add its effects later (i.e., the excitation current and core loss). Fig. 4 shows the equivalent transformer circuit during normal loading: only the effects of the series impedance are represented.

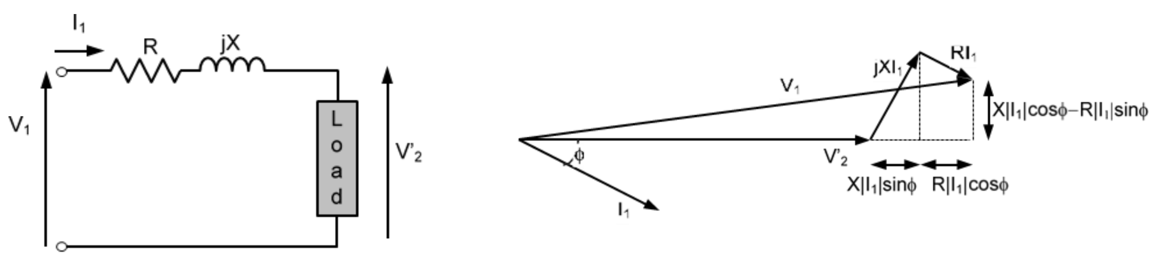

Fig. 4. The Transformer Equivalent Circuit and Phasor Diagram under Load.

$$V_1 = V'_2 + (R + jX)\, I_1 \qquad (2)$$

In (2), V'_2 is taken as the rated rms value (full load voltage). I_1 is calculated from the load (e.g., from the load power and power factor). The phasor diagram in the same figure shows a convenient approximation to obtain the rms value of the primary voltage. From the diagram, we see that the magnitude V_1 is approximately equal to its projection across the direction of V'_2. By inspection of the diagram:

$$\left|V_1\right| \approx \left|V'_2\right| + (R\cos(\phi) + Xsin(\phi))\left|I_1\right| \qquad (3)$$

Therefore, the voltage regulation is:

$$vr = \frac{V_{NL} - V_{FL}}{V_{FL}} 100\% = \frac{\left|V_1\right| - \left|V'_2\right|}{\left|V'_2\right|} 100\% \approx \frac{R\cos(\phi) + X\sin(\phi)}{rated\ rms} \left|I_1\right| 100\% \qquad (4)$$

Eq. (11) shows the effect of the load power factor on the voltage regulation. Since X>>R, a low power factor implies a higher value of the voltage regulation. This means that the voltage across the load will be appreciably less than its rated value.

The copper losses under load are:

$$P_{CU} = R|I|^2 \quad (5)$$

To calculate the total loss in the transformer, we must add to (12) the core losses—these are the no-load losses P_{OC} measured in the open circuit test that remain constant under load. Therefore, the total losses are:

$$P_{loss} = P_{CU} + P_{OC} \quad (6)$$

P_{loss} is the full load loss when the transformer draws its rated current. The power supplied to the primary winding equals the real power of the load PL plus the total losses in (6). Therefore, the power efficiency of the transformer is calculated as follows:

$$\eta = \frac{P_L}{P_L + P_{loss}} 100\% = \frac{P_L}{P_L + R|I|^2 + P_{OC}} 100\% \qquad (7)$$

2. EXPERIMENTAL PROCEDURES

2.1 **<u>Measurement of the transformer ratios</u>**: The purpose is to measure the turn ratios of a multi-terminal transformer.

<u>Equipment</u>: Hampden ET-100 Single-phase multi-terminal transformer.

<u>Procedure:</u>

1. **<u>Become familiar</u>** with the Hampden ET-100 transformer. This is a multi-input and multi-output transformer. Each side has two equal windings. All windings are wound in the same core. The windings of the same side can be combined to provide different voltage levels for input or output.
2. **<u>Connect the transformer primary and secondary</u>** windings in series, as shown in fig. 5. Make sure the terminal switches are in the <u>up</u> position. The transformer connected in this manner is used as a step- up transformer: the X side (low voltage) will be connected to the source and become the primary side; the H side (high voltage) will be connected to the load and become the secondary side.
3. **<u>Apply</u>** 60 V across X1-7, and **<u>measure</u>** with a hand-held voltmeter the voltages between H1-5, H2-5, and H4-5. Also measure the voltages between X1-4, X2-4, X5-7, and X6-7.

	VOLTAGE
H1-5	
H2-5	
H4-5	
X1-4	
X2-4	
X5-7	
X6-7	

THE GOAL IS TO CALCULATE THE TURNS RATIOS FROM THESE.

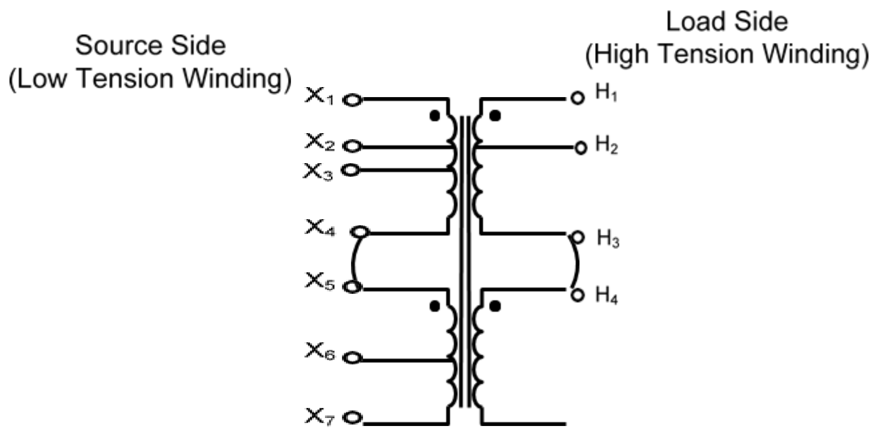

Fig. 5. The Hampden ET-100 transformer connected as a step-up transformer: windings on each side connected in series

2.2 Open circuit and short-circuit tests: perform the open circuit and short circuit tests on the transformer in order to determine its equivalent circuit.

Equipment: Hampden ET-100 Single-phase multi-terminal transformer. The transformer windings remain configured as per fig. 5. Use the handheld ammeter and a handheld wattmeter due to the small size of measurements.

Procedure:

① CONNECT

1. Before making any connections, make sure the power source is turned off and the voltage knob is turned to zero. Connect the transformer as in fig. 6 (for the OCT) or 7 (SCT), with the X side (primary side) connected to the variable source and the instruments shown in the figure.

② OPEN-CKT TEST @ 60V

2. Connect the transformer as in fig. 6. Using a similar procedure as in experiment 2, perform the OCT at the rated primary voltage (60 V).

③ SHRT-CKT TEST @ 0.8A

3. Make sure the power source is turned off and the voltage knob is turned to zero. Connect the transformer as in fig. 7. Using a similar procedure as in experiment 2, perform the SCT at 0.8 A primary current. BE CAREFUL the source voltage must be varied very slowly in this part.

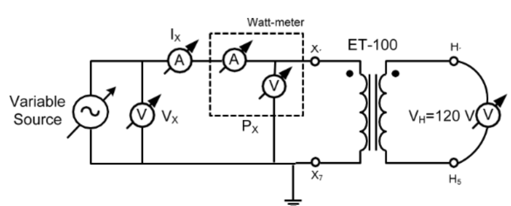

Fig. 6. The connections for the open-circuit test

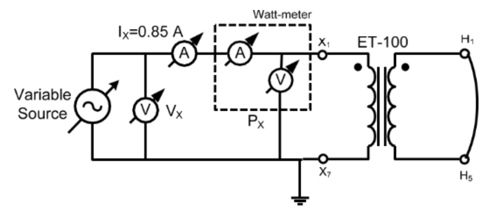

Fig. 7. The connections for the short-circuit test

2.3 Operation under load: to measure the transformer performance under load; to observe the effects of the load power factor on the transformer voltage regulation.

Equipment: Hampden ET-100 Single-phase multi-terminal transformer—configured as in the previous procedures, the Hampden RLC-100 variable resistive and reactive load.

Procedure:

I. Before performing any connections, make sure the power source is turned off and the voltage knob is turned to zero position. Make the connections in fig. 8. Connect the current and wattmeter to the secondary (H side). Connect the resistive and reactive part of one phase of the RLC-100 load across the secondary as shown in the figure. Leave the terminals of the other phases open.

II. Add resistive load. Turn switches 1 through 4 of the resistive loads to the up position and the remaining switches in the down position.

III. Turn the reactance knob to the full lagging position. do this for FULL LAG, ZERO, FULL LEAD.

IV. Adjust the primary voltage until the secondary voltage is 120 V. Record the primary voltage V_X, the load current I_H, the load power P_H.

V. Turn the reactance knob to zero position. Fine-tune the position by observing where the secondary current indication is at its minimum. Repeat 4.

VI. Turn the reactance knob to the full leading position. Repeat 4.

VII. Power down, break the connections, store the equipment. Experiment done.

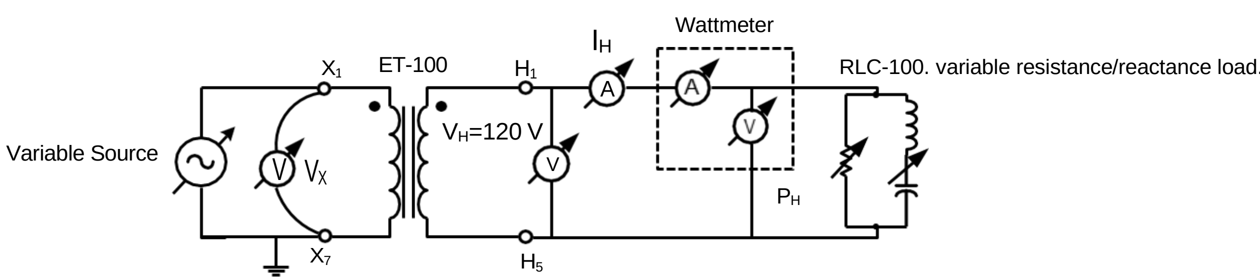

Fig. 8. The connections for the measurements under load

For the report:

- Calculate the turns ratios of this transformer from procedure 2.1.
- If 30 V are applied across X1-4, what will be the voltage across X1-2, X5-7, X6-7, H1-3, H2-3, and H4- 5?

- If the X side is connected in series (X1-7) and the H side as H1-**2**-**4**-5 and 60 V are applied across the X side, what voltage will develop across the H side? What voltage develops across X1-2?
- If the H-side windings were combined in parallel rather than in series (i.e. H1-3//H4-5), how much voltage will be developed across the secondary side when X1-7 is 60 V?
- Calculate the transformer equivalent circuit seen from the primary (X-side).
- How much are the no load losses of this transformer?
- How much reactive power is consumed by the core?
- Calculate for each load in part 2.3 (a) the power factor of the load, (b) the voltage regulation, and (c) calculated from the transformer equivalent circuit, the transformer efficiency.
- Discuss the previous results.

<u>Picture of the equipment:</u>

1. Hampden ET-100 Single Phase Multi Terminal Transformer

2. Hampden RLC-100 Variable Resistive and Reactive Load

3. Handheld Multi Meter

4. Handheld Watt Meter