EXPERIMENT P8: SINGLE-PHASE TRANSFORMER

Related course: KIE3009 (Energy Conversion and High Voltage Transmission)

OBJECTIVES:
1. To determine the turns ratio and the equivalent circuit parameters of a transformer from the open and short-circuit tests
2. To perform a load test with a resistive and a capacitive load and predict the results from the equivalent circuit

EQUIPMENT:
Transformer, voltmeter, ammeter, resistive load, capacitive load

INSTRUCTIONS:
1. Record all your results and observations in a log book / paper
2. Follow the experiment procedure properly

REFERENCE(S):
Refer to the main references of KIE3009

TEST:
TEST 1: Open-Circuit Test (no load test)
TEST 2: Short-Circuit Test (full load test)
TEST 3: Load Test

INTRODUCTION

A transformer is an electrical device designed on the concept of magnetic coupling. It uses magnetically coupled coils to transfer energy from one circuit to another. In power systems, it is used for stepping up or down the AC voltage or current. In electronic circuits (e.g. radio, TV), it is used for impedance matching, isolating one part of a circuit from another and stepping up or down AC voltage and current.

For transformers operating at 50 or 60 Hz in power systems, they can handle several hundred megawatts of power and weigh a hundred tons. In communication system, microwatts of power are involved and the frequency is hundreds of megacycles but the physical dimensions of the transformers are only fractions of an inch. Although the principles of operation are the same, the constructions vary widely.

Transformer equivalent circuit

An ideal transformer has no resistance and the magnetic material of the core has infinite permeability, no saturation, no hysteresis, no eddy currents under alternating magnetisation, no internal power dissipation, the voltage level is changed by the turns ratio and the instantaneous input and output power is always equal (efficiency = 100%).

In real transformers, the resistance of the windings and the losses in the core absorb some of the input power. Hence, the efficiency of a real transformer is not 100%. Since air is not a magnetic insulator, some of the flux leaks out of the iron and therefore, the two windings are not linked by exactly the same amount of flux. To indicate that the characteristics of a real transformer are related to an ideal transformer, a real transformer can be represented by an equivalent circuit as shown in Fig. 1.

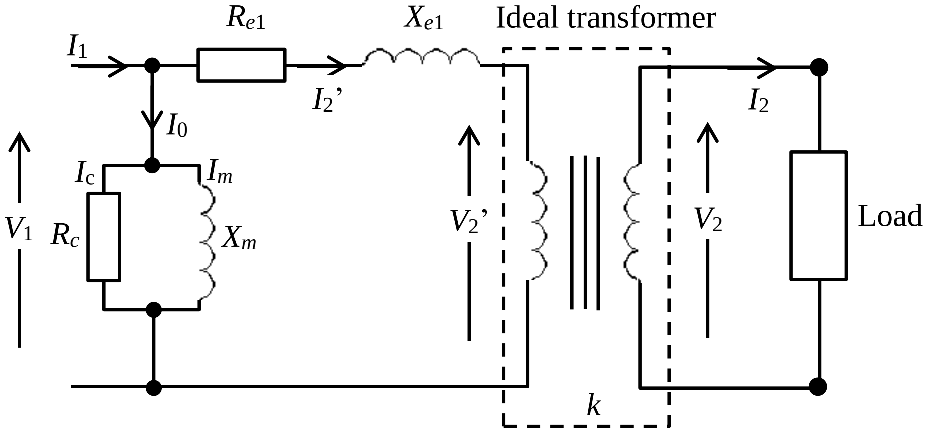

Fig.1: Equivalent circuit of a real transformer

where

X_1, X_2 = leakage reactance (represents voltage drop due to flux leakage)
R_1, R_2 = winding resistance
X_m = magnetising reactance
R_c = resistance representing core losses
I_0 = no-load current
I_m = magnetising current
I_c = eddy current and hysteresis loss in the core
I_2' = current to neutralize secondary Magnetomotive force (mmf)
V_1 = primary voltage
k = turns ratio of the ideal transformer = $N_1/N_2 = V_1/V_2 = I_2/I_1$
R_{e1} = equivalent primary resistance referred to primary side
X_{e1} = equivalent primary reactance referred to primary side

$$V_2' = (N_1/N_2)V_2$$
$$I_2' = (N_2/N_1)I_2$$

$$V_1 = V_2' + (R_{e1} + jX_{e1})I_2'$$

$$R_{e1} = R_1 + (N_1/N_2)^2 R_2$$
$$X_{e1} = X_1 + (N_1/N_2)^2 X_2$$
$$Z_{e1} = R_{e1} + jX_{e1}$$

When the real transformer is supplying a load, I_2' and I_2 in the equivalent circuit are no longer zero and the series resistance R_{e1} and X_{e1} represent the loss produced by the current in the transformer. As the transformer is loaded, the secondary voltage does not remain constant. Due to the power loss in R_{e1}, the output power is less than the input power.

Transformer Regulation

The equivalent circuit parameters can be used to deduce the voltage regulation of the transformer (i.e. variation of the secondary voltage with secondary current for constant primary voltage). This deduction can be easily made by referring to the vector diagram shown in Fig. 2 (developed from Fig. 1). Since the voltage drops in R_{e1} and X_{e1} are very small compared to V_1 and V_2, the angle θ is very small. Therefore,

$$V_1 = V_2' + R_{e1}\, I_2' \cos\phi + X_{e1}\, I_2' \sin\phi = V_2/k + kI_2\,(R_{e1} \cos\phi + X_{e1} \sin\phi) \qquad (1)$$

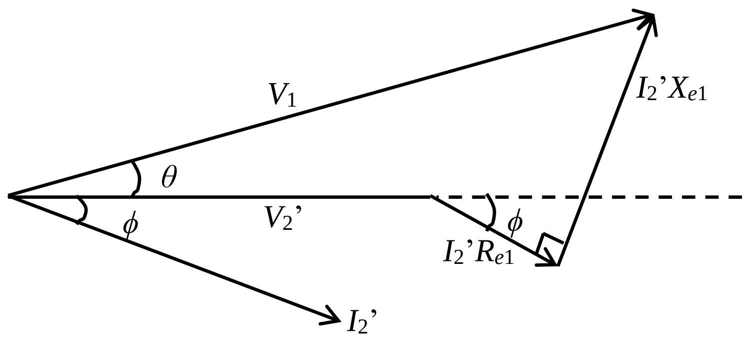

Fig 2: Transformer vector diagram

TEST 1: Open-Circuit Test (no load test)

The open-circuit test is performed to find the ideal turns ratio $k = V_1/V_2$ and to study the magnetising current I_m. The secondary side of the transformer is left open. Connecting a voltmeter across the secondary side does not complete the current path. If the wattmeter reading (iron core loss) is taken with V_1 at its rated value, R_c and X_m of the equivalent circuit could be obtained.

PROCEDURES:

1. For open-circuit test, connect the circuit as shown in Fig. 3. The metal frame of the transformer should be connected to the variac earth. The variable voltage AC supply is taken from a variable autotransformer, referred to as a "Variac."
2. Set the primary voltage V_1 (using variac) to 0, 40, 80, 120, 160, 200 and 240V. For each V_1, record the primary current I_1 using ammeter and secondary voltage V_2 using voltmeter. Record the results in a table with columns of V_1, I_1 and V_2.
3. Then, for each pair of V_1 and V_2, calculate the turns ratio $k = V_1 / V_2$.

Notes: When using the variac, it is important that the variac is set to 0V before the main supply switch is turned on and it is returned to 0V before the supply switch is turned OFF. The voltage scale and pointer on the variac gives only an approximate indication of voltage and should not be used as a substitute for voltmeter readings.

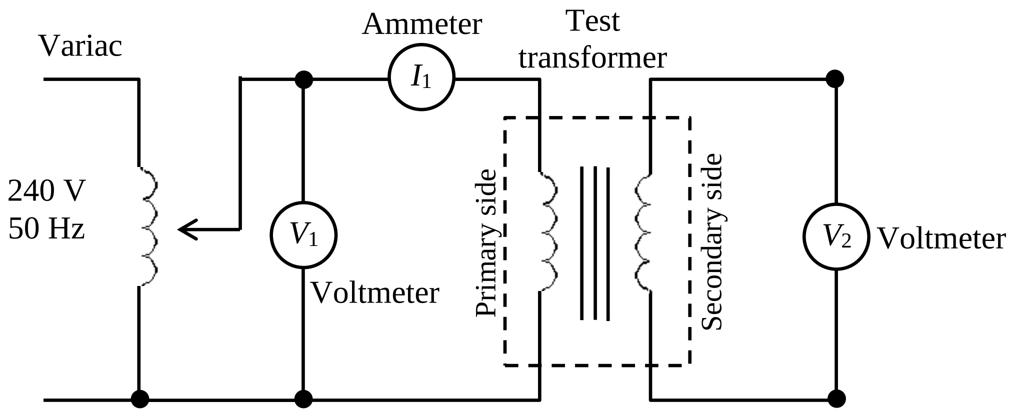

Fig. 3: Open-Circuit Test

TEST 2: Short-Circuit Test (full load test)

The short circuit test is performed to calculate the ideal turns ratio $k = I_2 / I_1$ and to find the value of R_{e1} and X_{e1} (the series impedance referred to the primary side). The secondary side of the transformer is short-circuited using an ammeter. If the wattmeter reading (copper loss) is taken with I_2 at its rated value, R_{e1} and X_{e1} could be calculated.

PROCEDURES:

1. Calculate the rated current I_2 from the information given in the transformer nameplate data. The nameplate data can be seen on top of the transformer. Hint: $S = V_2I_2$, where S is the transformer power in VA and V_2 is the secondary voltage in Volt.
2. For short-circuit test, connect the circuit as shown in Fig. 4.
3. When the secondary side is short-circuited, the voltage V_1 required to produce the rated current is much lower than the normal operating voltages. It is therefore very

important that at the beginning of this test, the variac is set to 0V. After switching on, only a small change in the variac from 0V is required to circulate full load current.

4. Set the primary voltage V_1 (using variac) to 0, 1, 2, 3, 4 and 5V. For each V_1, record the primary current I_1 and secondary current I_2 using ammeter. Record the results in a table with columns of V_1, I_1 and I_2.
5. Then, for each pair of I_1 and I_2, calculate the turns ratio $k = I_2 / I_1$.

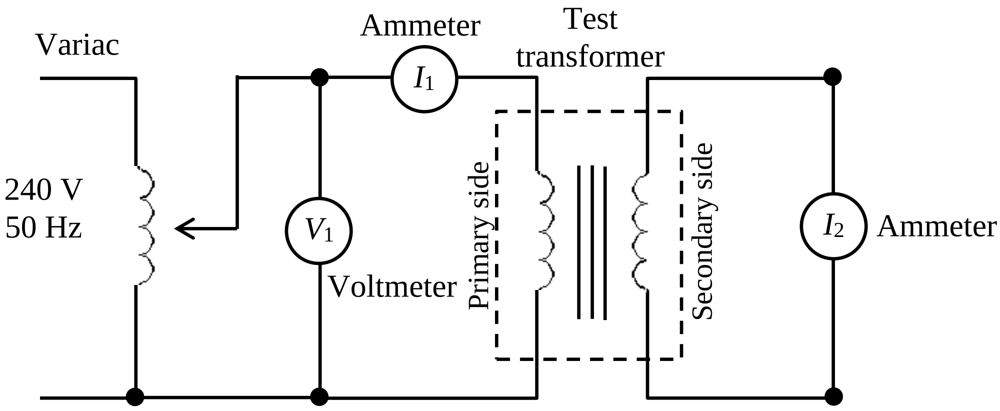

Fig. 4: Short-Circuit Test

TEST 3: Load Test

PROCEDURES:

1. Connect the circuit as shown in Fig. 5. For the load, use a purely resistive load.
2. Set the primary voltage V_1 to 240V by using the variac. Adjust the load so that the secondary current I_2 is as minimum as possible. Record I_2, I_1 and V_2 in a table.
3. Keeping V_1 constant at 240V, adjust the resistive load so that I_2 increases by 0.1 A. Record I_2, I_1 and V_2.
4. Repeat step 3 until the resistive load reaches the minimum point.
5. Switch OFF the power supply. Change the load to a purely capacitive load.
6. Keeping V_1 constant at 240V, turn ON one switch of the capacitive load and record I_2, I_1 and V_2. Turn ON another switch of the capacitive load and record I_2, I_1 and V_2. Repeat this step until all switches are turned ON.

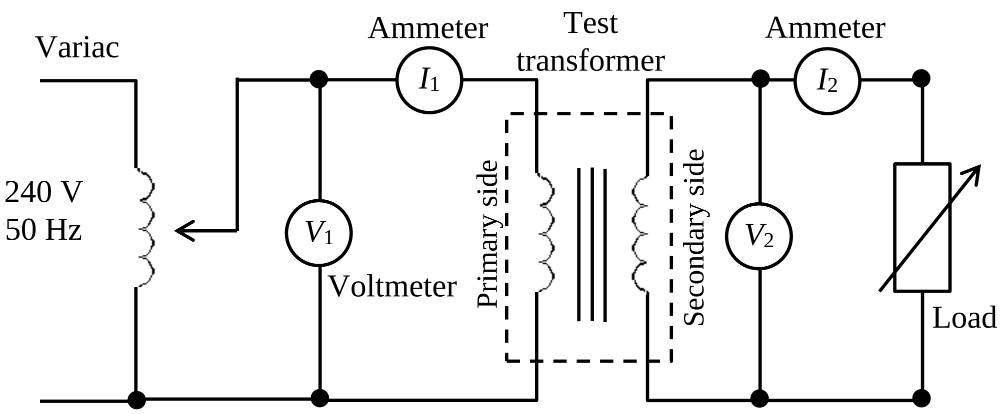

Fig. 5: Load Test

QUESTIONS:

A. Open Circuit Test (TEST 1)

1. Sketch a simplified equivalent circuit of the transformer at open-circuit test.
2. From your table, plot V_1 (on y-axis) against the current I_1 and calculate turns ratio $k = V_1/V_2$ for each I_1. Analyse and discuss your results.
3. From no. 2, notice that the current I_1 is not a linear function of V_1. Explain why.
4. What value is the transformer turns ratio k? (take the average value)
5. If P_{oc} = 8.5 Watt, which represents the iron core loss and V_1 = 240V, using I_1 value from your results, show that the magnetising current I_m is approximately equal to I_1. Hint: Use $P_{oc} = V_1 I_1 \cos\phi$ to find ϕ, then use it in $I_m = I_1 \sin\phi$

B. Short-circuit Test (TEST 2)

1. Sketch a simplified equivalent circuit of the transformer at short-circuit test.
2. Plot V_1 against I_1. Analyse and discuss your results.
3. What value is the turns ratio k (take the average value)? Compare this k from the open-circuit test.
4. From your V_1 vs. I_1 graph, determine the value of $Z_{e1} = V_1 / I_1$. Then, given that the primary and secondary winding resistance R_1 and R_2 as 1.9 and 0.05 Ω respectively, calculate R_{e1}. After that, calculate X_{e1} using $X_{e1} = \text{sqrt}(Z_{e1}^2 - R_{e1}^2)$.

C. Load Test (TEST 3)

1. Plot the secondary voltage V_2 against secondary current I_2 for each resistive load and capacitive load on separate graphs. Analyse and discuss your results.
2. Using V_1=240V, the calculated values of R_{e1} and X_{e1} from TEST 2, the average value of k from TEST 1 or 2 and using equation (1), determine the regulation characteristic equation V_2 for the purely resistive load ($\phi=0^o$) and purely capacitive load ($\phi=-90^o$). Hint: Find equation of V_2 in term of I_2 from equation (1).
3. Plot V_2 vs. I_2 from question C2 on the same graph plotted in question C1. If there is a difference between the predicted value (from question C2) and the actual value (from question C1), explain why.
4. Is the flux in the transformer core change considerably from no-load to full-load? Why?

END OF EXPERIMENT