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Single-phase Transformers

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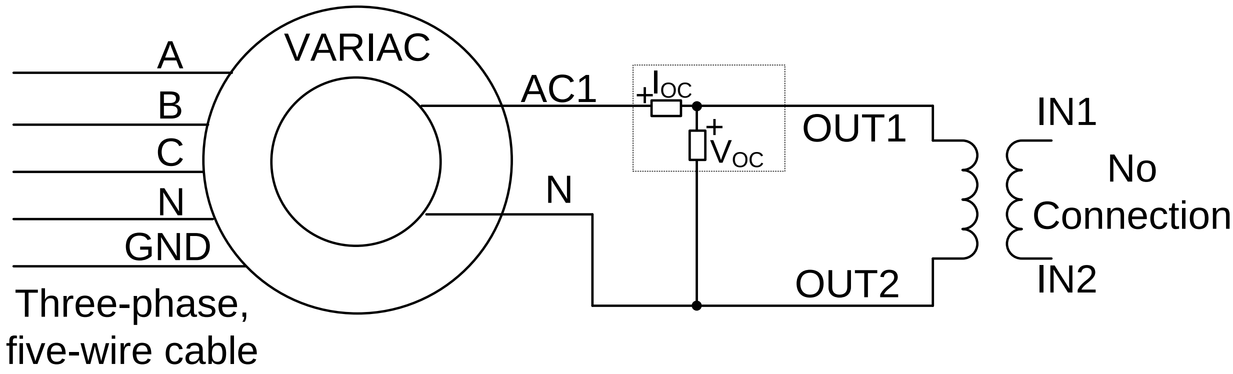

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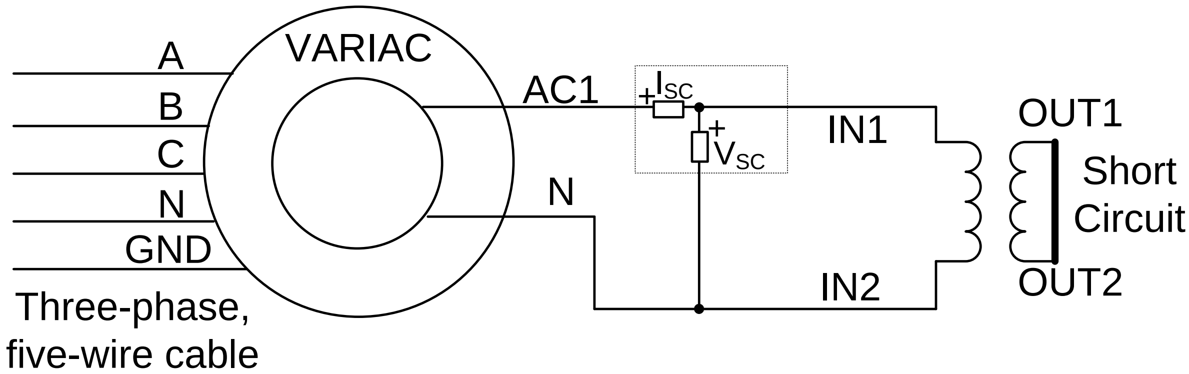

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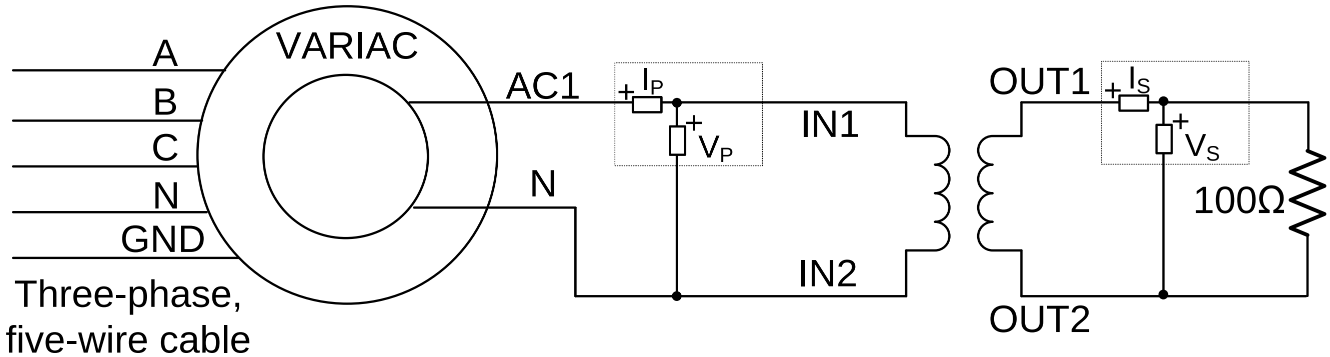

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Electrical Engineering Science Education Title: Single-phase Transformers

Overview:

This experiment characterizes a single-phase transformer by finding its equivalent circuit parameters. Three tests are performed: open-circuit test, short-circuit test, and DC test.

Transformers are stationary electric machines that step up or down AC voltage. They are typically formed of primary and secondary coils or windings, where the voltage on the primary is stepped up or down at the secondary, or the other way around. When a voltage is applied to one of the windings and current flows in that winding, flux is induced in the magnetic core, coupling both windings. With an AC current, AC flux is induced, and its rate of change induces voltage on the secondary winding (Faraday's law). Flux linkage between both windings depends on the number of turns of each winding;~~,~~ therefore, if the primary windings have more turns than the secondary winding, voltage will be higher on the primary than on the secondary, and vice versa.

Commented [AM1]: Could you provide more theoretical background on how the coils step voltage up or down? Discuss magnetic flux, etc.

The transformer used in this experiment is rated at 115 V/24 V, 100 VA. The voltage rating comes from the ability of the insulation of each winding to safely handle specific voltages, while the VA rating or power (Watt) rating come from current handling capability of these windings, specifically wire thickness. It is important not to mix primary and secondary with high- and low-voltage nomenclature. For this experiment, the primary side is assumed to have the 115 V rating, while the secondary side is rated at 24 V. The 115 V side has two terminals labeled IN1 and IN2, while the secondary side has two terminals labeled OUT1 and OUT2.

Commented [AM2]: Please discuss how to size a transformer, and what this rating nomenclature means/how it is determined.

The high-voltage side is commonly used for short-circuit testing to achieve more voltage resolution. For example, if a transformer is rated for 1200 V/120 V, a short-circuit on the 120 V probably has rated current flowing with less than 10% of the 1200 V, which makes a 0-120 V variable auto-transformer (VARIAC) on the 1200 V suitable for this test. The low-voltage side is commonly used for open-circuit testing, since this voltage is more accessible in the lab. Thus, this approach is followed as standard practice in this experiment.

Commented [DM3]: Does it make sense to briefly describe what this is at all?

Ali: This is described in the first safety experiment. You can use Variable Auto-transformer in place to define what a VARIAC is.

Commented [AM4]: What will these tests teach us? What information can we take away from each test?

The open-~~-~~circuit test helps estimate the mutual inductance between two windings, as well as core power losses ~~that are~~ caused by flux ~~being~~ induced in the core. The short-circuit test helps identify the leakage inductance of both windings, since maximum current is~~will be~~ drawn in the short circuit, and some flux ~~will~~ leaks from the core around the windings. The DC test helps measure wire resistance of both windings.

Procedure:

1. DC Test

   1.1. Turn on the low-voltage DC power supply available on the bench.

   1.2. Set its voltage output to 0 V, and set the current limit to 0.8 A.

   1.3. Double-check the circuit, then connect the power supply output across the primary side windings (IN1 and IN2). Leave the secondary side windings (OUT1 and OUT2) open.

1.4. Turn on the supply and slightly increase the voltage until the current limit is reached. Note that the supply might already be current-limited when the supply is turned on. *Do not increase the current limit.*

1.5. Record the voltage and current readings from the power supply display.

1.6. Set the voltage back to 0 V and disconnect the supply.

1.7. Adjust the current limit to 4 A, then connect the supply output across the secondary side windings (OUT1 and OUT2). Leave the primary side windings (IN1 and IN2) open.

1.8. Turn on the supply and slightly increase the voltage until the current limit is reached. Note that the supply might already be current-limited when the supply is turned on. *Do not increase the current limit.*

1.9. Record the voltage and current readings from the power supply display.

1.10. Set the voltage back to 0 V, turn the supply off, and disconnect it.

1.11. Measure the resistance across the primary windings with a multi-meter.

1.12. Measure the resistance across the secondary windings with a multi-meter.

~~1.12.~~1.13. It is common to have the higher voltage side resistance to be higher than the lower voltage side resistance due to the fact that power on both sides is ideally equal, and higher voltage means lower current and thus lower resistance. The DC test and measured resistance on the multi-meter should match closely.

2. Open-circuit Test

2.1. Make sure the three-phase source is off.

2.2. Connect the circuit for the open-circuit test (**Figure 1**). Use a digital power meter.

2.3. Make sure the VARIAC is at 0%.

2.4. Double~~-~~check that the~~your~~ circuit connections are as expected from **Figure 1**, ~~Check the circuit,~~ and then turn on the three-phase source.

2.5. Slowly adjust the VARIAC knob until the voltage reading on the digital power meter reaches 24 V.

2.6. Record the voltage, current, real power, and power factor of the power meter.

Commented [AM5]: Provide more detail on how and where you connect the circuit. I.e. Connection to the low voltage side only, etc.

What does the circuit look like? What are the components? We will need to identify them on camera.

The protocol will be read aloud as the circuit is connected in camera, so we need to provide clear descriptions with the visuals.

Ali: I am not sure what is meant by this comment. There will be electrical devices that are currently described in Figure 1 and which should be connected.

Commented [AM6]: What are you checking?

2.7. Set the VARIAC back to 0%, turn off the three-phase source, and disconnect the VARIAC output.

~~2.7.~~2.8. In the open-circuit or no-load test, the magnetizing reactance (X_m) and core loss resistance (R_C) are found from the current (I_{OC}), voltage (V_{OC}), and power (P_{OC}) measurements as follows:

$$R_C = V_{OC}^2/P_{OC} \text{ and } X_m = V_{OC}^2/Q_{OC} \text{ where } Q_{OC}^2 = (V_{OC}I_{OC})^2 - P_{OC}^2.$$

3. Short-circuit Test

3.1. Make sure the three-phase source is off.

3.2. Connect the circuit for the short-circuit test (**Figure 2**). Make sure IN1 and IN2 are connected to the VARIAC output.

Commented [AM7]: Provide more information here about what we will be seeing.

Ali: Same comment as above. This will be a practical connection that is done with real devices. If I describe all details of every connection here then that will take a very long time to do.

3.3. Make sure the VARIAC is at 0%.

3.4. Calculate the rated input current of the transformer. This is found by dividing the VA rating by the voltage rating on the input side. For example, if the input is 115 V and the VA rating is 100 VA, the input current rating is 100/115=0.87A.

Commented [DM8R7]: Amy, to further expand, the author says that:
1. We need to presuppose a certain level of knowledge from the audience. He said that the level of detail of what we're asking for in some of these would more apply to middle and high school students.
2. He also, as is touched upon in his comment above, thinks that what we've asked for in some instances will result in videos that are long and he thinks will be boring.

He's certainly willing to amend in some areas, as he's demonstrated, but his pushback is just due to scope/audience-level reasons.

Commented [AM9]: Provide calculation

3.5. Check the circuit, and then turn on the three-phase source.

3.6. Slowly and carefully adjust the VARIAC knob until the current reading on the digital power meter reaches rated input current.

3.7. Record the voltage, current, real power, and power factor on the power meter.

3.8. Set the VARIAC back to 0%, turn off the disconnect switch, and disconnect the VARIAC output. Keep the VARIAC three-phase cable connected.

3.9. Remove the short circuit placed across the transformer secondary.

Commented [AM10]: When was the short circuit placed across the secondary?

Ali: When the circuit shown in Figure 2 was built.

~~3.9.~~3.10. In the short-circuit test, the leakage reactance ($X_1+X_2'=X_{eq}$) and wire resistance ($R_1+R_2'=R_{eq}$) of both windings are found from the current (I_{SC}), voltage (V_{SC}), and power (P_{SC}) measurements as follows:

$$R_{eq}=P_{SC}/I_{SC}^2 \text{ and } X_{eq}= Q_{SC}/I_{SC}^2 \text{ where } Q_{SC}^2= (V_{SC}I_{SC})^2 - P_{SC}^2.$$

X_1 is assumed to be equal to X_2', while R_1 and R_2' can be used from the DC test (or at least one of them). If the DC test is not performed, it is common to assume that R_1 and R_2' are equal.

4. Load Test

4.1. Make sure the three-phase source is off.

4.2. Connect the circuit for the load test (**Figure 3**). Make sure IN1 and IN2 are connected to the VARIAC output.

4.3. Make sure the VARIAC is at 0%.

4.4. Connect an oscilloscope differential voltage probe across the primary with a 1/200 setting. Adjust the probe measurement for 0 V offset with an appropriate scaling factor.

4.5. Connect an oscilloscope current probe to measure the load current. Adjust the probe measurement for 0 mV offset with a 1X scaling factor for a 100 mV/A setting.

4.6. Check the circuit, and then turn on the three-phase disconnect switch.

4.7. Slowly adjust the VARIAC knob until V_P reads 115 V.

4.8. Record the voltage, current, real power, and power factor of both digital power meters.

4.9. Capture the oscilloscope screen with at least three cycles shown.

4.10. Turn off the three-phase source and set the VARIAC at 0%.

4.11. Replace the 100 Ω resistor with three 100 Ω resistors in parallel.

4.12. Turn on the three-phase source and slowly adjust the VARIAC knob until V_P reads 115 V.

4.13. Record the two digital power meter readings only (no oscilloscope screen capture).

4.14. Set the VARIAC back to 0%, turn off the disconnect switch, and disconnect the setup.

~~4.14.~~4.15. Load tests show how the current and voltage values correlate between the input and output sides of the transformer where ideally, $V_1/V_2 = I_2/I_1 = N_1/N_2 = a$ where N is the number of turns, subscripts 1 and 2 are for the primary and secondary sides, respectively, and a is the turns ratio. The impedance on the secondary side reflected to the primary side is $R' = a^2R$ or $X' = a^2X$.

Representative Results:

By performing the DC, open-circuit, short-circuit, and load tests, the transformer's equivalent circuit parameters were identified~~; and~~ therefore, simulating, operating, and analyzing realistic transformer behavior become possible.

Commented [AM11]: Provide more detail

Ali: Same comments as above.

Commented [AM12]: When was this connected? And where?

Ali: differential and current probes are connected to the oscilloscope.

Commented [AM13]: Please provide a takeaway message here. What did we learn from all four tests? How can we use the information from all four tests together to reach some conclusion about the system?

Commented [AM14]: I've moved the results to their respective tests. Since there are several tests here, it would be a challenge for the viewer/reader to remember and recall the difference between each test after viewing/reading other tests.

Ali: OK

Applications:

The described tests are critical in evaluating the impedance of a transformer and in determining its equivalent circuit parameters. Since transformer applications vary from simple chargers to high power AC transmission, appropriately characterizing different transformers for various applications is essential. Transformer impedance is used in power systems to determine possible fault impedances on either side of a transformer, approximate the efficiency of a transformer, calculate its line and load regulation, and simulate the transformer as part of larger electrical systems.

The short circuit test is usually done by applying an increasing voltage on the high voltage side, since only small voltages on that side may cause rated current to flow on the shorted low voltage side. This is useful in operating the transformer at rated current and, therefore, testing for current carrying capability. As for the open-circuit test, it is useful in ensuring that transformer voltage insulation capabilities are met when running rated voltages. Other tests, such as high-pot insulation tests for insulation material breakdown, mechanical vibration tests, etc., are also performed but for more advanced applications.

Legend:

Figure 1: DC test schematic.

Figure 2: Short-circuit test schematic.

Figure 3: Load test schematic.