EE3541, Experiment 13
Buck-Boost and Phase Shift Transformers

Jonathan Kimball, August 31, 2020

Abstract

This experiment uses LabVolt equipment that emulates common power system components, such as transmission lines and transformers. At a small scale, you will explore the use of buck-boost and phase shift transformers for active and reactive power flow control.

1 Introduction

In a practical electric power system, there are hundreds of interconnected lines which link the power stations and their widely-dispersed loads. This network, of which Figure 1 is a simplified example, is far more complex than a simple series-parallel circuit. The flow of active and reactive power through a given line depends not only upon its impedances, but also upon the relative magnitude and phase angles of the sender and receiver voltages. In such a system, the flow in a particular line may be too high (or too low), bearing in mind the capacity of the line and/or the economics of transmission.

Under this circumstance, the flow of active power can be modified by shifting the phase of either the receiver or the sender-end voltage. Similarly, reactive power flow can be modified by raising or lowering one of these two voltages. A tap changing transformer can be used to raise or lower the voltage magnitude at either end of the transmission line. A phase shift can be introduced by a rotatable transformer similar to a wound rotor induction motor. However, in most large installations, static phase shifting transformers are employed, the degree of shift depending upon the tap settings.

The operating principle of a phase shift transformer can be understood by referring to Figure 2 which shows the primary windings $a_1,\ b_1,\ c_1$ of a of a three phase wye connected transformed. Secondary windings $a_2,\ b_2,\ c_2$ are also connected in wye, but the tertiary windings $a_3,\ b_3,\ c_3$ are not connected together. Voltages induced in windings $a_1,\ a_2,\ a_3$ will all be in phase as will be the voltages induced in the windings $b_1,\ b_2,\ b_3$ and in $c_1,\ c_2,\ c_3$. However, these three groups of voltages are respectively 120° out of phase with each other, as shown in Figure 3.

If windings a_2 and a_3 are connected in series, and similarly b_2+b_3 and c_2+c_3, the voltage at terminals X, Y, Z will be in phase with the voltage at terminals A, B, C, as in Fig. 3. However, if we instead connect a_2 to b_3, and similarly b_2+c_3 and c_2+a_3 as in Fig. 4, the voltage at terminals X, Y, Z will be out of phase with the voltage at A, B, C. The amount of phase shift depends on the relative magnitudes of the coil voltages. If the ‘2’ and ‘3’ coils

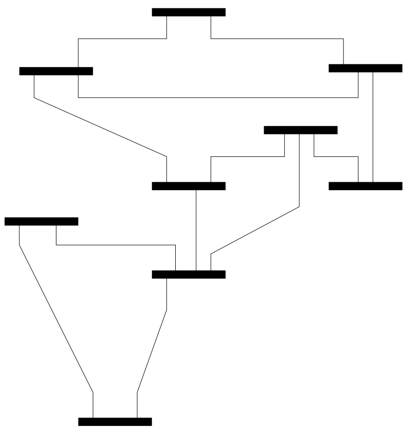

Figure 1: Example meshed network.

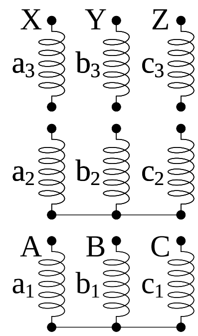

Figure 2: Multi-winding three-phase transformer.

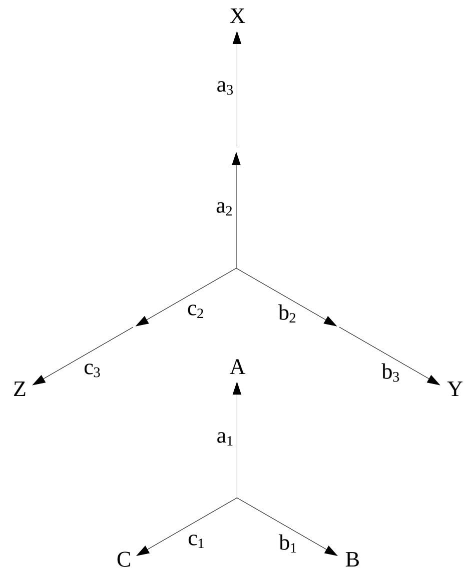

Figure 3: Phasors for windings of Fig. 2.

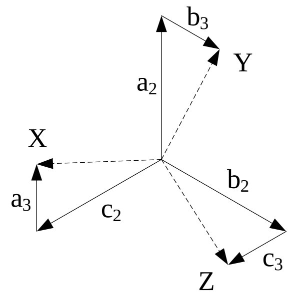

Figure 4: Phasor diagram with alternative connection that gives rise to phase shift.

have the same magnitude, the phase shift will be 60°. With appropriate taps on a three-phase transformer, and a selector switch, it is practically possible to shift the secondary voltage as much as 30°, either leading or lagging, relative to the primary voltage.

Suppose we want to modify the power flow in one of the lines in Fig. 1, say, the line between buses 1 and 2, with line reactance X. The active power flow will be

$$P_{12} = \frac{V_1 V_2}{X} \sin \delta_{12} \tag{1}$$

for bus voltages V_1, V_2 and phase difference δ_{12}. If a phase shift transformer is added, the phase difference may be increased or decreased, to increase or decrease the active power accordingly. This change in active power on one line will affect the active power on all of the other lines, especially those that connect to buses 1 and 2.

Similarly, the reactive power may be modified by adjusting the voltage up or down at

Figure 5: LabVolt equipment for low-power experiments on power distribution networks.

either end of the line (boosting or bucking, respectively). Reactive power at bus 2 is

$$Q_2 = \frac{V_1 V_2}{X} \cos \delta_{12} - \frac{V_2^2}{X} \tag{2}$$

Thus, raising or lowering the voltage at the bus 1 end of the transmission line will increase or decrease the reactive power flow at bus 2, respectively. (Only the voltage on the transmission line is affected, *not* the bus voltage itself!)

In this experiment, a "regulating transformer," that is, one that can increase or decrease the magnitude of the secondary voltage and introduce $\pm 15^\circ$ of phase shift, will be used to modify the power flow in two parallel lines.

2 Laboratory Software

In this set of experiments, you will use the LabVolt rack shown in Figure 5. Use four-wire wye connections throughout, and make sure that loads are always balanced.

The Yokogawa will be used to make two or three single-phase power measurements. Always measure phase A line-to-neutral.

The oscilloscope and two voltage probes will be used to measure phase angles.

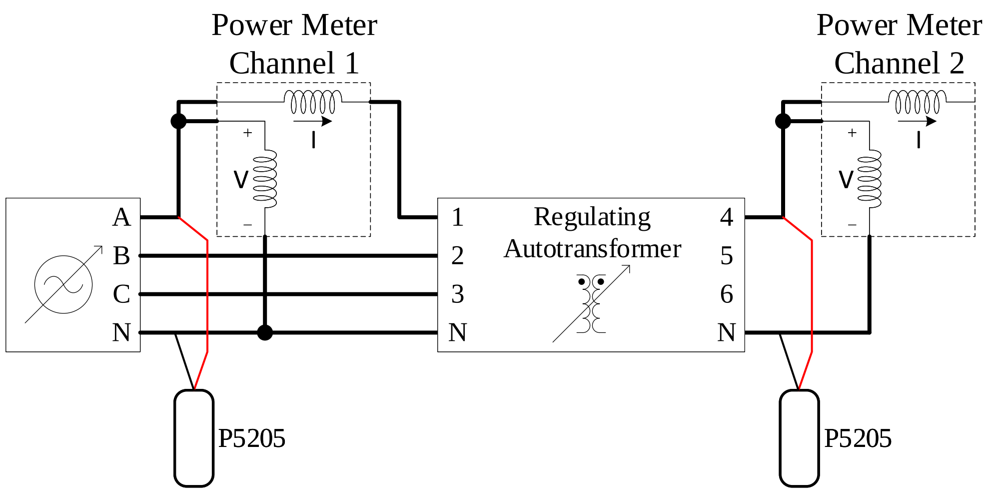

Figure 6: Configuration for experiment with just the transformer.

3 Laboratory Experiment

This experiment will be performed in two parts. For each configuration, you must use all of the setting combinations listed in Table 1.

Table 1: Regulating Transformer Settings

Buck-Boost	Phase Shift
0	0°
0	+15°
0	-15°
-15%	0°
-15%	+15°
-15%	-15°
+15%	0°
+15%	+15°
+15%	-15°

Part 1

Connect as in Figure 6. Notice that both power meter channels are connected to phase A, line-to-neutral. Turn on the breaker and adjust the source voltage to 200 V. Then sweep through the settings in Table 1. For each combination of settings, record: voltage magnitude at the source (V1, [V]), voltage magnitude at the load (V2, [V]), and the phase angle between them (θ, [°]). When you are done, turn off the breaker but leave the variac set at 200 V.

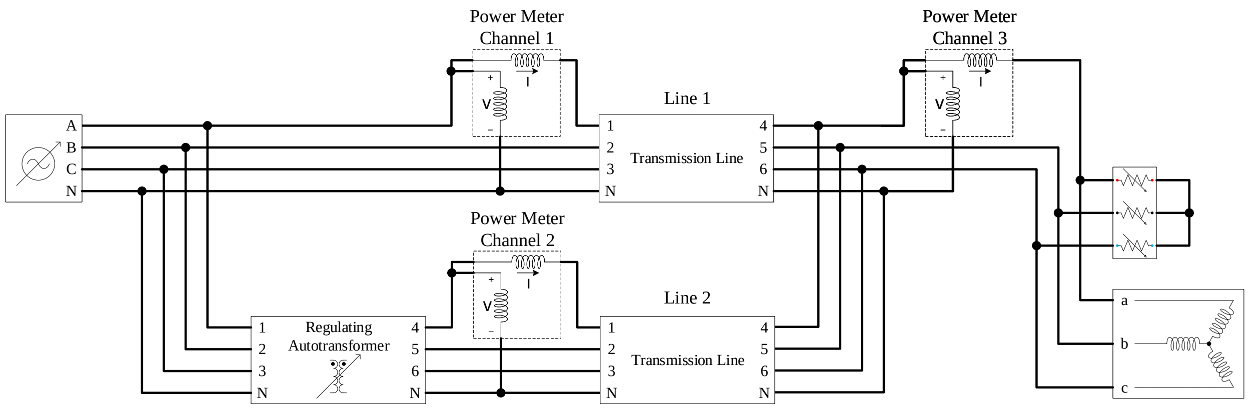

Figure 7: Circuit for Part 2, with two transmission lines feeding a load.

Part 2

Connect as in Figure 7. Notice that there are two lines in parallel, one of which is connected to the sending (source) bus through the regulating buck-boost phase-shift transformer. Also notice the location of the wattmeter, between the transformer and the transmission line. Set the resistive load to 300 Ω. The induction motor is being used as an inductive load.

Set both transmission line impedances to 60 Ω. Turn on the breaker and verify that the source voltage is 200 V. Sweep the settings in Table 1. For each point, record active power, reactive power, and voltage from all three meters (that is, P [W], Q [VAR], and V [V]).

Now leave transmission line 2 impedance at 60 Ω but set transmission line 2 to 0 Ω. Again sweep the settings in Table 1. For each point, record active power, reactive power, and voltage from all three meters (that is, P [W], Q [VAR], and V [V]).

4 Calculations and Question

1. From the results of Part 1, determine the accuracy of the stated buck-boost and phase-shift settings. Compare to the results of Part 2. Is there a significant effect due to the load?

2. Discuss the effect of phase shift on active and reactive power flow.

3. Discuss the effect of tap changing (buck-boost) on active and reactive power flow.

4. Consider the simple oneline diagram in Figure 8. Reactances are given per phase. Both the sending and receiving buses are fixed at 100 kV line voltage, but with varying phase.

   (a) With no phase shift transformer, what is the maximum total active power delivered by the two parallel lines? How is it distributed between them?

   (b) With a phase shift of up to ±15°, what is the maximum total active power delivered by the two parallel lines? How is it distributed between them?

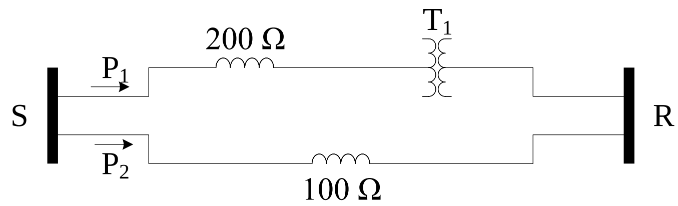

Figure 8: Example oneline diagram for problem 4.

(c) Does the phase shift transformer increase the maximum power capability? Explain.