Renewable Energy

AC Transmission Lines

Courseware Sample
86365-F0

Lab-Volt®

RENEWABLE ENERGY

AC TRANSMISSION LINES

Courseware Sample

by
the staff
of
Lab-Volt Ltd.

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Safety Symbols

The following safety symbols may be used in this manual and on the Lab-Volt equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
⚠	Caution, risk of electric shock
⚠	Caution, hot surface
⚠	Caution, risk of danger
⚠	Caution, lifting hazard
⚠	Caution, hand entanglement hazard
⎓	Direct current
∿	Alternating current
∿	Both direct and alternating current
3∿	Three-phase alternating current
⏚	Earth (ground) terminal
⏚	Protective conductor terminal
⏚	Frame or chassis terminal

Safety Symbols

Symbol	Description
⏚	Equipotentiality
|	On (supply)
◯	Off (supply)
▣	Equipment protected throughout by double insulation or reinforced insulation
⊓	In position of a bi-stable push control
⊓	Out position of a bi-stable push control

Foreword

AC transmission lines are a vital element of any ac power network. They are used to transfer electrical power from the power generating stations to the distribution system, which then supplies the electrical power to the consumers. As the power generating stations in an ac power network can be quite distanced from the centers of energy consumption, ac transmission lines often have to transfer electrical power over great distances. This particularity, coupled with the fact that ac transmission lines are primarily inductive, has many effects on the operation of ac transmission lines.

One of the main effects is that a significant voltage drop occurs at the receiver end of ac transmission lines. This voltage drop must be continually compensated in order to maintain the receiver voltage equal to the sender voltage. This is commonly achieved using capacitors connected in parallel to the line. When an ac transmission line is particularly long, substations containing parallel-connected (shunt) capacitors must be added at regular intervals along the line.

When ac transmission lines are used to transfer electrical power in interconnected power networks, the flow of active power and reactive power between any two regions must be carefully controlled. This can be achieved using special types of transformers which enable to adjust, firstly, the amount of active power transferred from one region to the next, and, secondly, the proportion of reactive power supplied by each of the two interconnected regions.

This course, AC Transmission Lines, teaches the basic concepts of ac transmission lines. Students are introduced to the voltage regulation characteristics of ac transmission lines. They learn how to maintain the voltage at both ends of ac transmission lines equal using shunt capacitors, as well as how to do so in long ac transmission lines by adding shunt capacitor substations along the line. Students also learn how to determine the power transmission capacity of ac transmission lines, and how to control the flow of active power and reactive power in interconnected ac power networks.

Figure 1. AC transmission lines.

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Sample Exercise

Extracted from

Student Manual

Control of Active and Reactive Power Flow

EXERCISE OBJECTIVE

When you have completed this exercise, you will know how to control the flow of active power in ac transmission lines used in interconnected power networks. You will be familiar with the flow of reactive power in ac transmission lines. You will also know how to control the flow of reactive power in ac transmission lines used in interconnected power networks. You will be introduced to the operating principles of regulating autotransformers.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Control of active power flow in interconnected power networks
- Reactive power flow in ac transmission lines
- Control of reactive power flow in interconnected power networks
- Effect of the line resistance on the operation of ac transmission lines
- Introduction to the regulating autotransformer

DISCUSSION

Control of active power flow in interconnected power networks

In Exercise 3, you saw that, in order for active power P to be transferred from the sender end to the receiver end of a voltage-compensated ac transmission line, it is necessary for the receiver voltage E_R to lag behind the sender voltage E_S. The greater the phase shift θ between the receiver voltage E_R and the sender voltage E_S, the greater the active power P transferred by the ac transmission line. You also saw that in a voltage-compensated ac transmission line, the phase shift θ between the receiver voltage E_R and the sender voltage E_S naturally increases as the active power P flowing through the line increases, i.e., as the load increases.

Controlling the active power P transferred by an ac transmission line is relatively easy in the simple ac transmission line circuits you have studied so far, i.e., circuits where one end of the ac transmission line is always sender and the other end, always receiver. It is basically a matter of limiting the maximum phase shift θ to values ensuring that the maximum power $P_{Max.}$ of the ac transmission line is not exceeded and providing stable operation (i.e., phase shift values generally well below 90°). However, this is not always the case in practice. This is because most ac power networks consist of more than two regions interconnected by a single ac transmission line. In such power networks, there are no definite sender and receiver ends, as the active power P transferred via each ac transmission line in the power network does not flow in the same direction at all times, depending on the power demand in each region. In these conditions, it becomes increasingly difficult to coordinate the phase shifts θ between the voltages at each region (node) of the power network with the amounts of active power P that need to be exchanged between the various nodes of the power network.

For example, consider the diagram of the interconnected power network shown in Figure 28. In this figure, each dot represents a region that can consume or supply active power, and each line represents an ac transmission line.
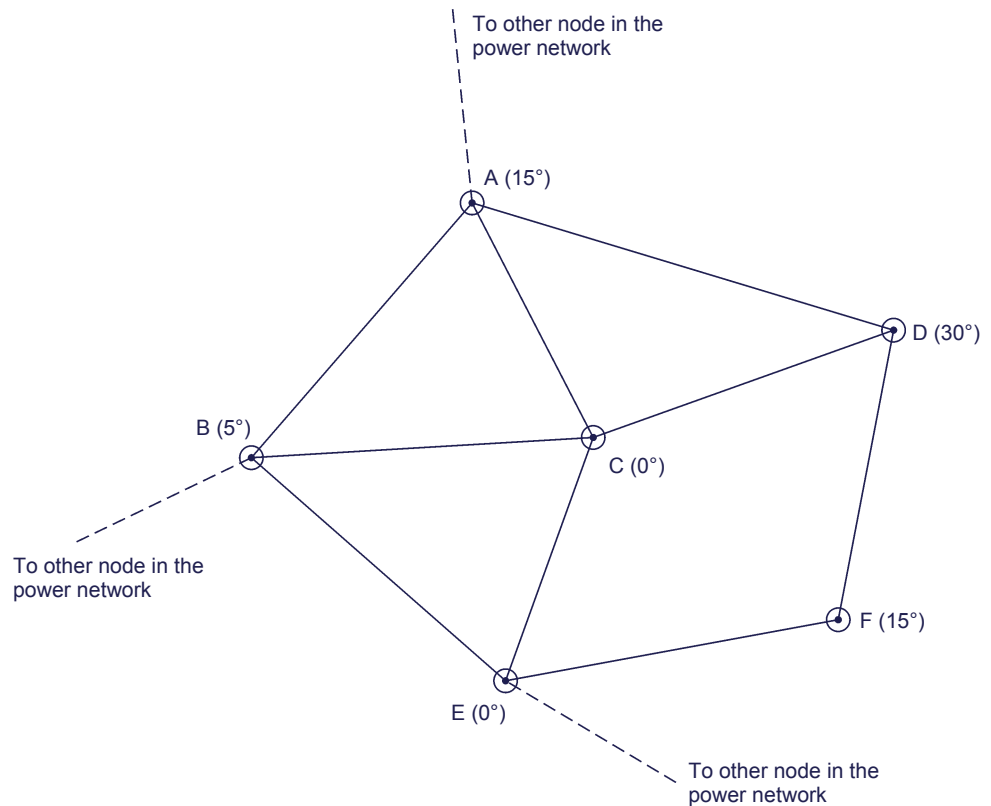
Figure 28. Diagram of an interconnected power network.

The portion of the interconnected power network illustrated in Figure 28 shows 6 regions that can be either receiver (the region consumes active power) or sender (the region supplies active power). Since the active power P transferred via an ac transmission line is proportional to the phase shift θ between the voltages at both ends, only the regions between which there is a non-null phase shift exchange active power P. This is the case for all regions in the interconnected power network shown above except regions C and E which have both a phase angle of 0°, leading to a phase shift θ of 0° and no active power transfer. Also, a very limited amount of active power is exchanged between regions B and C as well as between regions B and E as the phase shift θ over the corresponding ac transmission lines (B-C and B-E) is of only 5° (phase angle of 5° versus phase angle of 0°).

The polarity of the phase shift θ between the voltages at two regions of an interconnected power network is also very important because it determines the direction of the active power flow in the corresponding ac transmission line. The direction of the flow of active power P between two regions and the corresponding phasor diagrams are illustrated in the figure below.
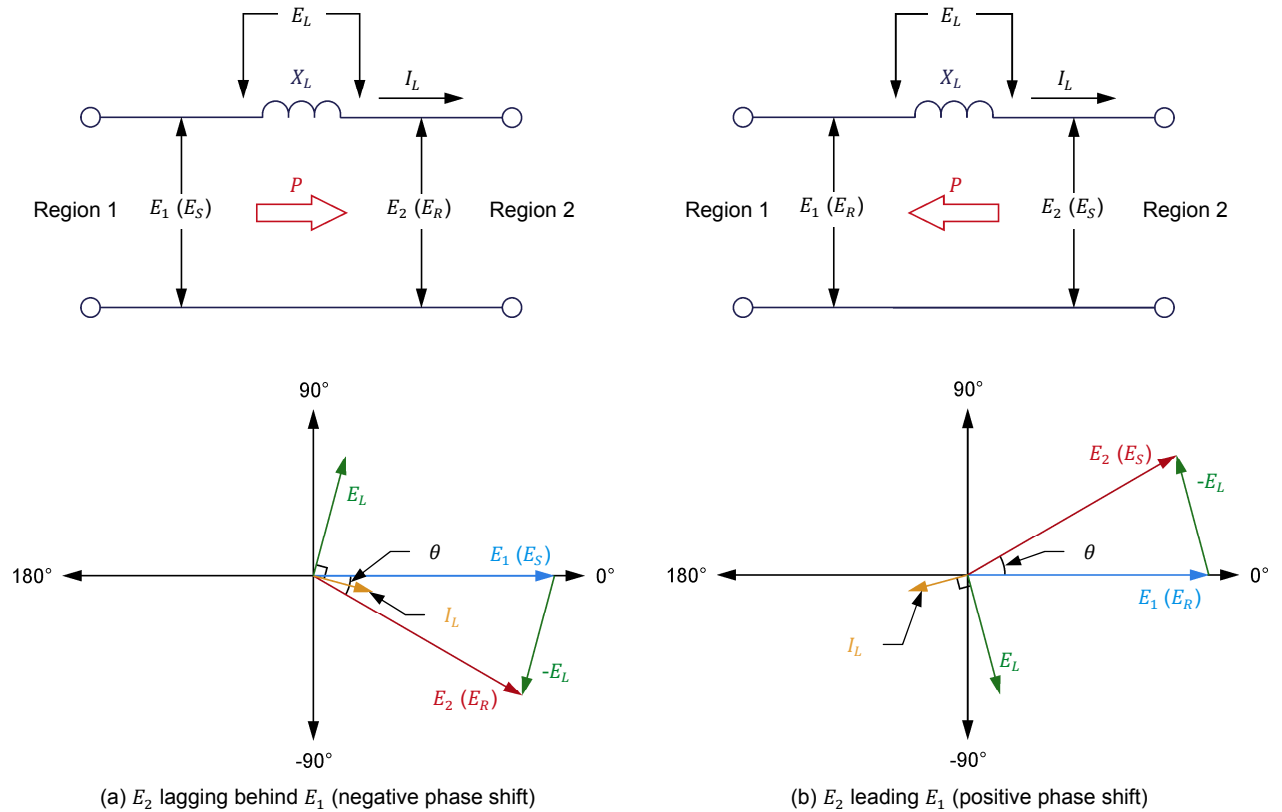
Figure 29. The direction of active power flow in an ac transmission line of an interconnected power network depends on the polarity of the phase shift θ between the voltages at both ends of the line.

As Figure 29 shows, the direction of the flow of active power P between two interconnected regions is always from the region with the leading voltage to the region with the lagging voltage. Thus, the region whose voltage sine wave leads that of the other region is designated as the sender end of the ac transmission line, while the region whose voltage sine wave lags behind that of the other region is designated as the receiver end of the ac transmission line. Note that in the equivalent circuits of the ac transmission line in Figure 29, the phase shift θ has the same magnitude, but the polarity of the phase shift in one circuit is opposite to the polarity of the phase shift in the other circuit. Consequently, the same amount of active power is transferred between regions 1 and 2 in both circuits. However, in the circuit of Figure 29a, the flow of active power is from region 1 to region 2 since voltage E_2 is lagging behind voltage E_1 (negative phase shift). Conversely, in the circuit of Figure 29b, the flow of active power is from region 2 to region 1 since voltage E_2 is leading voltage E_1 (positive phase shift).

When the phase angles of the voltages at the various regions of an interconnected power network are known, it is possible to determine the direction of the flow of active power P between all regions of the power network. Figure 30 shows the diagram of the interconnected power network in Figure 28 with the direction of the flow of active power P between each region. Notice that the length of each arrow indicating the direction of active power flow is proportional to the amount of active power transferred via the corresponding ac transmission line. As you can see, the amount of active power exchanged between

regions B, C, and E is severely limited as the phase angles of their respective voltages are equal or close to each other.
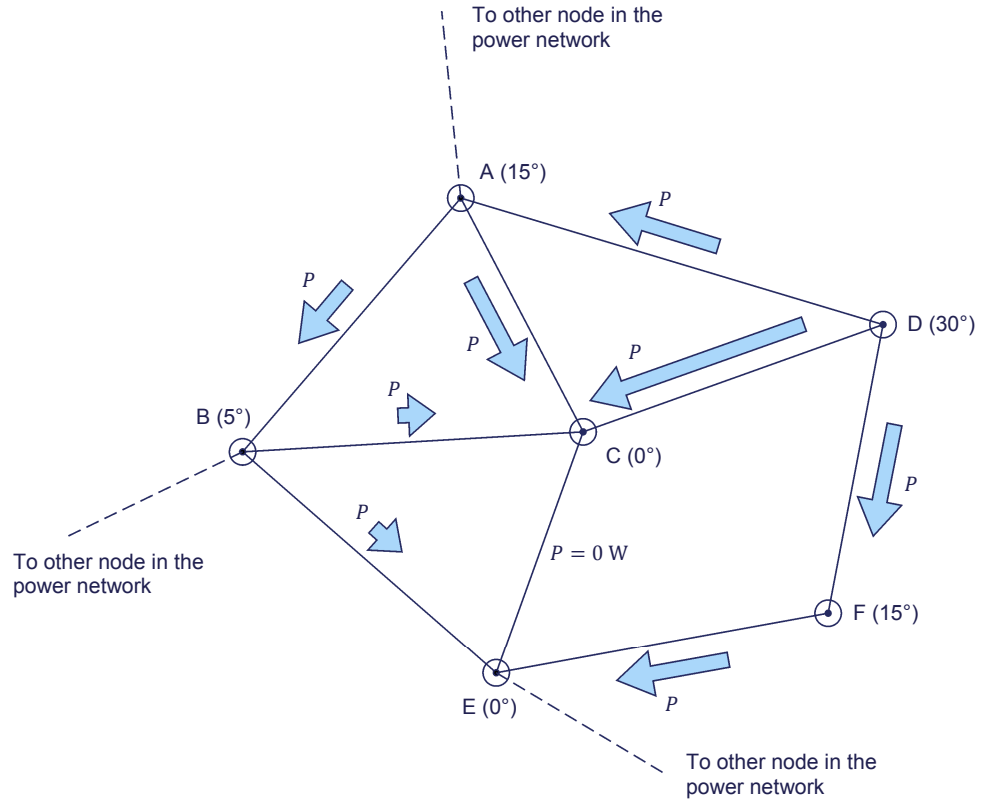
Figure 30. Diagram of the interconnected power network of Figure 28 with the direction of the flow of active power *P* between each region.

The figure above shows that, since the phase angle of the voltage at each region of an interconnected power network is constant, no flexibility is allowed in the flow of active power *P* between the various regions of the network. This is highly problematic when, in situations such as a power outage, the direction of active power flow between two regions needs to be reversed, or when the active power *P* transferred between two regions needs to be adjusted due to a variation in the power demand. Because of this, some means to control the flow of active power *P* in the ac transmission lines must be used in complex interconnected power networks.

Such a means of active power flow control consists of using **phase-shifting transformers**. Phase-shifting transformers are a special type of three-phase power transformer that have the ability to introduce a phase shift (usually ranging from about +30° to about -30°) between the incoming voltages and the outgoing voltages. Phase-shifting transformers are connected in series with ac transmission lines whenever the flow of active power between regions of an interconnected power network needs to be controlled. Phase-shifting transformers allow the phase angle of the voltage at one region of an interconnected power network to be modified before it is applied to the ac transmission line, without modifying the phase angle of the voltage at the region. This way, it is possible to control the flow of active power *P* between two regions of an interconnected power network without modifying the phase angle at any of the regions.

Figure 31 shows an example of how active power flow between two regions of an interconnected power network can be modified using a phase-shifting transformer. In this example, a phase-shifting transformer is added between the power station at region E and the ac transmission line going to region C, in the interconnected power network of Figure 30. Initially, when the phase-shifting transformer is set to produce no phase shift, no active power flows between regions E and C since the phase angle of the voltage at each of these two regions is the same (0°). Adjusting the phase-shifting transformer so as to advance the phase angle of the voltage applied to the ac transmission line (15° in this example) causes active power to flow from region E to region C, as indicated in the figure, without modifying the phase angle of the voltage at regions E and C. Conversely, if the phase-shifting transformer is adjusted so as to delay the phase angle of the voltage applied to the ac transmission line, this causes active power to flow from region C to region E.
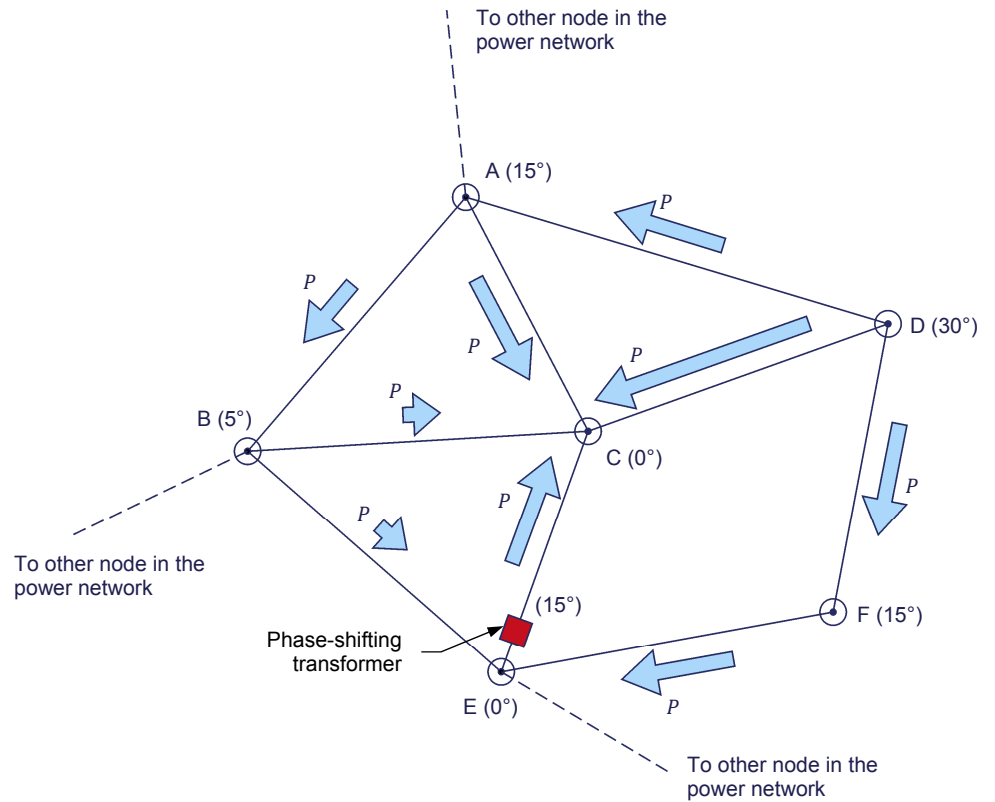
Figure 31. Diagram of the interconnected power network of Figure 30 when a phase-shifting transformer is added between region E and the ac transmission line going to region C.

Reactive power flow in ac transmission lines

It is generally accepted that inductive components absorb reactive power and capacitive components supply reactive power, although reactive components in fact exchange reactive power and neither absorb nor supply reactive power.

The amount of reactive power Q_L absorbed by the equivalent inductor of a voltage-compensated ac transmission line depends on the current I_L flowing in the line. The greater the line current I_L, the greater the amount of reactive power Q_L absorbed by the ac transmission line. When the value of the line current I_L is known, the reactive power Q_S at the sender end and the reactive power Q_R at the receiver end of the ac transmission line can be calculated. The difference between these two reactive power values is equal to the reactive power Q_L absorbed by the ac transmission line ($Q_L = Q_S - Q_R$).

Consider for example the voltage-compensated 230 kV ac transmission line (sender phase voltage E_S = 133 kV) having an inductive reactance of 120 Ω shown in Figure 32. Since the ac transmission line is voltage compensated, the receiver voltage E_R is equal to the sender voltage E_S. The receiver voltage E_R, however, lags behind the sender voltage E_S by 30°. The current I_L flowing in the line is equal to 574 A, and lags behind the sender voltage E_S by 15°. The voltage drop E_L across the ac transmission line is equal to 69 kV, and leads the sender voltage E_S by 75°.

Figure 32. Voltage-compensated 230 kV ac transmission line.

The phasors of the voltages and current for one phase of the ac transmission line in Figure 32 are illustrated in the phasor diagram of Figure 33.

Figure 33. Phasor diagram of the voltages and currents for one phase of the ac transmission line in Figure 32.

The different values of active power P and reactive power Q for one phase of the ac transmission line are calculated below.

$$P_S = E_S I_L \cos\theta_{E_S I_L} = 133\,000 \text{ V} \times 574 \text{ A} \times \cos 15 = 73\,741 \text{ kW}$$

$$Q_S = E_S I_L \sin\theta_{E_S I_L} = 133\,000 \text{ V} \times 574 \text{ A} \times \sin 15 = 19\,759 \text{ kvar}$$

$$P_R = E_R I_L \cos\theta_{E_R I_L} = 133\,000 \text{ V} \times 574 \text{ A} \times \cos -15 = 73\,741 \text{ kW}$$

$$Q_R = E_R I_L \sin\theta_{E_R I_L} = 133\,000 \text{ V} \times 574 \text{ A} \times \sin -15 = -19\,759 \text{ kvar}$$

The above calculations show that active power P is supplied from the sender end of the ac transmission line to the receiver end. Since it is assumed that the ac transmission line has no resistance, no active power P is dissipated in the line. Thus, the active power P_R at the receiver end is equal to the active power P_S at the sender end. The total reactive power Q_L absorbed by each phase of the ac transmission line is equal to 39 518 kvar [19 759 kvar − (−19 759 kvar)]. The calculations also show that the reactive power Q_L absorbed by each phase of the ac transmission line (39 518 kvar) is supplied equally by the sender end and the receiver end (19 759 kvar each). In other words, the sender end and the receiver end of the ac transmission line each supply 19 759 kvar to the line.

This example shows that, when the receiver voltage E_R and the sender voltage E_S of a voltage-compensated ac transmission line are phase shifted one another, active power is transferred via the line and reactive power is supplied in equal amounts to the line by the sender end and the receiver end. The greater the phase shift θ, the greater the amount of reactive power Q_L absorbed by the line (and thus, the greater the amount of reactive power supplied by the sender and receiver ends of the line). As long as the phase shift θ between the receiver voltage E_R and the sender voltage E_S of the ac transmission line is less than about 30°, the active power P transferred via the line considerably exceeds the reactive power Q_L absorbed by the line.

Control of reactive power flow in interconnected power networks

As seen in the previous section of this discussion, the amount of reactive power Q_L absorbed by an ac transmission line and supplied by the sender and receiver ends depends on the phase shift θ between the receiver voltage E_R and the sender voltage E_S, just as for the active power P. When the voltages at both ends of the ac transmission line are equal, the sender and the receiver ends of the line supply the same amount of reactive power to the line. In actual ac transmission lines, however, this proportion is generally slightly unbalanced due to the resistance in the wires of the line (this resistance is ignored in most equivalent circuits of ac transmission lines shown in this manual). This is demonstrated later in this discussion.

By increasing or decreasing the voltage at either end of an ac transmission line, it is possible to control the amounts of reactive power which the sender and receiver ends supply to the line. Using this technique, the reactive power that the sender and receiver ends supply to the ac transmission line can be modified as desired. For example, the voltage at one end of the ac transmission line can be adjusted so that all the reactive power absorbed by the line is supplied by only one end of the line. Adjusting the flow of reactive power Q modifies the

magnitude and phase angle of the voltage drop E_L as well as those of the line current I_L, as is demonstrated later in this discussion.

The control of the flow of reactive power Q in an ac transmission line connecting two regions of a power network can be achieved by adding a **buck-boost transformer** (step-down/step-up transformer) at either end of the line. Buck-boost transformers are a special type of three-phase power transformer (just as phase-shifting transformers) that have the ability to decrease (buck) or increase (boost) the value of incoming voltages by a variable proportion, thereby enabling the control of the reactive power Q that the sender end and the receiver end of the ac transmission line supply to the line. Just as for the control of the flow of active power P in interconnected power networks, the control of the flow of reactive power Q can be necessary under certain conditions, e.g., when one region of the ac power network is able to supply reactive power, while another one is not. Note that, although a buck-boost transformer modifies the voltage at one end of an ac transmission line, it has no effect on the actual voltages at the regions connected by the ac transmission line. In other words, the voltages at the regions connected by the line are maintained equal to the voltage of the ac power network.

To better illustrate this, consider the addition of a buck-boost transformer at the sender end of the voltage-compensated 230 kV ac transmission line in Figure 32, as is shown in Figure 34. The voltage E_R at the receiver end of the ac transmission line is maintained equal to 133 kV. The voltage E_S at the sender end of the ac transmission line, however, is increased to 153 kV (15% boost) by the buck-boost transformer. The current I_L now flowing in the line is equal to 638 A, and lags behind the sender voltage E_S by 29.6°. The voltage drop E_L across the ac transmission line is equal to 76.5 kV, and leads the sender voltage E_S by 60.4°.
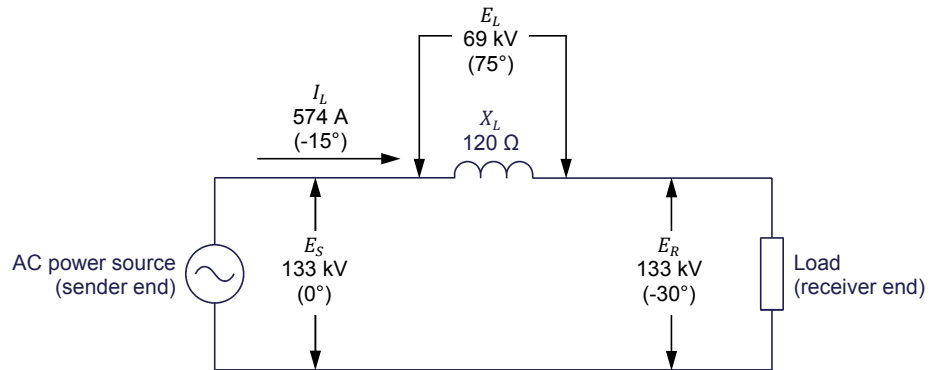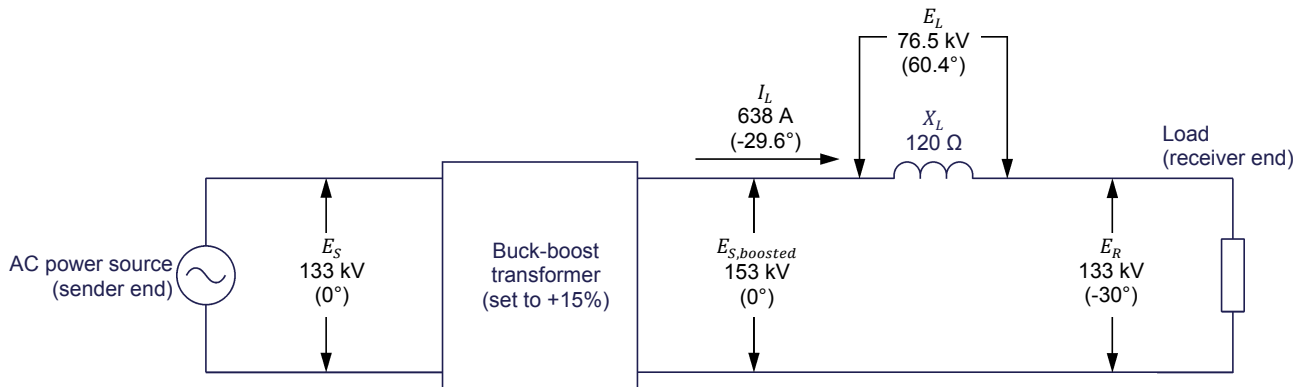

Figure 34. Voltage-compensated 230 kV ac transmission line of Figure 32 with a buck-boost transformer added at the sender end of the line.

The phasors of the voltages and current for one phase of the ac transmission line in Figure 34 are illustrated in the phasor diagram of Figure 35.
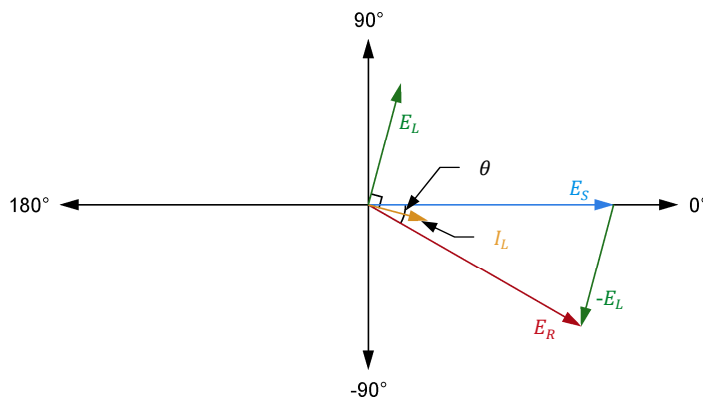

Figure 35. Phasor diagram of the voltages and current for one phase of the voltage-compensated 230 kV ac transmission line in Figure 34 when the sender voltage E_S is increased by 15%.

As the phasor diagram in Figure 35 shows, the magnitude and phase angle of the voltage drop E_L across the line is automatically modified due to the boosted sender voltage E_S when the line is properly voltage-compensated (i.e., when the sender voltage E_S before the modifications of the buck-boost transformer equals the receiver voltage E_R). This causes the line current I_L (which lags 90° behind the voltage drop E_L) to be similarly phase shifted. In this particular case, the phasor of the line current I_L is virtually in phase with that of the receiver voltage E_R.

The different values of active power P and reactive power Q for one phase of the ac transmission line are calculated below.

$$P_S = E_S I_L \cos \theta_{E_S I_L} = 153\,000 \text{ V} \times 638 \text{ A} \times \cos 29.6 = 84\,875 \text{ kW}$$

$$Q_S = E_S I_L \sin \theta_{E_S I_L} = 153\,000 \text{ V} \times 638 \text{ A} \times \sin 29.6 = 48\,216 \text{ kvar}$$

$$P_R = E_R I_L \cos \theta_{E_R I_L} = 133\,000 \text{ V} \times 638 \text{ A} \times \cos -0.4 = 84\,852 \text{ kW}$$

$$Q_R = E_R I_L \sin \theta_{E_R I_L} = 133\,000 \text{ V} \times 638 \text{ A} \times \sin -0.4 = -592 \text{ kvar}$$

The above calculations show that the amount of active power P transferred via one phase of the ac transmission line increases slightly (from about $73\,740$ kW to about $84\,850$ kW) as the sender voltage E_S is increased by 15%. The active power P_S at the sender end of the ac transmission line is virtually equal to the active power P_R at the receiver end. However, the sender end now supplies almost all the reactive power absorbed by the ac transmission line. Increasing (boosting) the sender voltage E_S by 15% thus has the effect of adjusting the flow of reactive power Q in the ac transmission line so that almost all reactive power is supplied by the sender end, and a negligible amount of reactive power is supplied by the receiver end. Conversely, decreasing (bucking) the sender voltage E_S while maintaining the receiver voltage E_R constant causes the amount of active power P transferred via the line to decrease slightly because the voltage at the sender end of the line is lowered. It also causes the amount of reactive power supplied to the ac transmission line by the receiver end to

increase, and the amount of reactive power supplied to the line by the sender end to decrease.

By using a buck-boost transformer to decrease (buck) or increase (boost) the voltage at the sender end or the receiver end of an ac transmission line connecting two regions of a power network, it is thus possible to obtain virtually any proportion of reactive power which the sender and receiver ends supply to the line. When the flow of reactive power is controlled in such a way, the greater portion of the reactive power Q_L supplied to the line always comes from the end whose voltage is higher than that of the other end.

Effect of the line resistance on the operation of ac transmission lines

In the ac transmission line circuits you have studied so far, the resistance of the line was assumed to be negligible. In actual ac transmission lines, however, the resistance of the line is generally high enough to have a significant effect on the values of the voltage, current, and power in the circuit. To better illustrate this, consider the voltage-compensated 230 kV ac transmission line of Figure 32, and assume that it has a line resistance R_L of 20 Ω. The resulting ac transmission line is illustrated in Figure 36. The different voltage and current values in the ac transmission line when a resistance is added to the line are indicated in the figure. As the figure illustrates, the total voltage drop E_L across the line is now equal to the sum of the voltage drop E_{R_L} caused by the equivalent resistance of the line and the voltage drop E_{X_L} caused by the equivalent inductance of the line.
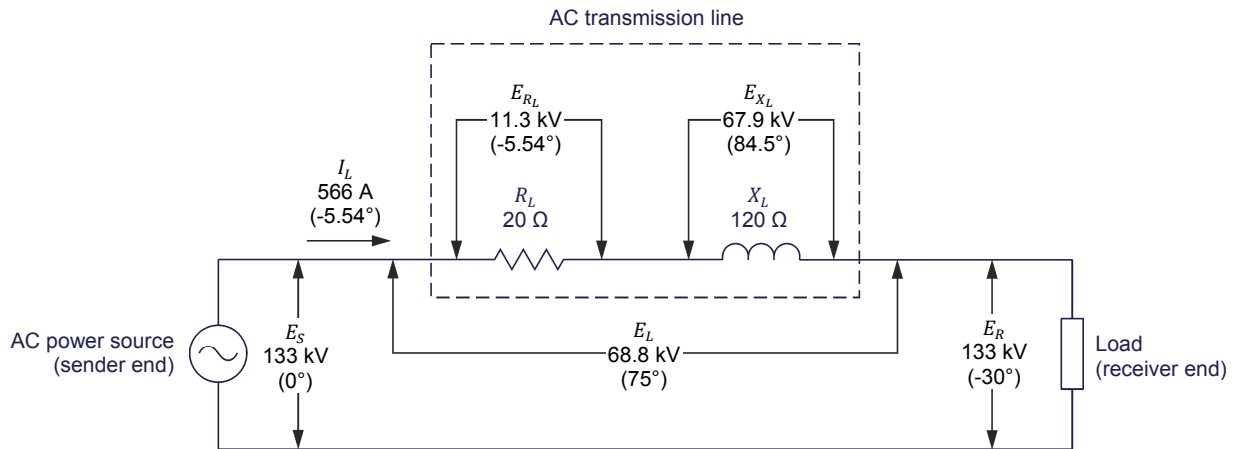
Figure 36. Voltage-compensated 230 kV ac transmission line of Figure 32 when the line resistance R_L is assumed to be equal to 20 Ω.

The phasors of the voltages and current for one phase of the ac transmission line in Figure 36 are illustrated in the phasor diagram of Figure 37.
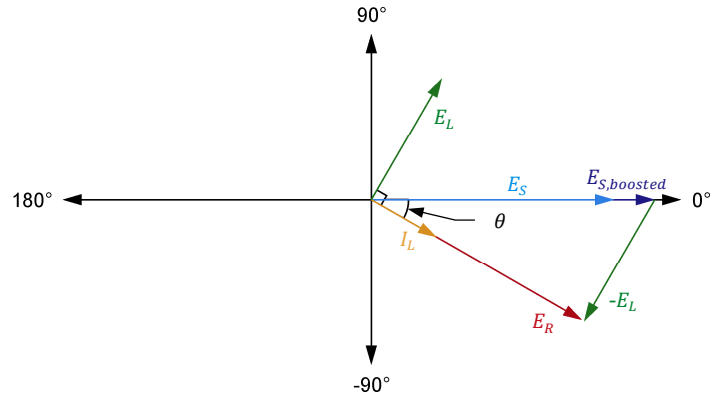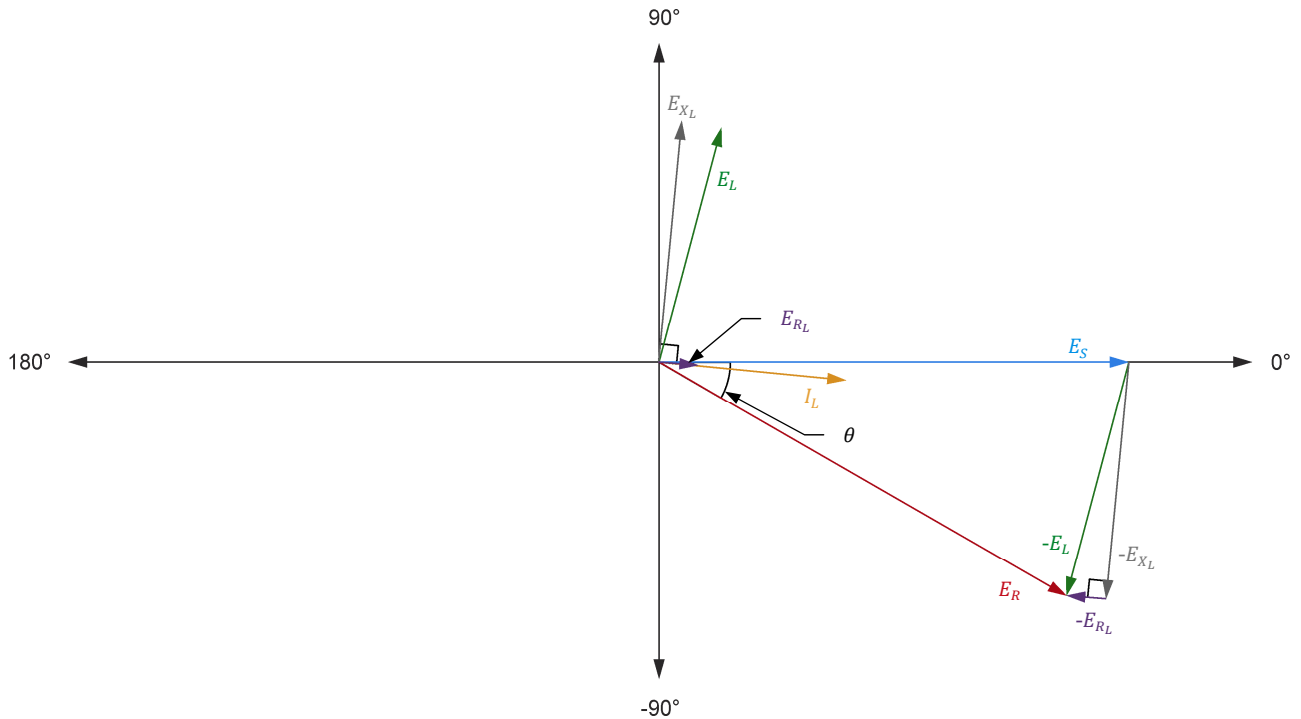

Figure 37. Phasor diagram of the voltages and currents for one phase of the voltage-compensated 230 kV ac transmission line in Figure 36.

As Figure 37 shows, the phasor of the line current I_L does not bisect the phase angle θ between the receiver voltage E_R and the sender voltage E_S when the resistance of the ac transmission line is taken into account.

The different values of active power P and reactive power Q for one phase of the ac transmission line are calculated below.

$$P_S = E_S I_L \cos \theta_{E_S I_L} = 133\ 000 \text{ V} \times 566 \text{ A } \times \cos 5.54 = 74\ 926 \text{ kW}$$

$$Q_S = E_S I_L \sin \theta_{E_S I_L} = 133\ 000 \text{ V} \times 566 \text{ A} \times \sin 5.54 = 7267 \text{ kvar}$$

$$P_R = E_R I_L \cos \theta_{E_R I_L} = 133\ 000 \text{ V} \times 566 \text{ A} \times \cos -24.5 = 68\ 500 \text{ kW}$$

$$Q_R = E_R I_L \sin \theta_{E_R I_L} = 133\ 000 \text{ V} \times 566 \text{ A} \times \sin -24.5 = -31\ 217 \text{ kvar}$$

The above calculations show that the amount of active power P_R at the receiver end of the ac transmission line (68 500 kW) is slightly lower than the amount of active power P_S at the sender end of the line (74 926 kW). This is due to the fact that some active power (74 926 kW − 68 500 kW = 6426 kW) is dissipated in the equivalent resistance of the line. The calculations also show that the receiver end of the ac transmission line supplies much more reactive power to the line (31 217 kvar) than the sender end of the line (7267 kvar). This unbalance in the proportion of reactive power supplied by the sender end and the receiver end of the ac transmission line is due to the fact that the equivalent resistance of the line is taken into account, thus modifying the phase angle of the line current I_L.

Since the phase angle of the line current I_L flowing in the line is much closer to that of the sender voltage E_S than to that of the receiver voltage E_R, less reactive power is supplied by the sender end than by the receiver end of the ac transmission line when the line is voltage-compensated.

Note that the equivalent resistance of the ac transmission line in Figure 36 is slightly exaggerated in order to better demonstrate the effects of the line resistance on the operation of the ac transmission line. In actual ac transmission lines, the equivalent resistance of the line has a lower value.

Introduction to the regulating autotransformer

A regulating autotransformer has the ability to act as either a phase-shifting transformer, a buck-boost transformer, or both at the same time. This enables a regulating autotransformer to control the flow of active power P and reactive power Q in an ac transmission line. Active power P can be controlled by decreasing or increasing the phase angle of the incoming voltages. Reactive power Q, on the other hand, can be controlled by decreasing or increasing the incoming voltages.

When a regulating autotransformer operates as a phase-shifting transformer, its principles of operation can be understood by examining the equivalent circuit of the regulating autotransformer shown in Figure 38.
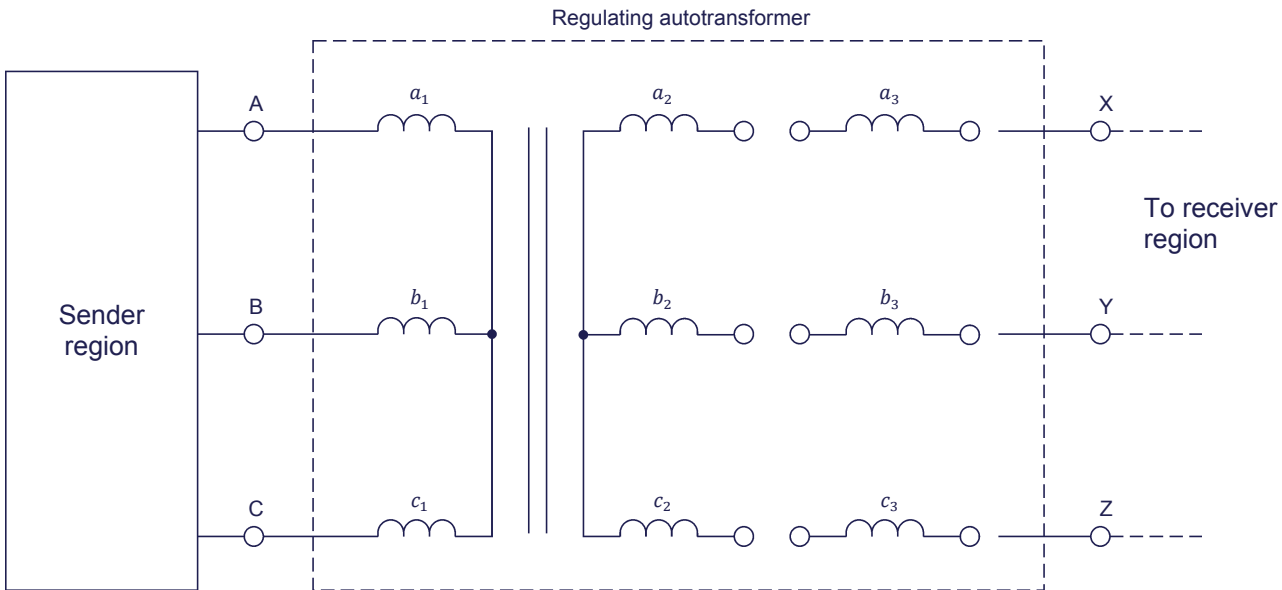
Figure 38. Equivalent circuit of a regulating autotransformer.

As the figure shows, the regulating autotransformer is equivalent to a three-phase power transformer with primary windings (a_1, b_1, and c_1) and secondary windings (a_2, b_2, and c_2) connected in a wye-wye configuration. The transformer also has a set of tertiary windings (a_3, b_3, and c_3) that can be connected to the secondary windings. The phasor diagrams of the voltages at the primary, secondary, and tertiary windings are shown in Figure 39.
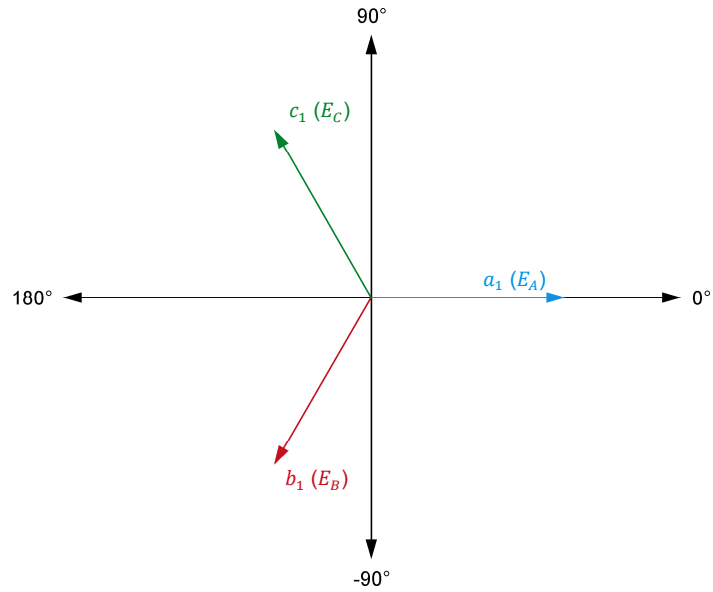
(a) Phasor diagram of the voltages at the primary windings
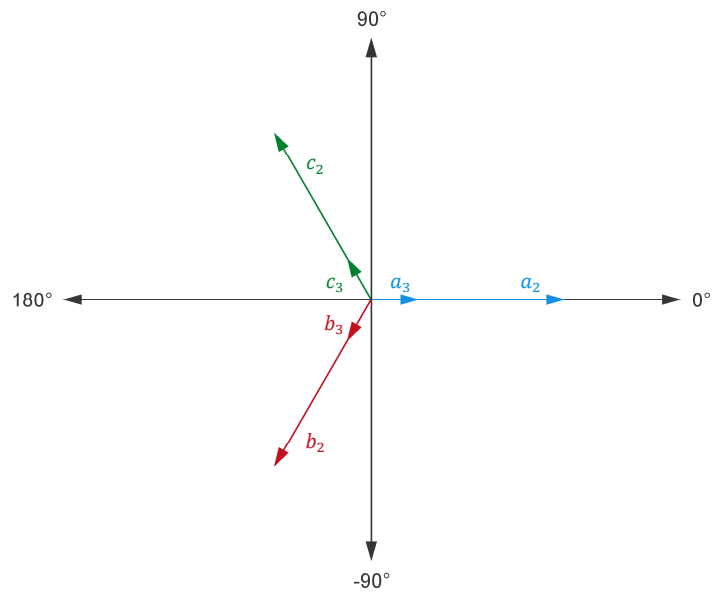
(b) Phasor diagram of the voltages at the secondary and tertiary windings

Figure 39. Phasor diagrams of the voltages at the primary, secondary, and tertiary windings of the regulating autotransformer of Figure 38.

As you can see, the voltages related to windings of the same phase (e.g., windings a_1, a_2, and a_3) are in phase with one another. When the regulating autotransformer is set to 0° phase shift, the tertiary windings are not used (i.e., the secondary windings a_2, b_2, and c_2 are connected directly to output terminals X, Y, and Z of the regulating autotransformer), and thus, the outgoing voltages (E_X, E_Y, and E_Z) are in phase with the incoming voltages (E_A, E_B, and E_C). However, when the tertiary windings are connected to the secondary windings, the incoming voltages can be phase shifted, as shown in Figure 40.
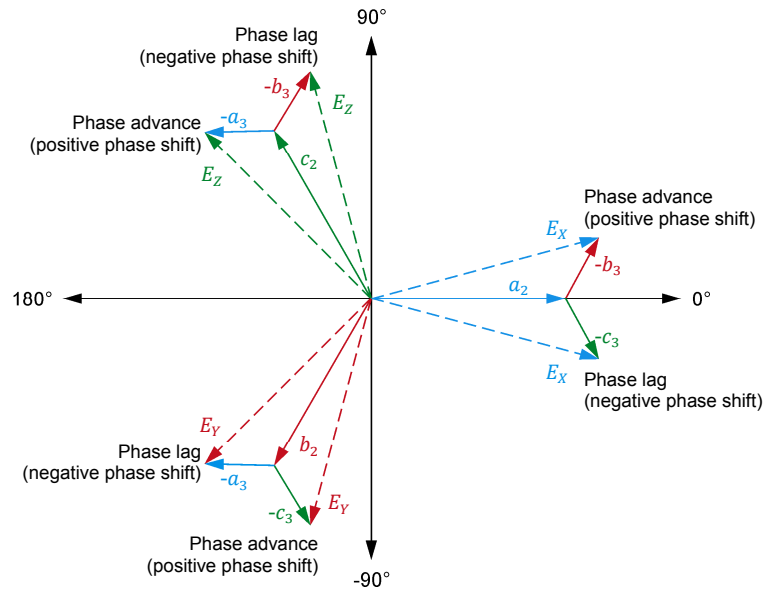
Figure 40. Phasor diagrams of the regulating autotransformer when it acts as a phase-shifting transformer.

As the figure shows, when the tertiary windings b_3, c_3, and a_3 of a regulating autotransformer are connected in series-opposing with the secondary windings a_2, b_2, and c_2, respectively, the resulting outgoing voltages E_X, E_Y, and E_Z lead the incoming voltages E_A, E_B, and E_C. Conversely, when the tertiary windings c_3, a_3, and b_3 of a regulating autotransformer are connected in series-opposing with the secondary windings a_2, b_2, and c_2, respectively, the resulting outgoing voltages E_X, E_Y, and E_Z lag behind the incoming voltages E_A, E_B, and E_C.

By modifying the ratio between the voltage at the tertiary windings and the voltage at the secondary windings of a regulating autotransformer (i.e., by modifying the turns ratio), it is possible to adjust the magnitude of the phase shift between the outgoing voltages E_X, E_Y, and E_Z and the incoming voltages E_A, E_B, and E_C. The higher the voltage at the tertiary windings in relation to the voltage at the secondary windings, the greater the phase shift between the outgoing voltages and the incoming voltages. In actual regulating autotransformers, the phase shift between the outgoing voltages and the incoming voltages can generally be adjusted between +30° and -30°.

Figure 40 also shows that the magnitude of the phase-shifted outgoing voltages E_X, E_Y, and E_Z across the regulating autotransformer is greater than that of the incoming voltages E_A, E_B, and E_C. To compensate for this increase in the magnitude of the phase-shifted outgoing voltages, multiple taps are available on the windings of the regulating autotransformer. Using these taps, it is possible to adjust the magnitude of the phase-shifted outgoing voltages so that it is maintained equal to the magnitude of the incoming voltages. The taps on the windings of the regulating autotransformer can also be used to step-up or step-down the incoming voltages. The ratio between the outgoing voltages and the incoming voltages of the step-up autotransformer [i.e., the percentage of decrease (buck) or increase (boost) of the outgoing voltages in relation to the

incoming voltages] can be adjusted by selecting the appropriate taps on the windings of the regulating autotransformer.

A phasor diagram showing the various outgoing voltages possible at one phase of a regulating autotransformer acting as both a phase-shifting transformer and a buck-boost transformer is illustrated in the figure below.
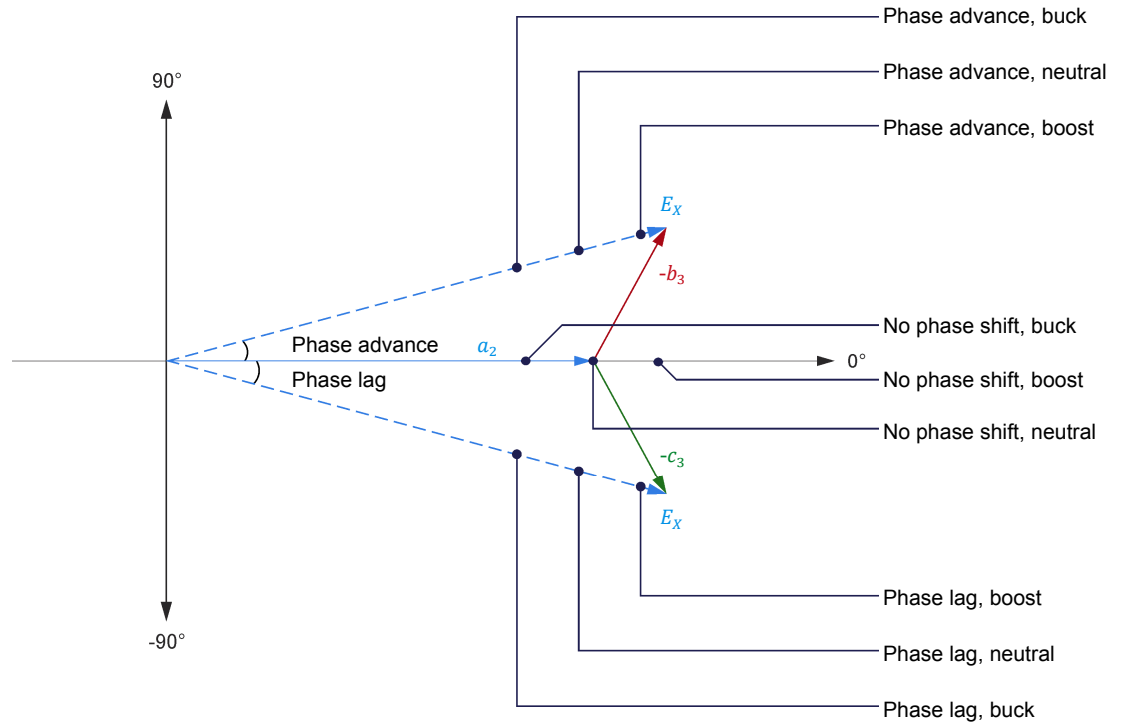
Figure 41. Phasor diagram of the outgoing voltages possible at one phase of a regulating autotransformer acting as both a phase-shifting transformer and a buck-boost transformer.

PROCEDURE OUTLINE   The Procedure is divided into the following sections:

- Set up and connections
- Reactive power flow in an ac transmission line
- Control of active power flow in an interconnected power network
- Control of active power and reactive power flow in an interconnected power network

PROCEDURE

<div align="center">

⚠ **WARNING**

</div>

High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

Set up and connections

In this section, you will set up a circuit containing an ac transmission line connected to a three-phase resistive load as well as to shunt capacitors for voltage compensation. You will then set the measuring equipment to observe the flow of reactive power in the ac transmission line.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform this exercise.

Install the required equipment in the Workstation.

If you are using the Three-Module Workstation, Model 8131, to perform this exercise, do not install the Three-Phase Transformer Bank in the workstation for the moment. This ensures that you have enough space in the workstation in order to install the six half-modules required to perform the first part of this exercise. The Three-Phase Transformer Bank module is only used later in this exercise.

2. Make sure that the ac and dc power switches on the Power Supply are set to the O (off) position, then connect the Power Supply to a three-phase ac power outlet.

Connect the *Power Input* of the Data Acquisition and Control Interface to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

4. Turn the host computer on, then start the LVDAC-EMS software.

In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface is detected. Make sure that the *Computer-Based*

Instrumentation function for the Data Acquisition and Control Interface is available. Also, select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

5. Connect the equipment as shown in Figure 42.
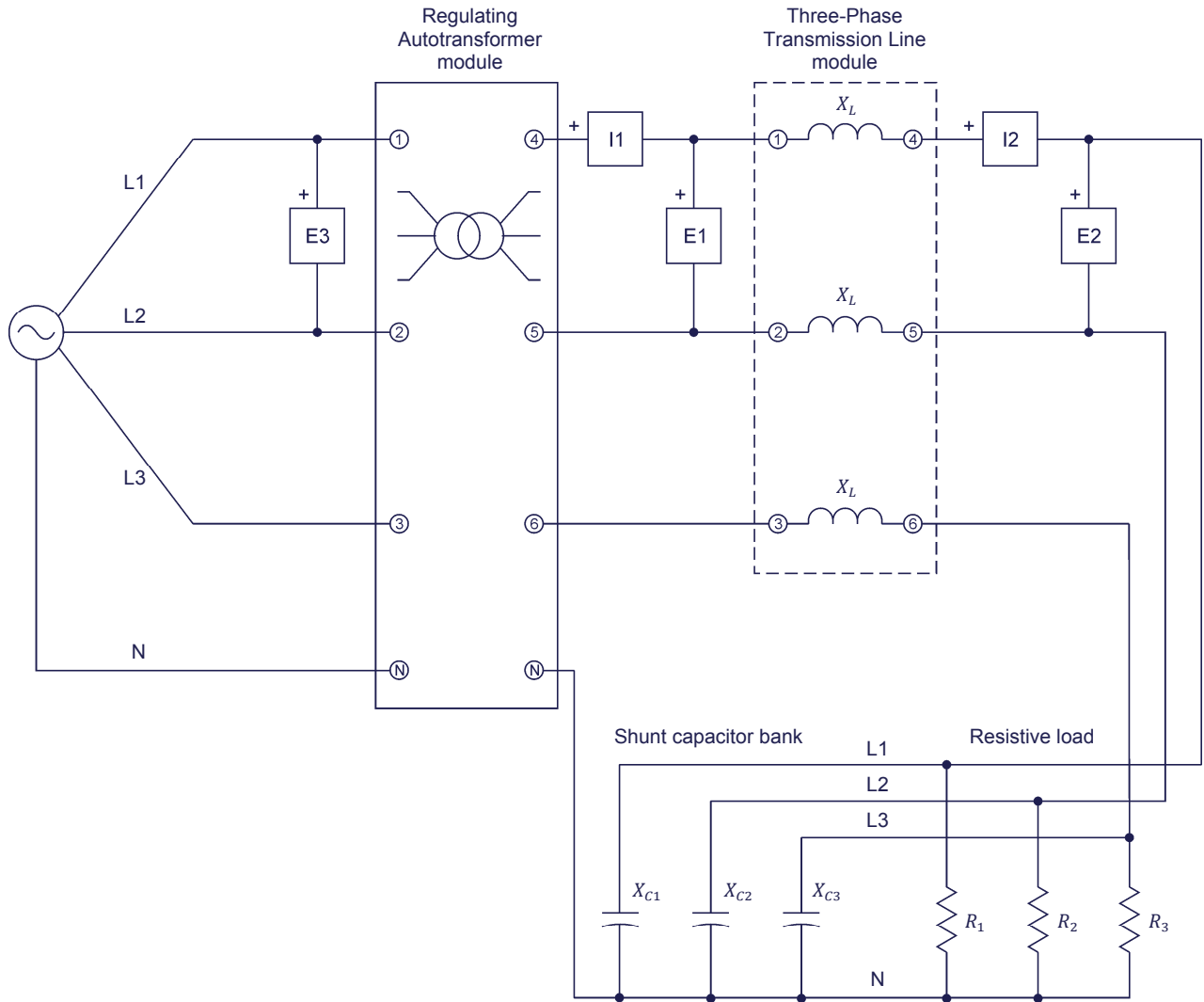
Local ac power network		Line inductive reactance X_L (Ω)	R_1, R_2, R_3 (Ω)	X_{C1}, X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)			
120	60	180	300	∞
220	50	600	1100	∞
240	50	600	1200	∞

Figure 42. Circuit used to observe the flow of reactive power in an ac transmission line.

6. Make sure that the I/O toggle switch on the Three-Phase Transmission Line is set to the I position.

On the Three-Phase Transmission Line, set the inductive reactance selector to the value indicated in the table of Figure 42.

Make sure that the *Buck-Boost* and *Phase Shift* selectors on the Regulating Autotransformer are set to 0% and 0°, respectively.

Make the necessary switch settings on the Resistive Load in order to obtain the resistance value required.

Open all switches on the Capacitive Load so that the reactances X_{C1}, X_{C2}, and X_{C3} of the shunt capacitors are infinite.

7. In LVDAC-EMS, open the Metering window. Make the required settings in order to measure the rms values (ac) of the modified voltage $E_{S,mod.}$ (input *E1*) at the sender end of the ac transmission line, the line current I_L (input *I1* or *I2*), and the voltage E_R (input *E2*) at the receiver end of the ac transmission line. Set two other meters to measure the three-phase reactive power Q_S at the sender end of the ac transmission line [metering function *PQS1 (E1, I1) 3~*] and the three-phase reactive power Q_R at the receiver end of the ac transmission line [metering function *PQS2 (E2, I2) 3~*]. Finally, set a meter to measure the rms value (ac) of the voltage E_S (input *E3*) at the sender end of the ac transmission line (i.e., the voltage at the sender end of the line before modification by the Regulating Autotransformer).

> *Metering functions* PQS1 (E1, I1) 3~ *and* PQS2 (E2, I2) 3~ *allow three-phase power measurement from the line voltage and current measured in one branch of a three-phase circuit. The power measurements obtained using these metering functions are only valid if the circuit to which the voltage and current inputs are connected is balanced.*

In the *Option* menu of the Metering window, select *Acquisition Settings* to open the corresponding dialog box. Set the *Sampling Window* to 8 cycles then click *OK* to close the dialog box. This enables a better accuracy when measuring the reactive power Q in the ac transmission line.

Reactive power flow in an ac transmission line

In this section, you will compensate the voltage at the receiver end of the ac transmission line, and measure the voltage and reactive power values at the sender and receiver ends of the line. You will calculate the percentage of the total reactive power that each end supplies to the line, and analyze the results. You will then repeat the steps described above for the following two settings on the Regulating Autotransformer: an increase (boost) of 15% and a decrease (buck) of 15%.

8. Turn the three-phase ac power source in the Power Supply on.

9. On the Capacitive Load, adjust the reactances X_{C1}, X_{C2}, and X_{C3} of the shunt capacitors so that the voltage E_R at the receiver end of the ac transmission line indicated in the Metering window is as close as possible to the voltage E_S at the sender end of the line.

10. In the Metering window, measure the following parameters. Record the values below.

    Sender voltage E_S = _____ V

    Modified sender voltage $E_{S,mod.}$ = _____ V

    Receiver voltage E_R = _____ V

    Sender reactive power Q_S = _____ var

    Receiver reactive power Q_R = _____ var

11. Using the reactive power values you recorded in the previous step, calculate the percentage of the total reactive power Q supplied by each end of the ac transmission line. Record the values below.

    Percentage of reactive power Q supplied by the sender end = _____%

    Percentage of reactive power Q supplied by the receiver end = _____%

    Are the percentage values of reactive power supplied by each end of the ac transmission line you just recorded relatively close to one another, as expected when the voltage E_R at the receiver end is virtually equal to the voltage E_S at the sender end? Explain briefly.

    _____

    _____

    _____

    _____

    _____

    _____

12. On the Regulating Autotransformer, set the *Buck-Boost* selector to +15%.

    On the Capacitive Load, adjust the reactances X_{C1}, X_{C2}, and X_{C3} of the shunt capacitors so that the voltage E_R at the receiver end of the ac transmission line indicated in the Metering window is as close as possible to the voltage E_S at the sender end of the ac transmission line.

13. In the Metering window, measure the following parameters. Record the values below.

Sender voltage E_S = _____ V

Modified sender voltage $E_{S,mod.}$ = _____ V

Receiver voltage E_R = _____ V

Sender reactive power Q_S = _____ var

Receiver reactive power Q_R = _____ var

14. Using the reactive power values you recorded in the previous step, calculate the percentage of the total reactive power Q supplied by each end of the ac transmission line. Record the values below.

Percentage of reactive power Q supplied by the sender end = _____ %

Percentage of reactive power Q supplied by the receiver end = _____ %

Does increasing the voltage at the sender end of the ac transmission line using a regulating autotransformer have any effect on the percentage of reactive power Q supplied by each end of the line? Explain briefly.

_____

_____

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15. On the Regulating Autotransformer, set the *Buck-Boost* selector to 0%.

On the Capacitive Load, adjust the reactances X_{C1}, X_{C2}, and X_{C3} of the shunt capacitors so that the voltage E_R at the receiver end of the ac transmission line indicated in the Metering window is as close as possible to the voltage E_S at the sender end of the ac transmission line.

16. On the Regulating Autotransformer, set the *Buck-Boost* selector to -15%.

On the Capacitive Load, adjust the reactances X_{C1}, X_{C2}, and X_{C3} of the shunt capacitors so that the voltage E_R at the receiver end of the ac transmission line indicated in the Metering window is as close as possible to the voltage E_S at the sender end of the ac transmission line.

17. In the Metering window, measure the following parameters. Record the values below.

Sender voltage E_S = _____ V

Modified sender voltage $E_{S,mod.}$ = _____ V

Receiver voltage E_R = _____ V

Sender reactive power Q_S = _____ var

Receiver reactive power Q_R = _____ var

18. Using the reactive power values you recorded in the previous step, calculate the percentage of the total reactive power Q supplied by each end of the ac transmission line. Record the values below.

Percentage of reactive power Q supplied by the sender end = _____ %

Percentage of reactive power Q supplied by the receiver end = _____ %

Does decreasing the voltage at the sender end of the ac transmission line using a regulating autotransformer have any effect on the percentage of reactive power Q supplied by each end of the line? Explain briefly.

_____

_____

_____

_____

19. Based on your observations, is adding a buck-boost transformer in series with an ac transmission line an effective way to control the amount of reactive power supplied by each end of the line without modifying the voltages at either end of the line?

❏ Yes   ❏ No

20. Turn the three-phase ac power source in the Power Supply off.

Control of active power flow in an interconnected power network

In this section, you will set up a circuit representing two regions (A and B) of a power network that are interconnected via an ac transmission line and a regulating autotransformer (located at region A). You will measure the three-phase active power at regions A and B when the phase shift value on the regulating autotransformer is 0°. You will observe in the Phasor Analyzer the voltage at region A, the voltage at region A after modification by the regulating autotransformer, and the voltage at region B, and analyze the results. You will then repeat the steps described above for phase shift values on the regulating autotransformer of 15° and -15°.

21. Connect the equipment as shown in Figure 43. This circuit represents the ac transmission line between two regions (A and B) of an interconnected ac power network. Region A and region B are identified on the circuit diagram. Since the voltage at region A and the voltage at region B both come from the same three-phase ac power source, the phase angle of the voltage at region A is the same as that of the voltage at region B. In other words, the phase shift θ between these two regions is zero when no phase shift is introduced by the Regulating Autotransformer. Input *E3* measures the voltage $E_{Reg.A}$ at region A, inputs *E1* and *I1* measure the voltage $E'_{Reg.A}$ at region A after modification by the Regulating Autotransformer and the line current I_L, and inputs *E2* and *I2* measure the voltage $E_{Reg.B}$ at region B and the line current I_L.
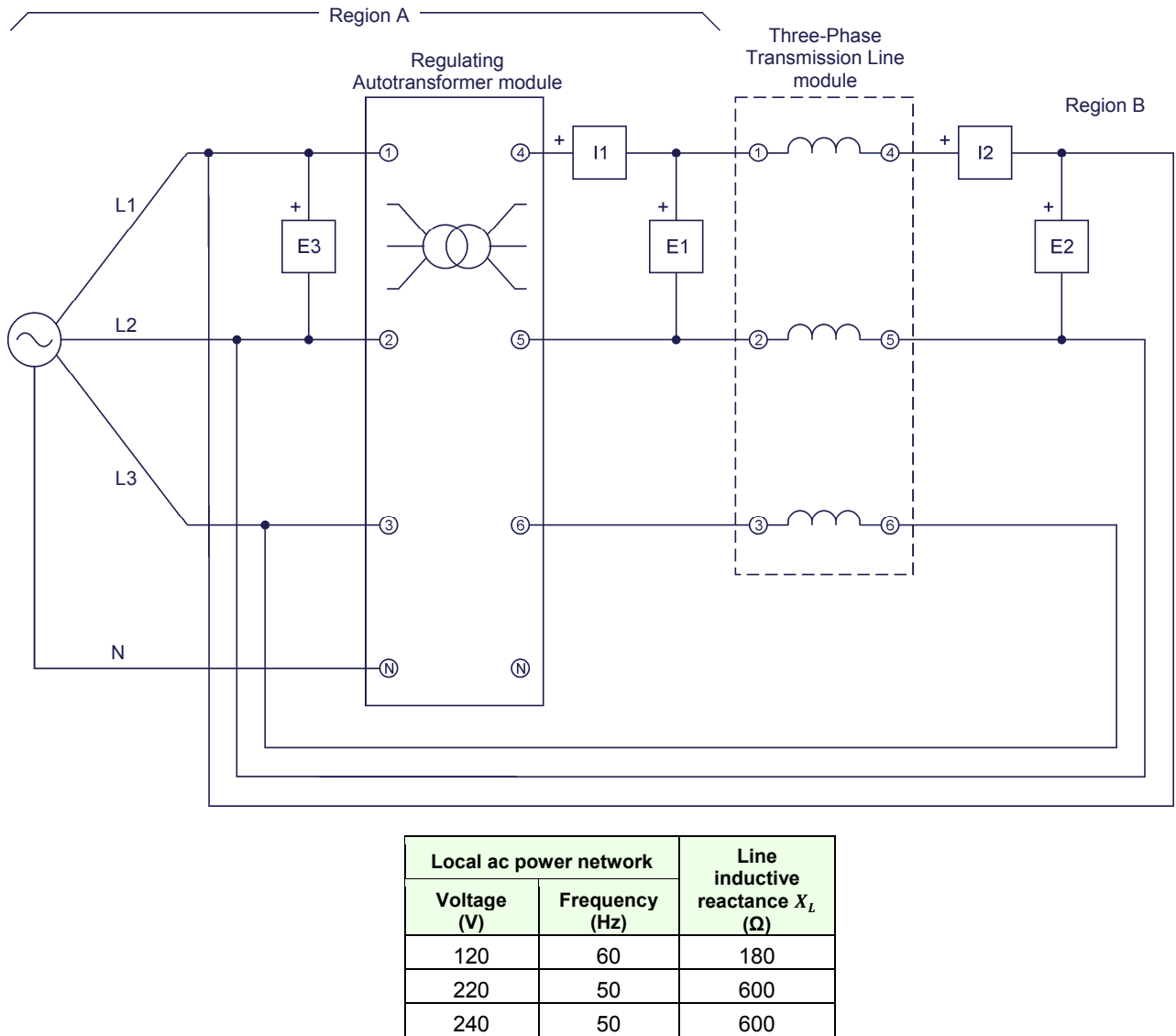
Figure 43. Circuit used to observe active power flow control in an ac transmission line of an interconnected ac power network.

Local ac power network		Line inductive reactance X_L (Ω)
Voltage (V)	Frequency (Hz)	
120	60	180
220	50	600
240	50	600

22. On the Three-Phase Transmission Line, make sure that the inductive reactance selector is set to the value indicated in the table of Figure 43.

On the Regulating Autotransformer, set the *Buck-Boost* selector to 0% and make sure that the *Phase Shift* selector is set to 0°.

23. In the Metering window, keep all meter settings you made earlier in this exercise, then set two other meters to measure the three-phase active power $P_{Reg.A}$ at region A (metering function *PQS1 (E1, I1) 3~*) and the three-phase active power $P_{Reg.B}$ at region B (metering function *PQS2 (E2, I2) 3~*).

24. Turn the three-phase ac power source in the Power Supply on.

25. In the Metering window, measure the active power $P_{Reg.A}$ at region A, as well as the active power $P_{Reg.B}$ at region B. Record the results in the corresponding cells of Table 14.

Table 14. Active power *P* measured at regions A and B for different settings of the Regulating Autotransformer.

Phase shift (°)	Region A Active power $P_{Reg.A}$ (W)	Region B Active power $P_{Reg.B}$ (W)
0		
+15		
-15		

26. In LVDAC-EMS, open the Phasor Analyzer. Make the required settings in order to observe the phasors of the voltage $E_{Reg.A}$ at region A, the modified voltage $E'_{Reg.A}$ at region A, and the voltage $E_{Reg.B}$ at region B. Set the phasor of the voltage $E_{Reg.A}$ as the reference phasor.

Observe the three voltage phasors. Are all voltage phasors in phase?

❑ Yes   ❑ No

Explain why no active power is transferred via the ac transmission line.

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_____

27. On the Regulating Autotransformer, set the *Phase Shift* selector successively to +15° and -15°. For each of these two settings, repeat step 25. As you do so, observe in the Phasor Analyzer the phasors of the voltage $E_{Reg.A}$ at region A, the modified voltage $E'_{Reg.A}$ at region A, and the voltage $E_{Reg.B}$ at region B.

What happens to these voltage phasors when a phase shift of +15° or -15° is introduced using the Regulating Autotransformer?

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28. Using the results you recorded in Table 14, determine the relationship between the phase shift θ between the voltages at both ends of the ac transmission line and the amount of active power P transferred via the ac transmission line.

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_____

_____

Does this confirm the theory presented in this exercise discussion?

❏ Yes   ❏ No

29. Do your observations thus far confirm that the Regulating Autotransformer allows the phase shift θ between the voltages at the two ends of an ac transmission line interconnecting two regions of an ac power network to be adjusted (for active power flow control purposes) without modifying the phase angle of the voltage at either region?

❏ Yes   ❏ No

**30.** Turn the three-phase ac power source in the Power Supply off.

Control of active power and reactive power flow in an interconnected power network

In this section, you will add a three-phase transformer bank connected in a wye-delta configuration in series with the three-phase ac power source in order to introduce a phase shift of 30° between the voltage at region B and that at region A. You will measure the active power and reactive power at regions A and B when the Buck-Boost and Phase Shift selectors of the Regulating Autotransformer are set to 0% and 0°, respectively. You will set the Phase Shift selector of the Regulating Autotransformer to +15° to adjust the amount of active power transferred via the ac transmission line and measure the active power and reactive power at regions A and B. You will then set successively the Buck-Boost selector of the Regulating Autotransformer to +15% and -15%, and measure for each setting the active power and reactive power at regions A and B. As you do so, you will also observe in the Metering window the magnitude of the voltage at region A, modified voltage at region A, and voltage at region B. Finally, you will analyze the results.

31. If you are using the Three-Module Workstation, Model 8131, to perform this exercise, remove the Resistive Load and Capacitive Load modules from the workstation. Then, install the Three-Phase Transformer Bank module in the workstation.

If you are not using the Three-Module Workstation, Model 8131, to perform this exercise, ignore the above manipulations.

32. Connect the equipment as shown in Figure 44. This circuit represents the ac transmission line between two interconnected regions (A and B) in an ac power network, just as the circuit used in the previous section of this exercise. In the circuit of Figure 44, however, a three-phase transformer bank connected in a wye-delta configuration is added in series with the three-phase ac power source. This has the effect of delaying the phase angle of the voltage at region B by 30°. In other words, the phase shift θ between region B and region A is 30° when no phase shift is introduced using the Regulating Autotransformer. Note that the turns ratio of the three-phase transformer bank in Figure 44 is $1 : \sqrt{3}$. This is necessary to compensate for the wye-delta configuration of the three-phase transformer bank, which decreases incoming voltages by a ratio of $\sqrt{3} : 1$. Since both ratios cancel each other, the resulting magnitude of the voltage $E_{Reg.B}$ is equal to the magnitude of the voltage $E_{Reg.A}$.
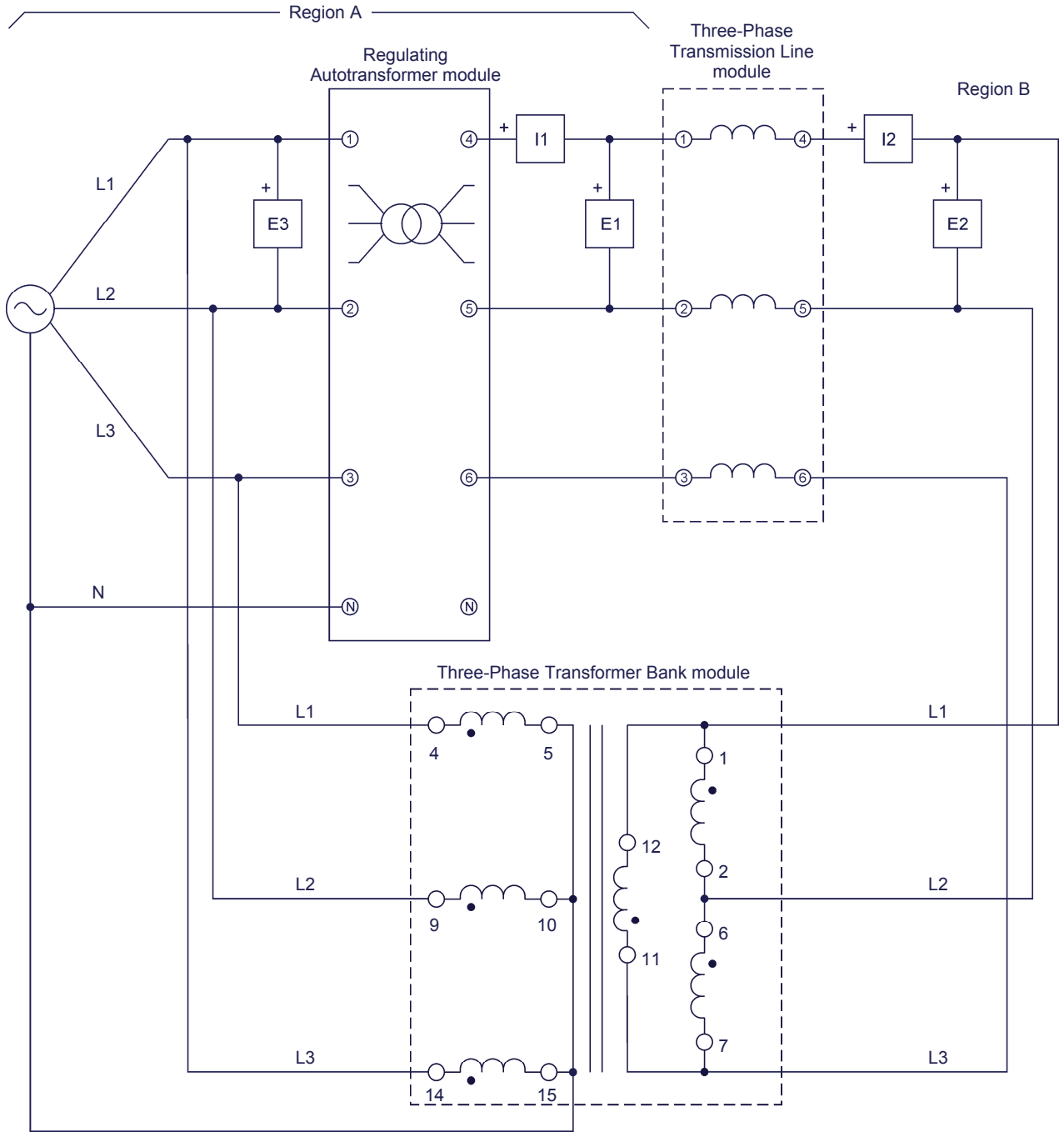
Figure 44. Circuit used to observe active power and reactive power flow control in an ac transmission line of an interconnected ac power network.

Local ac power network		Line inductive reactance X_L (Ω)
Voltage (V)	Frequency (Hz)	
120	60	180
220	50	600
240	50	600

33. On the Three-Phase Transmission Line, make sure that the inductive reactance selector is set to the value indicated in the table of Figure 44.

On the Regulating Autotransformer, set the *Phase Shift* and *Buck-Boost* selectors to 0° and 0%, respectively.

34. Turn the three-phase ac power source in the Power Supply on.

35. In the Metering window, measure the active power $P_{Reg.A}$ and reactive power $Q_{Reg.A}$ at region A, as well as the active power $P_{Reg.B}$ and reactive power $Q_{Reg.B}$ at region B. Record the results in the corresponding cells of Table 15.

Table 15. Active power P and reactive power Q measured at regions A and B for different settings of the Regulating Autotransformer.

Phase shift (°)	Buck-boost (%)	Region A		Region B	
		Active power $P_{Reg.A}$ (W)	Reactive power $Q_{Reg.A}$ (var)	Active power $P_{Reg.B}$ (W)	Reactive power $Q_{Reg.B}$ (var)
0	0				
+15	0				
+15	+15				
+15	-15				

36. Does the amount of active power P transferred via the ac transmission line indicate that the phase shift θ between the voltage at region B and the voltage at region A is not equal to zero?

❑ Yes   ❑ No

Does this confirm that the Three-Phase Transformer Bank module introduces a phase shift θ between the voltage at region B and the voltage at region A?

❑ Yes   ❑ No

37. On the Regulating Autotransformer, set the *Phase Shift* selector to +15°, then repeat step 35.

38. On the Regulating Autotransformer, set the *Buck-Boost* selector successively to +15° and -15°. For each of these two settings, repeat step 35. As you do so, observe in the Metering window the values of the voltage $E_{Reg.A}$ at region A, the modified voltage $E'_{Reg.A}$ at region A, and the voltage $E_{Reg.B}$ at region B.

What happens to these three voltage values depending on whether the Regulating Autotransformer operates as a step-up (boost) or a step-down (buck) transformer?

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39. Turn the three-phase ac power source in the Power Supply off.

40. Using the results you recorded in Table 15, determine the relationship between the difference in magnitude between the voltages at both ends of the ac transmission line interconnecting regions A and B (i.e., the difference between $E'_{Reg.A}$ and $E_{Reg.B}$), and the amount of reactive power Q which each region supplies to the ac transmission line.

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Does this confirm the theory presented in this exercise discussion?

❑ Yes   ❑ No

41. Do your observations in this exercise confirm that a regulating autotransformer allows control of both the active power flow and reactive power flow in an ac transmission line interconnecting two regions of an ac power network without modifying the magnitude and phase angle of the voltage at either region?

❑ Yes   ❑ No

42. Close LVDAC-EMS, then turn off all the equipment. Disconnect all leads and return them to their storage location.

CONCLUSION

In this exercise, you learned how to control the flow of active power in ac transmission lines used in interconnected power networks. You familiarized yourself with the flow of reactive power in ac transmission lines. You also learned how to control the flow of reactive power in ac transmission lines used in interconnected power networks. You were introduced to the operating principles of regulating autotransformers.

REVIEW QUESTIONS

1. How is it possible to determine the direction of the flow of active power P transferred by an ac transmission line connecting two regions of a power network?

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    _____

    _____

    _____

2. Explain how it is possible to control the flow of active power P transferred by an ac transmission line connecting two regions of a power network.

    _____

    _____

    _____

    _____

    _____

3. Explain how it is possible to control the flow of reactive power Q in an ac transmission line connecting two regions of a power network.

    _____

    _____

    _____

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    _____

4. Briefly explain the operating principles of a regulating autotransformer when it is used as a phase-shifting transformer.

    _____

    _____

    _____

    _____

    _____

    _____

    _____

5. Briefly explain the operating principles of a regulating autotransformer when it is used as a step-down (buck) or step-up (boost) transformer.

    _____

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    _____

Sample

Extracted from

Instructor Guide

Exercise 5   Control of Active and Reactive Power Flow

ANSWERS TO PROCEDURE STEP QUESTIONS

10. Sender voltage $E_S = 207$ V

Modified sender voltage $E_{S,mod.} = 207$ V

Receiver voltage $E_R = 209$ V

Sender reactive power $Q_S = 34.5$ var

Receiver reactive power $Q_R = -77.1$ var

11. The percentage values of the total reactive power Q supplied by each end of the ac transmission line are calculated below.

$$\text{Sender end} = \frac{34.5 \text{ var}}{34.5 \text{ var} - (-77.1 \text{ var})} \times 100\% = 31\%$$

$$\text{Receiver end} = \frac{77.1 \text{ var}}{34.5 \text{ var} - (-77.1 \text{ var})} \times 100\% = 69\%$$

Percentage of reactive power Q supplied by the sender end $= 31\%$

Percentage of reactive power Q supplied by the receiver end $= 69\%$

No. Due to the resistance of the ac transmission line, there is a significant unbalance in the reactive power Q supplied by each end of the line. Because of this, the proportion of reactive power supplied by each end of the line when the sender voltage E_S and the receiver voltage E_R are equal is not as evenly distributed as is expected in theory (Q_R is significantly higher than Q_S).

13. Sender voltage $E_S = 207$ V

Modified sender voltage $E_{S,mod.} = 237$ V

Receiver voltage $E_R = 215$ V

Sender reactive power $Q_S = 58.4$ var

Receiver reactive power $Q_R = -40.1$ var

The value of the receiver voltage E_R which can be obtained with the available shunt capacitors differs slightly from the value of the sender voltage E_S.

14. The percentage values of the total reactive power Q supplied by each end of the ac transmission line are calculated below.

$$\text{Sender end} = \frac{58.4 \text{ var}}{58.4 \text{ var} - (-40.1 \text{ var})} \times 100\% = 59\%$$

$$\text{Receiver end} = \frac{40.1 \text{ var}}{58.4 \text{ var} - (-40.1 \text{ var})} \times 100\% = 41\%$$

Percentage of reactive power Q supplied by the sender end $= 59\%$

Percentage of reactive power Q supplied by the receiver end $= 41\%$

Yes. Increasing the voltage at the sender end of the ac transmission line using a regulating autotransformer increases the percentage of reactive power Q which the sender end supplies to the line, and decreases the percentage of reactive power Q which the receiver end supplies to the line.

17. Sender voltage $E_S = 207$ V

Modified sender voltage $E_{S,mod.} = 175$ V

Receiver voltage $E_R = 216$ V

Sender reactive power $Q_S = 26.0$ var

Receiver reactive power $Q_R = -154$ var

The value of the receiver voltage E_R which can be obtained with the available shunt capacitors differs slightly from the value of the sender voltage E_S.

18. The percentage values of the total reactive power Q supplied by each end of the ac transmission line are calculated below.

$$\text{Sender end} = \frac{26.0 \text{ var}}{26.0 \text{ var} - (-154 \text{ var})} \times 100\% = 14\%$$

$$\text{Receiver end} = \frac{154 \text{ var}}{26.0 \text{ var} - (-154 \text{ var})} \times 100\% = 86\%$$

Percentage of reactive power Q supplied by the sender end $= 14\%$

Percentage of reactive power Q supplied by the receiver end $= 86\%$

Yes. Decreasing the voltage at the sender end of the ac transmission line using a regulating autotransformer decreases the percentage of reactive power Q which the sender end supplies to the line, and increases the percentage of reactive power Q which the receiver end supplies to the line.

19. Yes

25. The results are presented in the following table.

Active power P measured at regions A and B for different settings of the Regulating Autotransformer.

Phase shift (°)	Region A	Region B
	Active power $P_{Reg.A}$ (W)	Active power $P_{Reg.B}$ (W)
0	0.48	0.36
+15	64.3	62.6
-15	-60.3	-62.0

26. The resulting voltage phasors when the Regulating Autotransformer is set to a 0° phase shift are shown in the following figure.

Phasor Analyzer Settings
Reference Phasor.................................. E3
Voltage Scale...............................100 V/div
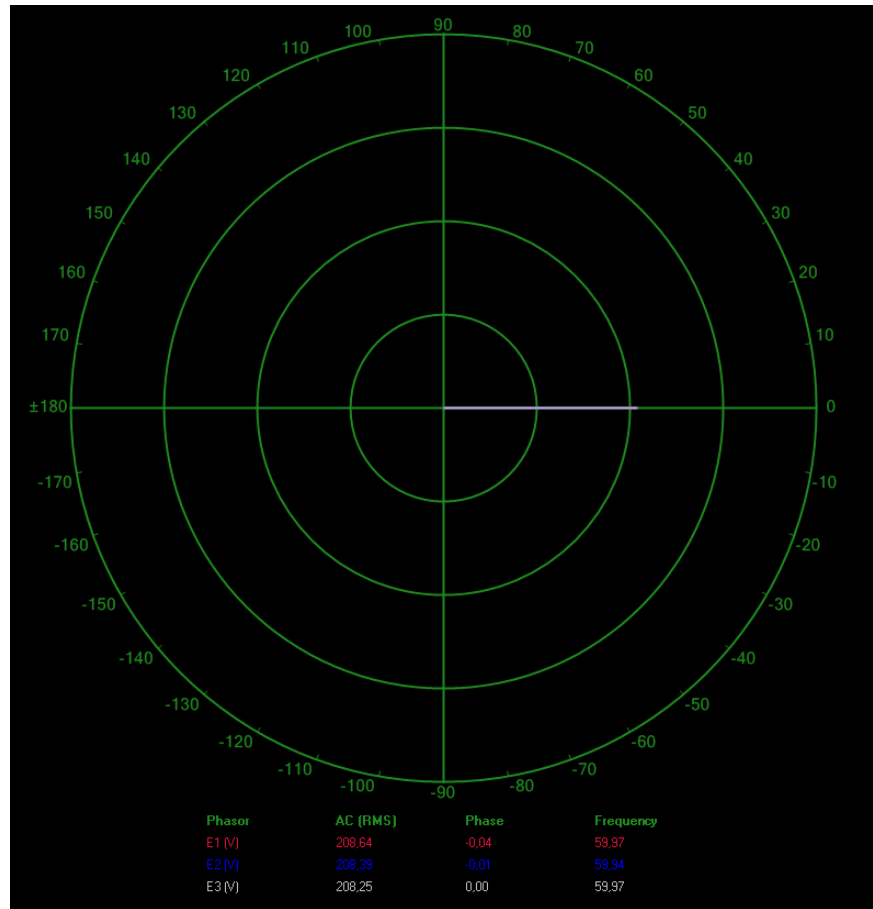
Phasors of the voltage $E_{Reg.A}$ at region A, the modified voltage $E'_{Reg.A}$ at region A, and the voltage $E_{Reg.B}$ at region B when the Regulating Autotransformer is set to a 0° phase shift.

Yes

No active power is transferred via the ac transmission line because the voltage at region A (before or after the Regulating Autotransformer) and the voltage at region B are in phase and have the same magnitude (because the line voltage is compensated). Consequently, the instantaneous values of the voltage at both regions are equal at all times, no current can flow between the two ends of the line, and thus, no active power is transferred.

27. The resulting voltage phasors when the Regulating Autotransformer is set to a +15° phase shift are shown in the following figure.

Phasor Analyzer Settings
Reference Phasor.................................. E3
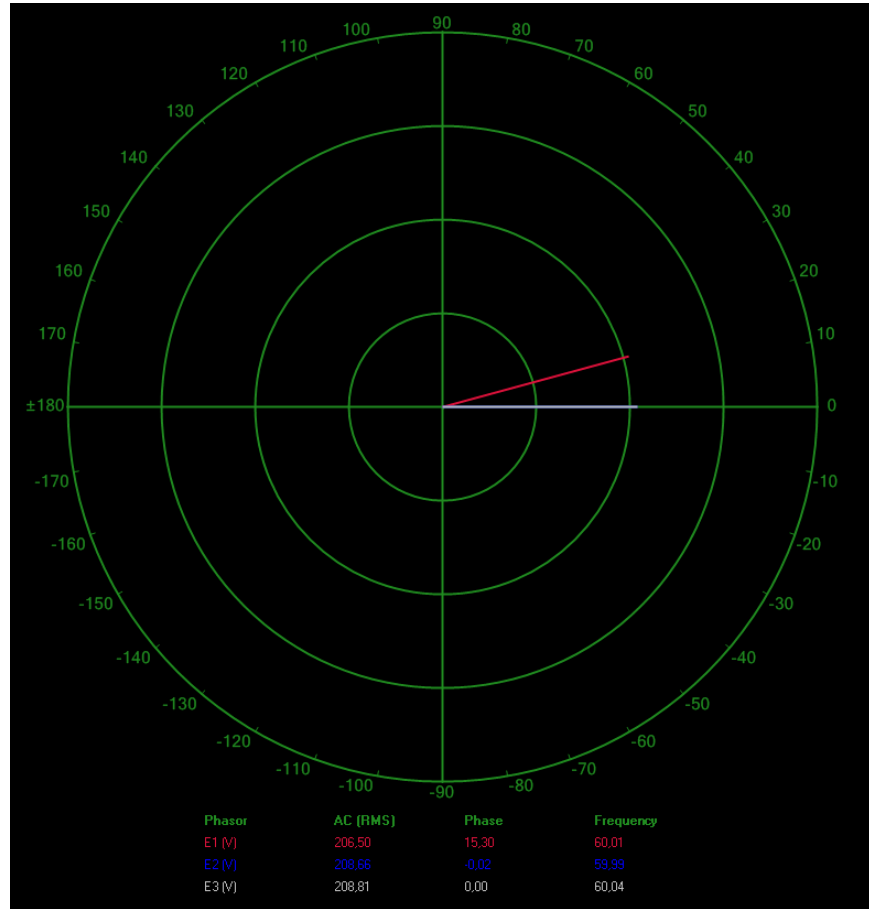Voltage Scale..............................100 V/div

Phasors of the voltage $E_{Reg.A}$ at region A, the modified voltage $E'_{Reg.A}$ at region A, and the voltage $E_{Reg.B}$ at region B when the Regulating Autotransformer is set to a +15° phase shift.

The resulting voltage phasors when the Regulating Autotransformer is set to a -15° phase shift are shown in the following figure.

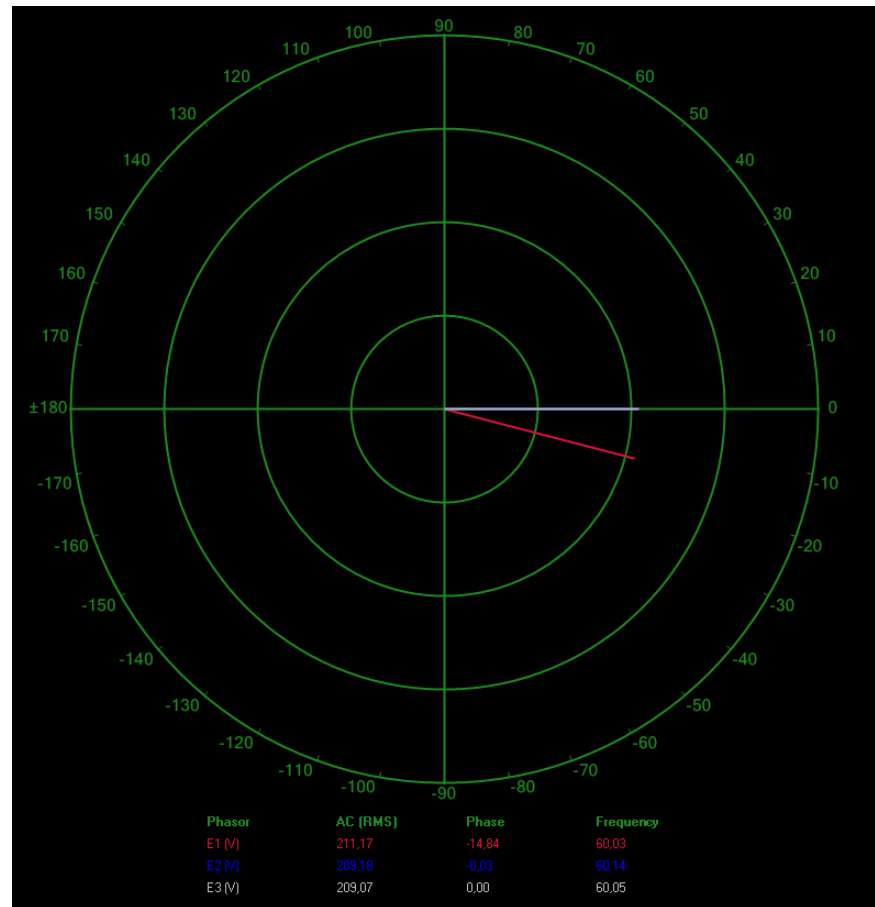Phasor Analyzer Settings
Reference Phasor................................ E3
Voltage Scale.............................100 V/div

Phasor	AC (RMS)	Phase	Frequency
E1 (V)	211,17	-14,84	60,03
E2 (V)	209,18	-0,03	60,14
E3 (V)	209,07	0,00	60,05

Phasors of the voltage $E_{Reg.A}$ at region A, the modified voltage $E'_{Reg.A}$ at region A, and the voltage $E_{Reg.B}$ at region B when the Regulating Autotransformer is set to a -15° phase shift.

The phasor of the modified voltage $E'_{Reg.A}$ at region A is advanced 15° when a phase shift of +15° is introduced using the Regulating Autotransformer. Conversely, the phasor of the modified voltage $E'_{Reg.A}$ at region A is delayed 15° when a phase shift of -15° is introduced using the Regulating Autotransformer. The phasors of the voltage $E_{Reg.A}$ and the voltage $E_{Reg.B}$ are not affected and remain in phase with one another.

28. When the phase shift θ is positive (i.e., when $E'_{Reg.A}$ leads $E_{Reg.B}$), active power is transferred from region A to region B (active power P values are positive). Conversely, when the phase shift θ is negative (i.e., when $E'_{Reg.A}$ lags behind $E_{Reg.B}$), active power is transferred from region B to region A (active power P values are negative). In other words, active power P is transferred from the region whose voltage leads that of the other region. When the phase angles at both regions are equal to one another, no active power P is transferred via the ac transmission line.

Yes

29. Yes

35. The results are presented in the following table.

Active power *P* and reactive power *Q* measured at regions A and B for different settings of the Regulating Autotransformer.

Phase shift (°)	Buck-boost (%)	Region A		Region B	
		Active power $P_{Reg.A}$ (W)	Reactive power $Q_{Reg.A}$ (var)	Active power $P_{Reg.B}$ (W)	Reactive power $Q_{Reg.B}$ (var)
0	0	121	15.9	116	-46.2
+15	0	173	42.7	161	-95.7
+15	+15	206	89.0	191	-75.3
+15	-15	143	6.41	131	-117

36. Yes

Yes

38. The value of the modified voltage $E'_{Reg.A}$ at region A increases by 15% when the Regulating Autotransformer operates as a step-up (boost) transformer, and decreases by 15% when the Regulating Autotransformer operates as a step-down (buck) transformer. The values of the voltage $E_{Reg.A}$ and the voltage $E_{Reg.B}$ are not affected and remain equal one another.

40. When the Regulating Autotransformer is set so as to neither increase nor decrease voltage, the modified voltage $E'_{Reg.A}$ at region A and the voltage $E_{Reg.B}$ at region B are equal and the reactive power Q in the ac transmission line is supplied by both regions, Q_R being significantly higher than Q_S. When the Regulating Autotransformer is set so as to increase voltage, $E'_{Reg.A}$ becomes higher than $E_{Reg.B}$ and Q_S increases while Q_R decreases. Conversely, when the Regulating Autotransformer is set so as to decrease voltage, $E'_{Reg.A}$ becomes lower than $E_{Reg.B}$ and Q_S decreases while Q_R increases. In other words, when the voltage at either region ($E'_{Reg.A}$ or $E_{Reg.B}$) is modified, reactive power Q is supplied primarily by the region whose voltage has the highest value.

Yes

41. Yes

ANSWERS TO REVIEW QUESTIONS

1. The direction of the flow of active power P transferred by an ac transmission line connecting two regions of a power network depends on the phase angle of the voltage at both regions. The direction of the flow of active power P is always from the region with the leading voltage to the region with the lagging voltage.

2. It is possible to control the flow of active power P transferred by an ac transmission line connecting two regions of a power network by adding a phase shifting transformer at either end of the line. By using the phase-shifting transformer to vary the phase shift θ between the voltages at both ends of the ac transmission line, the magnitude and direction of the flow of active power P transferred by the line can be adjusted as needed (within the limits of the power transmission capacity of the ac transmission line).

3. It is possible to control the flow of reactive power Q in an ac transmission line connecting two regions of a power network by adding a buck-boost transformer at either end of the ac transmission line. By varying the voltage at either end of the ac transmission line, the proportion of reactive power Q supplied by each end of the line can be adjusted as needed. Increasing the voltage at one end of the line increases the amount of reactive power which this end of the line supplies, and vice versa.

4. When a regulating autotransformer is used as a phase shifting transformer, it has the ability to phase shift the incoming voltages. This is achieved by connecting each tertiary winding of the regulating autotransformer to a secondary winding of a different phase (e.g., connecting tertiary windings b_3, c_3, and a_3 to secondary windings a_2, b_2, and c_2, respectively). Consequently, the voltages across the interconnected secondary and tertiary windings add to produce outgoing voltages that are phase shifted with respect to the incoming voltages. The higher the tertiary winding voltage with respect to the secondary winding voltage, the greater the phase shift produced.

5. When a regulating autotransformer is used as a step-down (buck) or step-up (boost) transformer, it has the ability to increase or decrease the value of the incoming voltages. This is achieved by using multiples taps on the windings of the regulating autotransformer so that the resulting turns ratio of the transformer corresponds to the desired increase or decrease in voltage.

Bibliography

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