Electricity and New Energy

2-kW Electric Power Transmission System

Courseware Sample

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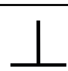
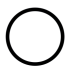
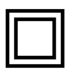
Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the 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
	Notice, non-ionizing radiation
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	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

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Preface

Power plants that generate electricity are linked to the user by means of a transmission and distribution system. Just as vital as the shaft between the engine and the wheels of a car, the electric transmission line is essential between the power station and its ultimate load.

This manual explains by hands-on exercises the principles of transmission of electric power – a subject which is usually taught in a strictly theoretical way.

The exercises show how changes in the source, the load, and the transmission line affect the overall performance of the system. In particular, they illustrate the meaning of active and reactive power, how the voltage at the end of a line can be lowered or raised, how power can be forced to flow over one transmission line instead of another, and how a system behaves when subjected to disturbances. The tests relating to switching transients, sudden overloads and momentary short-circuits dramatically demonstrate the mechanical swing of generator poles and the concurrent surges of power over the transmission line. More than any amount of theory could show, these exercises convey the meaning of power stability and the limits to power flow.

Alternators, motors, capacitors, reactors, resistors, meters, transformers, series compensators, and transmission lines are employed. Despite their small size, these electric machines and devices are designed to act in exactly the same way under steady-state and transient conditions, as their larger counterparts in industry.

This practical, hands-on course is presented in a way that is readily understandable by anyone who has knowledge of electricity at the technical school. (Such training can be provided by the Electric Power Technology learning system which employs modular laboratory equipment entirely compatible with the Electric Power Transmission System.)

We invite readers of this manual to send us their tips, feedback and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

Manual objectives

When you have completed this manual, you will be familiar with the principles of transmission of electric power.

Description

This Student Manual contains a number of exercises designed to present the subject matter in convenient instructional segments. In each exercise, principles and concepts are presented first followed by a step-by-step, hands-on procedure to complete the learning process.

Each exercise contains:

- A clearly defined Exercise Objective
- A Discussion Outline listing the main points presented in the Discussion
- A Discussion of the theory involved
- A Procedure Outline listing the main sections in the Procedure
- A step-by-step Procedure in which the student observes and measures the important phenomena, including questions to help in understanding the important principles.
- A Conclusion
- Review Questions

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Connection Diagrams

This manual can be used with the 2-kW Electric Power Transmission Training Systems, Models 8059-2 and 8059-3 (using analog meters), and Models 8059-4 and 8059-5 (using the Data Acquisition Interface module). If you are using a system with analog meters, refer to the Connection Diagrams in Appendix F.

About This Manual

Systems of units

Units are expressed using the International System of Units (SI) followed by the units expressed in the U.S. customary system of units (between parentheses).

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Make sure that the students correctly install the modules in the workbench. Refer to the manual 38486-E for more details on how to install the equipment.

Samples Exercises

Extracted from

the Student Manual

and the Instructor Guide

Effects of Series Compensation on the Power Transfer Capability and System Stability

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the effects of series compensation on the power transfer capability and stability of a transmission line.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Series Compensation
- System Stability

DISCUSSION

Series Compensation

When the power demand becomes high, there will come a time when an additional transmission line is required. Obtaining a corridor, environmental impact limitations, and line cost can all make provision of a new line difficult. A preferred option is to increase the power transfer capability of an already existing line by means of series compensation.

Series compensation consists in reducing the inductive reactance of a transmission line by connecting a capacitor in series with the line as shown in Figure 39. With this method, the active power transferred through the line becomes:

$$P_T = \frac{E_S \times E_R}{X_L - X_{CS}} \times \sin\theta \tag{25}$$

where P_T is the transferred power (W)
E_S is the line sender voltage (V)
E_R is the line receiver voltage (V)
X_L is the inductive reactance of the line (Ω)
X_{CS} is the capacitive reactance of the series compensator (Ω)
θ is the phase shift between the sender and receiver voltages (°)

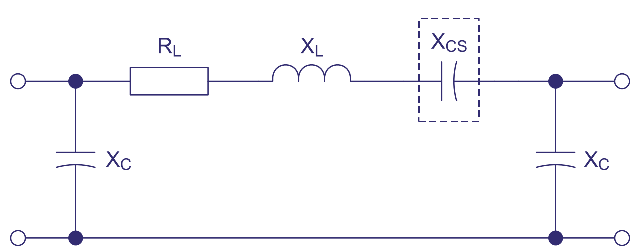

Figure 39. Equivalent circuit of a transmission line with series compensation.

The decrease in line reactance created by series compensation is named compensation factor, k. The value of k is given by:

$$k = \frac{X_{CS}}{X_L} \tag{26}$$

The power transfer capability of a line increases as the compensation factor is increased. The increase in power transfer capability, as a percentage, for a given compensation factor is given by:

$$increase\,in\,power\,transfer\,capability = \frac{k}{1-k} \times 100 \tag{27}$$

If, for example, the line is compensated 34%, the increase in power transfer capability will be 51,5%. Compensation factors between 20 and 70% are usual, thereby providing an increase in power transfer capability between 25 and 233%.

System Stability

Because series compensation increases the power transfer capability, it also improves the system stability. In effect, for any given phase shift between the sender and receiver voltages, the amount of transferred power is greater with a compensated line. As an example, Figure 40 shows the power transfer capability of a line with 50% compensation and without series compensation.

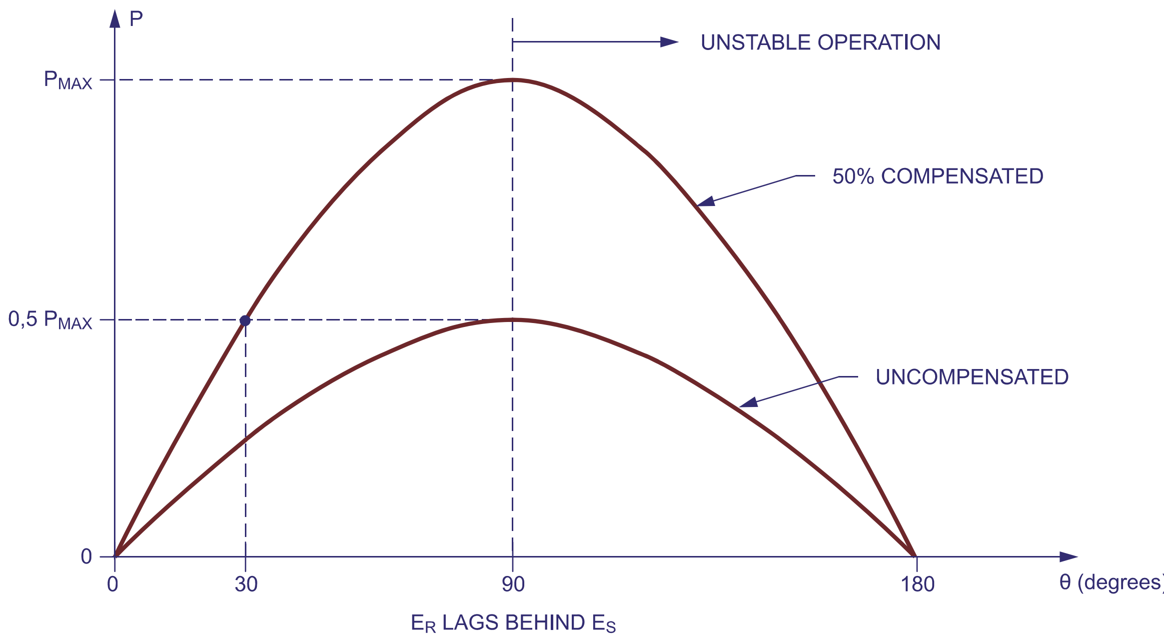

Figure 40. Power transfer capability of a transmission line with and without series compensation.

If the maximum power demand is 0,5 P_{MAX}, the phase shift between the sender and receiver voltages will be 30° for the compensated line, which corresponds to a stable operating point. However, the phase shift will be 90° for the uncompensated line, which is just on the edge of instability. In all likelihood, the uncompensated line will be unable to carry the load and its breakers will open.

Procedure Outline

The Procedure is divided into the following sections:

- Basic Setup
- Power Measurements

Procedure

Basic Setup

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

2. Set up the circuit shown in Figure 41.

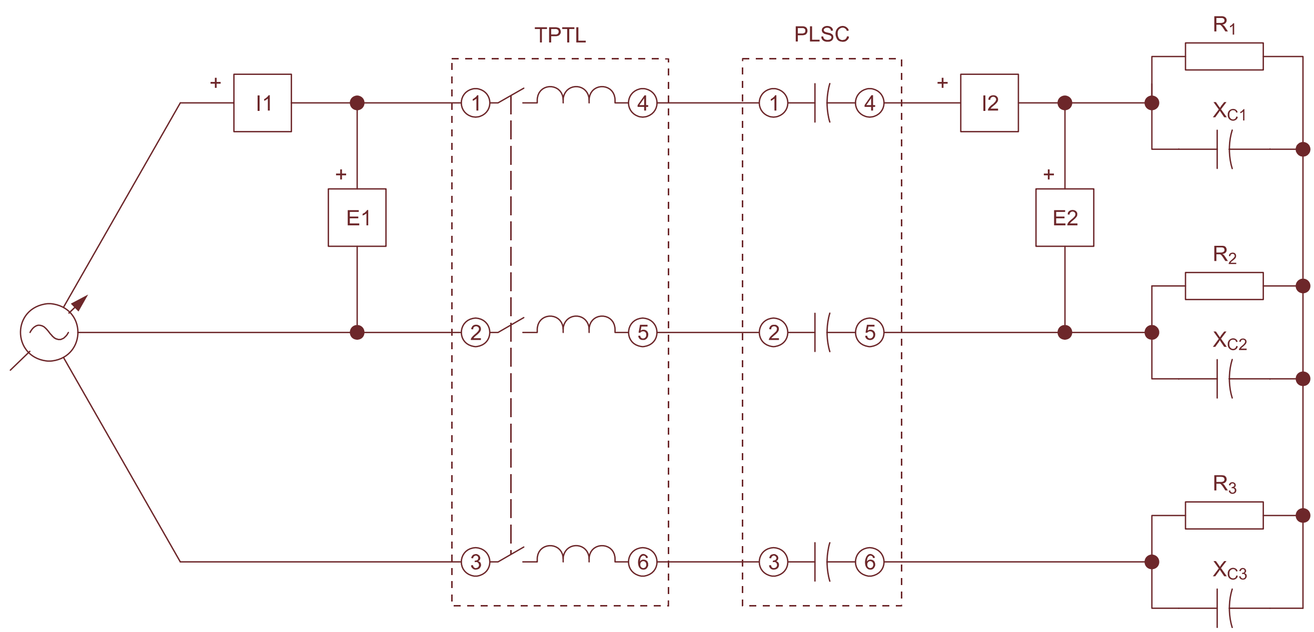

Figure 41. Transmission line with series compensation.

PLSC in Figure 41 means Power Line Series Compensator.

3. Set the Three-Phase Transmission Line to simulate a 125-km long transmission line (50 Ω).

   The Power Line Series Compensator requires 220 V for its operation. Connect its terminals L and N to a fixed-voltage line terminal and a neutral terminal on the Power Supply.

   Set the Power Line Series Compensator to 0 Ω.

4. Set the Resistive Load and Capacitive Load modules to obtain the maximum power transfer capability of the 125-km long transmission line without series compensation found in the previous exercise (values from the last row of Table 18).

Power Measurements

⚠ CAUTION

High voltages are present in this laboratory exercise! Do not make or modify any connections with the power on!

5. Turn on the Power Supply, and set the line voltage E_S to 380 V.

Run the LVDAM application and open configuration file 85279.dai. Make sure that the configuration file corresponds to the exercise needs.

6. Enter the measured values of voltage, power, and phase angle in the 0 Ω row of Table 19.

Table 19. Power flow without series compensation.

X_{CS} (Ω)	Es (V)	Ps (W)	E_R (V)	P_R (W)	θ (°)
0	380				
8,5	380				
17	380				

Table 19. Power flow without series compensation.

X_{CS} (Ω)	X_C [1] (Ω)	E_S (V)	P_S (W)	E_R (V)	P_R (W)	θ [2] (°)
0	880	380	931	371	911	-20,8
8,5	440	380	1142	383	1113	-21,3
17	293	380	1579	386	1499	-22,2

(1) Capacitive reactance of the shunt capacitor.
(2) E_S is the reference phasor.

7. Insert compensation by setting the Power Line Series Compensator to 8,5 Ω while observing the phase angle value.

Series compensation has decreased the phase angle required to transfer the same amount of power, which improves the stability of the system.

8. Increase the load by setting the Resistive Load modules to 125 Ω.

   Make sure the line voltage E_S is still set to 380 V, and readjust the shunt capacitor.

Enter the measured values of voltage, power, and phase angle in the appropriate row of Table 19.

9. Calculate the increase in power at the receiver end using your measured values and Equation (28).

$$increase\ in\ power\ (\%) = \frac{P_{compensated} - P_{uncompensated}}{P_{uncompensated}} \times 100 \qquad (28)$$

Increase in power from the measured values: ___________

22%.

10. Calculate the increase in power transfer capability using Equation (27).

Increase in power transfer capability: ___________

20,4%.

Both values should be approximately equal. However, the values will differ if the phase angle θ measured with compensation and without compensation is different.

11. Increase the series compensation by setting the Power Line Series Compensator to 17 Ω while observing the phase angle value.

Observe that the phase angle decreases when series compensation is increased.

12. Increase the load by setting the Resistive Load modules to 97 Ω.

Repeat Procedure step 8.

13. Calculate the increase in power at the receiver end from the measured values and the increase in power transfer capability.

Increase in power from the measured values: ___________

Increase in power transfer capability: ___________

Both values should be approximately equal. However, the values will differ if the phase angle θ measured with compensation and without compensation is different.

Increase in power from the measured values: 51,5%.

Increase in power transfer capability: 64,5%.

14. Turn off the Power Supply, disconnect the circuit, and return the equipment to the storage location.

Conclusion

In this exercise you observed that series compensation can improve the power transfer capability and the stability of a transmission line.

Review Questions

1. How does series compensation increase the power handling capability of a transmission line?

   By reducing the inductive reactance of the transmission line.

2. The power transfer capability of a transmission line decreases as the compensation factor is increased.

   ❑ Yes ❑ No

   Yes

3. Explain why series compensation also increases the system stability.

   For any given phase shift between the sender and receiver voltages, the amount of transferred power is greater with a compensated line.

Transmission Line Networks and the Three-Phase Regulating Autotransformer

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the division of power between two transmission lines in parallel.

You will learn the properties of a regulating autotransformer.

You will also learn how to modify the power division between two parallel lines using a regulating auto-transformer.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Transmission Line Networks
- Regulating Autotransformer

DISCUSSION

Transmission Line Networks

So far, we have observed the behavior of a single transmission line. However, in a practical electric power system there are hundreds of interconnected lines which link the power stations and their widely-dispersed loads.

This grid of transmission lines, of which Figure 58 is a simplified example, is far more complex than a simple series-parallel circuit. The flow of active and reactive power over the lines depends not only upon their impedances, but also upon the relative magnitude and phase angles of the sender and receiver voltages. In such a system, the power flow in a particular line may be too high (or too low), bearing in mind the capability of the line and/or the economics of transmission.

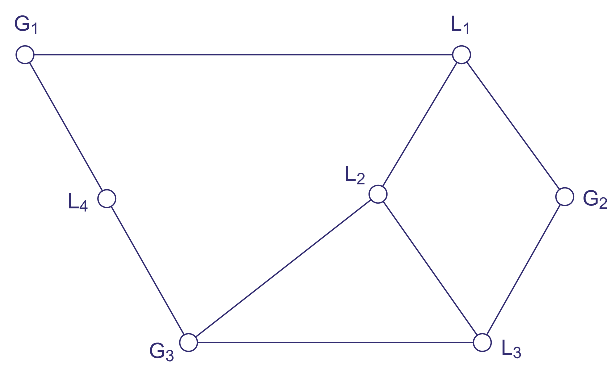

Figure 58. Grid of transmission lines.

Under these circumstances, 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.

To raise or lower the voltage is a simple matter which can be done by an automatic tap-changing autotransformer, located at either end of the transmission line.

A phase shift can be generated 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 setting.

Regulating Autotransformer

The principle of the regulating autotransformer can be understood by referring to Figure 59, which shows the primary windings a_1, b_1, and c_1 of a three-phase wye-connected transformer. Secondary windings a_2, b_2, and c_2 are also wye-connected, but secondary windings a_3, b_3, and c_3 are not yet connected together. Voltages inducted in windings a_1, a_2, and a_3 will all be in phase as will be the voltages induced in windings b_1, b_2, b_3, and c_1, c_2, c_3.

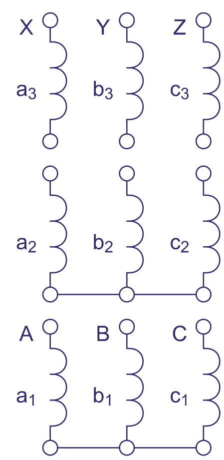

Figure 59. Primary and secondary windings of a three-phase transformer.

However, these three groups of voltages are respectively 120° out of phase with each other, as shown in Figure 60.

If windings $a_2\,a_3$, $b_2\,b_3$, and $c_2\,c_3$ are connected in series, the voltage between terminals X, Y, and Z will be in phase with the voltage between terminals A, B, and C as shown in Figure 60. However, if we connect in series windings $a_2\,b_3$, $b_2\,c_3$, and $c_2\,a_3$, the phasor diagram will be as shown in Figure 61, and the voltage between terminals X, Y and Z will be out of phase with the voltage between terminals A, B, and C. The degree of phase shift depends upon the relative magnitudes of the voltages $a_2\,b_2\,c_2$ and $a_3\,b_3\,c_3$ (if these voltages are all equal, the phase shift will be 60°).

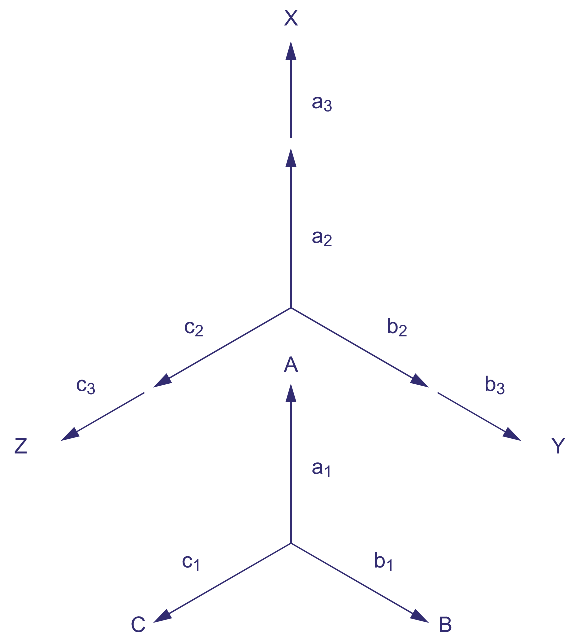

Figure 60. Phasor diagram when windings a_2 a_3, b_2 b_3, and c_2 c_3 are connected in series.

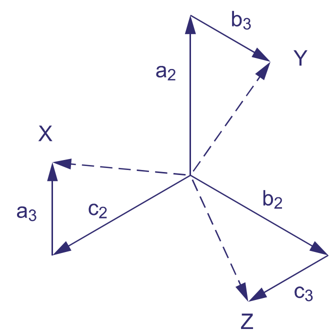

Figure 61. Phasor diagram when windings a_2 b_3, b_2 c_3, and c_2 a_3 are connected in series.

With appropriate taps on a three-phase transformer, and a selector switch, it is possible to step-shift the secondary voltage with respect to the primary by as much as 30°. Furthermore, provision can be made so that the phase angle can be progressively changed from lagging to leading and vice versa.

Referring to Figure 58, suppose that we wish to modify the active power flow in line L_2-L_3. If we wish to increase the active power, the phase angle between the voltages at L_2 and L_3 will have to be increased. On the other hand, should we wish to reduce the active power to zero, the two voltages will have to be brought in phase. Such phase angle changes can be accomplished by a phase-shift transformer located at either end of the line L_2-L_3.

A change in active power over line L_2-L_3 will affect the active power in the other lines, particularly those lines which converge at nodes L_2 and L_3. This is often the reason for modifying the power in line L_2-L_3 in the first place.

Reactive power can similarly be controlled by boosting (raising) or bucking (lowering) the voltage at either end of the line. Thus, if the voltage at L_2 is raised, reactive power will flow towards L_3. The same result will be obtained if the voltage is reduced at station L_3. In this regard, we should note that the voltage is only boosted or bucked on the transmission line itself – we must not change the voltage level of the other lines which are connected to points L_2 and L_3.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Basic Setup
- Familiarization with the Three-Phase Regulating Autotransformer
- Controlling the Power Flow Using a Regulating Autotransformer

PROCEDURE

Basic Setup

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

2. Set up the circuit shown in Figure 62.

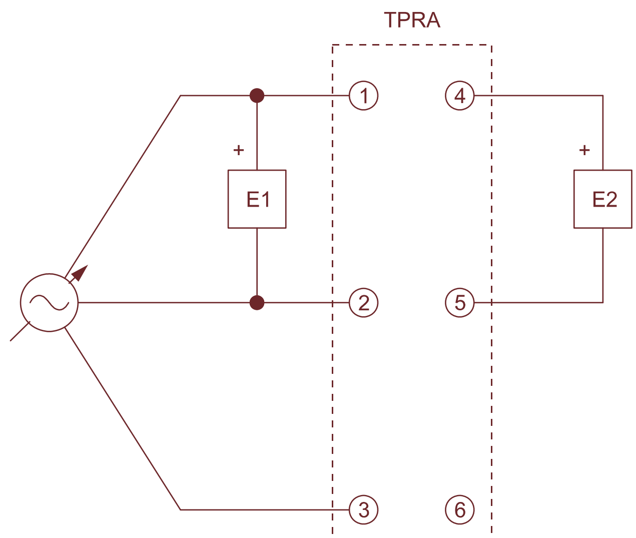

Figure 62. Familiarization circuit for the Three-Phase Regulating Autotransformer module.

Familiarization with the Three-Phase Regulating Autotransformer

⚠ CAUTION

High voltages are present in this laboratory exercise! Do not make or modify any connections with the power on!

Run the LVDAM application, then open configuration file 85279.dai. Make sure that the configuration file corresponds to the exercise needs.

Use the Phasor Analyzer to determine if the output voltage leads or lags.

3. Turn on the Power Supply, and set the supply line voltage to 380 V.

The supply line voltage must be kept constant for this part of the exercise.

4. Set the BUCK-BOOST and PHASE-SHIFT selectors on the Three-Phase Regulating Autotransformer as shown in Table 28. For each setting, enter the output voltage and phase angle between the supply and output voltages. Indicate also if the output voltage leads or lags the supply voltage.

Table 28. Regulating autotransformer.

Buck Boost (%)	Phase Shift (°)	Supply Voltage (V)	Output Voltage (V)	Phase Angle (°)	Leading or Lagging[1]
0	0	380			
0	+15	380			
0	-15	380			
+15	0	380			
+15	+15	380			
+15	-15	380			
-15	0	380			
-15	+15	380			
-15	-15	380			
(1) Use E1 as the reference phasor					

Table 28. Regulating autotransformer.

Buck Boost (%)	Phase Shift (°)	Supply Voltage (V)	Output Voltage (V)	Phase Angle (°)	Leading or Lagging[1]
0	0	380	380	0	–
0	+15	380	380	+15	leading
0	-15	380	380	-15	lagging
+15	0	380	437	0	–
+15	+15	380	437	+15	leading
+15	-15	380	437	-15	lagging
-15	0	380	323	0	–
-15	+15	380	323	+15	leading
-15	-15	380	323	-15	lagging
(1) Use E1 as the reference phasor					

5. Do your observations confirm that the Three-Phase Regulating Autotransformer allows the phase shift and the output voltage to be varied independently?

❑ Yes ❑ No

Yes

6. Modify the phase sequence at the input of the Three-Phase Regulating Autotransformer. Note the effect of an incorrect phase sequence upon the operation of the regulating autotransformer. Describe what happens.

Buck-boost settings are still correct but the phase shift settings are inverted.

Note that the Phase Sequence pilot lights show a wrong sequence.

Controlling the Power Flow Using a Regulating Autotransformer

7. Set up the circuit shown in Figure 63.

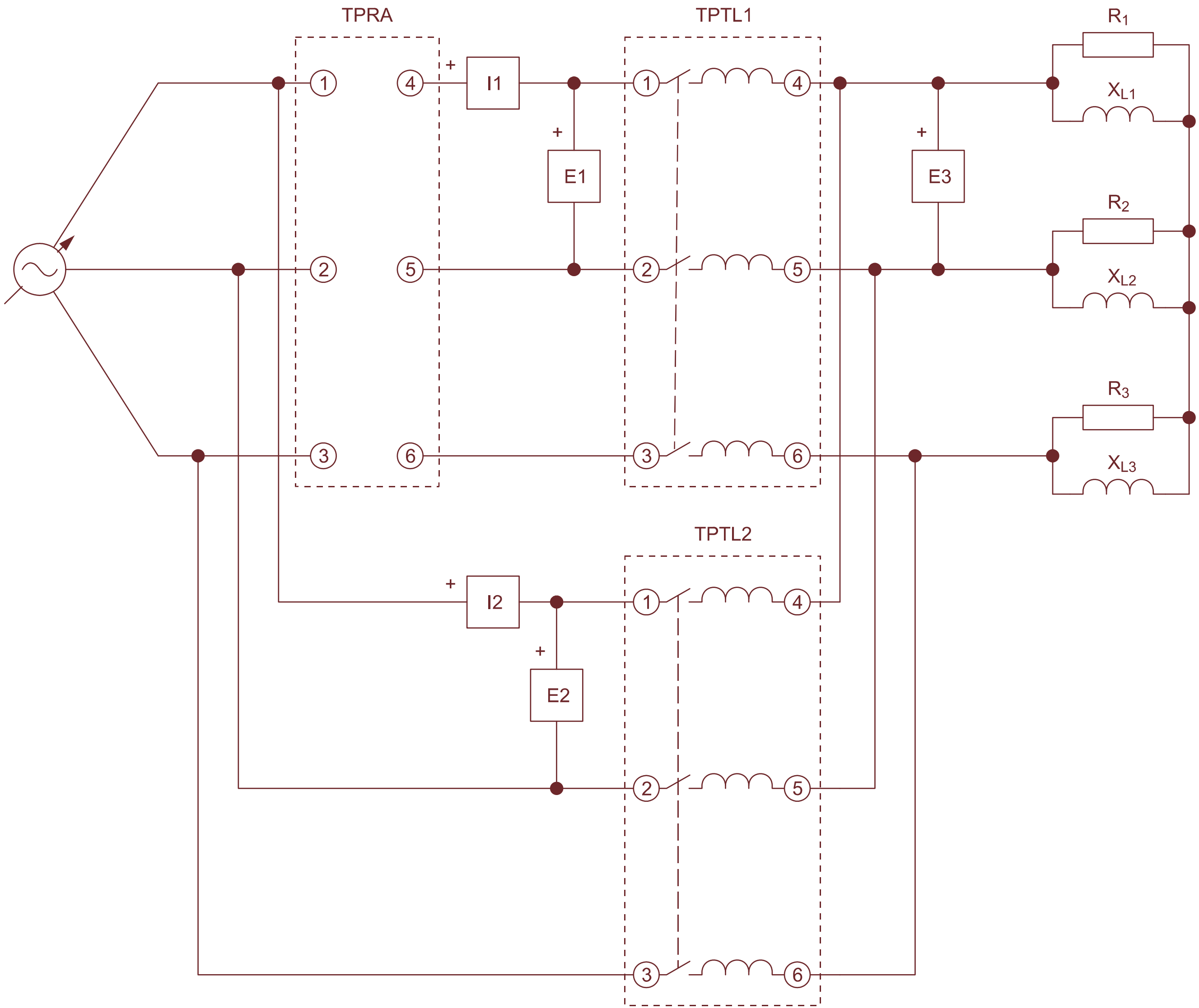

Figure 63. Circuit where an autotransformer is used to control the power flow.

8. Set the Resistive Load and Inductive Load modules to obtain a resistance and an inductive reactance of 880 Ω per phase.

   Set both Three-Phase Transmission Line modules to simulate two 42,5-km long lines (17 Ω).

9. Turn on the Power Supply, and set the supply line voltage E_S at TL2 to 220 V.

10. For each buck boost and phase shift value shown in Table 29, enter the power and voltage values in the appropriate cells.

Table 29. Power flow and voltage measurements (TL1 and TL2 = 43.5 km).

		TL1				TL2				
Buck Boost (%)	Phase Shift (°)	X_L (Ω)	E_S (V)	P_S (W)	Q_S (var)	X_L (Ω)	E_S (V)	P_S (W)	Q_S (var)	E_R (V)
0	0	17				17				
0	+15	17				17				
0	-15	17				17				
+15	0	17				17				
-15	0	17				17				
+15	+15	17				17				
-15	-15	17				17				
Resistive and inductive loads: 880 Ω per phase										

Table 29. Power flow and voltage measurements (TL1 and TL2 = 43.5 km).

		TL1				TL2				
Buck Boost (%)	Phase Shift (°)	X_L (Ω)	E_S (V)	P_S (W)	Q_S (var)	X_L (Ω)	E_S (V)	P_S (W)	Q_S (var)	E_R (V)
0	0	17	220	29	29	17	220	29	29	220
0	+15	17	218	389	69	17	220	-324	83	215
0	-15	17	223	-328	79	17	220	394	73	218
+15	0	17	254	56	280	17	220	15	-181	236
-15	0	17	189	11	-162	17	220	44	243	203
+15	+15	17	250	471	318	17	220	-395	-114	231
-15	-15	17	190	-300	-116	17	220	358	279	202
Resistive and inductive loads: 880 Ω per phase										

11. How does the active and reactive power of each transmission line compare without phase shift and buck boost?

Each line carries the same amount of active and reactive power when there is no phase shift and no buck-boost.

12. What is the effect of a phase shift on the active power?

The active power is positive on the line when the voltage is leading. Conversely it is negative on the line when the voltage is lagging.

13. Set the inductance X of TL2 to 0 Ω, and then repeat Procedure step 10. Record your results in Table 30.

Table 30. Power flow and voltage measurements (TL1 = 43,5 km, TL2 = 0 km).

		TL1				TL2				
Buck Boost (%)	**Phase Shift (°)**	**X[1] (Ω)**	**E_S (V)**	**P_S (W)**	**Q_S (var)**	**X[1] (Ω)**	**E_S (V)**	**P_S (W)**	**Q_S (var)**	**E_R (V)**
0	0	17				0				
0	+15	17				0				
0	-15	17				0				
+15	0	17				0				
-15	0	17				0				
+15	+15	17				0				
-15	-15	17				0				

Resistive and inductive loads: 880 Ω per phase.
(1) Inductance of the transmission line.

Table 30. Power flow and voltage measurements (TL1 = 43,5 km, TL2 = 0 km).

		TL1				TL2				
Buck Boost (%)	**Phase Shift (°)**	**X[1] (Ω)**	**E_S (V)**	**P_S (W)**	**Q_S (var)**	**X[1] (Ω)**	**E_S (V)**	**P_S (W)**	**Q_S (var)**	**E_R (V)**
0	0	17	220	0	0	0	220	61	56	220
0	+15	17	216	692	49	0	220	-617	191	220
0	-15	17	224	-696	132	0	220	763	106	220
+15	0	17	252	42	475	0	220	20	-355	220
-15	0	17	186	-32	-355	0	220	96	474	220
+15	+15	17	245	842	498	0	220	-763	-178	217
-15	-15	17	189	-639	-238	0	220	709	507	218

Resistive and inductive loads: 880 Ω per phase.
(1) Inductance of the transmission line.

Setting the inductance of the Three-Phase Transmission Line module to 0 Ω corresponds to a very short line, which naturally would tend to carry the entire active and reactive load. Observe that by changing the phase-shift and the voltage ratio (buck-boost) of the Three-Phase Regulating Autotransformer, the flow of power can be drastically modified.

14. Turn off the Power Supply, disconnect the circuit, and return the equipment to the storage location.

CONCLUSION

In this exercise, you saw how the power divides between two transmission lines in parallel.

You learned the properties of a regulating autotransformer.

You have also modified the power division between two parallel lines using a regulating auto-transformer.

REVIEW QUESTIONS

1. In Figure 64, two transmission lines having reactances per phase of 100 Ω and 200 Ω are connected in parallel. A phase-shift transformer T_1 is introduced into the 200 Ω line, close to the receiver, so that the active power is divided equally between the two lines. If the sender and receiver voltages are both 100 kV line, calculate the maximum active power delivered, and the phase angle needed for the phase-shift transformer.

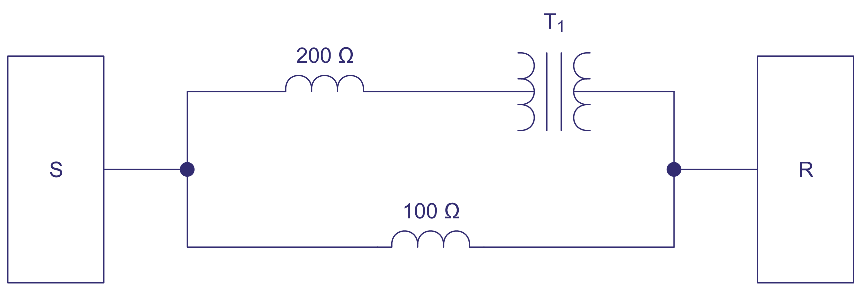

Figure 64. Circuit of Review Question 1.

Maximum active power delivered: 100 MW.

Phase angle: 60°leading.

2. In Review Question 1, if there were no phase-shift transformer, what would be the maximum power which could be delivered over both lines?

The maximum power through the 200 Ω line: 50 MW.

The maximum power through the 100 Ω line: 100 MW.

Total maximum power: 150 MW.

3. Does the phase-shift transformer in Review Question 1 increase the maximum power the 200 Ω line can deliver?

❑ Yes ❑ No

No

4. In the circuit of Figure 65 comprising two transmission lines in parallel, the sender and receiver voltages are both 100 kV line. A phase shift transformer T_1, and a buck-boost transformer T_2 are adjusted so that the sender delivers the same amount of active and reactive power to each line. If the receiver absorbs 50 MW, calculate:

   The phase shift of T_1

   Phase shift of T1: 15°.

   The voltage ratio of T_2

   Voltage ratio: 1.04 (E_R/E_S).

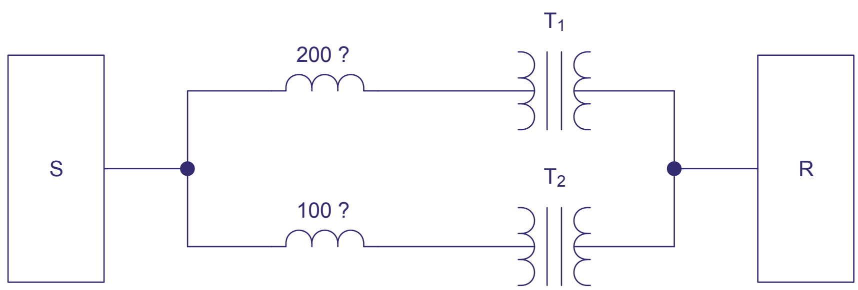

Figure 65. Circuit of Review Question 4.

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