EE3501, Experiment 3
EE3541, Experiment 5
Three-Phase Transformers

Jonathan Kimball, August 31, 2020

Abstract

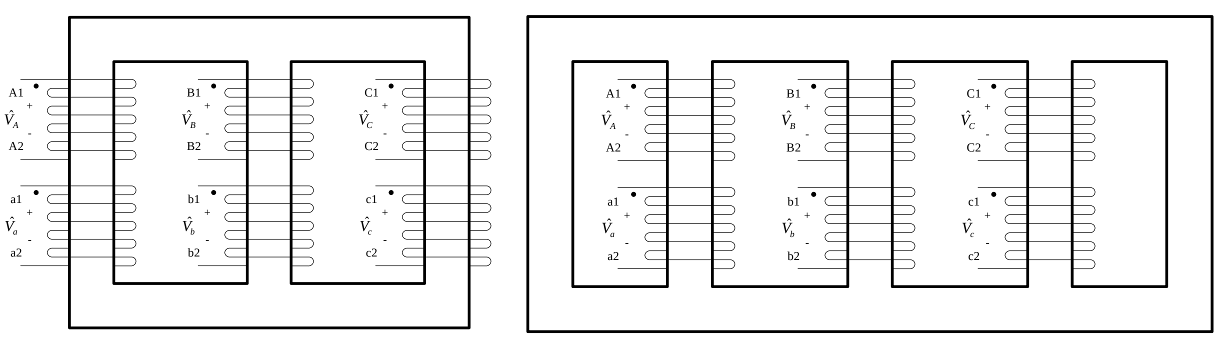
Because most large power systems are three-phase, transformer banks are also three-phase. There are a variety of configurations possible. In this lab, students will use the single-phase transformers to explore alternative three-phase configurations.

1 Introduction

Transformer power levels range from very small, low-power applications, such as in consumer electronics, to very high power applications, such as in power distribution systems. For higher-power applications, three-phase transformers are commonly used. At moderate scales, three single-phase transformers are used; at larger scales, a single multi-leg transformer is more common. Figure 1 illustrates two possible constructions. Three legs are the minimum. Frequently, a five-leg transformer structure is used instead—the extra legs provide paths for unbalanced flux. Regardless of the actual structure, the present lab exercise will treat a three-phase transformer as if it were three single-phase transformers.

The labeling convention is as follows, and is roughly standard:

- Primary side lines are ABC and neutral N; secondary side are abc and n



(a) Three leg

(b) Five leg

Figure 1: Common three-phase transformer constructions

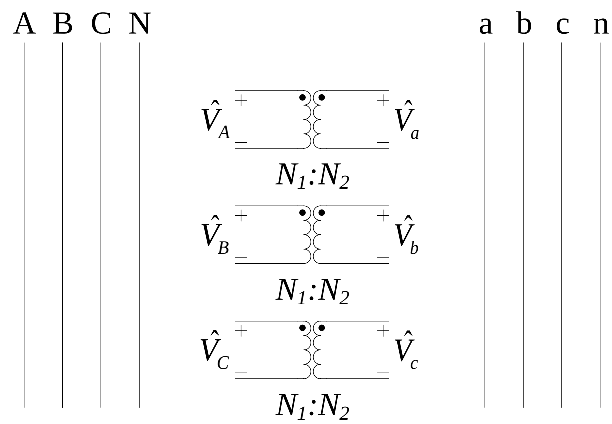


Figure 2: Three ideal transformers.

- Coils are labeled e.g. A1 and A2, where A1 is the end with the dot (polarity marking)
- All of the polarities are consistent
- A complete transformer bank will have terminals H1, H2, H3 and possibly H0 (neutral) on the high-voltage (primary) side, X1, X2, X3 and possibly X0 on the low-voltage (secondary) side
- For clarity, all line and phase voltages will be indicated with two subscripts; for example, $\hat{V}_{AB}$ is the voltage measured from line A (positive) to line B (negative)
- Coil voltages will be indicated as e.g. $\hat{V}_A$, meaning the voltage measured from terminal A1 (positive) to A2 (negative) of a single coil on a single transformer
- Positive (abc) sequence is assumed throughout

To begin the analysis, the transformers will be treated as if they were ideal. Figure 2 indicates the three transformers as well as the lines and neutrals on the two sides, which may be connected to the transformers in various ways. Being ideal, they satisfy the following voltage relationships:

$$\hat{V}_a = \frac{N_2}{N_1}\hat{V}_A \tag{1}$$

$$\hat{V}_b = \frac{N_2}{N_1}\hat{V}_B \tag{2}$$

$$\hat{V}_c = \frac{N_2}{N_1}\hat{V}_C \tag{3}$$

The three primary coils may be connected in delta or wye, and the three secondary coils may be connected in delta or wye, for four possible configurations[1]. For wye-wye and

[1] "Wye" is also called "star," and "delta" is also called "mesh."

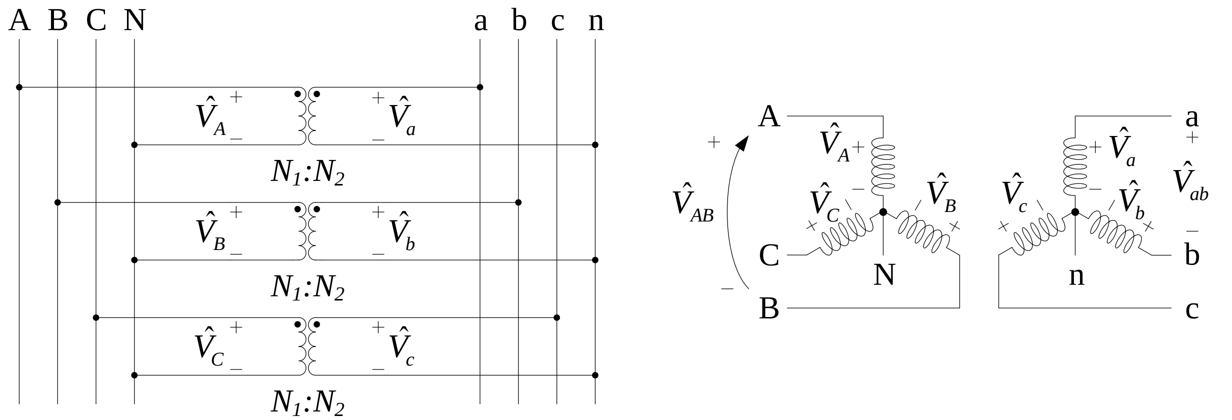


Figure 3: Wye-Wye connection.

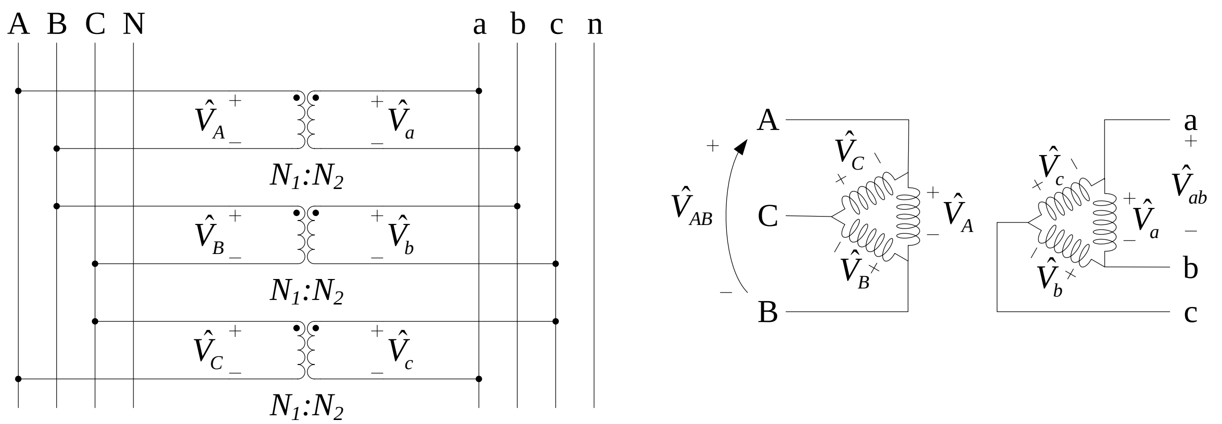


Figure 4: Delta-Delta connection.

delta-delta (Figures 3 and 4), the line voltages are related as

$$\hat{V}_{ab} = \frac{N_2}{N_1}\hat{V}_{AB} \tag{4}$$

$$\hat{V}_{bc} = \frac{N_2}{N_1}\hat{V}_{BC} \tag{5}$$

$$\hat{V}_{ca} = \frac{N_2}{N_1}\hat{V}_{CA} \tag{6}$$

The transformer coils are commonly drawn as shown to imply the 120° phase separation.

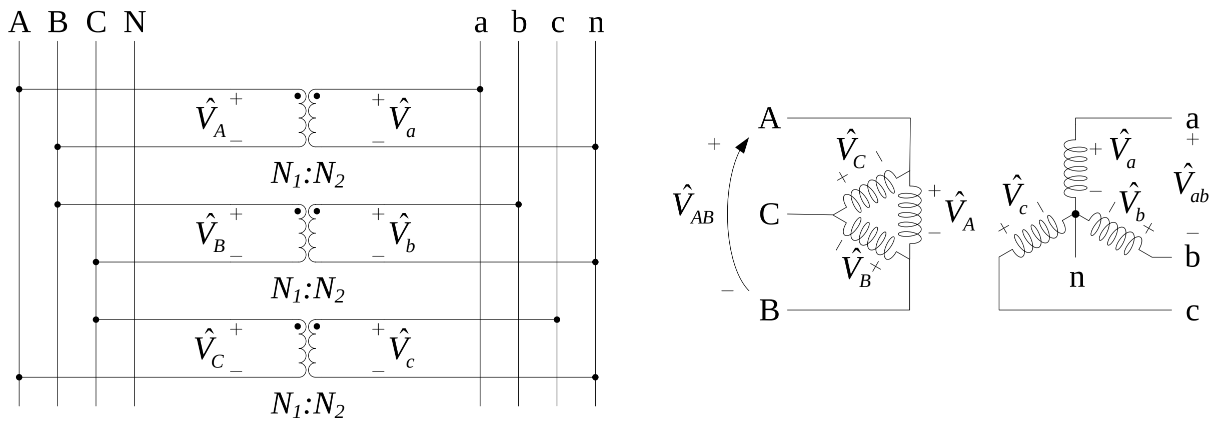


Figure 5: Delta-Wye connection.

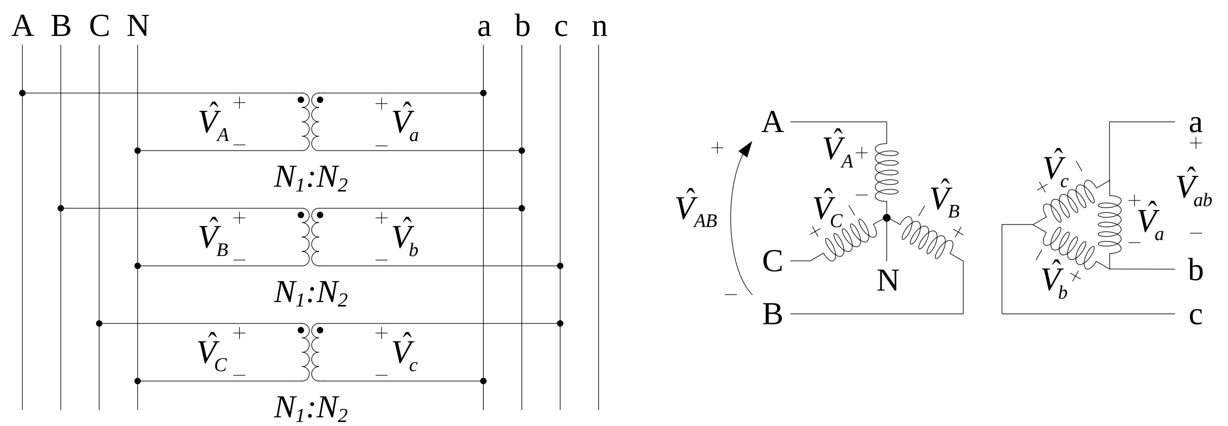


Figure 6: Wye-Delta connection.

A more common configuration is delta-wye, as shown in Figure 5. With abc sequence,

$$\hat{V}_{ab} = \hat{V}_a - \hat{V}_b \tag{7}$$

$$= \frac{N_2}{N_1}(\hat{V}_A - \hat{V}_B) \tag{8}$$

$$= \frac{N_2}{N_1}(\hat{V}_{AB} - \hat{V}_{BC}) \tag{9}$$

$$= \hat{V}_{AB} \times \frac{N_2}{N_1}\sqrt{3}\underline{/30^\circ} \tag{10}$$

That is, the secondary line voltage *leads* the primary voltage by 30°, and is scaled by both the turns ratio and $\sqrt{3}$.

Similarly, for the wye-delta configuration of Figure 6, the secondary voltage is

$$\hat{V}_{ab} = \hat{V}_{AB} \times \frac{N_2}{N_1}\frac{1}{\sqrt{3}}\underline{/-30^\circ} \tag{11}$$

That is, the secondary voltage *lags* the primary voltage by 30° and is scaled by both the turns ratio and $^1/_{\sqrt{3}}$.

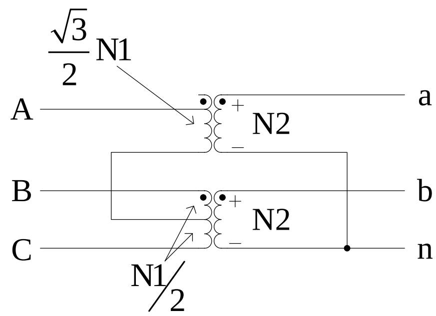


Figure 7: Scott-T connection.

Some early power systems were two-phase instead of three-phase, and a few examples remain (Philadelpha, PA; Hartford, CT). Whereas the phases in a three-phase set are displaced by 120°, the phases in a two-phase set are displaced by 90°. To provide two-phase power from a three-phase source, the Scott-T connection shown in Figure 7 may be used. The primary windings must have tap locations at $^1/_2$ and $^{\sqrt{3}}/_2$. In fact, many 240 V transformers have taps at 120 V and 208 V; $^{208}/_{240} = {}^{\sqrt{3}}/_2$ to three significant figures. In this case,

$$\hat{V}_a = \frac{N_2}{N_1}\frac{2}{\sqrt{3}}(\hat{V}_{AB} + \frac{1}{2}\hat{V}_{BC}) \tag{12}$$

$$\hat{V}_b = \frac{N_2}{N_1}\hat{V}_{BC} \tag{13}$$

Again assuming balanced positive sequence on the primary and rewriting in terms of $\hat{V}_{AB}$, the secondary voltages are

$$\hat{V}_a = \hat{V}_{AB} \times \frac{N_2}{N_1}\underline{/-30^\circ} \tag{14}$$

$$\hat{V}_b = \hat{V}_{AB} \times \frac{N_2}{N_1}\underline{/-120^\circ} \tag{15}$$

Thus, the secondary side has two voltages of equal magnitude, displaced by 90°, as required.

2 Laboratory Software

In this experiment, you will use the Yokogawa, two Flukes (#1 and #2), and the oscilloscope with two differential probes. Configure the Yokogawa as for the two-wattmeter method (3P3W), using channels 1 and 3. Configure the Flukes to measure ac voltage and current. Connect the differential probes to channels 2 and 3 of the oscilloscope.

3 Laboratory Experiment

Throughout the experiment, configure the load box as in Figure 8. **Turn on the load box fans.** You will be connecting three transformers in various configurations. For each configuration,

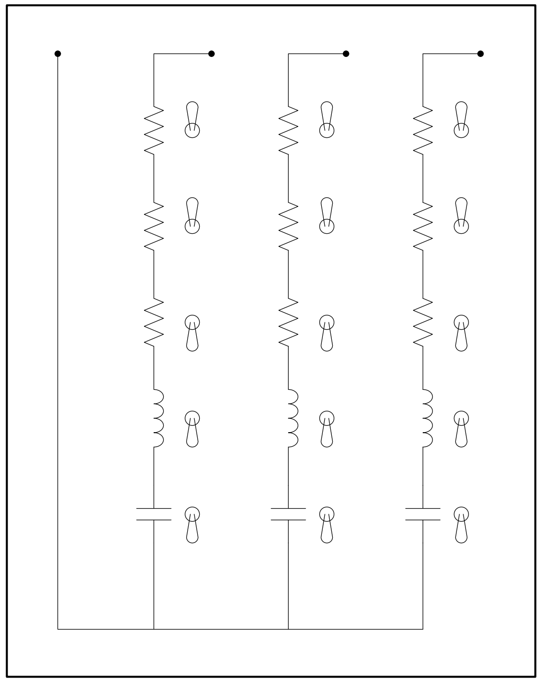


Figure 8: Load box settings

1. Energize the circuit and increase the variac to 100%.
2. Record the Yokogawa and Fluke data. Save the scope waveform and record the phase difference between primary and secondary.
3. Reduce the voltage to zero and switch off the source.

Perform these steps for the connection diagrams of Figures 9 through 12.

Finally, perform a similar experiment for the connections of Figure 13. Here, instead of monitoring the phase difference from primary to secondary, examine the phase difference between the output phases. Verify that this connection achieves two-phase output with a 90° phase difference.

4 Calculations and Question

1. Sketch the phasor diagram for the Scott-T connection, indicating the three primary line-to-line voltages and the two-phase secondary-side voltages. Verify the expected voltage and phase relationships using your measurements. Explain any discrepancies.
2. Verify the transformer relations (voltage and current) for delta-delta, delta-wye, wye-delta, and wye-wye connections using your measured data. Explain any discrepancies.

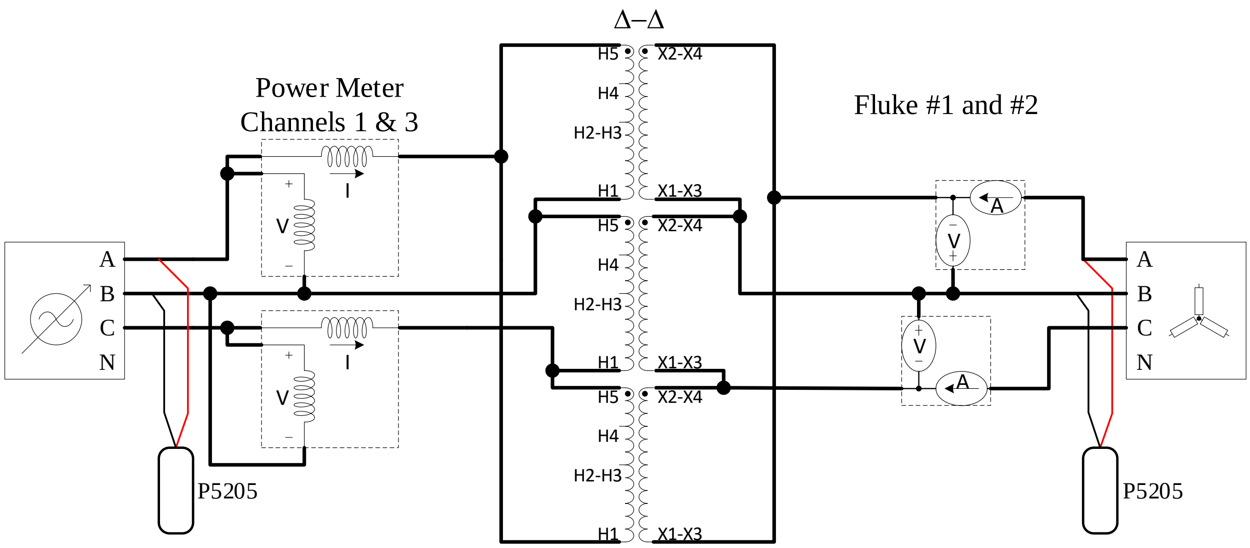


Figure 9: Experimental connections for $\Delta - \Delta$ test

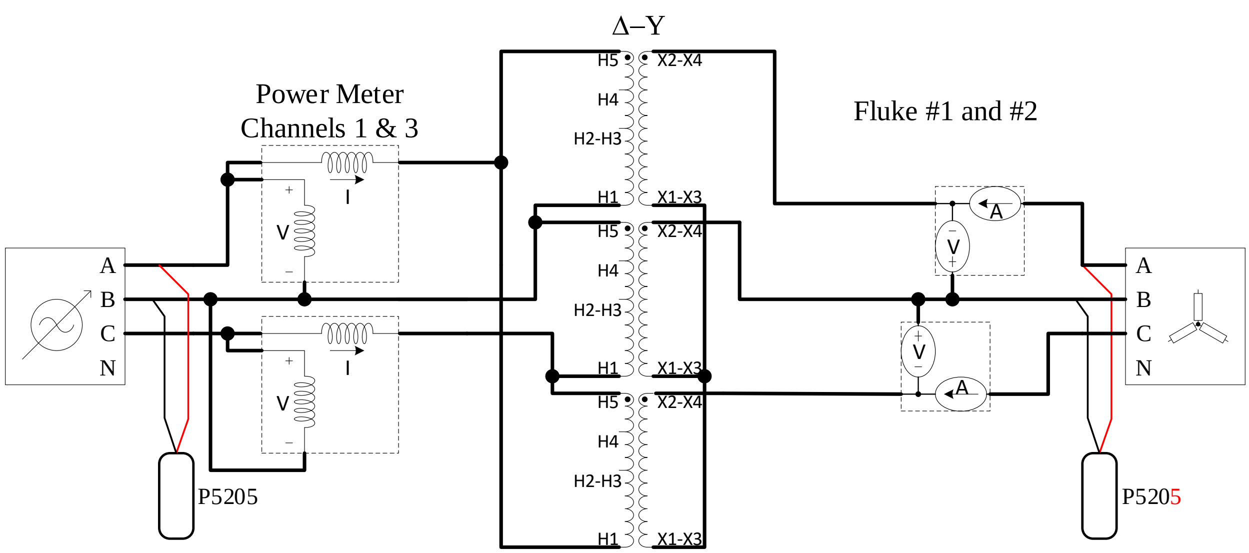


Figure 10: Experimental connections for Δ−Y test

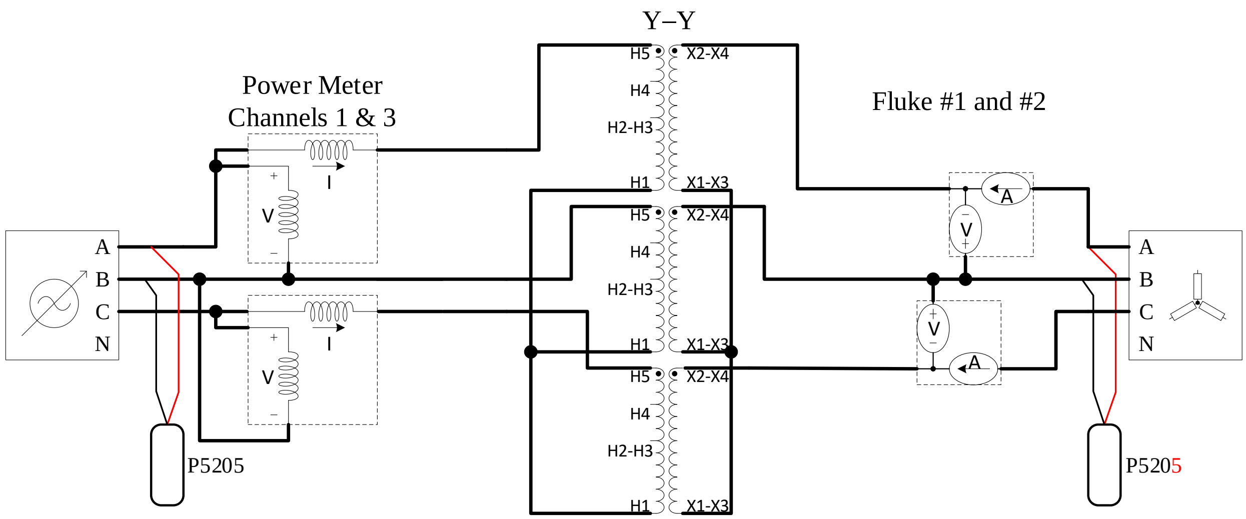


Figure 11: Experimental connections for Y-Y test

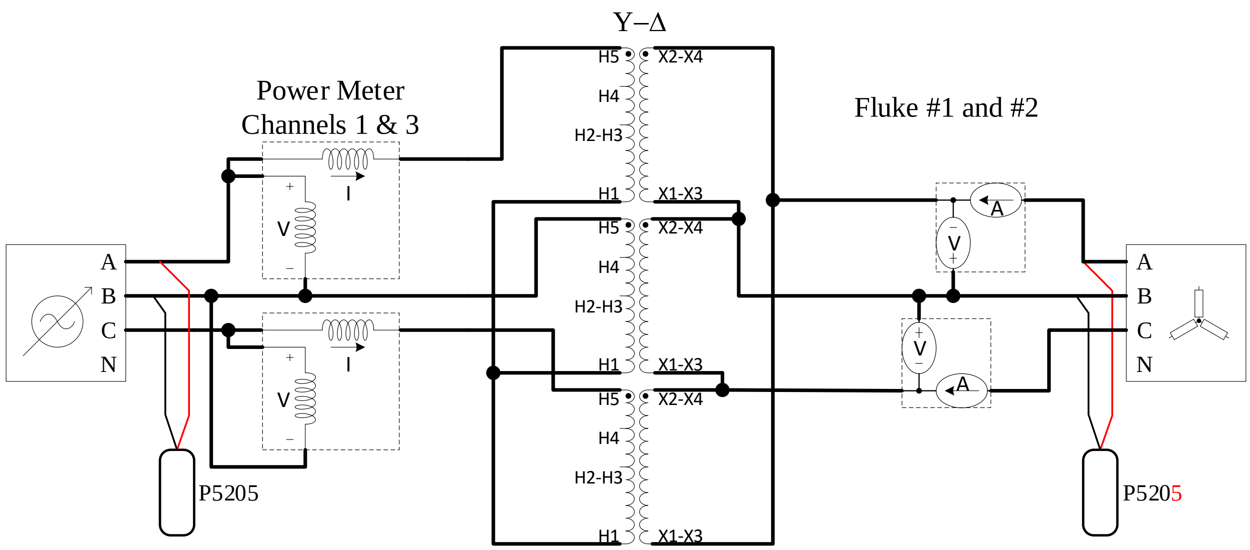


Figure 12: Experimental connections for Y−Δ test

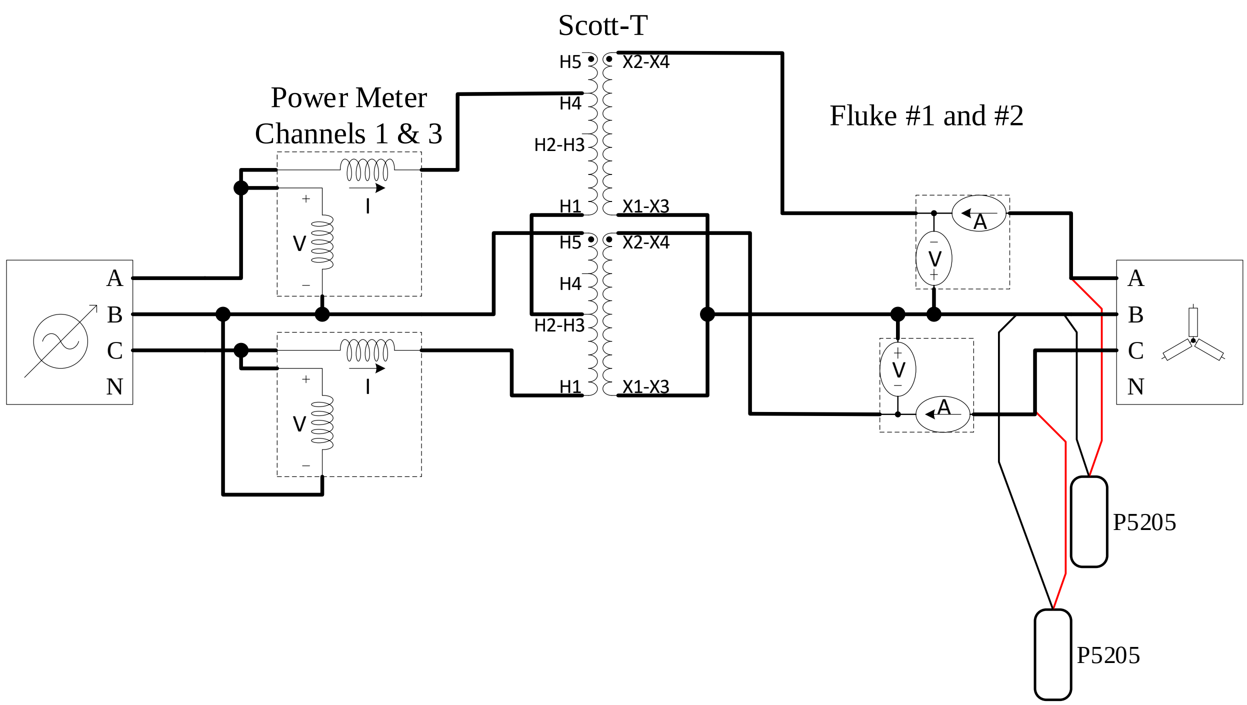


Figure 13: Experimental connections for Scott-T test