00005802040000000100

Germany
Festo Didactic SE
Rechbergstr. 3
73770 Denkendorf
Tel.: +49 711 3467-0
Fax: +49 711 347-54-88500
did@festo.com

United States
Festo Didactic Inc.
607 Industrial Way West
Eatontown, NJ 07724
Tel.: +1 732 938-2000
Toll Free: +1-800-522-8658
Fax: +1 732 774-8573
services.didactic@festo.com

Canada
Festo Didactic Ltée/Ltd
675, rue du Carbone
Québec (Québec) G2N 2K7
Tel.: +1 418 849-1000
Toll Free: +1-800-522-8658
Fax: +1 418 849-1666
services.didactic@festo.com

www.festo-didactic.com

FESTO
Student Manual
AC Transmission Lines

AC Transmission Lines

FESTO

Electricity and New Energy

LabVolt Series

Student Manual

Festo Didactic
en
580204

Electricity and New Energy

AC Transmission Lines

Student Manual

580204

Order no.: 580204
First Edition
Revision level: 08/2016

By the staff of Festo Didactic

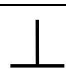
Internet: www.festo-didactic.com
e-mail: did@de.festo.com

Printed in Canada

ISBN 978-2-89747-116-3 (Printed version)
ISBN 978-2-89747-117-0 (CD-ROM)
Legal Deposit – Bibliothèque et Archives nationales du Québec, 2014
Legal Deposit – Library and Archives Canada, 2014

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

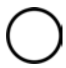
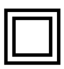
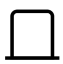
Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

Table of Contents

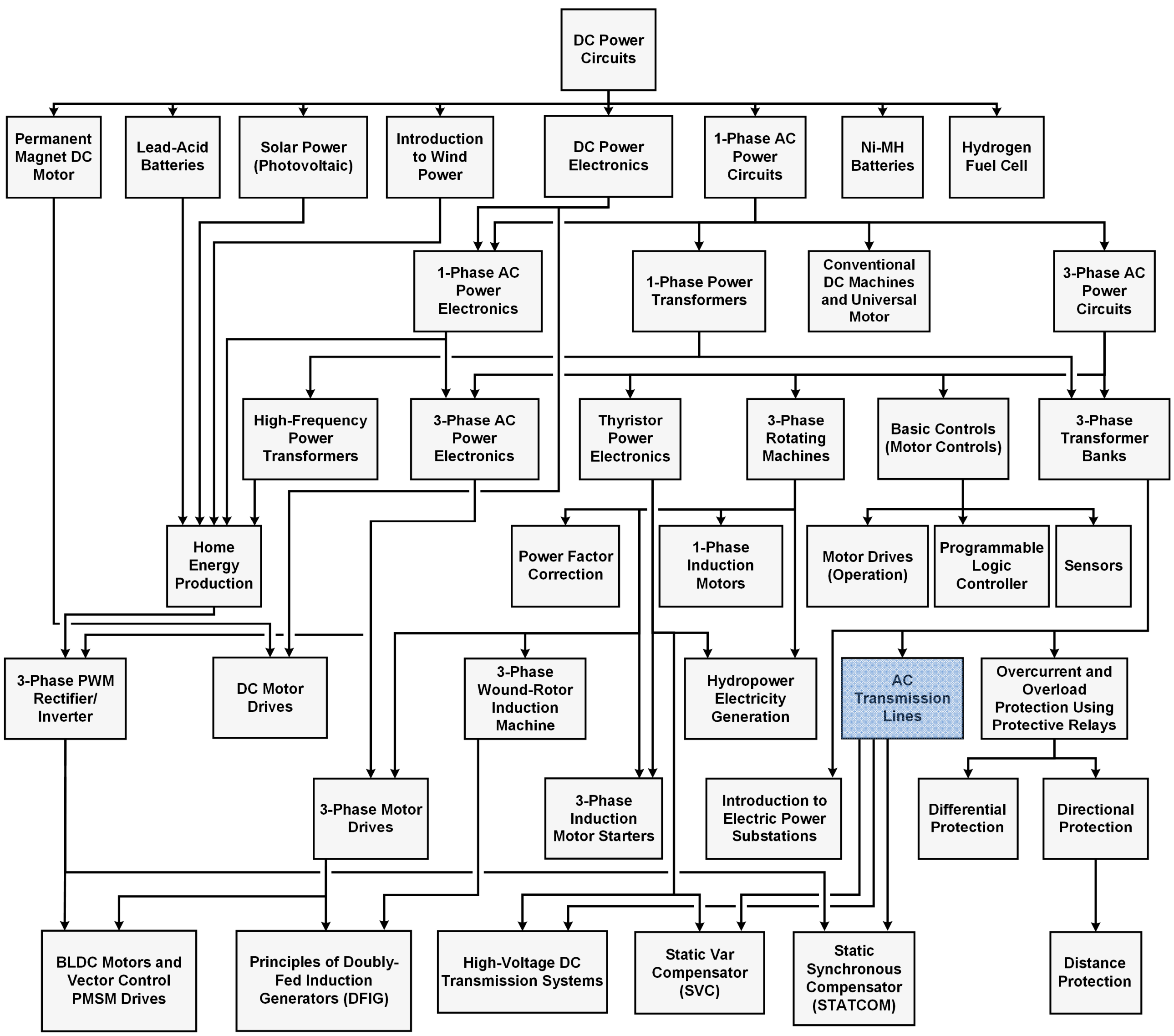
Table of Contents

Table of Contents

Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.



The Electric Power Technology Training Program.

Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.

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

High-voltage ac transmission lines are a vital element of any ac power network. They are used to transfer large amounts of electric power from the power generating stations to the distribution system, which then supplies electric 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 electric power over long distances. This particularity, coupled with the fact that ac transmission lines are both inductive and capacitive, has several effects on the operation of ac transmission lines. One of these effects is that the voltage at the receiver end of an ac transmission line significantly exceeds the voltage at the sender end of the line when the line operates with no load or with a light load. Consequently, an overvoltage and damage to equipment can occur when the load is loss. Another effect is that the voltage at the receiver end of the line varies significantly with the amount of active power which the line transmits.

The two effects described above are highly undesirable since they significantly impair voltage stability of the ac power network. Voltage compensation is thus required to maintain the voltage at the receiver end of an ac transmission line equal to the voltage at the sender end of the line regardless of the amount of active power transmitted by the line. Voltage compensation of an ac transmission line is primarily achieved by using a bank of switched shunt inductors at the receiver end of the line. Banks of switched shunt capacitors can even be required to voltage compensate an ac transmission line that operates at power levels significantly exceeding the natural load (P_0) of the line. This method of voltage compensation is commonly referred to as switched shunt compensation (SSC). In ac transmission lines that are particularly long, SSC must be distributed in several substations located along the line to ensure that the voltage at any point along the line is maintained close to the voltage at the sender end of the line.

High-voltage ac transmission lines.

About This Manual

When ac transmission lines are used to transfer electrical power in interconnected power networks, the flow of active power between any two regions generally needs to be carefully controlled. This can be achieved by using a power transformer that phase shifts the incoming voltage before it is applied to the ac transmission line. The amount of active power transferred from one region to another is controlled by selecting the phase shift produced by the power transformer.

This manual, AC Transmission Lines, introduces students to the characteristics and behavior of high-voltage ac transmission lines, as well as to the voltage compensation of these lines using switched shunt compensation (SSC). Students first study the voltage regulation characteristics of a simplified ac transmission line, i.e., a line consisting of series inductors only. This provides students with some basic knowledge that is useful later in the course. The students are then introduced to the fundamental characteristics, characteristic impedance (Z_0), natural load (P_0), corrected PI equivalent circuit, and power-voltage (P-V) curve of a high-voltage ac transmission line. Voltage compensation of a high-voltage ac transmission line using SSC is then covered in detail. In this section of the course, students also learn the relationship between the active power transmitted by a voltage-compensated line and the phase shift between the voltages at both ends of the line, as well as how to determine the maximal transmissible power of a voltage-compensated line. Students then discover how line length affects the characteristics and voltage compensation of a high-voltage ac transmission line. The students then learn how to remedy the negative effects of the line length using distributed SSC. Finally, students learn how to control the flow of active power in an ac transmission line using a phase-shifting transformer.

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.

Prerequisite

As a prerequisite to this course, you should have read the manuals titled *DC Power Circuits*, part number 86350, *Single-Phase AC Power Circuits*, part number 86358, *Single-Phase Power Transformers*, part number 86377, *Three-Phase AC Power Circuits*, part number 86360, and *Three-Phase Transformer Banks*, part number 86379.

AC Transmission Lines

MANUAL OBJECTIVE

When you have completed this manual, you will be familiar with the voltage regulation characteristics of a simplified ac transmission line (represented by a series inductor) obtained with resistive, inductive, and capacitive loads. You will also be familiar with the equivalent diagram and main characteristics (voltage regulation, characteristic (surge) impedance Z_0, natural load P_0) of high-voltage ac transmission lines. You will know how to compensate the voltage across a high-voltage ac transmission line using shunt reactive compensation. You will know how length affects the main characteristics of a high-voltage ac transmission line. You will be able to compensate the voltage across a long, high-voltage ac transmission line using distributed shunt reactive compensation. Finally, you will be familiar with the flow of active and reactive power in interconnected power networks, and know how to control the flow of both types of power.

DISCUSSION OF FUNDAMENTALS

Introduction to ac transmission lines

The main purpose of **transmission lines** is to transfer electrical power from the power generating stations (the **sender end** of transmission lines) to the distribution network (the **receiver end** of transmission lines), which then supplies electrical power to consumers. Transmission lines thus represent the second step in the transfer of electrical energy, as shown in the following figure.

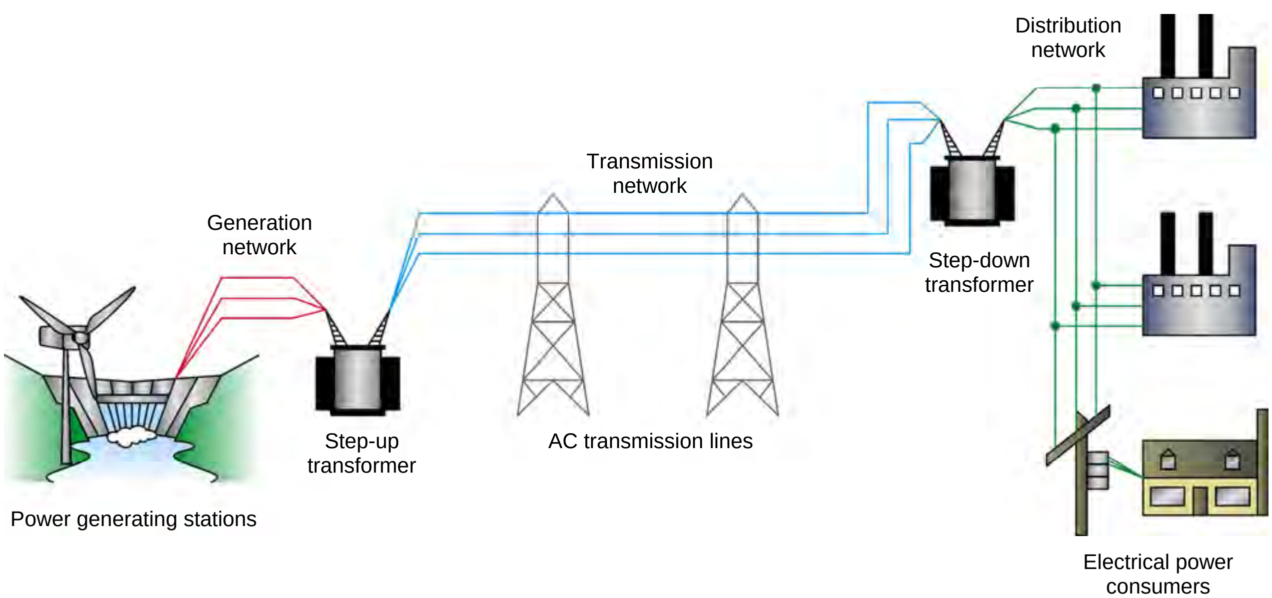


Figure 1. Typical electrical power generation, transmission, and distribution network.

As you can see from the figure, electrical power is produced at the power generating stations (e.g., hydropower plants, solar power plants, wind turbines). The electrical power is then transferred by transmission lines operating at very high voltages (generally from about 150 kV to about 765 kV). The very high voltages used for transmission lines enable the current flowing in the transmission line to be greatly decreased for the same amount of power transferred. In turn, a lower current flowing in the transmission line significantly reduces the amount of power losses P_{Loss} in the line (since $P_{Loss} = RI^2$), and also allows the size of the wires used for the transmission line to be decreased. Both of these factors are critical for transmission lines. This is because transmission lines often transfer electrical power over very long distances, which means that reducing power losses and wire size (and thus the weight and cost of the wires) of the transmission lines is very important. As the electrical power nears the electricity consumers, the voltage of the electrical power is progressively lowered by step-down transformers in transmission substations (see Figure 2 for an example of a transmission substation).

Most transmission lines carry three-phase alternating current (ac), and consist of three line wires with no neutral wire. Transmission lines are usually aerial (supported by large electrical transmission towers) rather than underground. This is due to the fact that aerial lines, although less aesthetically appealing, are much cheaper than underground lines. The conductors used in ac transmission lines are nearly always strands of an aluminum alloy, often reinforced with steel. This represents a compromise between the conductivity, rigidity, and low cost of the transmission lines.

The fundamental purpose of ac transmission lines is to transfer active power (i.e., power that can be used to do actual work). However, it is inevitable that some reactive power is supplied or absorbed by an ac transmission line. The proportion of reactive power exchanged by an ac transmission line to the active power transferred by the line must be kept at a minimum. It is also important that the voltage across an ac transmission line be maintained within normal operational limits all along the line to avoid problems related to overvoltage and undervoltage situations. Furthermore, this limits fluctuations in the voltage of the electrical power supplied to consumers, which can have negative effects on the operation of many electrical devices.

Figure 2. Transmission substation used for lowering the high voltage present in the ac transmission lines before the power is distributed to consumers.

Voltage Regulation Characteristics

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the simplified equivalent circuit of an ac transmission line. You will also be familiar with the voltage regulation characteristics of a simplified ac transmission line when it supplies power to a resistive, an inductive, or a capacitive load. You will know the concept of voltage regulation in an ac transmission line. You will know how to determine the voltage regulation of an ac transmission line.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Simplified equivalent circuit of an ac transmission line
- Voltage regulation characteristics of a simplified ac transmission line for resistive, inductive, and capacitive loads
- Voltage regulation of ac transmission lines
- Introduction to the Three-Phase Transmission Line module

DISCUSSION

Simplified equivalent circuit of an ac transmission line

As mentioned in the Introduction of this manual, a three-phase, high-voltage ac transmission line generally consists of three aerial conductors attached to large towers. Of course, each conductor has some resistance. Furthermore, each conductor also produces some inductive reactance since ac power flows through the line. Finally, an electric field builds up between the conductors and the ground, thereby introducing a capacitive effect and some capacitive reactance. Figure 3 shows the equivalent electric circuit representing a short segment (e.g., 1 km or 1 mile) of a high-voltage ac transmission line. It includes a resistor, an inductor, and two capacitors which reflect the resistance, inductive reactance, and capacitive reactance of the ac transmission line mentioned above.

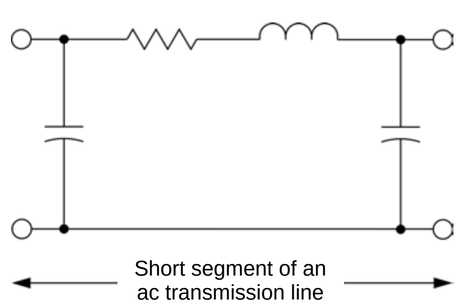


Figure 3. Equivalent electric circuit of a short segment (e.g., 1 km or 1 mile) of a high-voltage ac transmission line (one phase only).

Note that the equivalent electric circuit in Figure 3 represents only one phase of a short segment of a high-voltage ac transmission line. The complete equivalent electric circuit representing the three phases of a short segment of a high-voltage ac transmission line is shown in Figure 4.

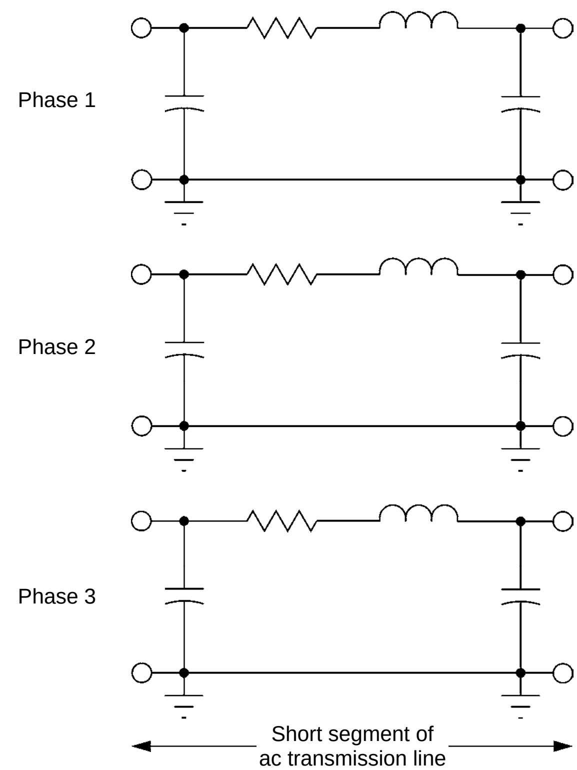


Figure 4. Complete equivalent electric circuit of a short segment (e.g., 1 km or 1 mile) of a high-voltage ac transmission line.

The circuit of Figure 3 must be repeated as many times as required to obtain the equivalent electric circuit of the complete ac transmission line. The resulting equivalent circuit, which is generally referred to as the **distributed-parameter equivalent circuit**, is shown in Figure 5.

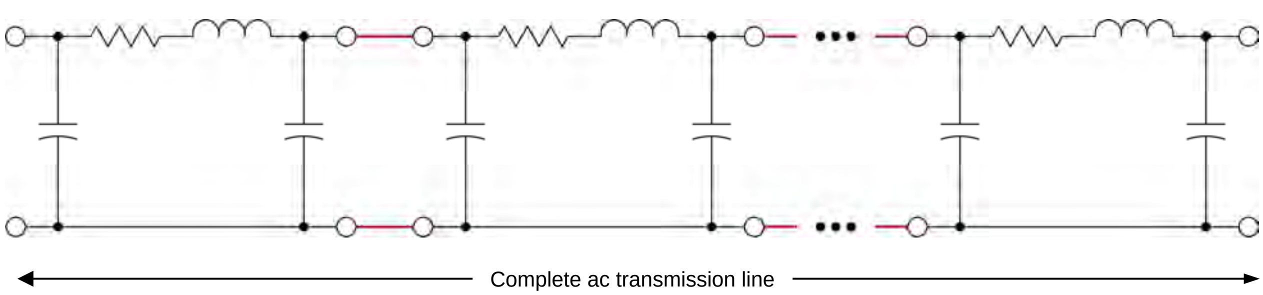


Figure 5. Distributed-parameter equivalent circuit of a high-voltage ac transmission line (one phase only).

This distributed-parameter equivalent circuit is an exact representation of a high-voltage ac transmission line and fully reproduces its characteristics. However, it is complex and not well suited for the study of ac transmission lines. The distributed-parameter equivalent circuit of an ac transmission line shown in Figure 5 can be greatly simplified by removing all resistors and capacitors, leaving only inductors connected in series. The resulting simplified equivalent circuit of the ac transmission line is a single series inductor representing all inductors in the distributed-parameter equivalent circuit of the ac transmission line, as shown in Figure 6. As a first approximation, the reactance of the series inductor in the simplified equivalent circuit of the ac transmission line is equal to the inductive reactance per line segment times the number of line segments in the distributed-parameter equivalent circuit. The simplified equivalent circuit of an ac transmission line shown in Figure 6 is an example of a lumped-parameter equivalent circuit because all inductors in the distributed-parameter equivalent circuit are lumped into a single inductor in the simplified equivalent circuit.

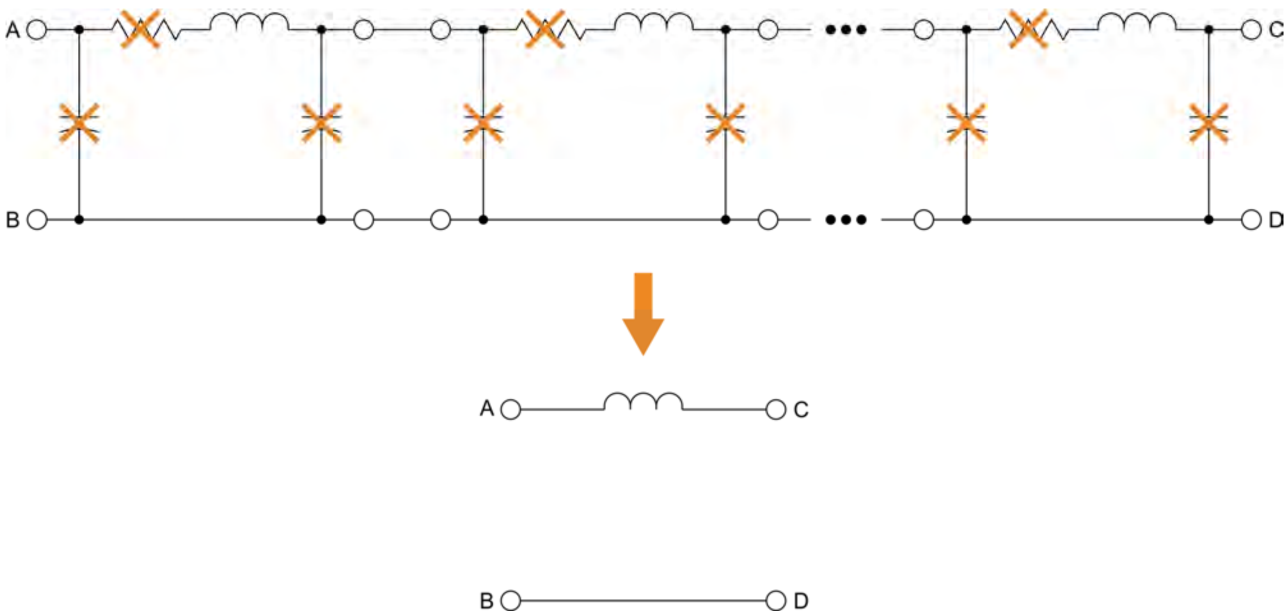


Figure 6. Lumped-parameter simplified equivalent circuit of an ac transmission line (one phase only).

The lumped-parameter simplified equivalent circuit shown in Figure 6 does not faithfully reproduce the electrical characteristics and behavior of a high-voltage ac transmission line. At best, it can be used to represent a line conveying ac power over a distance of less than about 30 km (about 20 miles), e.g., a power distribution line. However, the lumped-parameter simplified equivalent electric circuit in Figure 6 is useful in providing an introduction to the voltage regulation characteristics of ac transmission lines. The remainder of this exercise relies on the lumped-parameter simplified equivalent electric circuit of an ac transmission line.

Voltage regulation characteristics of a simplified ac transmission line for resistive, inductive, and capacitive loads

For brevity purposes, the voltages at the sender end and at the receiver end of ac transmission lines are often abbreviated to sender voltage and receiver voltage, respectively, throughout this manual.

The voltage E_R measured at the receiver end of an ac transmission line varies depending on the type of load to which power is supplied, as well as on the line current I_L flowing in the ac transmission line. Figure 7 shows the voltage regulation characteristics (i.e., curves of the voltage E_R at the receiver end of the ac transmission line as a function of the line current I_L flowing in the line) of a simplified ac transmission line (i.e., a transmission line represented by a single series inductor for each phase) for resistive, inductive, and capacitive loads. These voltage regulation characteristics are obtained with a constant voltage at the sender end of the simplified ac transmission line. The characteristics show that when the load is either resistive or inductive, the receiver voltage E_R decreases when the line current I_L increases (i.e., when the load increases). Conversely, when the load is capacitive, the receiver voltage E_R increases with the line current I_L (i.e., with the load). Consequently, for any significant current I_L flowing in the ac transmission line, the receiver voltage E_R is lower than the sender voltage E_S when the load is either resistive or inductive (the difference between the receiver voltage E_R and the sender voltage E_S when the load is inductive being larger than when the load is resistive). Conversely, the receiver voltage E_R is higher than the sender voltage E_S when the load is capacitive.

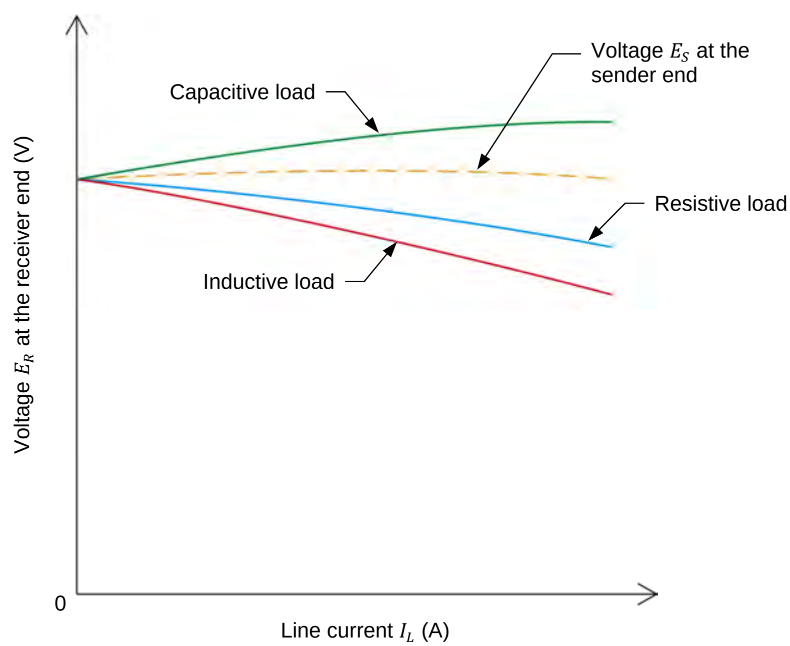


Figure 7. Typical voltage regulation characteristic curves of a simplified transmission line, i.e., a transmission line represented by a single series inductor for each phase.

The trends indicated by the characteristics in Figure 7 can be determined easily by resolving the circuits formed by one phase of a simplified ac transmission line connected successively to a resistive, an inductive, and a capacitive load. For example, consider the simplified equivalent circuit of an ac transmission line shown in Figure 8. In the figure, a 230 kV ac transmission line (sender phase voltage E_S = 133 kV) is represented by an inductive reactance X_L of 120 Ω. In the following three cases, the simplified ac transmission line is connected successively to a resistive load, an inductive load, and a capacitive load. The receiver voltage E_R is then calculated for each load type.

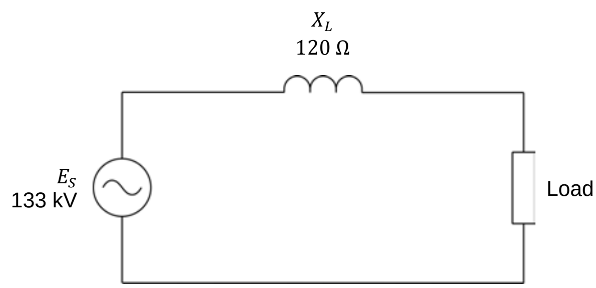


Figure 8. Simplified equivalent circuit of a 230 kV ac transmission line (sender phase voltage E_S = 133 kV).

Voltage calculations for a resistive load

When the ac transmission line shown in Figure 8 is connected to a resistive load having a resistance R_{Load} of 10 000 Ω, the receiver voltage E_R can be calculated as follows:

$$Z = \sqrt{{R_{Load}}^2 + {X_L}^2} = \sqrt{(10\ 000\ \Omega)^2 + (120\ \Omega)^2} = 10\ 001\ \Omega$$

$$I_L = E_S/Z = 133\ 000\ \text{V}/10\ 001\ \Omega = 13.3\ \text{A}$$

$$E_R = I_L \times R_{Load} = 13.3\ \text{A} \times 10\ 000\ \Omega = 133\ 000\ \text{V}$$

When the resistance R_{Load} of the resistive load is equal to 240 Ω, the receiver voltage E_R can be calculated as follows:

$$Z = \sqrt{{R_{Load}}^2 + {X_L}^2} = \sqrt{(240\ \Omega)^2 + (120\ \Omega)^2} = 268\ \Omega$$

$$I_L = E_S/Z = 133\ 000\ \text{V}/268\ \Omega = 496\ \text{A}$$

$$E_R = I_L \times R_{Load} = 496\ \text{A} \times 240\ \Omega = 119\ 040\ \text{V}$$

As you can see, the receiver voltage E_R decreases by a value of 13 960 V (133 000 V – 119 040 V) when the line current I_L increases from 13.3 A to 496 A. The receiver voltage E_R and the line current I_L calculated for the resistive load are plotted on a graph in Figure 9.

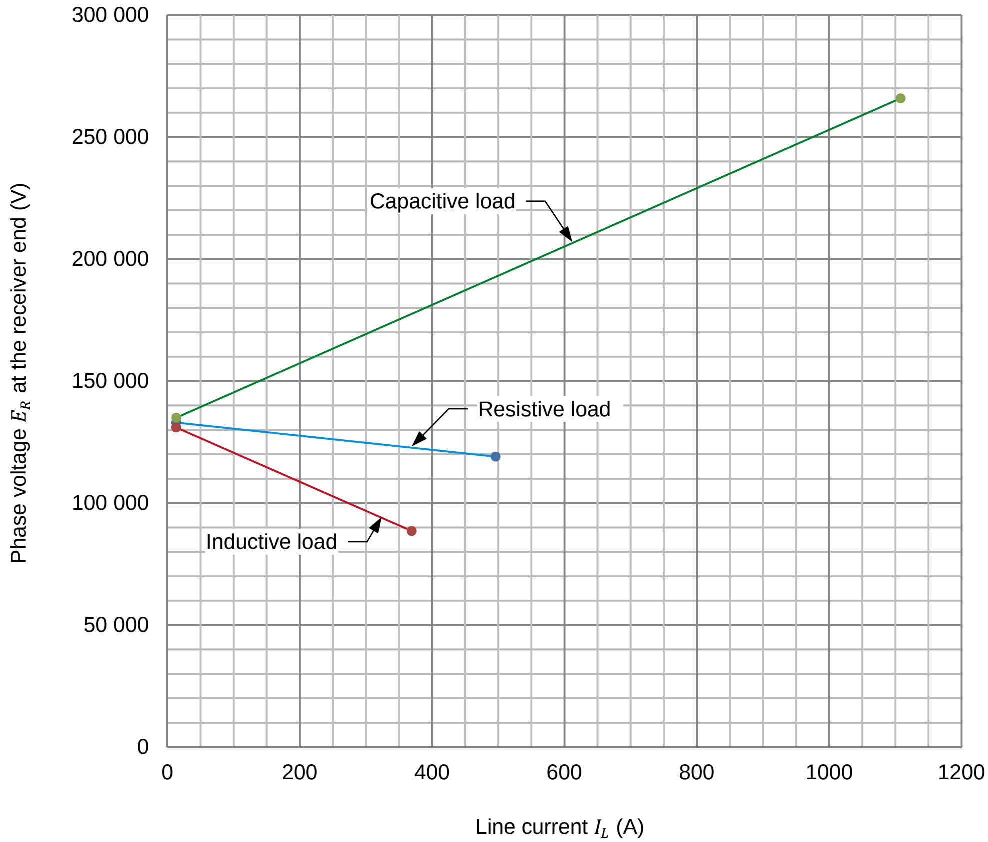


Figure 9. Calculated phase voltage E_R at the receiver end of the ac transmission line shown in Figure 8 as a function of the line current I_L for resistive, inductive, and capacitive loads.

Voltage calculations for an inductive load

When the ac transmission line shown in Figure 8 is connected to an inductive load having an inductive reactance $X_{L,load}$ of $10\ 000\ \Omega$, the receiver voltage E_R can be calculated as follows:

$$Z = X_T = X_L + X_{L,load} = 120\ \Omega + 10\ 000\ \Omega = 10\ 120\ \Omega$$

$$I_L = E_S/Z = 133\ 000\ \text{V}/10\ 120\ \Omega = 13.1\ \text{A}$$

$$E_R = I_L \times X_{L,load} = 13.1\ \text{A} \times 10\ 000\ \Omega = 131\ 000\ \text{V}$$

When the inductive reactance $X_{L,load}$ of the inductive load is equal to $240\ \Omega$, the receiver voltage E_R can be calculated as follows:

$$Z = X_T = X_L + X_{L,load} = 120\ \Omega + 240\ \Omega = 360\ \Omega$$

$$I_L = E_S/Z = 133\ 000\ \text{V}/360\ \Omega = 369\ \text{A}$$

$$E_R = I_L \times X_{L,load} = 369\ \text{A} \times 240\ \Omega = 88\ 560\ \text{V}$$

As you can see, the receiver voltage E_R decreases by a value of $42\ 440\ \text{V}$ ($131\ 000\ \text{V} - 88\ 560\ \text{V}$) when the line current I_L increases from $13.1\ \text{A}$ to $369\ \text{A}$. The receiver voltage E_R and the line current I_L calculated for the inductive load are plotted on the graph in Figure 9. The receiver voltage E_R for an inductive load is significantly lower than the receiver voltage E_R for a resistive load when the line current I_L increases.

Voltage calculations for a capacitive load

When the ac transmission line shown in Figure 8 is connected to a capacitive load having a capacitive reactance $X_{C,load}$ of $10\ 000\ \Omega$, the receiver voltage E_R can be calculated as follows:

$$Z = X_T = X_L - X_{C,load} = 120\ \Omega - 10\ 000\ \Omega = -9880\ \Omega = 9880\ \Omega$$

$$I_L = E_S/Z = 133\ 000\ \text{V}/9880\ \Omega = 13.5\ \text{A}$$

$$E_R = I_L \times X_{C,load} = 13.5\ \text{A} \times 10\ 000\ \Omega = 135\ 000\ \text{V}$$

When the capacitive reactance $X_{C,load}$ of the capacitive load is equal to $240\ \Omega$, the receiver voltage E_R can be calculated as follows:

$$Z = X_T = X_L - X_{C,load} = 120\ \Omega - 240\ \Omega = -120\ \Omega = 120\ \Omega$$

$$I_L = E_S/Z = 133\ 000\ \text{V}/120\ \Omega = 1108\ \text{A}$$

$$E_R = I_L \times X_{C,load} = 1108\ \text{A} \times 240\ \Omega = 265\ 920\ \text{V}$$

As you can see, the receiver voltage E_R increases by a value of $130\ 920\ \text{V}$ ($265\ 920\ \text{V} - 135\ 000\ \text{V}$) when the line current I_L increases from $13.5\ \text{A}$ to $1108\ \text{A}$. The receiver voltage E_R and the line current I_L calculated for the capacitive load are plotted on the graph in Figure 9. The receiver voltage E_R for a capacitive load is significantly higher than the receiver voltage E_R for a resistive load when the line current I_L increases.

Voltage regulation of ac transmission lines

The **voltage regulation** of an ac transmission line indicates the extent of the variation in the receiver voltage E_R that occurs when the load connected to the ac transmission line varies. As seen in the previous section, the voltage regulation characteristic of an ac transmission line depends on the type of load at the receiver end of the ac transmission line, and on the value of the inductive reactance X_L of the ac transmission line.

The voltage regulation of an ac transmission line can be calculated using Equation (1). As the equation shows, the lower the value of the voltage regulation of an ac transmission line, the better the regulation, i.e., the lower the variation in the receiver voltage E_R when the load connected to the ac transmission line varies.

$$\text{Voltage regulation (\%)} = \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100\% \tag{1}$$

where E_{NL} is the no-load voltage at the receiver end of the ac transmission line, expressed in volts (V).

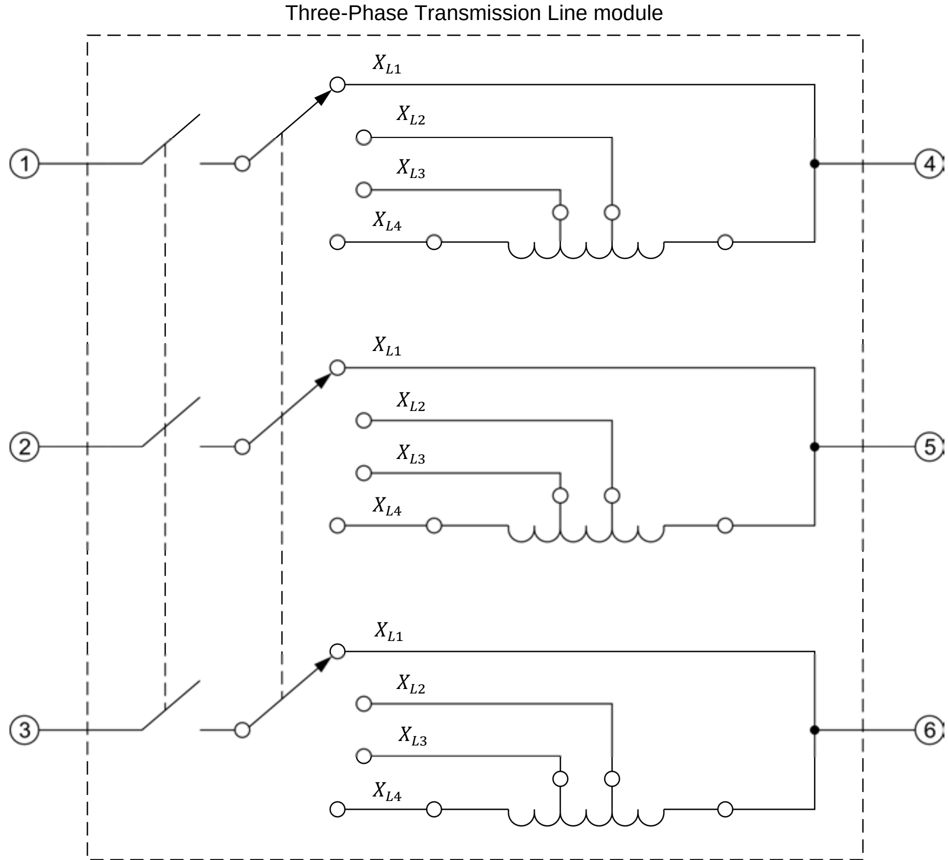
E_{FL} is the full-load voltage at the receiver end of the ac transmission line, expressed in volts (V).

Generally, ac transmission lines often operate at close to full load current (i.e., nominal current) and with a resistive load. However, if, for some reason, the load connected to an ac transmission line is removed or greatly decreased, it is important for the ac transmission line to have a good voltage regulation (i.e., a voltage regulation value as low as possible) in order to minimize the voltage increase at the receiver end of the line. This prevents too high a voltage from developing at the receiver end of the ac transmission line that could trip overvoltage protection or cause equipment failure. Having a good (low value) voltage regulation is also desirable because it minimizes the voltage fluctuations at the receiver end of the ac transmission line when the load varies.

Introduction to the Three-Phase Transmission Line module

The Three-Phase Transmission Line module has essentially the same electrical properties as those of a simplified ac transmission line represented by three inductors (one per phase). The length of the simplified ac transmission line represented by the module can be changed by varying the reactance of the inductors in the module using the inductive reactance selector on the front panel of the module. The higher the selected inductive reactance, the longer the length of the simplified ac transmission line represented by the Three-Phase Transmission Line module. The inductive reactance of aerial ac transmission lines operating at a frequency of 50 Hz is generally between 0.25 Ω/km (0.40 Ω/mile) to 0.42 Ω/km (0.68 Ω/mile), while the inductive reactance of aerial ac transmission lines operating at a frequency of 60 Hz is generally between 0.30 Ω/km (0.48 Ω/mile) to 0.50 Ω/km (0.80 Ω/mile). This is true no matter the line voltage across the ac transmission line or the active power that the line conveys.

Figure 10 shows the equivalent circuit of the Three-Phase Transmission Line module. The table in Figure 10 gives the inductive reactance values X_{L1}, X_{L2}, X_{L3}, and X_{L4} that can be obtained with the Three-Phase Transmission Line module at different local ac power network voltages and frequencies.



Local ac power network		Inductive reactance (Ω)			
Voltage (V)	**Frequency (Hz)**	X_{L1}	X_{L2}	X_{L3}	X_{L4}
120	60	0	60	120	180
220	50	0	200	400	600
240	50	0	200	400	600
220	60	0	200	400	600

Figure 10. Equivalent circuit of the Three-Phase Transmission Line module.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Voltage regulation characteristics of a simplified ac transmission line for resistive, inductive, and capacitive loads

PROCEDURE

⚠ WARNING

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 connect a circuit containing a simplified ac transmission line supplying power to a three-phase resistive load. You will then set the measuring equipment to study the voltage regulation characteristics of the simplified 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.

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.

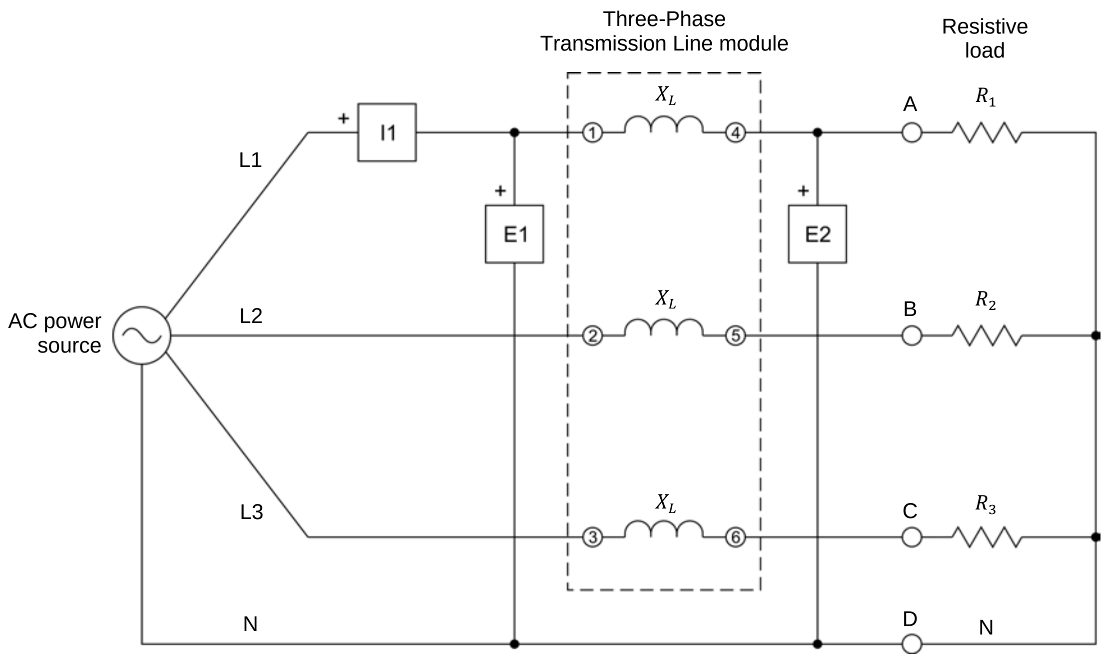
   Connect the *Power Input* of the Data Acquisition and Control Interface to a 24 V ac power supply. Turn the 24 V ac power supply on.

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. 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 11. Use one resistor section of the Resistive Load module to implement each of resistors R_1, R_2, and R_3.



Local ac power network		Line inductive reactance X_L (Ω)	R_1, R_2, R_3 (Ω)
Voltage (V)	Frequency (Hz)		
120	60	120	∞
220	50	400	∞
240	50	400	∞
220	60	400	∞

Figure 11. Simplified AC transmission line connected to a three-phase resistive load.

The value of the line inductive reactance, as well as those of the resistive, inductive, and capacitive loads used in the circuits of this manual depend on your local ac power network voltage and frequency. Whenever necessary, a table below the circuit diagram indicates the value of each component for ac power network voltages of 120 V, 220 V, and 240 V, and for ac power network frequencies of 50 Hz and 60 Hz. Make sure to use the component values corresponding to your local ac power network voltage and frequency.

6. On the Three-Phase Transmission Line, make sure that the I/O toggle switch is set to the *I* position, then set the inductive reactance selector to the value indicated in the table of Figure 11.

On the Resistive Load, open all switches so that the load resistance R_{Load} is infinite.

7. In LVDAC-EMS, open the Metering window. Make the required settings in order to measure the rms values (ac) of the sender voltage E_S and receiver voltage E_R (inputs *E1* and *E2*, respectively), as well as of the line current I_L (input *I1*). Set the meters to continuous refresh mode.

Voltage regulation characteristics of a simplified ac transmission line for resistive, inductive, and capacitive loads

In this section, you will measure the sender voltage of the simplified ac transmission line, and make sure that it is equal to the nominal value. You will record the receiver voltage and line current of the simplified ac transmission line while varying the resistance of the three-phase resistive load. You will then replace the resistive load with a three-phase inductive load, and record the receiver voltage and line current of the simplified ac transmission line while varying the reactance of the inductive load. Finally, you will replace the inductive load with a three-phase capacitive load, and record the receiver voltage and line current of the simplified ac transmission line while varying the reactance of the capacitive load. On the same graph, you will plot the voltage regulation characteristics of the simplified ac transmission line for a resistive load, an inductive load, and a capacitive load. You will compare the resulting voltage regulation characteristics.

Voltage regulation characteristic when the simplified ac transmission line is connected to a resistive load

8. On the Power Supply, turn the three-phase ac power source on.

9. Measure the voltage E_S at the sender end of the simplified ac transmission line. Record the value below.

   Sender voltage $E_S =$ _______ V

   Is the voltage E_S at the sender end of the simplified ac transmission line virtually equal to your ac power network voltage?

   ❑ Yes ❑ No

10. In LVDAC-EMS, open the Data Table window.

    Set the Data Table to record the receiver voltage E_R and line current I_L indicated in the Metering window.

    In the Data Table, click the *Record Data* button to record the values of the receiver voltage E_R and line current I_L.

11. Set the resistance of resistors R_1, R_2, and R_3 successively to each value indicated in Table 1 (the resistance values to be used depend on your local ac power network voltage and frequency). For each resistance value, record the parameters of the simplified ac transmission line in the Data Table.

Table 1. Resistance values used to obtain the voltage regulation characteristics of the simplified ac transmission line.

Local ac power network		R_1, R_2, R_3 (Ω)	R_1, R_2, R_3 (Ω)	R_1, R_2, R_3 (Ω)	R_1, R_2, R_3 (Ω)	R_1, R_2, R_3 (Ω)	R_1, R_2, R_3 (Ω)	R_1, R_2, R_3 (Ω)
Voltage (V)	Frequency (Hz)							
120	60	1200	600	400	300	240	200	171
220	50	4400	2200	1467	1100	880	733	629
240	50	4800	2400	1600	1200	960	800	686
220	60	4400	2200	1467	1100	880	733	629

Appendix C lists the switch settings required on the Resistive Load, the Inductive Load, and the Capacitive Load in order to obtain various resistance (or reactance) values.

12. On the Power Supply, turn the three-phase ac power source off.

13. In the Data Table window, save the recorded data.

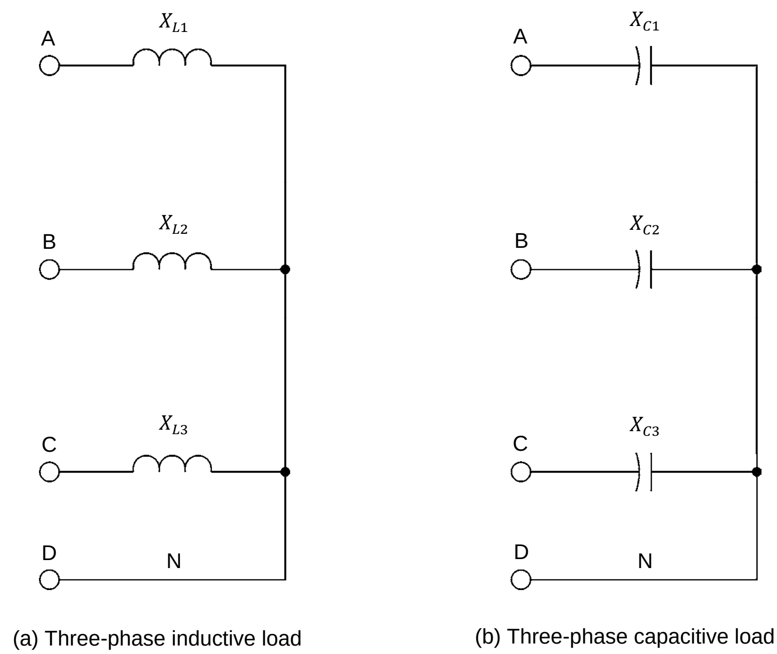
14. In the Data Table, clear the recorded data without clearing the record settings.

Voltage regulation characteristic when the simplified ac transmission line is connected to an inductive load

15. Remove the three-phase resistive load from the circuit in Figure 11 by disconnecting the load at points A, B, C, and D.

Add the three-phase inductive load shown in Figure 12a to the circuit by connecting points A, B, C, and D of the load to the corresponding points in the circuit.

16. On the Inductive Load, open all switches so that the reactance of the load inductors (X_{L1}, X_{L2}, and X_{L3}) is infinite.



Local ac power network		X_{L1}, X_{L2}, X_{L3} X_{C1}, X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)	
120	60	∞
220	50	∞
240	50	∞
220	60	∞

Figure 12. Three-phase inductive and capacitive loads used to study the voltage regulation characteristics of the simplified ac transmission line.

17. On the Power Supply, turn the three-phase ac power source on.

18. In the Data Table window, click the *Record Data* button to record the values of the receiver voltage E_R and line current I_L.

19. Set the reactance of the load inductors successively to each value indicated in Table 2 (the inductive reactance values to be used depend on your local ac power network voltage and frequency). For each inductive reactance value, record the parameters of the simplified ac transmission line in the Data Table.

Table 2. Inductive reactance values used to obtain the voltage regulation characteristics of the simplified ac transmission line.

Local ac power network		X_{L1}, X_{L2}, X_{L3} (Ω)	X_{L1}, X_{L2}, X_{L3} (Ω)	X_{L1}, X_{L2}, X_{L3} (Ω)	X_{L1}, X_{L2}, X_{L3} (Ω)	X_{L1}, X_{L2}, X_{L3} (Ω)	X_{L1}, X_{L2}, X_{L3} (Ω)	X_{L1}, X_{L2}, X_{L3} (Ω)
Voltage (V)	Frequency (Hz)							
120	60	1200	600	400	300	240	200	171
220	50	4400	2200	1467	1100	880	733	629
240	50	4800	2400	1600	1200	960	800	686
220	60	4400	2200	1467	1100	880	733	629

20. On the Power Supply, turn the three-phase ac power source off.

21. In the Data Table window, save the recorded data.

22. In the Data Table, clear the recorded data without clearing the record settings.

Voltage regulation characteristic when the simplified ac transmission line is connected to a capacitive load

23. Remove the three-phase inductive load from the circuit in Figure 11 by disconnecting the load at points A, B, C, and D.

Add the three-phase capacitive load shown in Figure 12b to the circuit by connecting points A, B, C, and D of the load to the corresponding points in the circuit.

24. On the Capacitive Load, open all switches so that the reactance of the load capacitors (X_{C1}, X_{C2}, and X_{C3}) is infinite.

25. On the Power Supply, turn the three-phase ac power source on.

26. In the Data Table window, click the *Record Data* button to record the values of the receiver voltage E_R and line current I_L.

27. Set the reactance of the load capacitors successively to each value indicated in Table 3 (the capacitive reactance values to be used depend on your local ac power network voltage and frequency). For each capacitive reactance value, record the parameters of the simplified ac transmission line in the Data Table.

CAUTION

It is important that you do not decrease the reactance of the load capacitors below the lowest value indicated in Table 3 corresponding to your local ac power network voltage and frequency. Otherwise, the voltage across the load capacitors will exceed the ratings of the Capacitive Load, which could damage the module.

Table 3. Capacitive reactance values used to obtain the voltage regulation characteristics of the simplified ac transmission line.

Local ac power network		X_{C1}, X_{C2}, X_{C3} (Ω)	X_{C1}, X_{C2}, X_{C3} (Ω)	X_{C1}, X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)			
120	60	1200	600	400
220	50	4400	2200	1467
240	50	4800	2400	1600
220	60	4400	2200	1467

28. On the Power Supply, turn the three-phase ac power source off.

29. In the Data Table window, save the recorded data.

Transfer the data you saved to a spreadsheet application, then plot curves of the receiver voltage E_R as a function of the line current I_L (voltage regulation characteristics) measured when the simplified ac transmission line is connected to a resistive load, an inductive load, and a capacitive load. Plot all three curves on the same graph.

30. Compare the voltage regulation characteristics you plotted in the previous step for the different load types connected to the simplified ac transmission line.

31. Calculate the voltage regulation of the simplified ac transmission line for each load type (resistive, inductive, and capacitive). The no-load voltage E_{NL} corresponds to the voltage value you recorded at no load (when the line current I_L is closest to 0 A). The full-load voltage E_{FL} can be estimated using the voltage regulation characteristics you plotted in step 29 by determining the receiver voltage value corresponding to the full-load current of the simplified ac transmission line for each load type. The full-load current of the simplified ac transmission line depends on your local ac power network voltage and frequency, as indicated in Table 4.

Table 4. Full-load current of the ac transmission line.

Local ac power network		Full-load current (A)
Voltage (V)	Frequency (Hz)	
120	60	0.33
220	50	0.18
240	50	0.20
220	60	0.18

Voltage regulation with resistive load = _______%

Voltage regulation with inductive load = _______%

Voltage regulation with capacitive load = _______%

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

Conclusion

In this exercise, you became familiar with the equivalent circuit of a simplified ac transmission line. You also became familiar with the voltage regulation characteristic of a simplified ac transmission line when it is connected to a resistive, an inductive, or a capacitive load. You were introduced to the concept of voltage regulation in ac transmission lines. You learned how to determine the voltage regulation of an ac transmission line.

Review Questions

1. What is the main purpose of ac transmission lines? Which element of an ac power network is immediately before ac transmission lines and which element is immediately after?

____

____

____

2. Complete the following figure representing the simplified equivalent circuit of one phase of an ac transmission line.

Simplified equivalent circuit of one phase of an ac transmission line.

3. What happens to the receiver voltage E_R of a simplified ac transmission line connected to a capacitive load as the line current I_L increases?

4. What happens to the receiver voltage E_R of a simplified ac transmission line connected to a resistive load as the line current I_L increases? What happens if the simplified ac transmission line is connected to an inductive load instead?

5. Consider two ac transmission lines: the no-load and full-load voltages across the first line are equal to 244 kV and 230 kV, respectively, while the no-load and full-load voltages across the second line are equal to 765 kV and 735 kV, respectively. Which of the two ac transmission lines has the better voltage regulation? Explain briefly.

Characteristics of a High-Voltage AC Transmission Line

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the corrected PI equivalent circuit of a high-voltage ac transmission line. You will also be familiar with the no load receiver voltage and voltage regulation characteristic of a high-voltage ac transmission line. You will be able to define and calculate two important characteristics of a high-voltage ac transmission line: the characteristic impedance Z_0 and the natural load P_0. You will be able to describe the complete voltage regulation characteristic (power-voltage curve) of a high-voltage ac transmission line, i.e., for operation from no load to a short-circuit at the receiver end of the line.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Corrected PI equivalent circuit of a high-voltage ac transmission line
- Non-corrected PI equivalent circuit of a high-voltage ac transmission line
- No load receiver voltage and voltage regulation characteristic of a high-voltage ac transmission line
- Characteristic impedance Z_0 and natural load P_0 of a high-voltage ac transmission line
- Power-voltage curve of a high-voltage ac transmission line

DISCUSSION

Corrected PI equivalent circuit of a high-voltage ac transmission line

As stated in the discussion of Exercise 1, the equivalent electric circuit of a short segment (e.g., 1 km or 1 mile) of a high-voltage ac transmission line consists of a resistor, an inductor, and two capacitors connected as shown in Figure 13. The components in this figure represent the resistance R, inductive reactance X_L, and capacitive reactance X_C of the ac transmission line. These three parameters are fundamental electrical characteristics of any high-voltage ac transmission line. These characteristics are usually expressed in ohms per kilometer (Ω/km) or in ohms per mile (Ω/mile). Consequently, the values of the resistance and inductive reactance of the resistor and inductor in the equivalent circuit of Figure 13 are equal to the resistance R and inductive reactance X_L of the ac transmission line, respectively. On the other hand, since two shunt-connected capacitors are used in the equivalent circuit of Figure 13 to represent the capacitive reactance of the ac transmission line, the capacitive reactance of each capacitor is equal to twice the capacitive reactance X_C of the ac transmission line. The values of the fundamental electrical characteristics R, X_L, and X_C of the transmission line in Figure 13 are typical for a high-voltage ac transmission line.

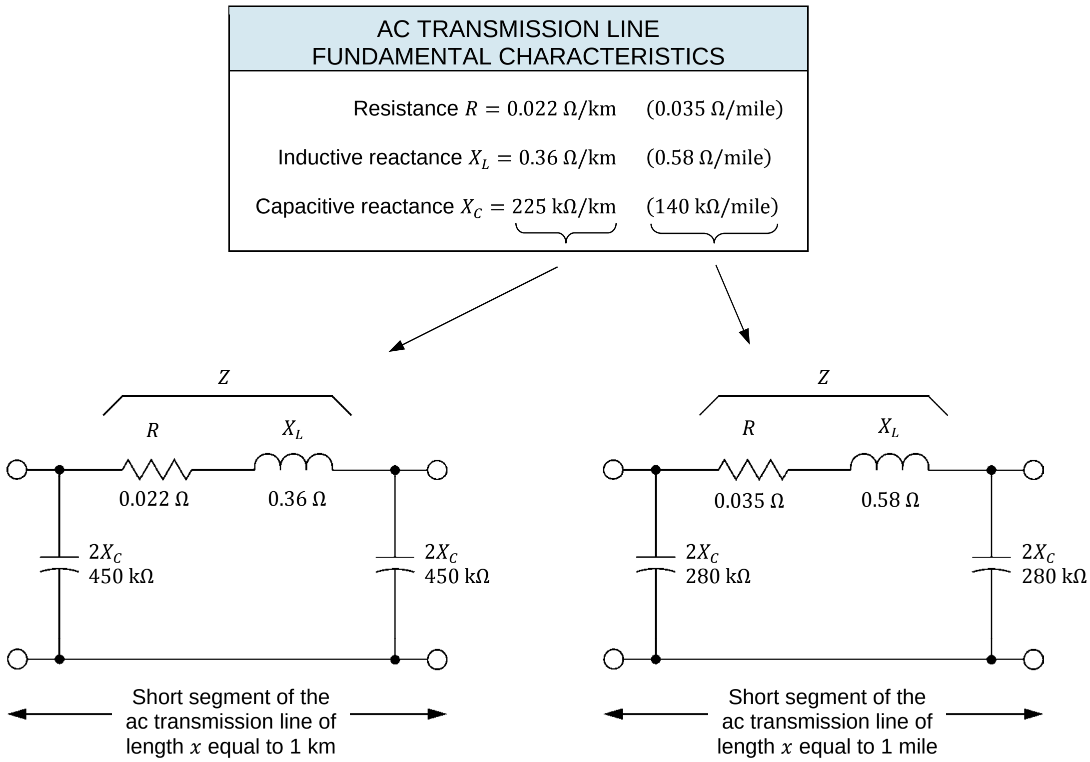


Figure 13. Equivalent electric circuit of a short segment of a typical high-voltage (315 kV) ac transmission line (one phase only).

The equivalent circuit of Figure 13 must be repeated as many times as required to obtain the distributed-parameter equivalent circuit of the complete ac transmission line, as shown in Figure 14. For instance, the circuit is repeated 250 times to obtain the distributed-parameter equivalent circuit of a 250 km line or a 250 mile line.

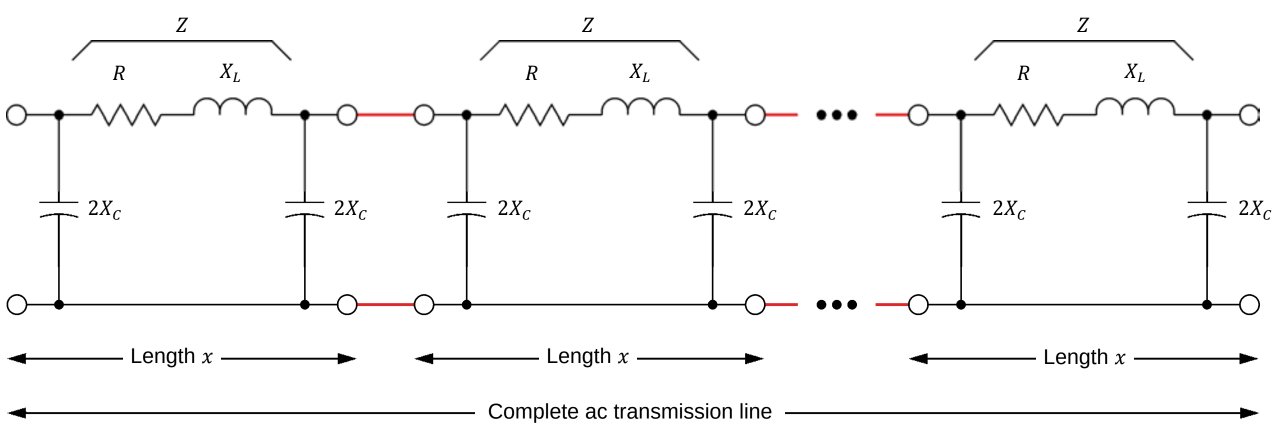
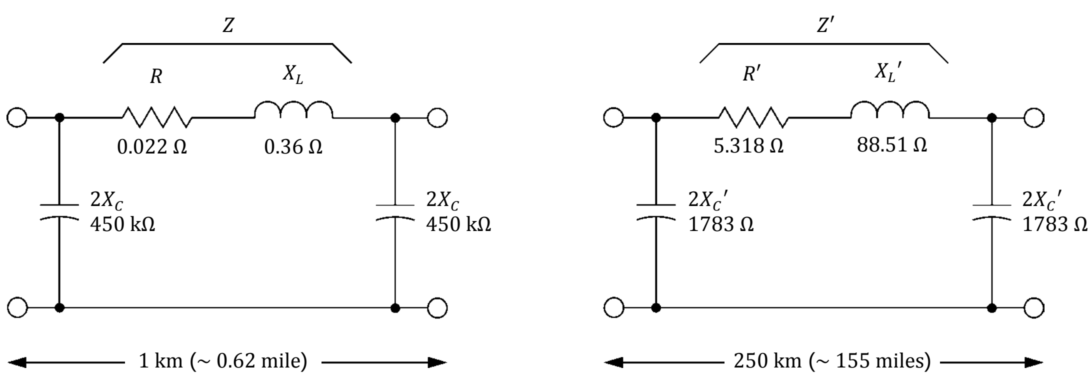


Figure 14. Distributed-parameter equivalent circuit of a high-voltage ac transmission line (one phase only).

The distributed-parameter equivalent circuit of a high-voltage ac transmission line shown in Figure 14 is an exact representation of an ac transmission line and fully reproduces its electrical characteristics and behavior. However, this equivalent circuit is not well suited for the study of ac transmission lines because resolving this circuit is complex and time consuming. Fortunately, mathematical calculations, that are beyond the scope of this manual, allow the distributed-parameter equivalent circuit of any high-voltage ac transmission line to be reduced to a lumped-parameter equivalent circuit having the same configuration (reminiscent of the Greek letter π) as the equivalent circuit of a short segment of this high-voltage ac transmission line. This lumped-parameter equivalent circuit is commonly referred to as the **corrected PI (π) equivalent circuit** of the ac transmission line. Figure 15 shows the fundamental characteristics of a high-voltage ac transmission line, the equivalent circuit of a short segment of this high-voltage ac transmission line, and the corrected PI equivalent circuit of this high-voltage ac transmission line for a length of 250 km (about 155 miles).

AC TRANSMISSION LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 0.36\ \Omega/\text{km}$	$(0.58\ \Omega/\text{mile})$
Capacitive reactance $X_C = 225\ \text{k}\Omega/\text{km}$	$(140\ \text{k}\Omega/\text{mile})$

(a) AC transmission line fundamental characteristics



(b) Equivalent circuit of a short segment of the transmission line

(c) Corrected PI equivalent circuit of the transmission line

Figure 15. Fundamental characteristics of a high-voltage (315 kV) ac transmission line, equivalent circuit (one phase only) of a short segment of this high-voltage ac transmission line, and corrected PI equivalent circuit (one phase only) of this high-voltage ac transmission line for a length of 250 km (about 155 miles).

Notice that the resistance R' of the resistor in the corrected PI equivalent circuit (Figure 15c) of the transmission line is not exactly equal to 250 times the resistance R of the resistor in the equivalent circuit (Figure 15b) of a short segment of the transmission line. Similarly, the inductive reactance $X_L{}'$ of the inductor in the corrected PI equivalent circuit (Figure 15c) of the transmission line is not exactly equal to 250 times the inductive reactance X_L of the inductor in the equivalent circuit (Figure 15b) of a short segment of the transmission line. Also, the capacitive reactance $2X_C{}'$ of the capacitors in the corrected PI equivalent circuit (Figure 15c) of the transmission line is not exactly equal to the capacitive reactance $2X_C$ of the capacitors in the equivalent circuit (Figure 15b) of a short segment of the transmission line divided by 250.

Although simple, the corrected PI equivalent circuit of an ac transmission line shown in Figure 15c operates like 250 equivalent circuits of a short segment of this ac transmission line connected in series. More precisely, the voltage and current at the sender and receiver ends of the corrected PI equivalent circuit of the ac transmission line are the same as those obtained at the sender and receiver ends of 250 equivalent circuits of a short segment of this ac transmission line connected in series. The characteristics and behavior observed with the corrected PI equivalent circuit of an ac transmission line, which are very similar to those of actual high-voltage ac transmission lines, differ considerably from the characteristics and behavior observed with the lumped-parameter simplified equivalent circuit of an ac transmission line (i.e., a series inductor) used in Exercise 1.

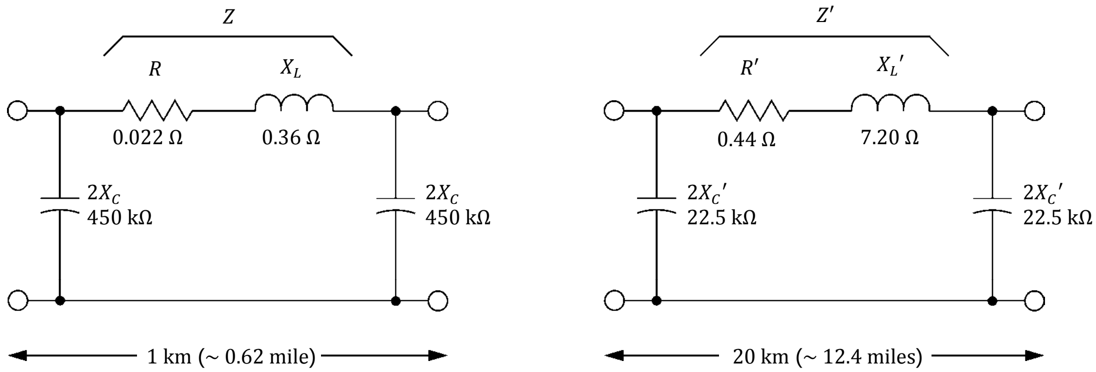
Finally, note that the corrected PI equivalent circuit of an ac transmission line provides very accurate results for line lengths up to about 625 km (about 388 miles) when the ac power network frequency is 60 Hz, and for line lengths up to about 750 km (about 466 miles) when the frequency of the ac power network is 50 Hz. An equivalent circuit can be obtained for any ac transmission line longer than the above limits by dividing it into a number of segments and representing these segments by the corresponding corrected PI equivalent circuits connected in series. For instance, a 1200 km (about 746 miles) ac transmission line can be divided in four segments of 300 km (about 186.5 miles) and represented by four corrected PI equivalent circuits of a 300 km (about 186.5 miles) line connected in series.

Non-corrected PI equivalent circuit of a high-voltage ac transmission line

A lumped-parameter, non-corrected PI equivalent circuit of an ac transmission line can also be obtained. This equivalent circuit provides very accurate results for line lengths lower than about 50 km (about 30 miles). The non-corrected PI equivalent circuit is obtained by multiplying the resistance R of the resistor and the reactance X_L of the inductor in the equivalent circuit of a short segment of the transmission line by the number of line segments in the line, and dividing the reactance $2X_C$ of the capacitors in the equivalent circuit of a short segment of the transmission line by the number of line segments in the line. Figure 16 shows the fundamental characteristics of a high-voltage ac transmission line, the equivalent circuit of a short segment of this high-voltage ac transmission line, and the non-corrected PI equivalent circuit of this high-voltage ac transmission line for a length of 20 km (about 12.4 miles).

AC TRANSMISSION LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 0.36\ \Omega/\text{km}$	$(0.58\ \Omega/\text{mile})$
Capacitive reactance $X_C = 225\ \text{k}\Omega/\text{km}$	$(140\ \text{k}\Omega/\text{mile})$

(a) AC transmission line fundamental characteristics



(b) Equivalent circuit of a short segment of the transmission line

(c) Non-corrected PI equivalent circuit of the transmission line

Figure 16. Fundamental characteristics of a high-voltage (315 kV) ac transmission line, equivalent circuit (one phase only) of a short segment of this high-voltage ac transmission line, and non-corrected PI equivalent circuit (one phase only) of this high-voltage ac transmission line for a length of 20 km (about 12.4 miles).

No load receiver voltage and voltage regulation characteristic of a high-voltage ac transmission line

Figure 17 shows the voltage regulation characteristic of a high-voltage ac transmission line for a resistive load. As in the simplified ac transmission line discussed in Exercise 1, the voltage E_R at the receiver end of the high-voltage ac transmission line decreases when the line current I_L increases (i.e., when the load increases). However, notice that the receiver voltage E_R exceeds the sender voltage E_S when no load is connected to the receiver end of the line.

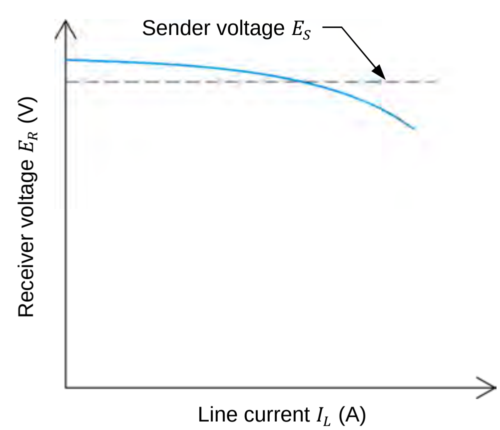


Figure 17. Voltage regulation characteristic of a high-voltage ac transmission line for a resistive load.

A high-voltage ac transmission line (represented by its corrected PI equivalent circuit) with no load at the receiver end is shown in Figure 18. Current flows through the line (via resistor R', inductive reactance $X_L{}'$, and capacitive reactance $X_C{}'$) even with no load at the receiver end. Neglecting the resistor R' in this situation, the high-voltage ac transmission line can be represented by a simplified ac transmission line (i.e., a series inductor) connected in series with a capacitive load, as shown in Figure 18. A capacitive load connected to a simplified ac transmission line makes the receiver voltage E_R exceed the sender voltage E_S, as demonstrated in Exercise 1. This explains why the receiver voltage E_R exceeds the sender voltage E_S when no load is connected to the receiver end of an ac transmission line.

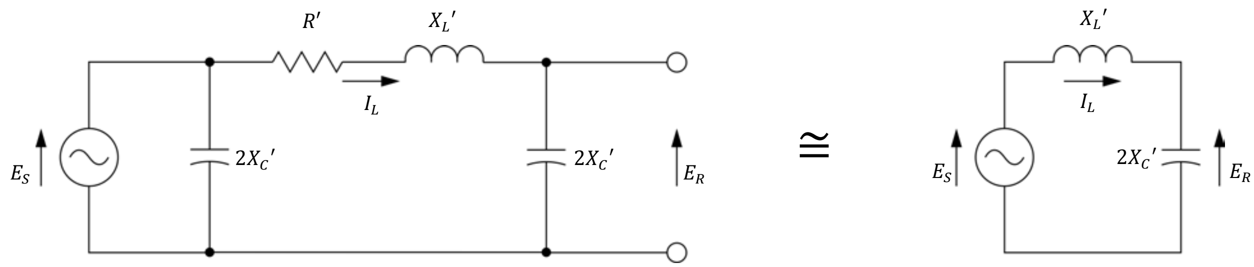
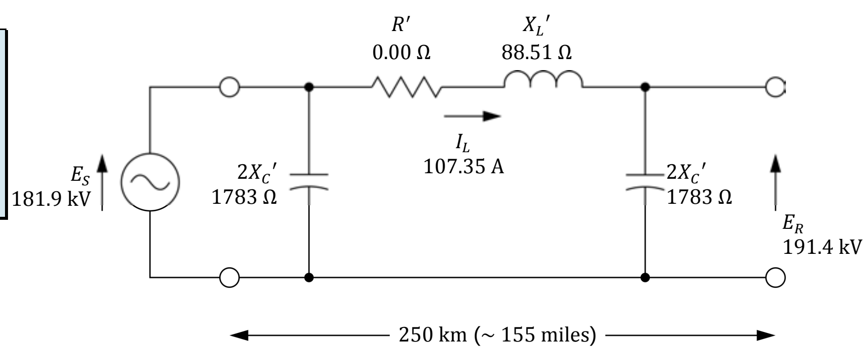


Figure 18. Voltage E_R exceeds `voltage E_S when no load is connected to the receiver end of an ac transmission line, as when a simplified ac transmission line is connected to a capacitive load. One phase of the ac transmission line is shown.

Another way of explaining the overvoltage that occurs when an ac transmission line is left open is by comparing the reactive power $Q_{L\,Line}$ due to the line inductance with the reactive power $Q_{C\,Line}$ due to the line capacitance (see Figure 19). In this situation, the reactive power $Q_{C\,Line}$ greatly exceeds the reactive power $Q_{L\,Line}$, as shown in Figure 19. The large unbalance between the reactive power $Q_{C\,Line}$ and reactive power $Q_{L\,Line}$ is what causes the receiver voltage E_R to exceed the sender voltage E_S.

Notice that the ac transmission line shown in Figure 19 is assumed to be lossless (i.e., the resistance R' is made equal to 0 Ω).



$$Q_{C\,Line} = \frac{{E_S}^2}{2X_C{}'} + \frac{{E_R}^2}{2X_C{}'} = \frac{(181.9\text{ kV})^2}{1783\ \Omega} + \frac{(191.4\text{ kV})^2}{1783\ \Omega} = 39.1\text{ Mvar}$$

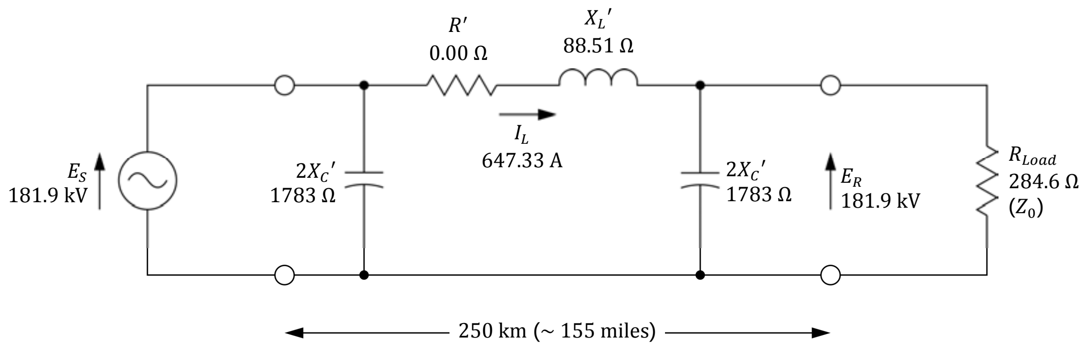
$$Q_{L\,Line} = X_L{}' \cdot {I_L}^2 = 88.51\ \Omega \cdot (107.35\text{ A})^2 = 1.02\text{ Mvar}$$

Figure 19. Voltage E_R exceeds voltage E_S when no load is connected to the receiver end of an ac transmission line because the line is largely unbalanced ($Q_{C\,Line} \gg Q_{L\,Line}$). One phase of a 315 kV ac transmission line (length of 250 km or about 155 miles) is shown.

Characteristic impedance Z_0 and natural load P_0 of a high-voltage ac transmission line

Notice that the ac transmission line shown in Figure 20 is assumed to be lossless (i.e., the resistance R' is made equal to 0 Ω).

The voltage E_R at the receiver end of a high-voltage ac transmission line connected to a resistive load decreases when the line current I_L increases (i.e., when the load increases), as mentioned in the previous section of this discussion. At some point, the voltage E_R becomes equal to voltage E_S as the reactive power $Q_{L\ Line}$ due to the line inductance becomes equal to the reactive power $Q_{C\ Line}$ due to the line capacitance, as shown in Figure 20. At this particular point, the line is said to be naturally balanced.



$$Q_{C\ Line} = \frac{{E_S}^2}{2X_C'} + \frac{{E_R}^2}{2X_C'} = \frac{181.9\ \text{kV}^2}{1783\ \Omega} + \frac{181.9\ \text{kV}^2}{1783\ \Omega} = 37.1\ \text{Mvar}$$

$$Q_{L\ Line} = X_L' \cdot {I_L}^2 = 88.51\ \Omega \cdot 647.33\ \text{A}^2 = 37.1\ \text{Mvar}$$

Figure 20. Voltage E_R equals voltage E_S when the value of the load at the receiver end equals the characteristic impedance Z_0 of the ac transmission line because the line is naturally balanced (i.e., $Q_{C\ Line} = Q_{L\ Line}$). One phase of a 315 kV ac transmission line (length of 250 km or about 155 miles) is shown.

The value of the load impedance (i.e., the resistance in the case of a purely resistive load) required at the receiver end of an ac transmission line to make voltage E_R equal to voltage E_S is known as the **characteristic impedance Z_0**. The characteristic impedance Z_0 of an ac transmission line is also referred to as the **surge impedance**. The value of the characteristic impedance Z_0 depends on the fundamental electrical characteristics of the ac transmission line and can be calculated using Equation (2).

$$Z_0 = \sqrt{X_L \cdot X_C} \tag{2}$$

where X_L is the inductive reactance of the ac transmission line, expressed in Ω/km or Ω/mile.

X_C is the capacitive reactance of the ac transmission line, expressed in Ω/km or Ω/mile.

For instance, the inductive reactance X_L and capacitive reactance X_C of the 315 kV ac transmission line shown in Figure 19 and Figure 20 are equal to 0.3600 Ω/km (0.5794 Ω/mile) and 225.0 $\mathrm{k}\Omega/\mathrm{km}$ (139.8 $\mathrm{k}\Omega/\mathrm{mile}$), respectively, which results in a characteristic impedance Z_0 of 284.6 Ω.

The active power delivered to a resistive load whose resistance is equal to the characteristic impedance Z_0 of the ac transmission line is referred to as the **natural load** P_0 of the line. The natural load P_0 of an ac transmission line is also referred to as the **surge impedance load** (SIL). The value of the natural load P_0 can be calculated using Equation (3).

$$P_0 = \frac{{E_R}^2}{Z_0} \cdot 3 \qquad (3)$$

where E_R is the phase voltage at the receiver end of the ac transmission line, expressed in V.

Z_0 is the characteristic impedance of the ac transmission line, expressed in Ω.

For instance, the natural load P_0 of the 315 kV ac transmission line shown in Figure 19 and Figure 20 is 348.8 MW.

Note that Equation (2) and Equation (3) are based on the assumption that the ac transmission line is lossless (i.e., the line resistance is zero). In actual ac transmission lines, however, the resistance is not zero. Thus, the load impedance actually required to make the receiver voltage E_R equal to the sender voltage E_S is higher than the characteristic impedance Z_0 calculated with Equation (2). Consequently, the active power actually supplied to the load is lower than the natural load P_0 calculated with Equation (3). In fact, when the line resistance is not zero, the reactive power $Q_{C\ Line}$ due to the line capacitance must slightly exceed the reactive power $Q_{L\ Line}$ due to the line inductance to make the receiver voltage E_R equal to the sender voltage E_S. The higher the resistance of the ac transmission line per unit of distance (i.e., per km or per mile), the larger the difference between the actual values and calculated values.

The natural load P_0 of an ac transmission line is not the maximal amount of active power which the line can supply to the load, and consequently, the characteristic impedance Z_0 of the line is not the minimal value of resistive load that can be connected to the line. The natural load P_0 and characteristic impedance Z_0 of the line, however, are important reference parameters obtained when the line is naturally balanced (i.e., $Q_{C\ Line} = Q_{L\ Line}$). Any ac transmission line can be operated beyond the natural load P_0, provided that other limiting factors (like thermal considerations due to line losses) are respected. In other words, any ac transmission line can operate with a load having a resistance lower than the characteristic impedance Z_0, provided that other limiting factors are respected.

Power-voltage curve of a high-voltage ac transmission line

The power-voltage curve shown in Figure 21 assumes a lossless ($R' = 0\ \Omega$) ac transmission line. This has no impact on the observations made using this curve.

Figure 21 shows the complete voltage regulation characteristic of the 315 kV high-voltage ac transmission line shown in the previous figures, i.e., for operation from no load at the receiver end of the line to a short-circuit at the receiver end of the line. Observe that the vertical (voltage) axis of the characteristic represents the ratio (E_R/E_S) of the receiver voltage E_R over the sender voltage E_S instead of the receiver voltage E_R. Similarly, observe that the horizontal axis of the characteristic represents the ratio (P/P_0) of the active power P which the line conveys over the natural load P_0 instead of the line current I_L. The complete voltage regulation characteristic of a high-voltage ac transmission line shown in Figure 21 is also referred to as the power-voltage curve of the ac transmission line. The power-voltage curve is a useful tool as it makes it easy to relate the point at which the ac transmission line operates (i.e., the receiver voltage E_R and the load power P) to the sender voltage E_S and the natural load P_0.

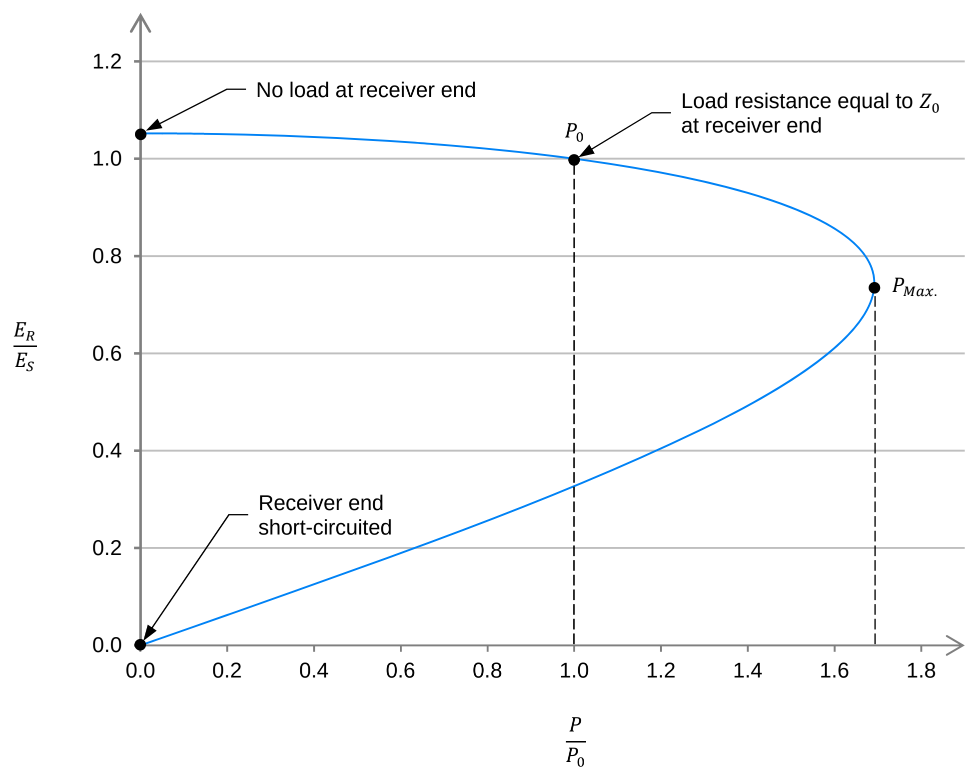


Figure 21. Power-voltage curve of a high-voltage ac transmission line (315 kV ac transmission line shown in the previous figures).

Although any ac transmission line can be operated beyond the natural load P_0 (provided that other limiting factors are respected) as mentioned earlier in this discussion, the power-voltage curve in Figure 21 shows that there is actually a limit ($P_{Max.}$) to the amount of active power that an ac transmission line can convey to a load. This limit is a fundamental limit of any ac transmission line and is not related to other limiting factors like thermal considerations due to line losses. For this particular ac transmission line, the maximal power $P_{Max.}$ is about 1.7 times the natural load P_0 (348.8 MW), which corresponds to about 593 MW.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Calculation of the characteristic impedance Z_0 and natural load P_0 of the ac transmission line
- Power-voltage curve of the ac transmission line

PROCEDURE

WARNING

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 connect a circuit representing one phase of a 350 km (217 miles) 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.

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.

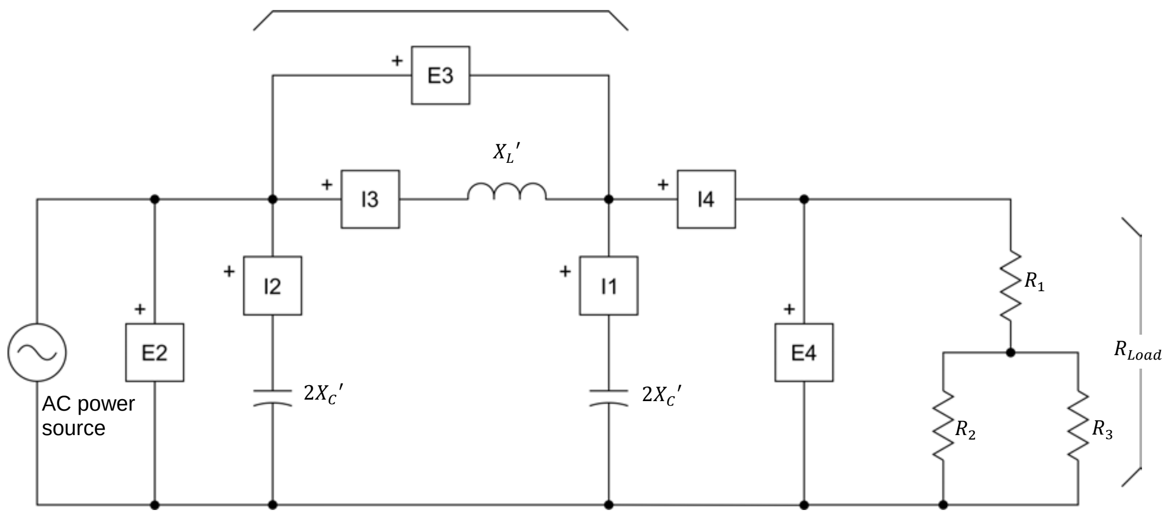
Connect the *Power Input* of the Data Acquisition and Control Interface to a 24 V ac power supply. Turn the 24 V ac power supply on.

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. 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. Set up the circuit shown in Figure 22, which represents one phase of a three-phase power transmission system. The circuit consists of an ac power source supplying power to a resistive load via a 350 km (about 217 miles) ac transmission line represented by its corrected PI equivalent circuit. The inductor of the transmission line is implemented using one phase of the Three-Phase Transmission Line. The capacitor at each end of the line is implemented with one capacitor section (group of 3 parallel-connected capacitors) of the Capacitive Load. The load consists of a series-parallel arrangement of three resistors. Each of these resistors is implemented with one resistor section (group of 3 parallel-connected resistors) of the Resistive Load.



Local ac power network		X_L' (Ω)	$2X_C'$ (Ω)
Voltage (V)	Frequency (Hz)		
120	60	120	1200
220	50	400	4400
240	50	400	4800
220	60	400	4400

Figure 22. 350 km (217 miles) ac transmission line supplying power to a resistive load (one phase only).

6. On the Three-Phase Transmission Line, make sure that the I/O toggle switch is set to the I position, then set the reactance X_L' of the line inductor to the value indicated in the table of Figure 22.

   On the Capacitive Load, set the reactance $2X_C'$ of the capacitor at each end of the line to the value indicated in the table of Figure 22.

   On the Resistive Load, open all switches so that the load resistance R_{Load} is infinite.

Calculation of the characteristic impedance Z_0 and natural load P_0 of the ac transmission line

In this section, you will calculate the characteristic impedance Z_0 and natural load P_0 of the ac transmission line.

7. The corrected PI equivalent circuit of the ac transmission line in Figure 22 represents a 350 km (about 217 miles) line having the fundamental characteristics indicated in Table 5.

Calculate the characteristic impedance Z_0 of the ac transmission line, using Equation (2) in the Discussion and the fundamental characteristics in Table 5 corresponding to your local ac power network voltage and frequency.

____

____

Table 5. Fundamental characteristics of the 350 km (about 217 miles) ac transmission line represented by the PI equivalent circuit in Figure 22.

Local ac power network		Line fundamental characteristics		
Voltage (V)	**Frequency (Hz)**	R	X_L	X_C
120	60	0.022 Ω/km (0.035 Ω/mile)	0.355 Ω/km (0.571 Ω/mile)	213.6 kΩ/km (132.7 kΩ/mile)
220	50	0.022 Ω/km	1.179 Ω/km	782.2 kΩ/km
240	50	0.022 Ω/km	1.177 Ω/km	852.1 kΩ/km
220	60	0.022 Ω/km	1.179 Ω/km	782.2 kΩ/km

The fundamental characteristics X_L and X_C of the 315 km (about 217 miles) ac transmission line shown in Figure 22, at ac power network voltage values of 220 V and 240 V, have been specifically adjusted to take into account the nominal operating power (0.2 kW) of the equipment supplied. Consequently, the fundamental characteristics X_L and X_C of the ac transmission line at ac power network voltage values of 220 V and 240 V differ significantly from those of actual ac transmission lines. However, this does not affect the behavior of the ac transmission line implemented with the equipment supplied, which is very similar to that of actual ac transmission lines.

8. Calculate the natural load P_0 of the ac transmission line, using Equation (3) in the Discussion, the characteristic impedance Z_0 calculated in the previous step, and the nominal value of the receiver voltage E_R (i.e., the local ac power network phase voltage).

____

____

Power-voltage curve of the ac transmission line

In this section, you will set the measuring equipment to measure the parameters of the ac transmission line. You will gradually decrease the resistance of the resistive load connected to the receiver end of the line, and record (for each load resistance value) the sender voltage, receiver voltage, load current and load active power, as well as the reactive power in the inductor of the line and in the capacitors at the sender and receiver ends of the line. You will then use the results to plot the power-voltage curve of the line, and analyze the results.

9. In LVDAC-EMS, open the Metering window, then open the Acquisition Settings dialog box. Set the *Sampling Window* to 8 cycles, then click *OK* to close the dialog box. This provides better accuracy when measuring certain parameters (e.g., reactive power) of the ac transmission line.

In the Metering window, make the required settings in order to measure the sender voltage E_S (input *E2*), the receiver voltage E_R (input *E4*), the load current I_{Load} (input *I4*), the active power P_{Load} supplied to the load [*PQS4(E4,I4)*], the reactive power $Q_{L\,Line}$ in the line [*PQS3(E3,I3)*], the reactive power $Q_{2X_C'\,Sender}$ in the capacitor at the sender end of the line [*PQS2(E2,I2)*], and the reactive power $Q_{2X_C'\,Receiver}$ in the capacitor at the receiver end of the line [*PQS(E4,I1)*]. Set the meters to continuous refresh mode.

10. On the Power Supply, turn the three-phase ac power source on.

11. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the circuit parameters (i.e., the sender voltage E_S, the receiver voltage E_R, the load current I_{Load}, the active power P_{Load}, the reactive power $Q_{L\,Line}$, the reactive power $Q_{2X_C'\,Sender}$, and the reactive power $Q_{2X_C'\,Receiver}$).

Record the circuit parameters in the Data Table.

12. Examine the recorded data. Is the receiver voltage E_R significantly higher than the sender voltage E_S when no load is connected to the receiver end of the line? Explain.

____

____

____

Calculate the reactive power $Q_{C\,Line}$ in the line, using the following equation and the values of $Q_{2X_C'\,Sender}$. and $Q_{2X_C'\,Receiver}$ recorded in the Data Table.

$$Q_{C\,Line} = Q_{2X_C'\,Sender} + Q_{2X_C'\,Receiver}$$

Reactive power $Q_{C\,Line}$ in the line = _______ var

Compare the reactive power $Q_{C\,Line}$ in the line (recorded above) to the measured reactive power $Q_{L\,Line}$ in the line (recorded in the Data Table). Is the line severely unbalanced? Explain.

____

____

____

13. Gradually increase the load at the receiver end of the line. To do so, change the switch settings on the Resistive Load to make the load resistance R_{Load} vary between the maximum and minimum values indicated in Table 6 for your local ac power network, in about 20 steps. For each load resistance value, record the circuit parameters in the Data Table.

Resistor R_1 must be short-circuited to obtain the lowest resistance values.

Table 6. Maximum and minimum values of load resistance R_{Load}.

Local ac power network		Load resistance R_{Load} (Ω)	
Voltage (V)	Frequency (Hz)	Maximum value	Minimum value
120	60	2400	86
220	50	8800	314
240	50	9600	343
220	60	8800	314

14. Short-circuit the receiver end of the line ($R_{Load} = 0\ \Omega$), then record the circuit parameters in the Data Table.

On the Power Supply, turn the three-phase ac power source off.

In the Data Table window, save the recorded data.

15. Transfer the data you saved to a spreadsheet application. Use the values of the receiver voltage E_R and active power P_{Load} to plot the power-voltage curve of the ac transmission line.

The receiver voltage E_R and active power P_{Load} are used to plot the power-voltage curve of the ac transmission line to allow direct comparison with the values of the natural load P_0 and characteristic impedance Z_0 of the ac transmission line calculated earlier in this exercise.

16. Observe the upper portion of the power-voltage curve of the ac transmission line you plotted in the previous step. Does the receiver voltage E_R decrease as the load increases?

❑ Yes ❑ No

Observe that at some point of the power-voltage curve of the ac transmission line, the receiver voltage E_R becomes equal to the sender voltage E_S. Using the circuit parameters recorded in the Data Table, find the amount of active power supplied to the load when the receiver voltage E_R is equal (or virtually equal) to the sender voltage E_S.

Active power $P_{Load}\ (E_R = E_S) =$ _______ W

Compare the amount of active power supplied to the load when the receiver voltage E_R equals the sender voltage E_S (value found above) to the natural load P_0 of the ac transmission line calculated in step 8 of this exercise.

When performing the comparison, the amount of active power supplied to the load when the receiver voltage E_R equals the sender voltage E_S must be multiplied by three because this value is for one phase only.

Is the active power supplied to the load when the receiver voltage E_R equals the sender voltage E_S significantly lower than the natural load P_0 of the ac transmission line? Why?

____

____

____

____

____

17. Using the circuit parameters recorded in the Data Table, calculate the resistance of the load when the amount of active power supplied to the load makes the receiver voltage E_R equal to the sender voltage E_S.

____

____

18. Compare the resistance of the load resistor found in the previous step to the characteristic impedance Z_0 of the ac transmission line calculated in step 7 of this exercise. Is the resistance of the load resistor required to make the receiver voltage E_R equal to the sender voltage E_S significantly higher than the characteristic impedance Z_0 of the ac transmission line? Why?

____

____

____

____

____

19. Using the circuit parameters recorded in the Data Table, determine the amount of reactive power $Q_{L\,Line}$ and reactive power $Q_{C\,Line}$ ($Q_{C\,Line} = Q_{2X_C{}'\,Sender} + Q_{2X_C{}'\,Receiver}$) in the line when the receiver voltage E_R is equal to the sender voltage E_S.

Reactive power $Q_{L\,Line}$ in the line ($E_R = E_S$) = _______ var

Reactive power $Q_{C\,Line}$ in the line ($E_R = E_S$) = _______ var

Does the reactive power $Q_{C\,Line}$ exceed the reactive power $Q_{L\,Line}$ when the receiver voltage E_R is virtually equal to the sender voltage E_S? Explain.

____

____

____

____

____

20. Observe the power-voltage curve of the 350 km (about 217 miles) ac transmission line again. Does it confirm that there is a fundamental limit ($P_{Max.}$) to the amount of active power that an ac transmission line can convey to the load? Explain.

____

____

____

____

21. On the Power Supply, turn the three-phase ac power source off.

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

CONCLUSION

In this exercise, you became familiar with the corrected PI equivalent circuit of a high-voltage ac transmission line. You saw that when a resistive load is connected to the receiver end of a high-voltage ac transmission line, the receiver voltage E_R decreases when the line current increases. You also saw that when no load is connected to the receiver end of the line, the receiver voltage E_R exceeds the sender voltage E_S because the line is largely unbalanced (i.e., $Q_{C\,Line} \gg Q_{L\,Line}$). You learned how to calculate two important characteristics of a high-voltage ac transmission line: the characteristic impedance Z_0 and natural load P_0. You learned that a high-voltage ac transmission line is said to be balanced when the sender voltage E_S and receiver voltage E_R are equal. In that case, the reactive power due to the line inductance is equal to the reactive power due to the line capacitance (assuming a lossless line). Finally, you became familiar with the complete voltage regulation characteristic (power-voltage curve) of a high-voltage ac transmission line. You learned that this curve makes it easy to relate the point at which the line operates to the sender voltage and natural load P_0. You saw that although any ac transmission line can be operated beyond the natural load P_0, there is a fundamental limit ($P_{Max.}$) to the amount of active power that a line can convey to a load.

REVIEW QUESTIONS

1. Complete the following figure representing the corrected PI (π) equivalent circuit of one phase of a high-voltage ac transmission line.

Corrected PI (π) equivalent circuit of a high-voltage ac transmission line (one phase only).

2. What happens to the receiver voltage E_R of a high-voltage ac transmission line connected to a resistive load as the line current I_L increases? What happens if no load is connected to the receiver end of the high-voltage ac transmission line?

3. When is a lossless high-voltage ac transmission line naturally balanced?

4. Explain what the characteristic impedance Z_0 and natural load P_0 of a high-voltage ac transmission line are. Give the equations used to calculate the values of these parameters. Assume that the line is lossless.

5. Describe what the complete voltage regulation characteristic of a high-voltage ac transmission line is. According to this characteristic, can any ac transmission line be operated beyond the natural load P_0 (provided that other limiting factors are respected), but not beyond a certain limit ($P_{Max.}$)? Explain.

Voltage Compensation of a High-Voltage AC Transmission Line Using Switched Shunt Compensation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with voltage compensation of high-voltage ac transmission lines using switched shunt compensation. You will know the relationship between the active power conveyed by a voltage-compensated ac transmission line and the phase shift between the voltages at the receiver and sender ends of the line. You will be able to calculate the maximal transmissible power of a voltage-compensated ac transmission line.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Voltage compensation of an ac transmission line using switched shunt inductors
- Voltage compensation of an ac transmission line operating beyond the line natural load P_0 using switched shunt capacitors
- Maximal transmissible power of a voltage-compensated ac transmission line

DISCUSSION

Voltage compensation of an ac transmission line using switched shunt inductors

Figure 23 shows the power-voltage curve of a high-voltage ac transmission line. This curve indicates that the receiver voltage E_R is equal to the sender voltage E_S only when the active power which the line conveys is equal to the natural load P_0 of the line (a lossless line is assumed here). This situation is possible in any ac power network but it occurs rarely since the amount of active power that the transmission lines in the network must convey depends entirely on the power demand of consumers, which varies greatly depending on the time of the day. Consequently, the receiver voltage E_R is rarely equal to the sender voltage E_S, which is considered the nominal voltage.

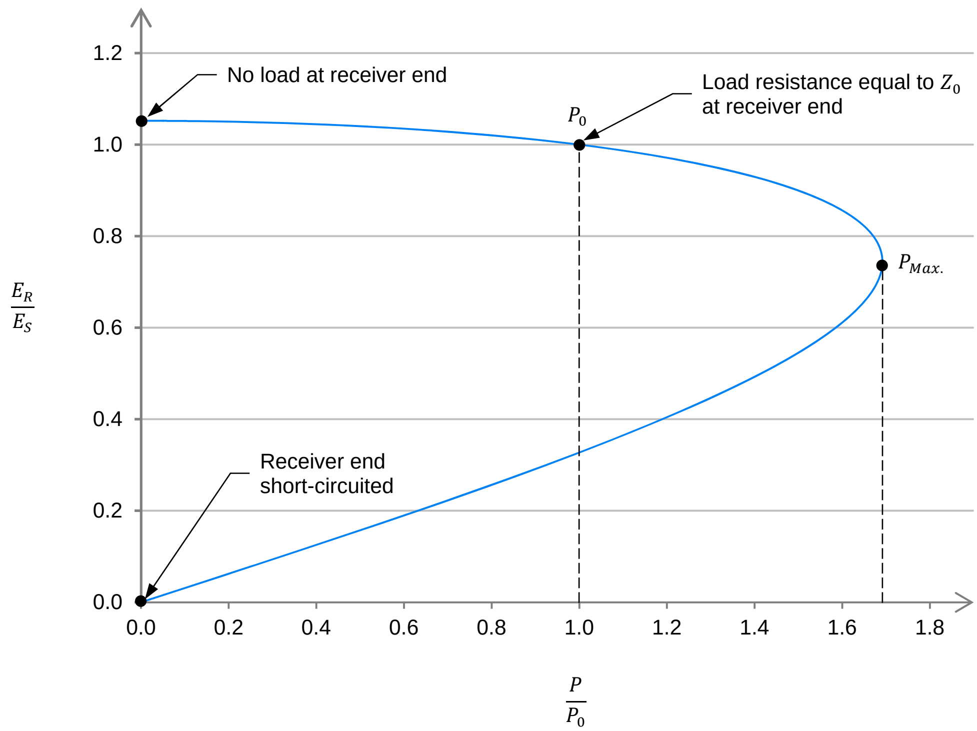


Figure 23. Power-voltage curve of an ac transmission line.

In general, it is not desirable that the receiver voltage E_R differs too much from the nominal value, as this is often a source of problems in any ac power network. Therefore, some means of compensating voltage is required to maintain the receiver voltage E_R equal (or at least as close as possible) to the sender voltage E_S, no matter what amount of active power an ac transmission line has to convey.

For instance, whenever the power demand is less than the natural load P_0 of the line, the receiver voltage E_R systematically exceeds the sender voltage E_S, the worst case occurring when the line operates without load. In this situation, the reactive power $Q_{C\,Line}$ due to the line capacitance largely exceeds the reactive power $Q_{L\,Line}$ due to the line inductance, as mentioned in the discussion of the previous exercise. The unbalance between the reactive power $Q_{C\,Line}$ and reactive power $Q_{L\,Line}$ is what causes the receiver voltage E_R to exceed the sender voltage E_S. This reactive power unbalance can be eliminated by connecting, at each end of the line, a shunt inductor having the same reactance value as the capacitors in the corrected PI equivalent circuit of the line, as Figure 24 shows. In this situation, the ac power source current I_S and the line current I_L are zero, and thus the receiver voltage E_R is equal to the sender voltage E_S.

It is common in ac power networks to set the value of the shunt inductors so that the ac transmission line is perfectly balanced when operating with no load. This ensures that no overvoltage occurs in the event the load is lost.

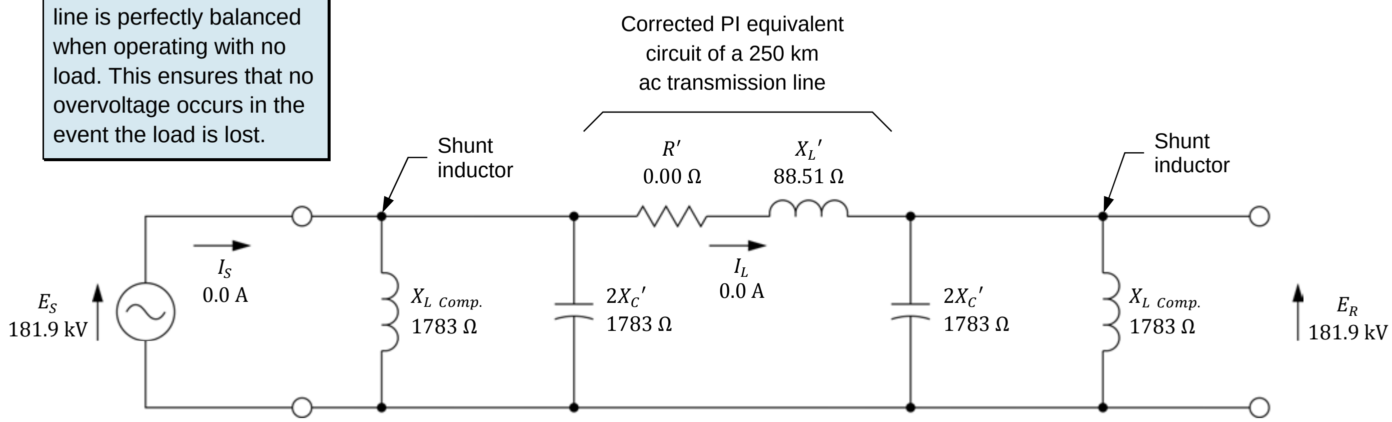


Figure 24. Voltage compensation of a 315 kV ac transmission line using a fixed (permanently-connected) shunt inductor at both ends (one phase is shown).

Figure 25 shows the effect that adding fixed (i.e., permanently-connected) shunt inductors has on the power-voltage curve of the ac transmission line in Figure 24. As expected, the receiver voltage E_R is equal to the sender voltage E_S when no load ($P = 0$) is connected to the line. However, as the load P increases, the receiver voltage E_R decreases and differs more and more from the sender voltage E_S. Therefore, adding a fixed shunt inductor at both ends of the line prevents the receiver voltage E_R from exceeding the sender voltage E_S, but does not prevent the receiver voltage E_R from becoming increasingly lower than the sender voltage E_S as the load P increases. The red shaded area in Figure 25 shows the difference between the receiver voltage E_R and the sender voltage E_S.

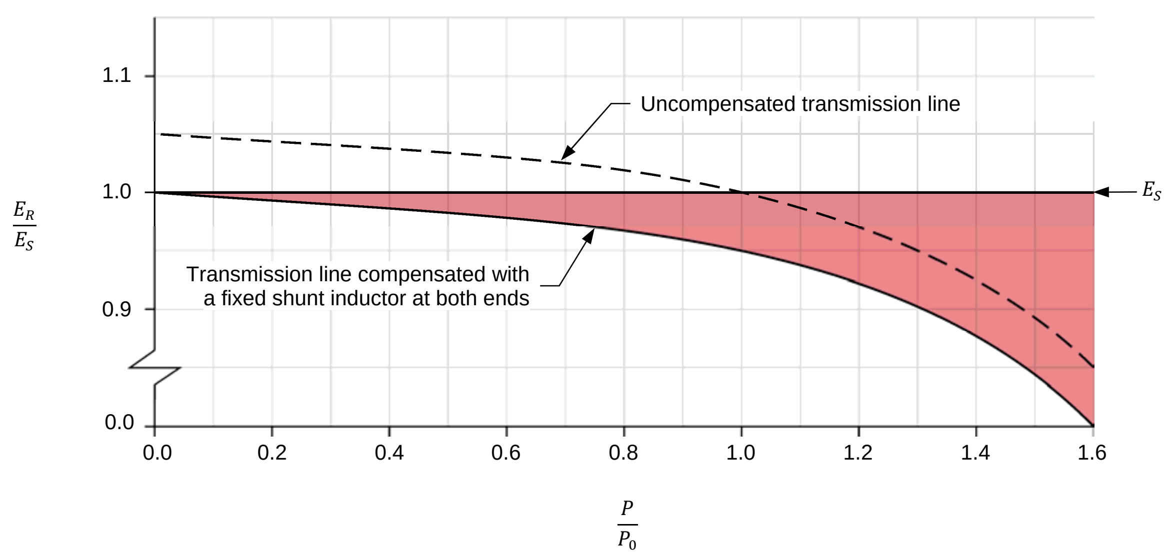


Figure 25. Effect on the power-voltage curve of adding fixed (i.e., permanently-connected) shunt inductors at both ends of the ac transmission line in Figure 24.

One way of reducing the difference between the receiver voltage E_R and the sender voltage E_S as the load increases is to add a switch in series with each shunt inductor. The inductors are switched in (both switches are closed) as long as the receiver voltage E_R remains higher than a certain minimal voltage limit. When the load P increases sufficiently to make the receiver voltage E_R decrease to this minimal voltage limit, the shunt inductors are switched out (both switches are open).

Figure 26 shows the power-voltage curve of the ac transmission line in Figure 24 obtained when voltage compensation is performed using switched shunt inductors. As Figure 26 shows, the difference between the receiver voltage E_R and the sender voltage E_S (see red shaded area in Figure 26) is reduced significantly up to a load P slightly exceeding the natural load P_0 of the ac transmission line (about $1.2\ P_0$ in the present case). Notice that the receiver voltage E_R becomes slightly higher than the sender voltage E_S when the shunt inductors are switched out because the reactive power $Q_{L\ Line}$ is lower than the reactive power $Q_{C\ Line}$ at this load level. The receiver voltage E_R then starts to decrease again as the load P continues to increase. The receiver voltage E_R decreases down to the sender voltage value as the load P increases up to the natural load P_0. The receiver voltage E_R further decreases and reaches the minimal voltage limit once again when the load P increases slightly above the natural load P_0 (value close to $1.2\ P_0$ in the present case).

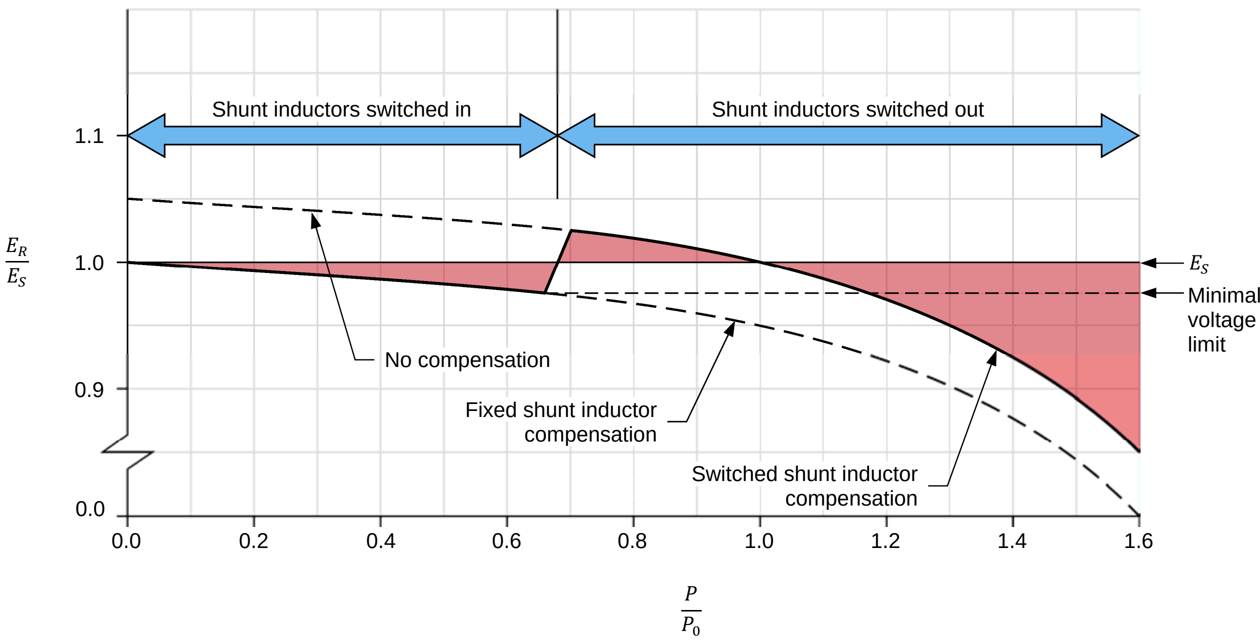


Figure 26. Power-voltage curve of the ac transmission line obtained when voltage compensation is performed using switched shunt inductors.

The shunt inductors are switched out when the load P increases sufficiently to make the receiver voltage E_R decrease to the minimal voltage limit, as previously mentioned. Conversely, when the shunt inductors are switched out and the load P decreases, the receiver voltage E_R increases and eventually exceeds the sender voltage E_S. When the load P decreases sufficiently to make the receiver voltage E_R increase up to a certain maximal voltage limit, the shunt inductors are switched in (both switches are closed), thereby making the receiver voltage E_R decrease a little below the sender voltage E_S. The minimal and maximal voltage limits thus determine the range of variation of the receiver voltage E_R, as Figure 27 shows. Notice that when the load P increases sufficiently to make the receiver voltage E_R decrease to the minimal voltage limit, the inductors are switched out and the receiver voltage E_R increases a little above the sender voltage E_S. This also causes the load P to increase a little. Conversely, when the load P decreases sufficiently to make the receiver voltage E_R increase to the maximal voltage limit, the inductors are switched in and the receiver voltage E_R decreases a little below the sender voltage E_S. This also causes the load P to decrease a little. This causes some hysteresis on the resulting power-voltage curve.

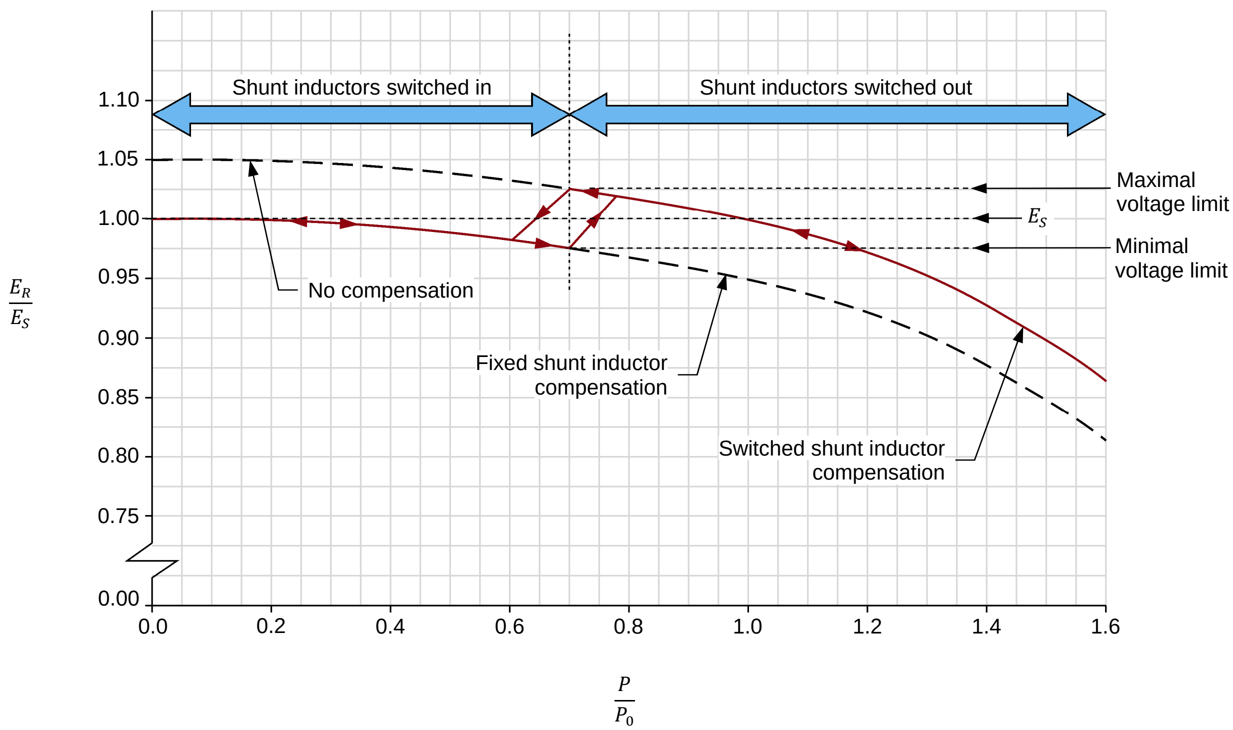


Figure 27. The maximal and minimal voltage limits determine when the shunt inductors are switched in and switched out, respectively.

Voltage compensation using banks of switched shunt inductors is sufficient to maintain the receiver voltage E_R virtually equal to the sender voltage E_S in ac transmission lines that do not have to operate at load levels significantly exceeding the natural load P_0, under normal operating conditions.

To further reduce the variation of the receiver voltage E_R as the load P varies, a bank of switched shunt inductors can be used at each end of the line instead of a single switched shunt inductor, as Figure 28 shows. All shunt inductors are switched in when no load is connected to the ac transmission line. The shunt inductors are switched out one at a time as the load P increases, until they are all removed. This makes the reactance ($X_{L\,Comp.}$) of each shunt inductor (i.e., the reactance of each bank of shunt inductors) increase in steps as the load increases, thereby keeping the receiver voltage E_R close to the sender voltage E_S. The higher the number of shunt inductors in the banks, the smaller the range of variation of the receiver voltage E_R as the load P varies, (i.e., the closer to the sender voltage E_S the receiver voltage E_R is maintained as the load P varies).

The bank of switched shunt inductors at the sender end of the ac transmission line in Figure 28 can be omitted when the ac power source is able to absorb the amount of reactive power required to compensate the line.

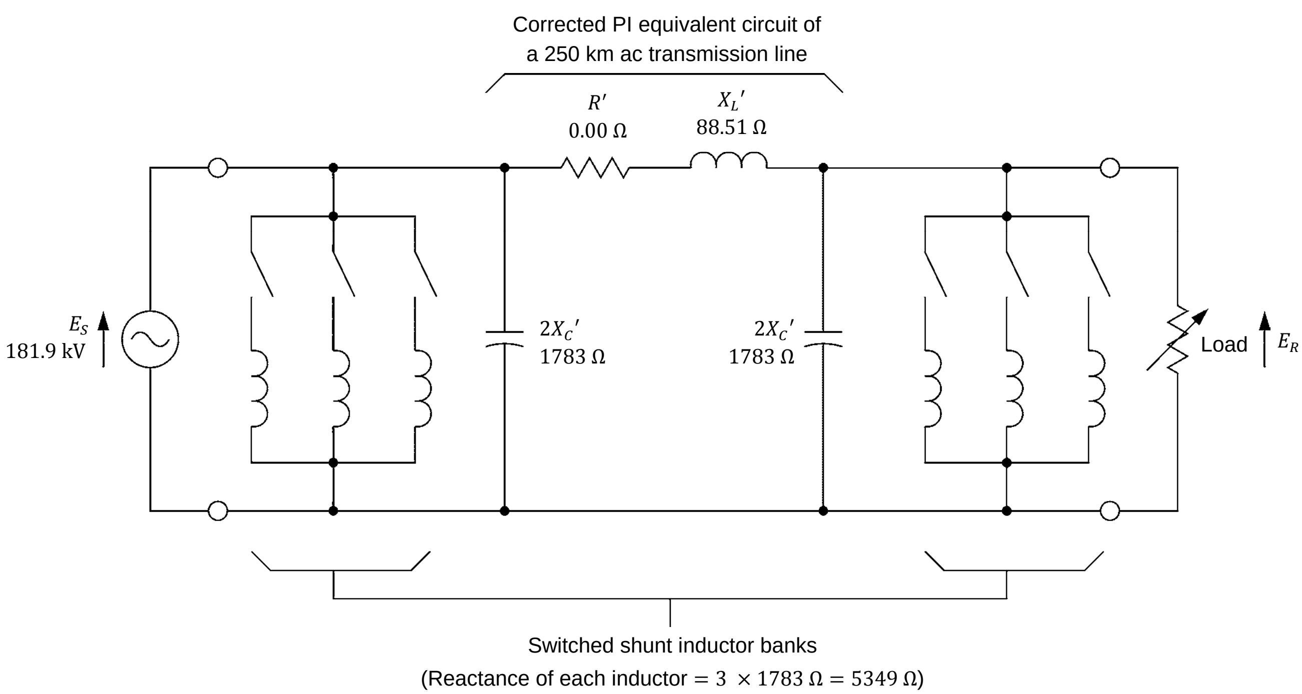


Figure 28. Voltage compensation of a 315 kV ac transmission line using a switched shunt inductor bank at both ends (one phase is shown).

Voltage compensation of an ac transmission line operating beyond the line natural load P_0 using switched shunt capacitors

Switched shunt compensation (SSC) modifies the capacitive reactance XC of an ac transmission line so that the characteristic impedance ($Z_{0\ Comp.}$) of the compensated line is as close as possible to the load resistance. In other words, switched shunt compensation makes an ac transmission line virtually balanced, and voltage E_R virtually equal to voltage E_S, at any load value. Because of this, switched shunt compensation is also referred to as characteristic impedance compensation or surge impedance compensation.

Voltage compensation of an ac transmission line using switched shunt inductors allows the receiver voltage E_R to be maintained virtually equal to the sender voltage E_S up to a load slightly exceeding the natural load P_0 of the line, as discussed in the previous section. At this load level, all shunt inductors are switched out, the receiver voltage E_R is equal to the minimal voltage limit, and the reactive power $Q_{L\ Line}$ due to the line inductance slightly exceeds the reactive power $Q_{C\ Line}$ due to the line capacitance. When the load P increases beyond this load level, the unbalance toward the reactive power $Q_{L\ Line}$ continues to increase and thus the receiver voltage E_R continues to decrease and becomes lower than the minimal voltage limit. To prevent the receiver voltage E_R from decreasing too much when the load P goes well beyond the natural load P_0, a bank of switched shunt capacitors can be added at each end of the ac transmission line, as Figure 29 shows.

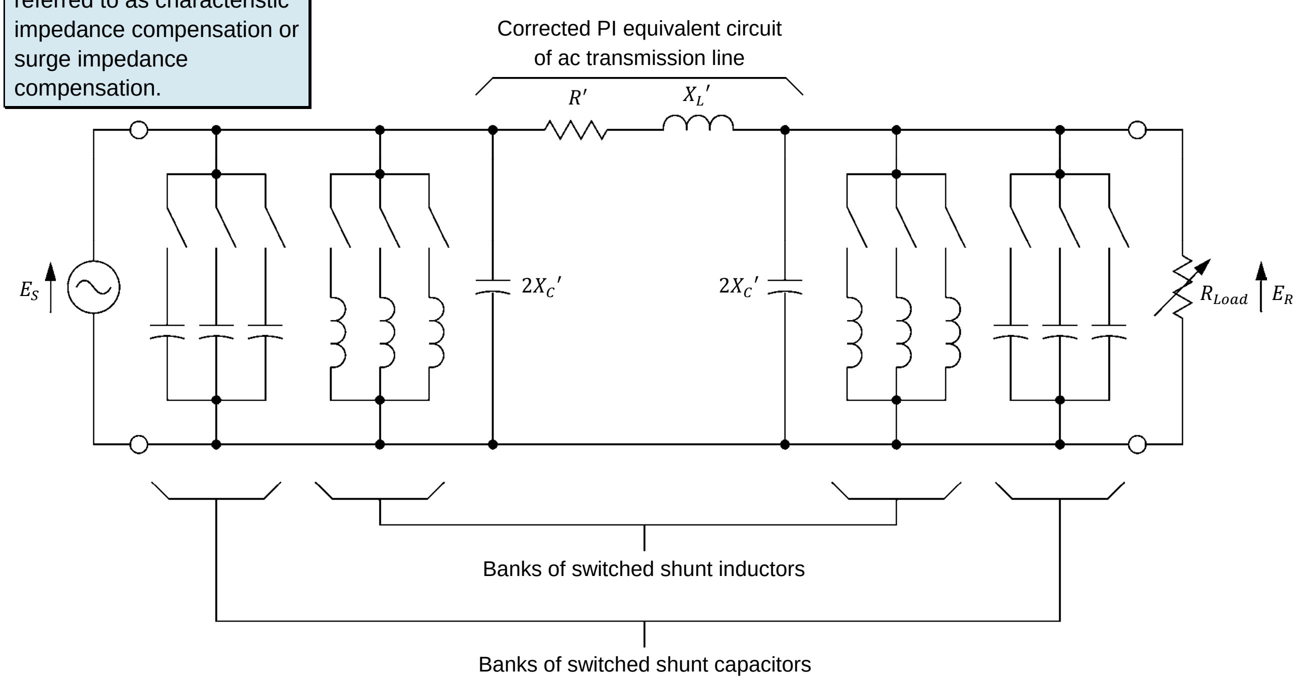


Figure 29. Switched shunt compensation of an ac transmission line using banks of switched inductors and switched capacitors. One phase of the ac transmission line is shown.

Figure 30. Shunt inductor (three-phase unit) used for voltage compensation of a high-voltage ac transmission line. Each long arm on the top of the unit shown in the picture is an insulator providing access to one end of an inductor (©Siemens AG 2014, all rights reserved).

Figure 31. Bank of shunt capacitors used to compensate the voltage at the receiver end of a high-voltage ac transmission line.

Maximal transmissible power of a voltage-compensated ac transmission line

The amount of active power $P_{(Comp.)}$ that is transmitted by a voltage-compensated ac transmission line can be calculated using Equation (4).

$$P_{(Comp.)} = 3\left(\frac{E_S\,E_R}{X_L{}'}\sin\delta\right) \tag{4}$$

where E_S is the phase voltage at the sender end of the voltage-compensated ac transmission line, expressed in volts (V).

E_R is the phase voltage at the receiver end of the voltage-compensated ac transmission line, expressed in volts (V).

$X_L{}'$ is the inductive reactance in the corrected PI equivalent circuit of the ac transmission line, expressed in ohms (Ω).

δ is the phase shift between the receiver voltage E_R and sender voltage E_S, the receiver voltage E_R being used as the reference voltage phasor [i.e., phase shift δ = phase angle E_S − phase angle E_R, expressed in degrees (°)].

Equation (4) shows that when the sender voltage E_S and receiver voltage E_R are held constant, which is usually the case when an ac transmission line is properly compensated, the active power $P_{(Comp.)}$ conveyed by the line is a function of the phase shift δ only since the inductive reactance $X_L{}'$ of the line is a constant. Figure 32 shows the relationship between the active power $P_{(Comp.)}$ and the phase shift δ in this situation. Notice that the relationship is a plot of the phase shift δ as a function of the active power $P_{(Comp.)}$ because in actual ac power networks, it is the amount of active power transmitted by the line that determines the phase shift δ.

As Figure 32 shows, the active power $P_{(Comp.)}$ increases from 0 to a maximal value $P_{Max.\ (Comp.)}$ when the phase shift δ passes from 0° to 90° as $\sin\delta$ passes from 0 to 1 (maximal value). Conversely, the active power $P_{(Comp.)}$ decreases from the maximal value $P_{Max.\ (Comp.)}$ to 0 when the phase shift δ passes from 90° to 180° as $\sin\delta$ passes from 1 to 0. Consequently, the maximal amount of active power $P_{Max.\ (Comp.)}$ which a voltage-compensated ac transmission line can convey is given by Equation (5).

$$P_{Max.\ (Comp.)} = 3\,\frac{E_S\,E_R}{X_L{}'} \tag{5}$$

where E_S is the phase voltage at the sender end of the voltage-compensated ac transmission line, expressed in volts (V).

E_R is the phase voltage at the receiver end of the voltage-compensated ac transmission line, expressed in volts (V).

$X_L{}'$ is the inductive reactance in the corrected PI equivalent circuit of the ac transmission line, expressed in ohms (Ω).

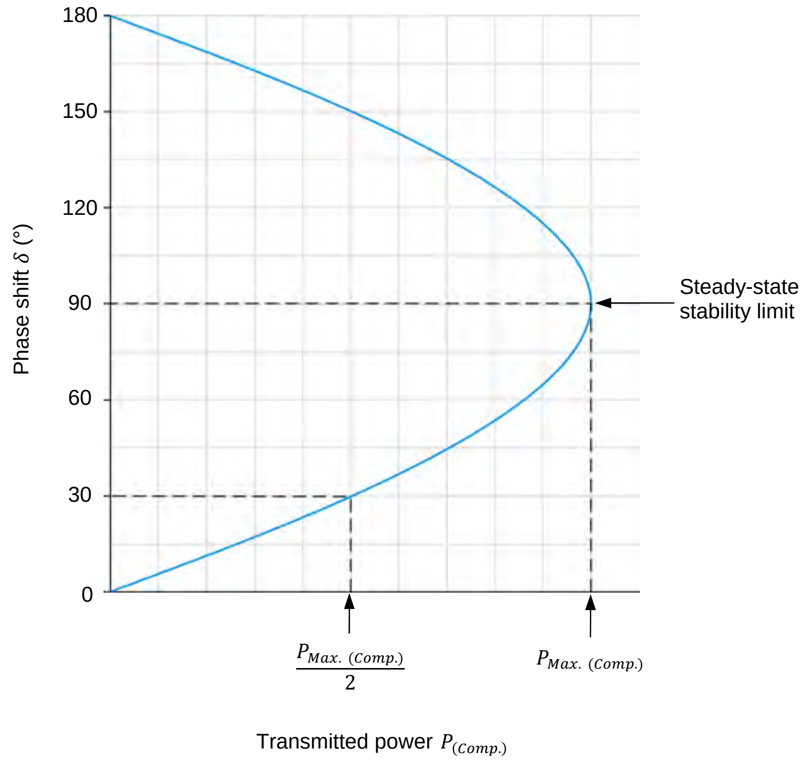


Figure 32. Phase shift δ between the sender voltage and receiver voltage as a function of the active power $P_{(Comp.)}$ transmitted by a voltage-compensated line.

Under normal operating conditions, the amount of active power $P_{(Comp.)}$ which any voltage-compensated ac transmission line conveys is controlled so that the phase shift δ remains below 90°. This is required to maintain stable operation of the ac transmission line. It is even common in ac power networks to limit the amount of active power $P_{(Comp.)}$ which any ac transmission line conveys so that the phase shift δ never exceeds 30°. This gives a safety margin of 100%, i.e., if a transmission line fails, the active power it conveys can all be transferred to another transmission line without causing the phase shift δ to exceed 90°.

Procedure Outline

The Procedure is divided into the following sections:

- Set up and connections
- Voltage compensation of an ac transmission line using a single switched shunt inductor
- Voltage compensation of an ac transmission line using switched shunt compensation

Procedure

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 connect a circuit representing one phase of a 350 km (217 miles) ac transmission line. You will then set the measuring equipment to measure the parameters of 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.

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.

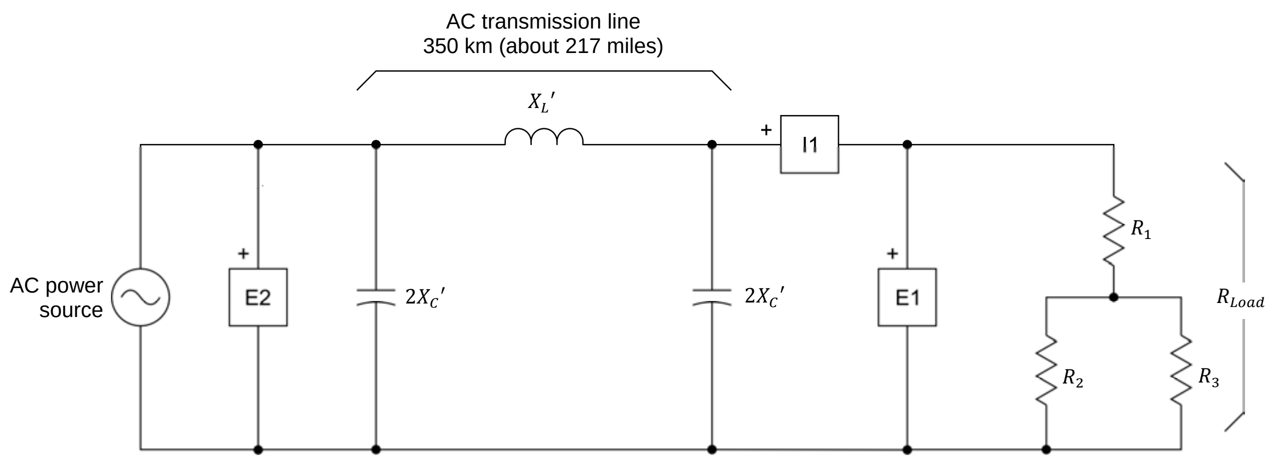
   Connect the *Power Input* of the Data Acquisition and Control Interface to a 24 V ac power supply. Turn the 24 V ac power supply on.

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. 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 circuit shown in Figure 33, which represents one phase of a three-phase power transmission system. The circuit, which is the same as in the previous exercise, consists of an ac power source supplying power to a resistive load via a 350 km (about 217 miles) ac transmission line represented by its corrected PI equivalent circuit. The inductor of the transmission line is implemented using one phase of the Three-Phase Transmission Line. The capacitor at each end of the line is implemented with one capacitor section (group of 3 parallel-connected capacitors) of the Capacitive Load. The load consists of a series-parallel arrangement of three resistors. Each of these resistors is implemented with one resistor section (group of 3 parallel-connected resistors) of the Resistive Load.



Local ac power network		X_L' (Ω)	$2X_C'$ (Ω)	R_{Load} (Ω)
Voltage (V)	Frequency (Hz)			
120	60	120	1200	∞
220	50	400	4400	∞
240	50	400	4800	∞
220	60	400	4400	∞

Figure 33. 350 km (about 217 miles) ac transmission line supplying power to a resistive load (one phase only).

6. On the Three-Phase Transmission Line, make sure that the I/O toggle switch is set to the I position, then set the reactance X_L' of the line inductor to the value indicated in the table of Figure 33.

   On the Capacitive Load, set the reactance $2X_C'$ of the capacitor at each end of the line to the value indicated in the table of Figure 33.

   On the Resistive Load, open all switches so that the load resistance R_{Load} is infinite.

7. The corrected PI equivalent circuit of the ac transmission line in Figure 33 represents a 350 km (about 217 miles) line having the fundamental characteristics indicated in Table 7.

Table 7. Fundamental characteristics of the 350 km (about 217 miles) ac transmission line represented by the PI equivalent circuit in Figure 33.

Local ac power network		Line fundamental characteristics		
Voltage (V)	Frequency (Hz)	R	X_L	X_C
120	60	0.022 Ω/km (0.035 Ω/mile)	0.355 Ω/km (0.571 Ω/mile)	213.6 kΩ/km (132.7 kΩ/mile)
220	50	0.022 Ω/km	1.179 Ω/km	782.2 kΩ/km
240	50	0.022 Ω/km	1.177 Ω/km	852.1 kΩ/km
220	60	0.022 Ω/km	1.179 Ω/km	782.2 kΩ/km

8. In LVDAC-EMS, open the Metering window, then open the Acquisition Settings dialog box. Set the *Sampling Window* to 8 cycles, then click *OK* to close the dialog box. This provides better accuracy when measuring certain parameters of the ac transmission line.

In the Metering window, make the required settings in order to measure the sender voltage E_S (input *E2*), the receiver voltage E_R (input *E1*), the load current I_{Load} (input *I1*), the active power P_{Load} supplied to the load [*PQS1(E1,I1)*], as well as the phase shift δ between the receiver voltage E_R and sender voltage E_S [*PS(E1,E2)*]. Set the meters to continuous refresh mode.

The phase shift δ indicated by the phase shift meter is with respect to the receiver voltage E_R, i.e., it is equal to the phase angle of the sender voltage E_S minus the phase angle of the receiver voltage E_R. Therefore, positive values of phase shift δ indicate that the sender voltage E_S leads the receiver voltage E_R.

Voltage compensation of an ac transmission line using a single switched shunt inductor

In this section, you will connect a shunt inductor to the receiver end of the line to compensate the receiver voltage E_R (without load at the receiver end). You will gradually decrease the resistance of the resistive load connected to the receiver end of the line until the receiver voltage E_R decreases to a certain minimal value. For each load resistance value, you will record the circuit parameters. You will then disconnect the shunt inductor from the receiver end of the line and continue to decrease the resistance of the resistive load and record the circuit parameters. You will use the results to plot the power-voltage curve of the line. You will analyze the results.

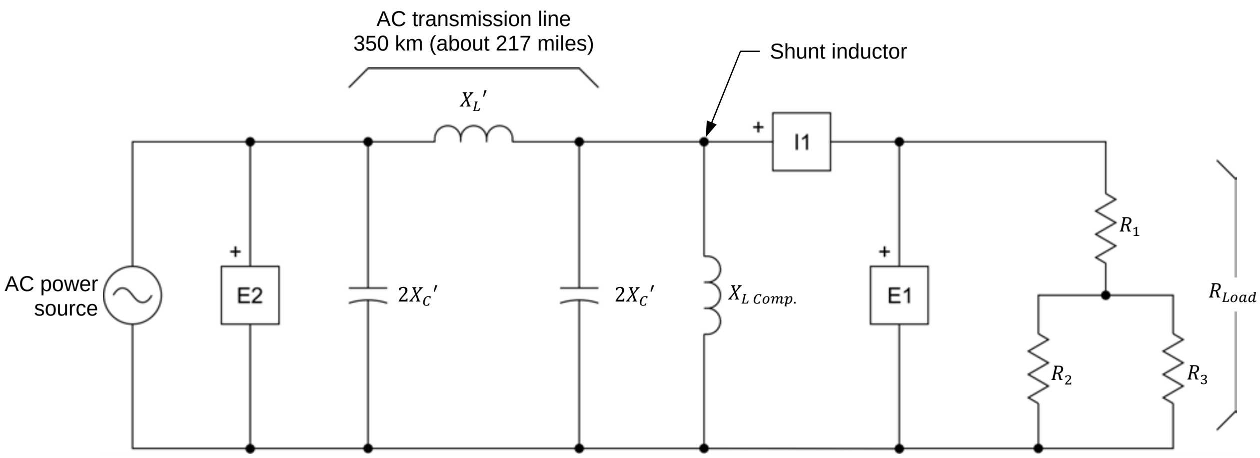
9. On the Power Supply, turn the three-phase ac power source on. Does the receiver voltage E_R exceed the sender voltage E_S significantly? Explain why.

____

____

10. On the Power Supply, turn the three-phase ac power source off. Connect a shunt inductor to the receiver end of the line, as Figure 34 shows. To do so, use one inductor section (group of 3 parallel-connected inductors) of the Inductive Load to implement the shunt inductor. Set the reactance $X_{L\ Comp.}$ of the shunt inductor to the value indicated in Figure 34. Notice that the reactance $X_{L\ Comp.}$ of the shunt inductor is equal to the reactance $2X_C{}'$ of the capacitors in the corrected PI equivalent circuit of the ac transmission line.

To limit the amount of equipment required to perform this exercise, no shunt inductor is used at the sender end of the ac transmission line. This is not problematic because the reactive power required at the sender end of the line for voltage compensation is provided by the ac power source.



Local ac power network		$X_L{}'$ (Ω)	$2X_C{}'$ (Ω)	$X_{L\ Comp.}$ (Ω)	R_{Load} (Ω)
Voltage (V)	Frequency (Hz)				
120	60	120	1200	1200	∞
220	50	400	4400	4400	∞
240	50	400	4800	4800	∞
220	60	400	4400	4400	∞

Figure 34. 350 km (about 217 miles) ac transmission line compensated with a shunt inductor at the receiver end (one phase only).

11. On the Power Supply, turn the three-phase ac power source on. Compare the receiver voltage E_R to the sender voltage E_S. Are they virtually equal? Why?

12. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the circuit parameters, i.e., the sender voltage E_S, the receiver voltage E_R, the load current I_{Load}, the active power P_{Load} supplied to the load, as well as the phase shift δ between the receiver voltage E_R and sender voltage E_S.

Record the circuit parameters in the Data Table.

13. Gradually increase the load at the receiver end of the line until the receiver voltage E_R becomes about 5% lower than the sender voltage E_S (e.g., if the sender voltage E_S is 120 V, the load must be increased until the receiver voltage E_R decreases to about 114 V). To do so, change the switch settings on the Resistive Load to decrease the load resistance R_{Load} in steps, starting with the initial value indicated in Table 8 for your local ac power network. For each load resistance value, record the circuit parameters in the Data Table.

Table 8. Initial value of load resistance R_{Load}.

Local ac power network		Initial value of load resistance R_{Load} (Ω)
Voltage (V)	Frequency (Hz)	
120	60	2400
220	50	8800
240	50	9600
220	60	8800

14. When the receiver voltage E_R is about 5% lower than the sender voltage E_S, disconnect the shunt inductor connected to the receiver end of the ac transmission line by setting the corresponding switch on the Inductive Load to the O (off) position. Record the circuit parameters in the Data Table.

Observe that removing the shunt inductor at this point causes the receiver voltage E_R to increase significantly (it becomes about 5% higher than the sender voltage E_S). Explain why this occurs.

15. Continue to gradually increase the load at the receiver end of the line until the receiver voltage E_R becomes about 15% lower than the sender voltage E_S (e.g., if the sender voltage E_S is 120 V, the load must be increased until the receiver voltage E_R decreases to about 102 V). To do so, change the switch settings on the Resistive Load so as to decrease the load resistance R_{Load} in steps. For each load resistance value, record the circuit parameters in the Data Table.

At some point, you will have to short-circuit resistor R_1 to continue to increase the load.

16. On the Power Supply, turn the three-phase ac power source off.

In the Data Table, save the recorded data.

17. Transfer the data you saved to a spreadsheet application. Use the values of the receiver voltage E_R and active power P_{Load} to plot the power-voltage curve of the ac transmission line when a single switched shunt inductor is used for voltage compensation. Also, use the recorded values to plot, in the same graph, a curve of the sender voltage E_S as a function of the active power P_{Load}. This graph makes it easy to relate the receiver voltage E_R to the sender voltage E_S.

18. Using the circuit parameters recorded in the Data Table, find the amount of active power supplied to the load when the receiver voltage E_R is equal (or virtually equal) to the sender voltage E_S and the shunt inductor is disconnected (operating point at which the line is naturally balanced). This amount of power is considered the actual natural load $P_{0\ Actual}$ of the ac transmission line since it accounts for the resistance of the line.

Actual natural load $P_{0\ Actual}$ = _______ W

19. Is using a single switched shunt inductor sufficient to maintain the receiver voltage E_R fairly close to the sender voltage E_S up to a load power slightly exceeding the actual natural load $P_{0\ Actual}$ of the ac transmission line? Explain.

____

____

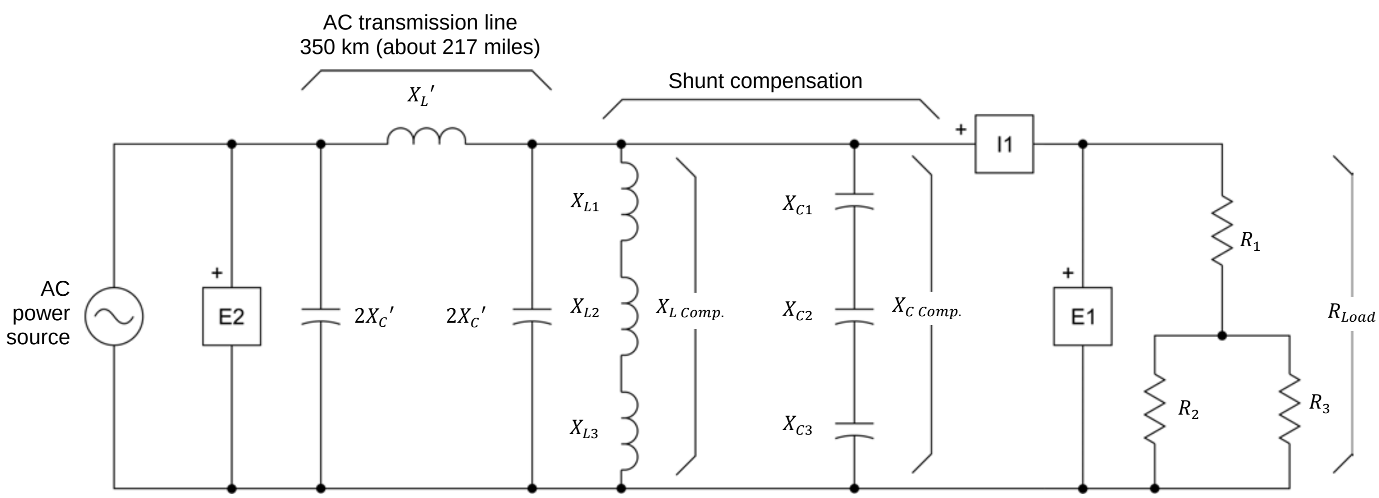
____

Voltage compensation of an ac transmission line using switched shunt compensation

In this section, you will connect a bank of switched shunt inductors and a bank of switched shunt capacitors to the receiver end of the line. You will first switch all shunt inductors in, and keep all shunt capacitors switched out. You will gradually decrease the resistance of the resistive load connected to the receiver end of the line by steps, and adjust the switched shunt compensation (by switching shunt inductors out then switching shunt capacitors in) so that the receiver voltage E_R remains close to the sender voltage E_S. While doing so, you will record the circuit parameters for each load resistance value. You will use the results to plot the power-voltage curve of the line. You will also plot a curve of the phase shift δ between voltages E_R and E_S versus the load power P_{Load}. You will analyze the results.

20. Connect a bank of switched shunt inductors and a bank of switched shunt capacitors to the receiver end of the line, as shown in Figure 35. Connect the three sections of inductors of the Inductive Load in series to implement inductors X_{L1}, X_{L2}, and X_{L3} in the bank of switched shunt inductors. Connect the three sections of capacitors of a second Capacitive Load in series to implement capacitors X_{C1}, X_{C2}, and X_{C3} in the bank of switched shunt capacitors. The inductive reactance $X_{L\ Comp.}$ of the bank of switched shunt inductors and the capacitive reactance $X_{C\ Comp.}$ of the bank of switched shunt capacitors in this circuit can be changed to implement switched shunt compensation.

To obtain the maximal value of inductive reactance $X_{L\ Comp.}$ ($3 \times 2X_C{}'$) required for the switched shunt compensation using the sections of inductors available in the Inductive Load, the inductors (X_{L1}, X_{L2}, and X_{L3}) are connected in series, not in parallel, as is usual when compensating an actual ac transmission line. However, the reactance $X_{L\ Comp.}$ of the bank of switched shunt inductors implemented with the series-connected inductors can be varied in the same way as if a bank of three parallel-connected switched shunt inductors (each inductor having a reactance value of $3 \times 2X_C{}'$) were used, as shown in Figure 28 of the Discussion. The same approach is used to implement the bank of switched shunt capacitors.



Local ac power network		$X_L{}'$ (Ω)	$2X_C{}'$ (Ω)	$X_{L\ Comp.}$ (Ω)	$X_{C\ Comp.}$ (Ω)	R_{Load} (Ω)
Voltage (V)	Frequency (Hz)					
120	60	120	1200	1200	∞	∞
220	50	400	4400	4400	∞	∞
240	50	400	4800	4800	∞	∞
220	60	400	4400	4400	∞	∞

Figure 35. 350 km (about 217 miles) ac transmission line compensated with a bank of switched shunt inductors and a bank of switched shunt capacitors at the receiver end (one phase only).

21. On the Three-Phase Transmission Line, make sure that the reactance $X_L{}'$ of the line inductor is set to the value indicated in the table of Figure 35.

On the Capacitive Load used to implement the ac transmission line, make sure that the reactance $2X_C{}'$ of the capacitor at each end of the line is set to the value indicated in the table of Figure 35.

On the Inductive Load, set the reactance $X_{L\ Comp.}$ of the bank of switched shunt inductors to the value indicated in the table of Figure 35.

On the Capacitive Load used to implement the bank of switched shunt capacitors, open all switches to set the reactance $X_{C\ Comp.}$ of the shunt capacitor to infinite. This is equivalent to switching all shunt capacitors out.

On the Resistive Load, open all switches so that the load resistance R_{Load} is infinite.

22. In the Data Table, clear the recorded data without clearing the record settings.

On the Power Supply, turn the three-phase ac power source on, then record the circuit parameters in the Data Table.

23. Gradually increase the load at the receiver end of the line until the receiver voltage E_R becomes about 1.7% lower than the sender voltage E_S (e.g., if the sender voltage is 240 V, the load must be increased until the receiver voltage E_R decreases to about 236 V). To do so, change the switch settings on the Resistive Load to decrease the load resistance R_{Load} in steps, starting with the initial value indicated in Table 9 for your local ac power network. For each load resistance value, record the circuit parameters in the Data Table.

Table 9. Initial value of load resistance R_{Load}.

Local ac power network		Initial value of load resistance R_{Load} (Ω)
Voltage (V)	Frequency (Hz)	
120	60	2400
220	50	8800
240	50	9600
220	60	8800

24. When the receiver voltage E_R is about 1.7% lower than the sender voltage E_S, increase the reactance $X_{L\ Comp.}$ of the bank of switched shunt inductors to the value given in Table 10 for your local ac power network by changing the switch settings on the Inductive Load. Record the circuit parameters in the Data Table.

Table 10. Value of reactance $X_{L\,Comp.}$.

Local ac power network		Value of reactance $X_{L\,Comp.}$ (Ω)
Voltage (V)	Frequency (Hz)	
120	60	1800
220	50	6600
240	50	7200
220	60	6600

25. Continue to gradually increase the load at the receiver end of the line until the receiver voltage E_R once again becomes about 1.7% lower than the sender voltage E_S. To do so, change the switch settings on the Resistive Load so as to decrease the load resistance R_L in steps. For each load resistance value, record the circuit parameters in the Data Table.

26. When the receiver voltage E_R is once again about 1.7% lower than the sender voltage E_S, increase the reactance $X_{L\,Comp.}$ of the bank of switched shunt inductors to the value given in Table 11 for your local ac power network by changing the switch settings on the Inductive Load. Record the circuit parameters in the Data Table.

Table 11. Value of reactance $X_{L\,Comp.}$.

Local ac power network		Value of reactance $X_{L\,Comp.}$ (Ω)
Voltage (V)	Frequency (Hz)	
120	60	3600
220	50	13 200
240	50	14 400
220	60	13 200

27. Continue to gradually increase the load at the receiver end of the line until the receiver voltage E_R once again becomes about 1.7% lower than the sender voltage E_S. To do so, change the switch settings on the Resistive Load so as to decrease the load resistance R_{Load} in steps. For each load resistance value, record the circuit parameters in the Data Table.

28. When the receiver voltage E_R is once again about 1.7% lower than the sender voltage E_S, disconnect the shunt inductor connected to the receiver end of the ac transmission line by setting all switches on the Inductive Load to the O (off) position. Record the circuit parameters in the Data Table.

29. Continue to gradually increase the load at the receiver end of the line until the receiver voltage E_R once again becomes about 1.7% lower than the sender voltage E_S. To do so, change the switch settings on the Resistive Load so as to decrease the load resistance R_{Load} in steps. For each load resistance value, record the circuit parameters in the Data Table.

30. When the receiver voltage E_R is once again about 1.7% lower than the sender voltage E_S, set the reactance $X_{C\ Comp.}$ of the bank of switched shunt capacitors to the value indicated in Table 12 by making the proper switch settings on the Capacitive Load module used to implement the switched shunt capacitors. Record the circuit parameters in the Data Table.

Table 12. Value of reactance $X_{C\ Comp.}$.

Local ac power network		Value of reactance $X_{C\ Comp.}$ (Ω)
Voltage (V)	Frequency (Hz)	
120	60	3600
220	50	13 200
240	50	14 400
220	60	13 200

31. Continue to gradually increase the load at the receiver end of the line until the receiver voltage E_R once again becomes about 1.7% lower than the sender voltage E_S. To do so, change the switch settings on the Resistive Load so as to decrease the load resistance R_{Load} in steps. For each load resistance value, record the circuit parameters in the Data Table.

You may have to short-circuit resistor R_1 using a safety banana plug lead to increase the load to the value required.

32. When the receiver voltage E_R is once again about 1.7% lower than the sender voltage E_S, decrease the reactance $X_{C\ Comp.}$ of the bank of switched shunt capacitors to the value indicated in Table 13 by changing the switch settings on the Capacitive Load module used to implement the switched shunt capacitors. Record the circuit parameters in the Data Table.

Table 13. Value of reactance $X_{C\ Comp.}$.

Local ac power network		Value of reactance $X_{C\ Comp.}$ (Ω)
Voltage (V)	Frequency (Hz)	
120	60	1800
220	50	6600
240	50	7200
220	60	6600

33. Continue to gradually increase the load at the receiver end of the line until the receiver voltage E_R once again becomes about 1.7% lower than the sender voltage E_S. To do so, change the switch settings on the Resistive Load so as to decrease the load resistance R_{Load} in steps. For each load resistance value, record the circuit parameters in the Data Table.

You may have to short-circuit resistor R_1 using a safety banana plug lead to increase the load to the value required.

34. When the receiver voltage E_R is once again about 1.7% lower than the sender voltage E_S, decrease the reactance $X_{C\ Comp.}$ of the bank of switched shunt capacitors to the value indicated in Table 14 by changing the switch settings on the Capacitive Load module used to implement the switched shunt capacitors. Record the circuit parameters in the Data Table.

Table 14. Value of reactance $X_{C\ Comp.}$.

Local ac power network		Value of reactance $X_{C\ Comp.}$ (Ω)
Voltage (V)	Frequency (Hz)	
120	60	1200
220	50	4400
240	50	4800
220	60	4400

35. Continue to gradually increase the load at the receiver end of the line until the receiver voltage E_R once again becomes about 1.7% lower than the sender voltage E_S. To do so, change the switch settings on the Resistive Load so as to decrease the load resistance R_{Load} in steps. For each load resistance value, record the circuit parameters in the Data Table.

You may have to short-circuit resistor R_1 using a safety banana plug lead to increase the load to the value required.

36. On the Power Supply, turn the three-phase ac power source off.

In the Data Table, save the recorded data.

37. Transfer the data you saved to a spreadsheet application. Use the values of the receiver voltage E_R and active power P_{Load} to plot the power-voltage curve of the ac transmission line obtained when switched shunt compensation (inductive and capacitive) is used for voltage compensation. Also, use the recorded values to plot, in the same graph, a curve of the sender voltage E_S as a function of the active power P_{Load}. This graph makes it easy to relate the receiver voltage E_R to the sender voltage E_S.

38. Compare the power-voltage curve of the ac transmission line obtained with switched shunt compensation (inductive and capacitive) to that obtained when a single switched shunt inductor is used for voltage compensation (see step 17). Does using banks of multiple shunt reactive components to implement switched shunt compensation reduce the variation of the receiver voltage E_R as the load power varies? Explain briefly.

____

____

____

____

39. Observe the power-voltage curve of the ac transmission line obtained with switched shunt compensation (inductive and capacitive). Does using switched shunt compensation (inductive and capacitive) allow the receiver voltage E_R to be maintained close to the sender voltage E_S up to a load power significantly exceeding the actual natural load $P_{0\ Actual}$ (recorded in step 18) of the ac transmission line?

____

____

____

40. Use the values recorded in the Data Table to plot a curve of the phase shift δ between the receiver voltage E_R and the sender voltage E_S as a function of the active power P_{Load} that is obtained when the ac transmission line is voltage compensated using switched shunt compensation (inductive and capacitive).

41. Does the obtained curve confirm that the phase shift δ between the receiver voltage E_R and the sender voltage E_S increases as the active power supplied to the load increases?

❑ Yes ❑ No

42. Do the values of the sender voltage E_S, receiver voltage E_R, active power P_{Load}, and phase shift δ recorded in the Data Table confirm the equation below (same as the one given in the discussion)? Explain.

$$P_{(Comp.)} = 3\left(\frac{E_S\,E_R}{X_L{}'}\sin\delta\right)$$

____

____

____

____

____

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

Conclusion

In this exercise, you became familiar with voltage compensation of high-voltage ac transmission lines using shunt compensation. You learned that ac transmission lines compensated with switched shunt inductor banks can maintain the receiver voltage E_R virtually equal to the sender voltage E_S up to load levels slightly exceeding the natural load P_0 of the line. You learned that when ac transmission lines have to operate at load levels well beyond the natural load P_0, banks of switched shunt capacitors are added to prevent the receiver voltage E_R from decreasing and becoming lower than the minimal voltage limit. You became familiar with the relationship between the active power conveyed by a voltage-compensated ac transmission line and the phase shift δ between the receiver voltage E_R and sender voltage E_S. You learned that under normal operating conditions, the amount of active power $P_{(Comp.)}$ which any voltage-compensated ac transmission line conveys is controlled so that the phase shift δ remains below 90°, to maintain stable operation of the line. Finally, you learned that it is common practice, in ac power networks, to limit the amount of active power $P_{(Comp.)}$ which any ac transmission line conveys so that the phase shift δ never exceeds 30°. This gives a safety margin of 100%, so that if any transmission line fails, the active power it conveys can all be transferred to another transmission line without causing the phase shift δ to exceed 90°.

Review Questions

1. Describe voltage compensation of a high-voltage ac transmission line using a bank of switched shunt inductors at each end of the line.

____

____

____

____

____

____

2. Which type of voltage compensation is sufficient to properly compensate the receiver voltage E_R in a high-voltage ac transmission line that operates at load levels up to the natural load P_0 of the line?

3. Which type of voltage compensation is used to properly compensate the receiver voltage E_R in a high-voltage ac transmission line that can operate at load levels well beyond the natural load P_0 of the line?

4. Describe voltage compensation of a high-voltage ac transmission line operating at load levels significantly exceeding the natural load P_0 of the line. Assume that the line is voltage compensated using switched compensation (inductive and capacitive).

5. How does the phase shift δ between the receiver voltage E_R and sender voltage E_S vary as a function of the amount of active power $P_{(Comp.)}$ transmitted by a voltage-compensated ac transmission line?

Effect of Length on the Characteristics and Voltage Compensation of a High-Voltage AC Transmission Line

EXERCISE OBJECTIVE

When you have completed this exercise, you will know the effects that the length of a high-voltage ac transmission line has on the corrected PI equivalent circuit, characteristic impedance Z_0, natural load P_0, and power-voltage curve of the line. You will also know the effect that the length of a high-voltage ac transmission line has on the voltage profile along the line when it is voltage-compensated at both ends.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Effect of the line length on the corrected PI equivalent circuit of an ac transmission line
- Effect of the line length on the characteristic impedance Z_0 and natural load P_0 of an ac transmission line
- Effect of the line length on the power-voltage curve of an ac transmission line
- Effect of the line length on the voltage profile along a voltage-compensated ac transmission line
- Measuring the voltage in the middle of a long ac transmission line emulated in the lab

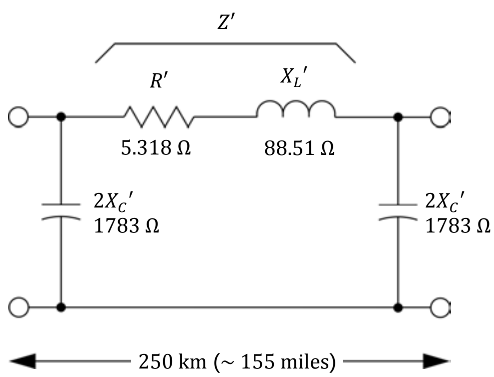
DISCUSSION

Effect of the line length on the corrected PI equivalent circuit of an ac transmission line

Figure 36 shows the fundamental characteristics of a high-voltage ac transmission line and the corrected PI equivalent circuit (one phase only) of this line for a length of 250 km (about 155 miles).

AC TRANSMISSION LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 0.36\ \Omega/\text{km}$	$(0.58\ \Omega/\text{mile})$
Capacitive reactance $X_C = 225\ \text{k}\Omega/\text{km}$	$(140\ \text{k}\Omega/\text{mile})$

(a) AC transmission line fundamental characteristics



(b) Corrected PI equivalent circuit of the transmission line

Figure 36. Fundamental characteristics of a high-voltage (315 kV) ac transmission line and corrected PI equivalent circuit (one phase only) of this high-voltage ac transmission line for a length of 250 km (about 155 miles).

Figure 37 shows the corrected PI equivalent circuit (one phase only) of a high-voltage ac transmission line having the same fundamental characteristics but twice the length, i.e., 500 km (about 310 miles).

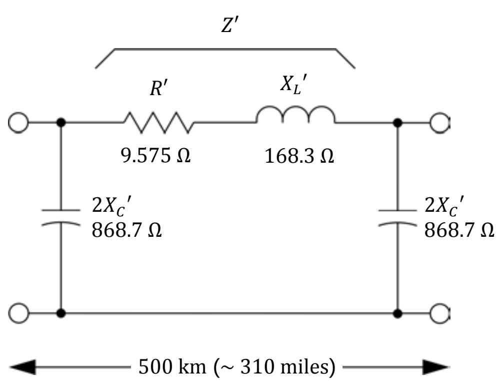


Figure 37. Corrected PI equivalent circuit (one phase only) of a high-voltage (315 kV) ac transmission line having twice the length (500 km or about 310 miles) of the line is shown in Figure 36.

Comparing the corrected PI equivalent circuits of these two transmission lines shows that the resistance R' and inductive reactance X_L' both increase with the line length, while the capacitive reactance $2X_C'$ decreases with the line length.

Effect of the line length on the characteristic impedance Z_0 and natural load P_0 of an ac transmission line

Although the length of an ac transmission line directly affects the value of the components in the corrected PI equivalent circuit of the line, it has no effect on the fundamental characteristics of the line, i.e., the resistance R, inductive reactance X_L, and capacitive reactance X_C of the line per unit of length. Consequently, the characteristic impedance Z_0 of an ac transmission line, which is equal to $\sqrt{X_L \cdot X_C}$, is independent of the line length. Furthermore, the natural load P_0 of an ac transmission line is also independent of the line length since it depends on the characteristic impedance Z_0 and the receiver voltage E_R, as indicated by Equation (6).

$$P_0 = \frac{{E_R}^2}{Z_0} \cdot 3 \qquad (6)$$

As mentioned in Exercise 2, the equation for calculating the characteristic impedance Z_0 is based on the assumption that the ac transmission line is lossless (i.e., the line resistance is zero). In actual ac transmission lines, however, the resistance is not zero. Thus, the load impedance actually required to make the receiver voltage E_R equal to the sender voltage E_S is higher than the characteristic impedance Z_0 calculated with the equation. Consequently, the active power actually supplied to the load is lower than the natural load P_0 calculated with Equation (6). The higher the resistance of the ac transmission line per unit of distance (i.e., per km or per mile), the greater the difference between the actual values and calculated values.

Effect of the line length on the power-voltage curve of an ac transmission line

The power-voltage curves shown in Figure 38 are based on the assumption that the ac transmission lines are lossless ($R = 0\ \Omega$). This has no impact on the observations made using these curves.

Figure 38 shows the power-voltage curves of the 250 km and 500 km (about 155 miles and 310 miles) high-voltage (315 kV) ac transmission lines shown in Figure 36 and Figure 37.

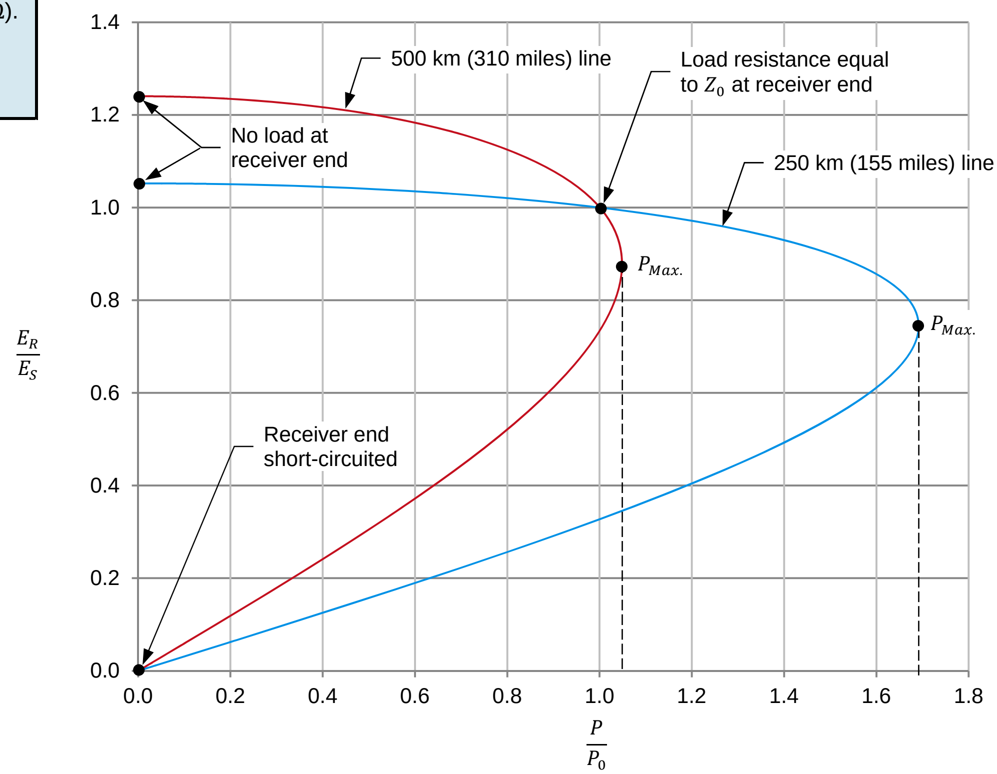


Figure 38. Power-voltage curves of the 250 km and 500 km (about 155 miles and 310 miles) high-voltage (315 kV) ac transmission lines in Figure 36 and Figure 37.

Comparing the power-voltage curves of these two ac transmission lines allows the following generic observations to be made:

1. Increasing the length of an ac transmission line makes the voltage obtained at the receiver end of the line increase significantly when the line is left open. For instance, in this particular case, the voltage at the receiver end of the line passes from $1.05E_S$ to $1.24E_S$ when the line length increases from 250 km to 500 km (about 155 miles to 310 miles).

2. Increasing the length of an ac transmission line makes the maximal amount of active power $P_{Max.}$ that the line can convey to a load decrease significantly. For instance, in this particular case, the maximal amount of active power that the line can convey passes from about $1.7P_0$ to about $1.05P_0$ when the line length increases from 250 km to 500 km (about 155 miles to 310 miles).

3. Increasing the length of an ac transmission line makes the variation of the receiver voltage E_R produced by a given change in the amount of active power P conveyed by the line increase significantly. For instance, in this particular case, the receiver voltage E_R of the 250 km (about 155 miles) line passes from $1.02E_S$ to $1.00E_S$ when the active power P changes from $0.80P_0$ to $1.00P_0$. On the other hand, the receiver voltage E_R of the 500 km (about 310 miles) line passes from $1.13E_S$ to $1.00E_S$ when the active power P changes from $0.80P_0$ to $1.00P_0$ (a variation 6.5 times greater).

In brief, increasing the length of an ac transmission line has undesirable effects. The increased voltage occurring at the receiver end when the line is open results in a more severe overvoltage when the load is lost for some reason. This can cause damage to the line itself as well as to equipment connected to the line even if voltage compensation is used to bring the receiver voltage back to its normal value. Obviously, the reduction of the maximal amount of active power which the line can convey is not desirable. Finally, the increased fluctuation of the receiver voltage E_R with changes in the load power is annoying as it makes the transmission line operation less stable. This, in turn, can contribute in reducing the stability of the ac power network, which is clearly undesirable.

Effect of the line length on the voltage profile along a voltage-compensated ac transmission line

Like any other ac transmission line, the 500 km (about 310 miles) line in Figure 37 can be voltage compensated using switched shunt compensation at both ends, starting with a shunt inductor having a reactance of 868.7 Ω when no load is applied to the receiver end of the line. This allows the receiver voltage E_R to be kept close to the sender voltage E_S over a wide range of load power. However, it does not prevent the voltage at any intermediate point along the line from differing from the sender voltage E_S. The reason why this occurs is explained below.

Remember that both the inductive reactance (X_L) and capacitive reactance (X_C) in any ac transmission line are distributed all along the line and not lumped into a few components as in the corrected PI equivalent circuit of the line. In fact, the voltage at various points distributed all along the ac transmission line (i.e., the profile of voltage along the line) can be found by resolving the distributed-parameter equivalent circuit of the line. Figure 39 shows the resulting voltage profile along an ac transmission line that is voltage compensated using switched shunt compensation (SSC) at both ends, and operates at a load power less than the natural load P_0.

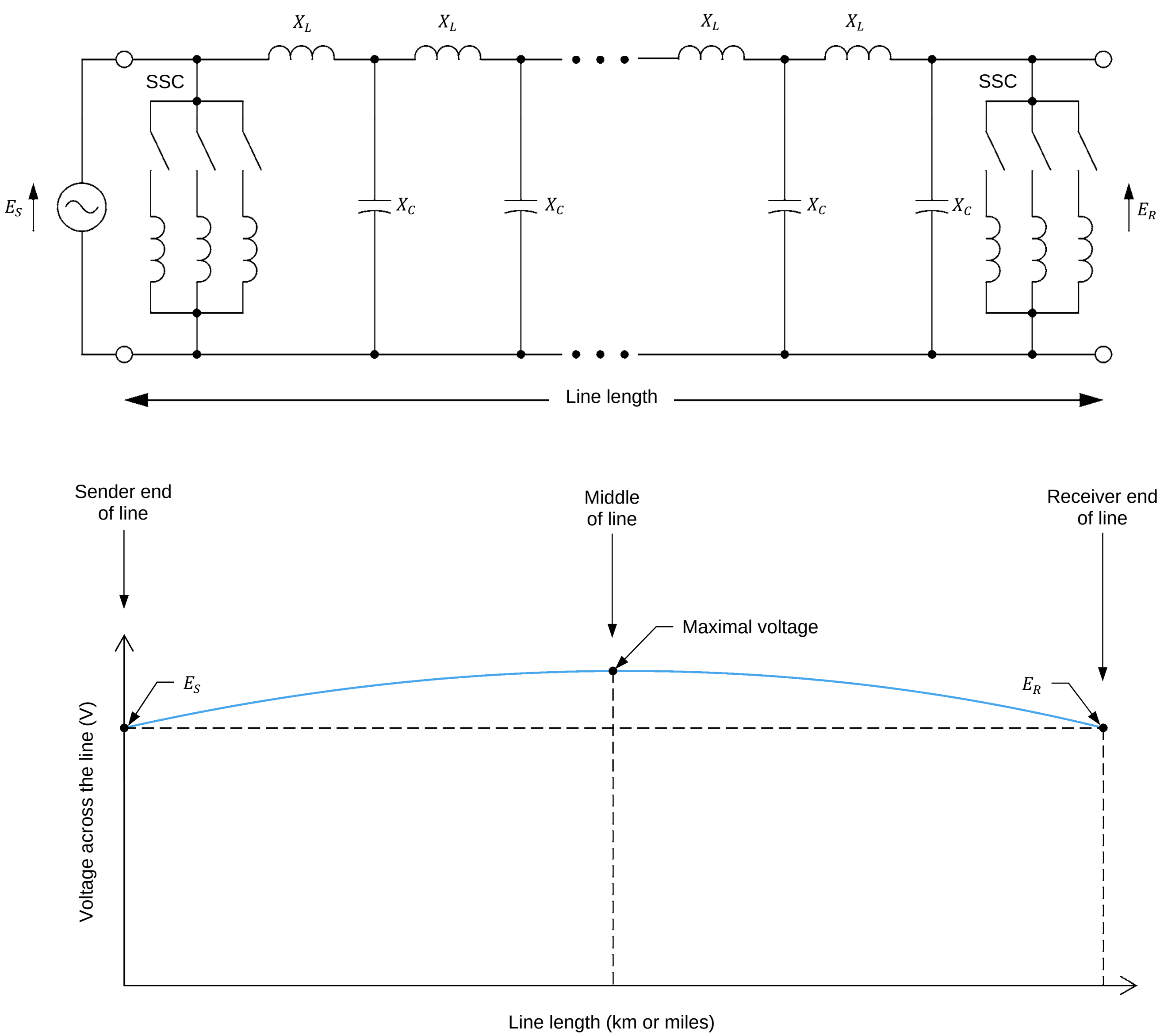


Figure 39. Voltage profile along an ac transmission line that is voltage compensated using switched shunt compensation at both ends and operates at a load power less than the natural load P_0. One phase of the ac transmission line is shown.

As expected, the voltage is the same at the sender and receiver ends of the line since the line is voltage compensated. However, the voltage across the line increases as one moves from either end of the line toward the middle of the line, the voltage reaching a maximal value in the middle of the line. This confirms the statement made earlier that using voltage compensation, like switched shunt compensation, at both ends of an ac transmission line does not prevent the voltage at any intermediate point along the line from differing from the sender voltage E_S.

The line length has a direct effect on the value which the voltage in the middle of the ac transmission line reaches. The longer the line, the higher the voltage in the middle of the line. This is illustrated in Figure 40, which shows the voltage profiles along the 250 km and 500 km (about 155 miles and 310 miles) lines in Figure 36 and Figure 37, when they are voltage compensated using switched shunt compensation at both ends, and operate without load. In this particular case, the voltage in the middle of the line (i.e., the maximal voltage along the complete line) reaches only $1.012E_S$ for the 250 km line, whereas it reaches $1.052E_S$ for the 500 km line.

The voltage profile along an ac transmission line that is voltage compensated using switched shunt compensation at both ends also depends on the amount of active power conveyed to the load. The voltage profile flattens out as the amount of power conveyed to the load increases. Assuming a lossless ac transmission line, the voltage profile becomes perfectly flat when the load power increases up to the natural load P_0.

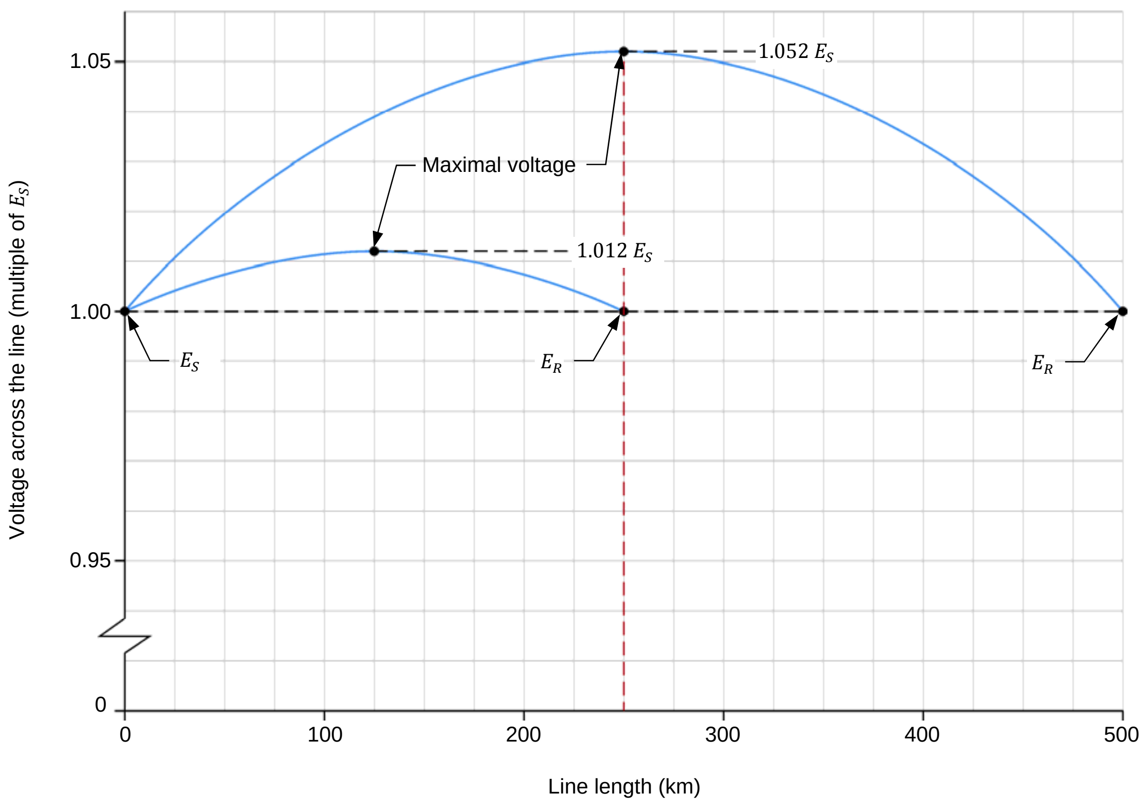


Figure 40. Voltage profiles along the 250 km (155 miles) and 500 km (310 miles) ac transmission lines shown in Figure 36 and Figure 37 when they are voltage compensated using switched shunt compensation at both ends and operate without load.

Figure 40 demonstrates that, as the line length increases, voltage-compensation at both ends of an ac transmission line becomes less effective in preventing the voltage at any point along the line from differing from the sender voltage E_S. In fact, voltage compensation at both ends of an ac transmission line can be used effectively as long as the voltage in the middle of the line does not go beyond the voltage range at which the line can operate. Consequently, this limits the maximal line length for which voltage compensation at both ends of the line can be used. For ac transmission lines exceeding this maximal length, voltage compensation must be distributed over several points along the line to ensure that the voltage all along the line remains within the normal operating range of the line. This is discussed in the next exercise of this manual.

Measuring the voltage in the middle of a long ac transmission line emulated in the lab

Any long ac transmission line can be represented by connecting, in series, several corrected PI equivalent circuits of a shorter ac transmission line having the same fundamental characteristics (i.e., with the same values of R, X_L, and X_C per unit of length), as mentioned in Exercise 2 of this manual. For instance, the 500 km (about 310 miles) ac transmission line in Figure 37 can be represented by connecting two corrected PI equivalent circuits of the 250 km (about 155 miles) line in Figure 36. This is shown in Figure 41.

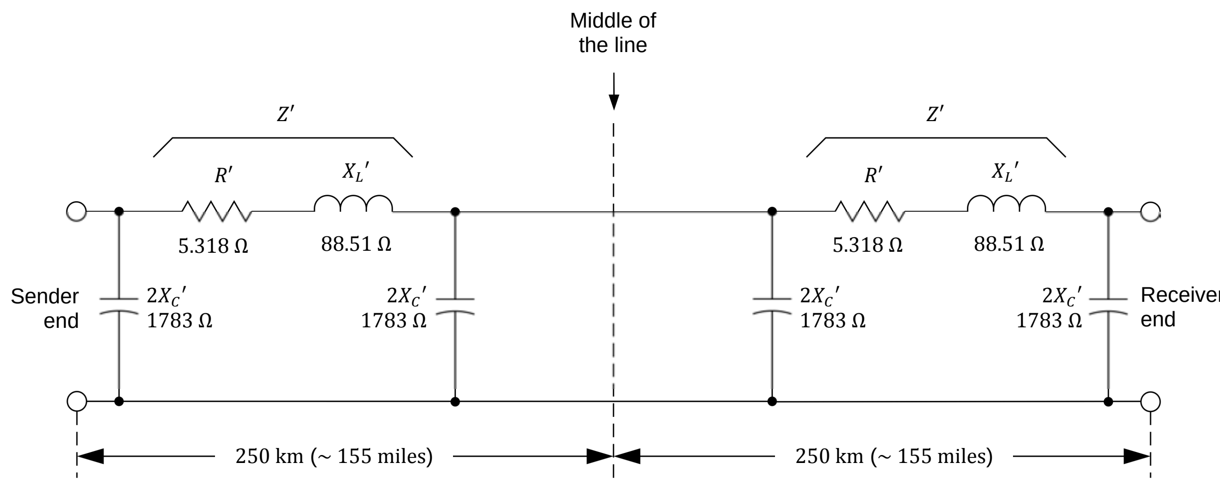


Figure 41. 500 km (about 310 miles) ac transmission line represented using two corrected PI equivalent circuits of a 250 km (about 155 miles) line (with the same fundamental characteristics) connected in series. One phase of the ac transmission line is shown.

The corrected PI equivalent circuit of any ac transmission line of reasonable length provides very accurate values of the voltage and current at the sender and receiver ends of the line, as mentioned in Exercise 2 of this manual. Consequently, the voltage at the receiver end of the corrected PI equivalent circuit representing the first half of the 500 km (about 310 miles) ac transmission line in Figure 41 provides the exact value of the voltage in the middle of the line, i.e., the maximal voltage along the whole line when it is properly voltage compensated. This technique is used in the hands-on manipulations of this exercise to emulate a long ac transmission line because it permits measurement of voltage at both ends of the line as well as in the middle of the line.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Power-voltage curve of the ac transmission line
- Voltage in the middle of a long ac transmission line voltage compensated at both ends

PROCEDURE

WARNING

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 connect a circuit representing one phase of a 700 km (about 435 miles) ac transmission line. You will set the measuring equipment to measure the parameters of 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.

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.

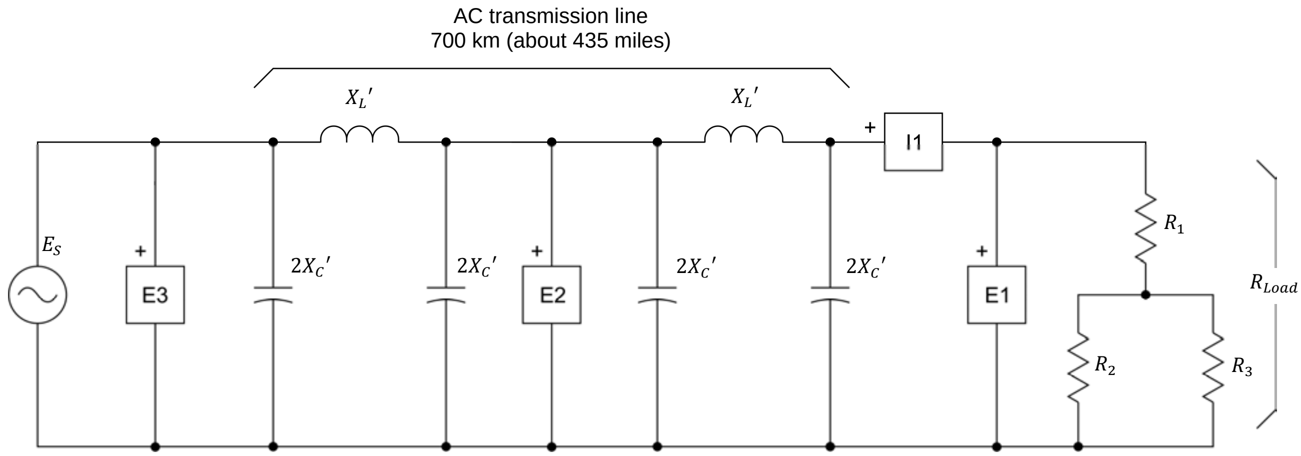
3. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

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. 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 circuit shown in Figure 42, which represents one phase of a three-phase power transmission system. The circuit, which is similar to the one used in the previous exercise, consists of an ac power source supplying power to a resistive load via a 700 km (about 435 miles) ac transmission line represented by two corrected PI equivalent circuits of a 350 km (about 217 miles) line having the same fundamental characteristics. Notice that the corrected PI equivalent circuit of the 350 km (about 217 miles) line is identical to that used in the previous exercises. A voltmeter (input *E2*) connected between the two corrected PI equivalent circuits permits measurement of the voltage in the middle of the 700 km line.

   Each of the two inductors in the ac transmission line is implemented using one phase of the Three-Phase Transmission Line. Each of the four capacitors in the ac transmission line is implemented with one capacitor section (group of 3 parallel-connected capacitors) in one of the two Capacitive Load modules. The load consists of a series-parallel arrangement of three resistors. Each of these resistors is implemented with one resistor section (group of 3 parallel-connected resistors) of the Resistive Load.



Local ac power network		X_L' (Ω)	$2X_C'$ (Ω)	R_{Load} (Ω)
Voltage (V)	Frequency (Hz)			
120	60	120	1200	∞
220	50	400	4400	∞
240	50	400	4800	∞
220	60	400	4400	∞

Figure 42. 700 km (about 435 miles) ac transmission line supplying power to a resistive load (one phase only).

6. On the Three-Phase Transmission Line, make sure that the I/O toggle switch is set to the I position, then set the reactance X_L' of the line inductors to the value indicated in the table of Figure 42.

On the Capacitive Load modules, set the reactance $2X_C$' of the capacitors in the line to the value indicated in the table of Figure 42.

On the Resistive Load, open all switches so that the load resistance R_{Load} is infinite.

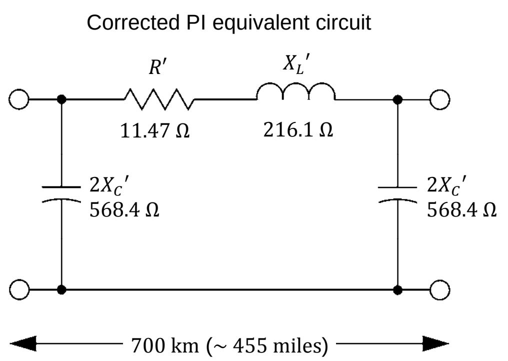
7. Figure 43 shows the fundamental characteristics and corrected PI equivalent circuit of the 700 km (about 435 miles) ac transmission line in Figure 42, for the various voltage-frequency combinations of the local ac power network.

The fundamental characteristics of the 700 km (about 455 miles) ac transmission line in Figure 42, at ac power network voltage values of 220 V and 240 V, have been specifically adjusted to take into account the nominal operating power (0.2 kW) of the equipment supplied. Consequently, the fundamental characteristics X_L and X_C of the ac transmission line at ac power network voltage values of 220 V and 240 V differ significantly from those of actual ac transmission lines. However, this does not affect the behavior of the ac transmission line implemented with the equipment supplied, which is very similar to that of actual ac transmission lines.

8. In LVDAC-EMS, open the Metering window, then open the Acquisition Settings dialog box. Set the *Sampling Window* to 8 cycles, then click *OK* to close the dialog box. This provides better accuracy when measuring certain parameters of the ac transmission line.

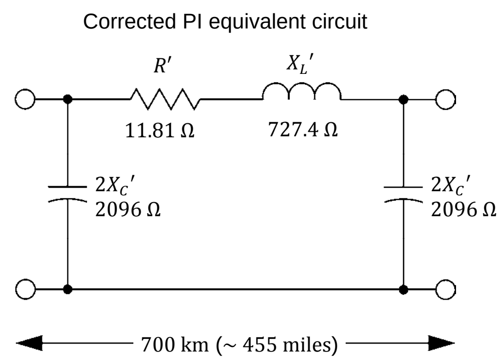
In the Metering window, make the required settings in order to measure the sender voltage E_S (input *E3*), the voltage E_{Middle} in the middle of the line (input *E2*), the receiver voltage E_R (input *E1*), the load current I_{Load} (input *I1*), and the active power P_{Load} supplied to the load [*PQS1(E1,I1)*]. Set the meters to continuous refresh mode.

LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 0.355\ \Omega/\text{km}$	$(0.571\ \Omega/\text{mile})$
Capacitive reactance $X_C = 213.6\ \text{k}\Omega/\text{km}$	$(132.7\ \text{k}\Omega/\text{mile})$



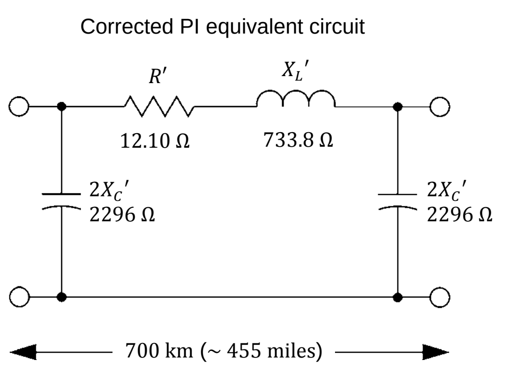
(a) 120 V, 60 Hz

LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 1.179\ \Omega/\text{km}$	$(1.898\ \Omega/\text{mile})$
Capacitive reactance $X_C = 782.2\ \text{k}\Omega/\text{km}$	$(486.0\ \text{k}\Omega/\text{mile})$



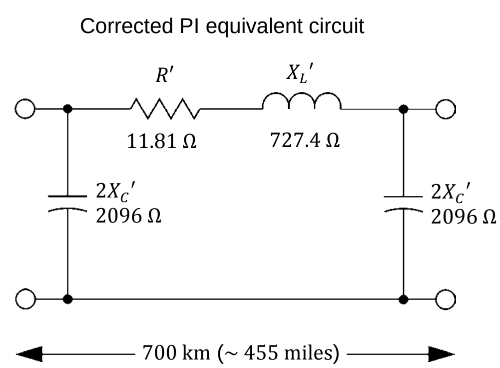
(b) 220 V, 50 Hz

LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 1.177\ \Omega/\text{km}$	$(1.894\ \Omega/\text{mile})$
Capacitive reactance $X_C = 852.1\ \text{k}\Omega/\text{km}$	$(529.4\ \text{k}\Omega/\text{mile})$



(c) 240 V, 50 Hz

LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 1.179\ \Omega/\text{km}$	$(1.898\ \Omega/\text{mile})$
Capacitive reactance $X_C = 782.2\ \text{k}\Omega/\text{km}$	$(486.0\ \text{k}\Omega/\text{mile})$



(d) 220 V, 60 Hz

Figure 43. Fundamental characteristics and corrected PI equivalent circuit (one phase only) of the 700 km (about 435 miles) ac transmission line shown in Figure 42 for the various voltage-frequency combinations of the local ac power network.

Power-voltage curve of the ac transmission line

In this section, you will gradually decrease the resistance of the resistive load connected to the receiver end of the 700 km (about 435 miles) ac transmission line, and for each load resistance value, record the sender voltage, voltage in the middle of the line, receiver voltage, load current, and load active power. You will then use the results to plot the power-voltage curve of the line. You will compare your results to those obtained in Exercise 2 for the 350 km (about 217 miles) ac transmission line.

9. On the Power Supply, turn the three-phase ac power source on.

10. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the circuit parameters, i.e., the sender voltage E_S, the voltage E_{Middle} in the middle of the line, the receiver voltage E_R, the load current I_{Load}, and the active power P_{Load} supplied to the load.

11. Record the circuit parameters in the Data Table.

12. Gradually increase the load at the receiver end of the line. To do so, change the switch settings on the Resistive Load to make the load resistance R_{Load} vary between the maximum and minimum values indicated in Table 15 for your local ac power network, in about 20 to 25 steps. For each load resistance value, record the circuit parameters in the Data Table.

Resistor R_1 must be short-circuited to obtain the lowest resistance values.

Table 15. Maximum and minimum values of load resistance R_{Load}.

Local ac power network		Load resistance R_{Load} (Ω)	
Voltage (V)	**Frequency (Hz)**	**Maximum value**	**Minimum value**
120	60	2400	86
220	50	8800	314
240	50	9600	343
220	60	8800	314

13. Short-circuit the receiver end of the line ($R_{Load} = 0\ \Omega$), then record the circuit parameters in the Data Table.

On the Power Supply, turn the three-phase ac power source off.

In the Data Table window, save the recorded data.

14. Transfer the data you saved to a spreadsheet application. Use the values of the receiver voltage E_R and active power P_{Load} to plot the power-voltage curve of the ac transmission line.

15. Compare the power-voltage curve of the 700 km (about 435 miles) ac transmission line plotted in the previous step to the power-voltage curve of the 350 km (about 217 miles) ac transmission line plotted in step 15 of Exercise 2 to answer the following three questions.

How does increasing the line length affect the receiver voltage E_R obtained when the line is left open? Explain.

____

____

____

____

How does increasing the line length affect the maximal amount of active power $P_{Max.}$ that the line can convey to a load? Explain.

____

____

____

____

How does increasing the line length affect the variation of the receiver voltage E_R produced by a given change in the amount of active power P conveyed by the line?

____

____

____

____

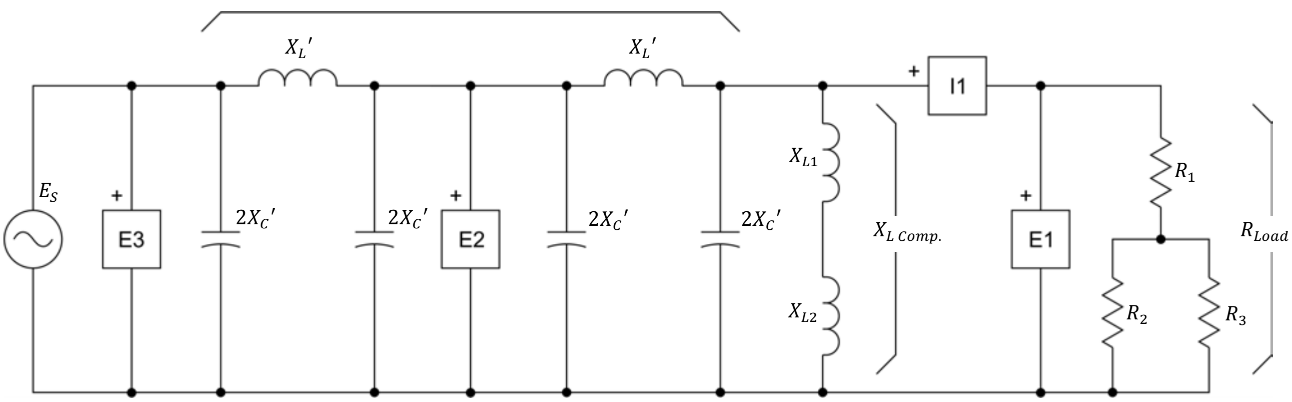
____

Voltage in the middle of a long ac transmission line voltage compensated at both ends

In this section, you will connect a bank of switched shunt inductors to the receiver end of the line and adjust the reactance $X_{L\,(Comp.)}$ of this bank of inductors so that the receiver voltage is as close as possible to the sender voltage. You will then measure the voltage in the middle of the line and determine if the voltage compensation is sufficient to keep the voltage all along the line close to the sender voltage.

16. Connect a bank of switched shunt inductors to the receiver end of the 700 km (about 435 miles) line, as shown in Figure 44. To do so, connect two inductor sections (groups of 3 parallel-connected inductors) of the Inductive Load module in series to implement inductors X_{L1} and X_{L2} in the bank of switched shunt inductors.

To limit the amount of equipment required to perform this exercise, no switched shunt compensation (SSC) is used at the sender end of the ac transmission line. This is not problematic because the reactive power required at the sender end of the line for voltage compensation is provided by the ac power source. In other words, the line is voltage compensated at both ends in a way similar as when switched shunt compensation is used at both ends of the line.



Local ac power network		X_L' (Ω)	$2X_C'$ (Ω)	$X_{L\ Comp.}$ (Ω)	R_{Load} (Ω)
Voltage (V)	Frequency (Hz)				
120	60	120	1200	∞	∞
220	50	400	4400	∞	∞
240	50	400	4800	∞	∞
220	60	400	4400	∞	∞

Figure 44. 700 km (about 435 miles) ac transmission line with switched shunt compensation at the receiver end (one phase only).

17. On the Three-Phase Transmission Line, make sure that the reactance X_L' of the line inductors is set to the value indicated in the table of Figure 44.

On the Capacitive Load modules, make sure that the reactance $2X_C'$ of the capacitors in the line are set to the value indicated in the table of Figure 44.

On the Inductive Load, open all switches to set the reactance $X_{L\ Comp.}$ of the bank of switched shunt inductors to infinite for now. The reactance $X_{L\ Comp.}$ of the bank of switched shunt inductors will be readjusted later in the exercise.

On the Resistive Load, open all switches so that the load resistance R_{Load} is infinite.

18. On the Power Supply, turn the three-phase ac power source on. Does the receiver voltage E_R greatly exceed the sender voltage E_S? Expain.

____

____

____

19. On the Inductive Load, set the reactance $X_{L\,Comp.}$ of the bank of switched shunt inductors so that the receiver voltage E_R is as close as possible to the sender voltage E_S. Then, record the value of the reactance $X_{L\,Comp.}$ of the bank of switched shunt inductors.

$X_{L\,Comp.}$ $(E_R = E_S)$, open line = _______ Ω

Is the reactance $X_{L\,Comp.}$ of the bank of switched shunt inductors required for voltage compensation of the open line virtually equal to the reactance $2X_C{}'$ of the capacitors in the corrected PI equivalent circuit of the 700 km (about 435 miles) ac transmission line shown in Figure 43? Explain.

____

____

____

____

20. Record the value of the sender voltage E_S, receiver voltage E_R, and voltage E_{Middle} in the middle of the line, when the line is open (no load condition).

E_S = _______ V

E_R = _______ V

E_{Middle} = _______ V

Compare the voltage E_{Middle} measured in the middle in the line to the sender voltage E_S and receiver voltage E_R. Are they different? Explain.

____

____

____

From your observations, is voltage compensation at both ends of a long ac transmission line sufficient to keep the voltage all along the line close to the sender voltage E_S?

❑ Yes ❑ No

21. 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 that the length of a high-voltage ac transmission line directly affects the value of the components in the corrected PI equivalent circuit of the line. However, the line length has no effect on the characteristic impedance Z_0 and the natural load P_0 of the line. You also learned that increasing the length of a high-voltage ac transmission line changes the power-voltage curve of the line, and that this has several undesirable effects on the line operation. Finally, you saw that as the line length increases, voltage-compensation at both ends of an ac transmission line becomes less effective in preventing the voltage at any point along the line from differing from the sender voltage E_S.

Review Questions

1. How do the values of the components in the corrected PI equivalent circuit of a high-voltage ac transmission line vary when the line length increases?

2. Does the length of an ac transmission line affect the values of the characteristic impedance Z_0 and natural load P_0 of the line? Explain why.

3. When the length of a high-voltage ac transmission line is doubled, e.g., from 250 km to 500 km (from about 155 miles to 310 miles), explain how the following parameters vary: the receiver voltage E_R obtained when the line is left open, the maximal amount of active power $P_{Max.}$ that the line can convey to a load, and the variation of the receiver voltage E_R produced by a given change in the amount of active power P conveyed by the line.

4. Describe the undesirable effects of increasing the length of a high-voltage ac transmission line.

5. What is the effect of line length on the value which the voltage in the middle of an ac transmission line can reach, when this line is voltage compensated at both ends? Explain.

Voltage Compensation of a Long, High-Voltage AC Transmission Line Using Distributed, Switched Shunt Compensation

EXERCISE OBJECTIVE

When you have completed this exercise, you will know how to smooth the voltage profile of a high-voltage ac transmission line by using switched shunt compensation (SSC) distributed along the line. You will also know how to use the equations presented in Exercise 3 to calculate the maximal transmissible power of a high-voltage ac transmission line compensated using distributed SSC. You will know the relationship between the line length and the phase shift δ between the receiver and sender voltages in a voltage-compensated ac transmission line. You will also know the effect that the line length has on the stability of an ac transmission line voltage compensated using SSC.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Smoothing the voltage profile of an ac transmission line by distributing switched shunt compensation along the line
- Maximal transmissible power of an ac transmission line voltage compensated using distributed SSC
- Relationship between the line length and the phase shift in a voltage-compensated ac transmission line
- Effect of the line length on the stability of an ac transmission line voltage compensated using switched shunt compensation

DISCUSSION

Smoothing the voltage profile of an ac transmission line by distributing switched shunt compensation along the line

In the previous exercise, it has been demonstrated that, as the line length increases, voltage-compensation of an ac transmission line using switched shunt compensation at both ends of the line becomes less effective in preventing the voltage at any point along the line from differing from the sender voltage E_S. Consequently, this limits the maximal line length for which voltage compensation using switched shunt compensation at both ends can be used to prevent the voltage along the line from exceeding the maximal voltage at which the line can operate. This is illustrated in Figure 45, which shows the voltage profiles along the 250 km and 500 km (about 155 miles and 310 miles) lines shown in the discussion of Exercise 4, when they are voltage compensated using switched shunt compensation at both ends, and operate without load.

In this example, the voltage profile along the 250 km line is always below the maximal voltage at which the line can operate. On the other hand, the voltage profile along the 500 km line significantly exceeds the maximal voltage at which the line can operate.

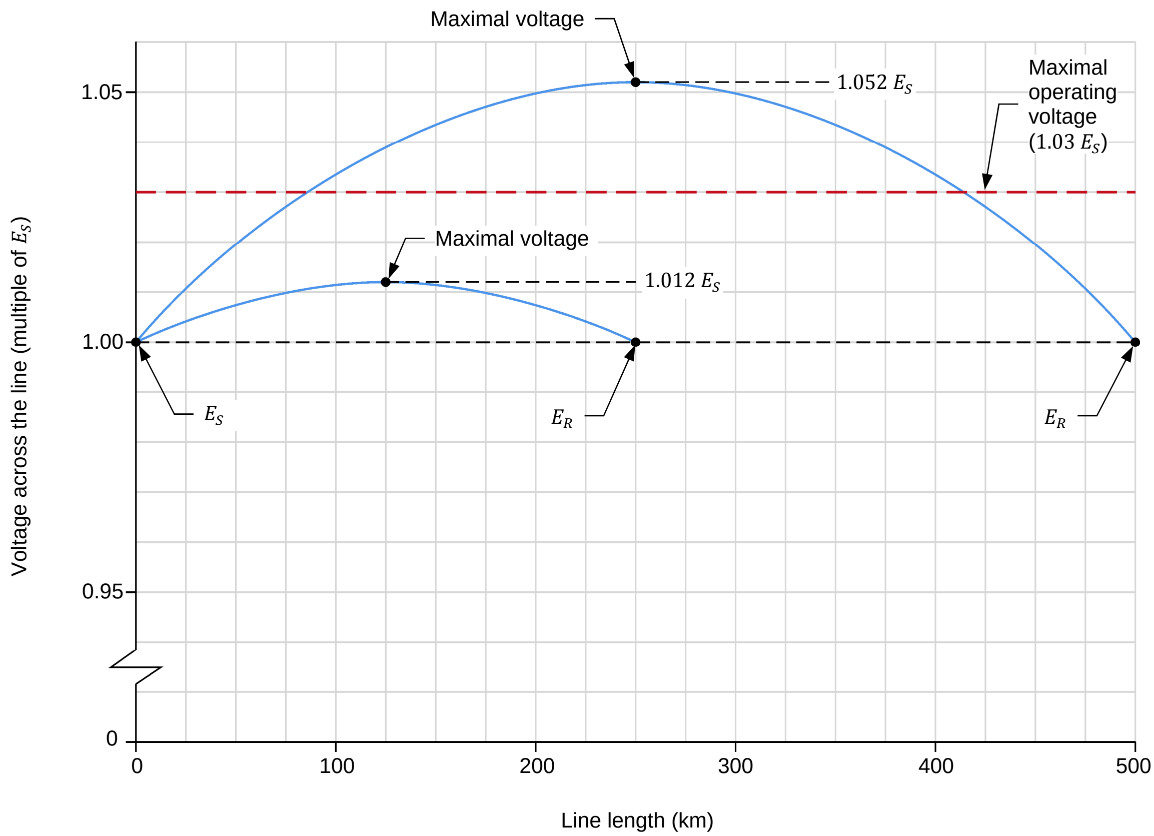


Figure 45. Voltage profiles along the 250 km (155 miles) and 500 km (310 miles) ac transmission lines shown in the discussion of Exercise 4 when they are voltage compensated using switched shunt compensation at both ends and operate without load.

This problem can be solved by adding switched shunt compensation (SSC) in the middle of the ac transmission line, as shown in Figure 46. In this example, the 500 km (about 310 miles) ac transmission line mentioned above is represented by two identical corrected PI equivalent circuits connected in series, each corrected PI equivalent circuit representing one half of the line. Notice that adding SSC in the middle of the ac transmission line is in fact like having SSC at both ends of each half of the line.

Adding SSC in the middle of the ac transmission line maintains the voltage at this point of the line close to the sender voltage E_S and modifies the whole voltage profile of the line markedly. Figure 47 shows the voltage profiles along the 500 km (about 310 miles) ac transmission line mentioned above when SSC is used at both ends of the line only, and when SSC is used at both ends of the line and in the middle of the line. Notice that the voltage profile along the 500 km line does not exceed the maximal voltage at which the line can operate when SSC is used at both ends of the line and in the middle of the line. Also, notice that in this situation, the voltage profile along each half of the 500 km line is the same as the voltage profile (shown in Figure 45) along the 250 km (about 155 miles) line when it is voltage compensated using switched shunt compensation at both ends only.

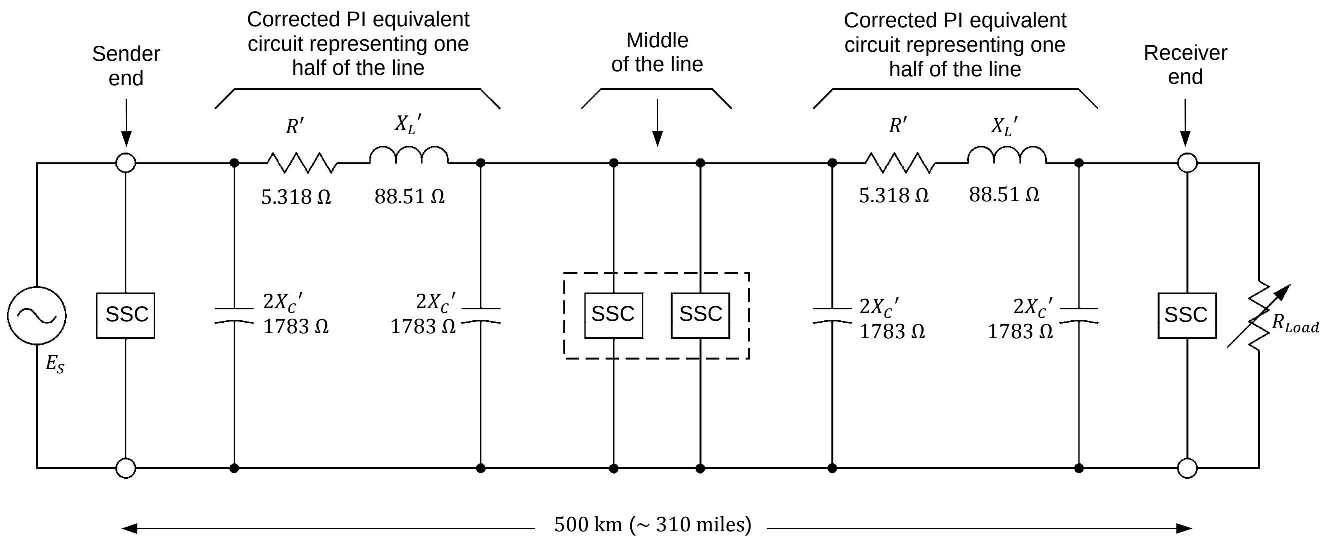


Figure 46. 500 km (about 310 miles) ac transmission line with switched shunt compensation (SSC) at both ends of the line and in the middle of the line. One phase of the ac transmission line is shown.

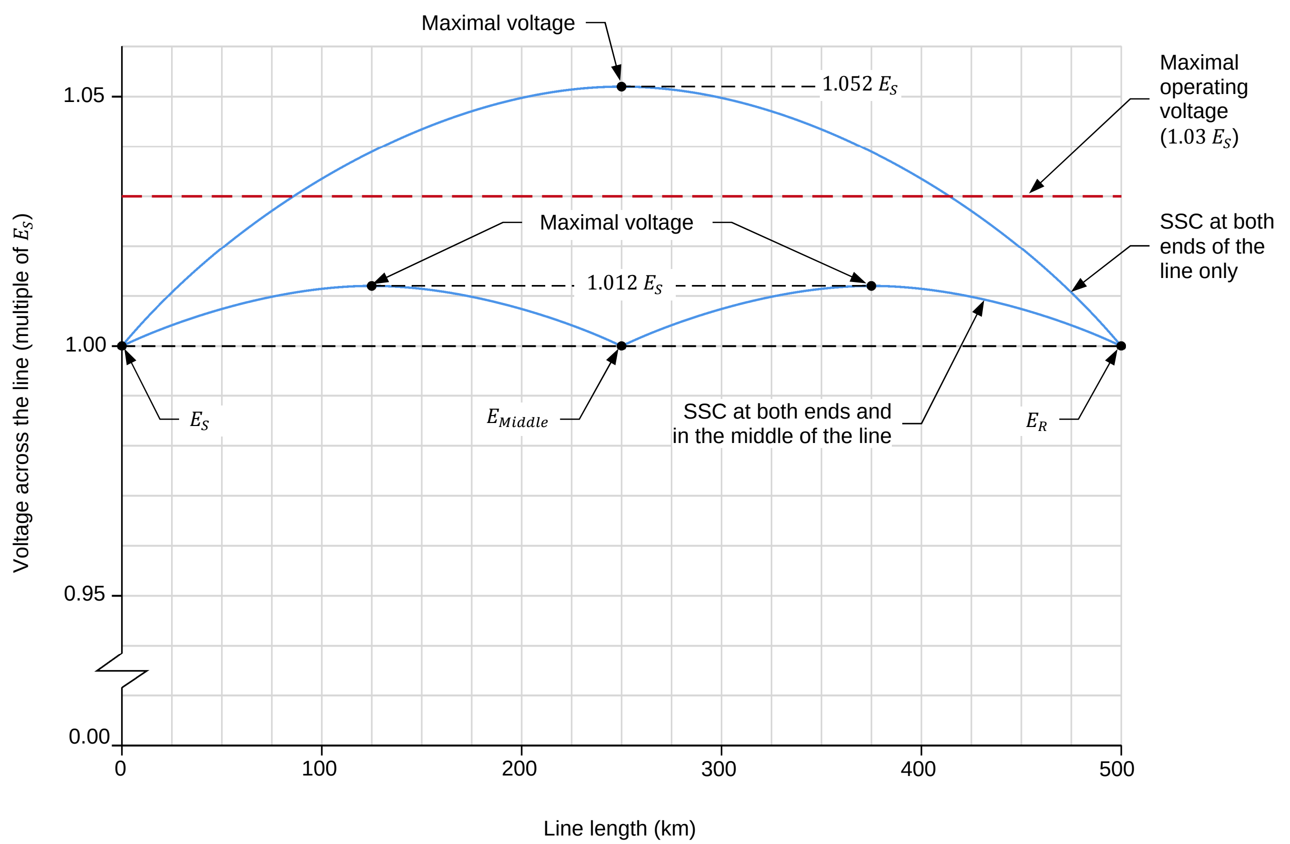


Figure 47. Voltage profiles along the 500 km (about 310 miles) ac transmission line in Figure 46 when SSC is used at both ends of the line only, and when SSC is used at both ends of the line and in the middle of the line.

In the example of Figure 47, dividing the ac transmission line into two segments, and using SSC at both ends of the line and at the junction between the two line segments (i.e., in the middle of the line), is sufficient to obtain a satisfactory voltage profile. Long ac transmission lines can be divided into as many segments as required, and SSC can be applied at both ends of the line and between each line segment, to obtain a satisfactory voltage profile. This is referred to as **distributed, switched shunt compensation (distributed SSC)**.

Maximal transmissible power of an ac transmission line voltage compensated using distributed SSC

When an ac transmission line is voltage compensated using distributed SSC, each line segment can be analyzed individually. The amount of active power $P_{(Comp.)}$ conveyed by a line segment and the maximal amount of active power $P_{Max.\ (Comp.)}$ which a line segment can convey are calculated using the equations presented in the discussion of Exercise 3 (these equations are repeated below). However, when using these equations, the sender voltage E_S is the phase voltage at the end of the line segment that is on the ac power source side, the receiver voltage E_R is the phase voltage at the end of the line segment that is on the load side, the reactance $X_L{}'$ is the reactance of the inductor in the corrected PI equivalent circuit representing the line segment, and the phase shift δ is the phase shift between the voltages at both ends of the line segment.

$$P_{(Comp.)} = 3\left(\frac{E_S\,E_R}{X_L{}'}\sin\delta\right) \tag{7}$$

$$P_{Max.\ (Comp.)} = 3\,\frac{E_S\,E_R}{X_L{}'} \tag{8}$$

The longest segment of an ac transmission line that is voltage compensated using distributed SSC has the highest inductive reactance $X_L{}'$, and thus the lowest maximal transmissible power. In other words, the longest segment of the ac transmission line is the most restrictive. Consequently, the maximal transmissible power $P_{Max.\ (Comp.)}$ of an ac transmission line that is voltage compensated using distributed SSC is equal to that of the longest segment of the line. Nonetheless, this is a major gain in most cases as the maximal transmissible power $P_{Max.\ (Comp.)}$ of an ac transmission line obtained when using distributed SSC is significantly higher than the one that would be obtained if SSC were used at both ends of the line only. This is because the inductive reactance $X_L{}'$ of the longest segment of the ac transmission line is generally much lower than the inductive reactance $X_L{}'$ of the complete ac transmission line.

Relationship between the line length and the phase shift in a voltage-compensated ac transmission line

The phase shift δ between the receiver voltage E_R and sender voltage E_S in a voltage-compensated ac transmission line increases with the active power $P_{(Comp.)}$ and the inductive reactance $X_L{}'$ in the corrected PI equivalent circuit representing the line. This is confirmed by Equation (9), which is obtained by rearranging the equation [Equation (7)] used for calculating the active power $P_{(Comp.)}$ that a voltage compensated ac transmission line conveys.

$$\delta = \arcsin\left(\frac{P_{(Comp.)}\,X_L{}'}{3\,E_S\,E_R}\right) \tag{9}$$

where $P_{(Comp.)}$ is the amount of active power transmitted by the voltage-compensated ac transmission line, expressed in watts (W).

$X_L{}'$ is the inductive reactance in the corrected PI equivalent circuit of the ac transmission line, expressed in ohms (Ω).

E_S is the phase voltage at the sender end of the voltage-compensated ac transmission line, expressed in volts (V).

E_R is the phase voltage at the receiver end of the voltage-compensated ac transmission line, expressed in volts (V).

Since the inductive reactance $X_L{}'$ of the line is proportional to the line length, the phase shift δ, for any given value of active power $P_{(Comp.)}$, thus increases with the line length. This is easily understood by considering an ac transmission line that is voltage compensated using distributed SSC. In this case, each segment of the line phase shifts (delays) the incoming voltage when the line conveys active power. The phase shift δ between the receiver voltage E_R and sender voltage E_S of the ac transmission line is equal to the sum of the phase shifts produced by each line segment. For instance, if an ac transmission line is divided into three equal segments, and each segment phase shifts (delays) the voltage by 20° when the line conveys a certain amount of active power, the phase shift δ between the receiver voltage E_R and sender voltage E_S in this situation is equal to 60°.

The phase shift δ produced by an ac transmission line directly affects the phase angle of the receiver voltage E_R. The phase angle of voltage is an important parameter in any interconnected power network as it has a direct impact on the amount of active power flowing between nodes of the network. This is discussed further in the next exercise of this manual.

Effect of the line length on the stability of an ac transmission line voltage compensated using switched shunt compensation

Using distributed SSC to voltage compensate an ac transmission line improves the voltage profile along the line, as well as the maximal transmissible power $P_{Max.\ (Comp.)}$ of the line, as covered earlier in this discussion. However, distributed SSC (as well as SSC) has no effect on the variation of the receiver voltage E_R produced by a given change in the amount of active power conveyed by the line, which increases with the line length, as mentioned earlier in the discussion of Exercise 4. Consequently, the range within which the receiver voltage E_R can be maintained using a given arrangement of switched shunt compensation (i.e., the number and values of the reactive components used for voltage compensation of the line) also increases with the line length. This causes the operation of an ac transmission line voltage compensated using SSC or distributed SSC to become less stable as the line length increases.

Figure 48. To smooth the voltage profile of high-voltage ac transmission lines, distributed, switched shunt compensation (SSC) can be used.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Voltage compensation of an ac transmission line using distributed, switched shunt compensation

PROCEDURE

WARNING

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 connect a circuit representing one phase of a 700 km (about 435 miles) ac transmission line that is voltage compensated using switched shunt compensation in the middle of the line and at the receiver end. You will set the measuring equipment to measure the parameters of 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.

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. 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 circuit shown in Figure 49, which represents one phase of a three-phase power transmission system. The circuit, which is similar to the one used in the previous exercise, consists of an ac power source supplying power to a resistive load via a 700 km (about 435 miles) ac transmission line represented by two corrected PI equivalent circuits of a 350 km (about 217 miles) line having the same fundamental characteristics. The 700 km ac transmission line is voltage compensated using switched shunt compensation in the middle of the line and at the receiver end of the line.

To limit the amount of equipment required to perform this exercise, no switched shunt compensation (SSC) is used at the sender end of the ac transmission line. This is not problematic because the reactive power required at the sender end of the line for voltage compensation is provided by the ac power source.

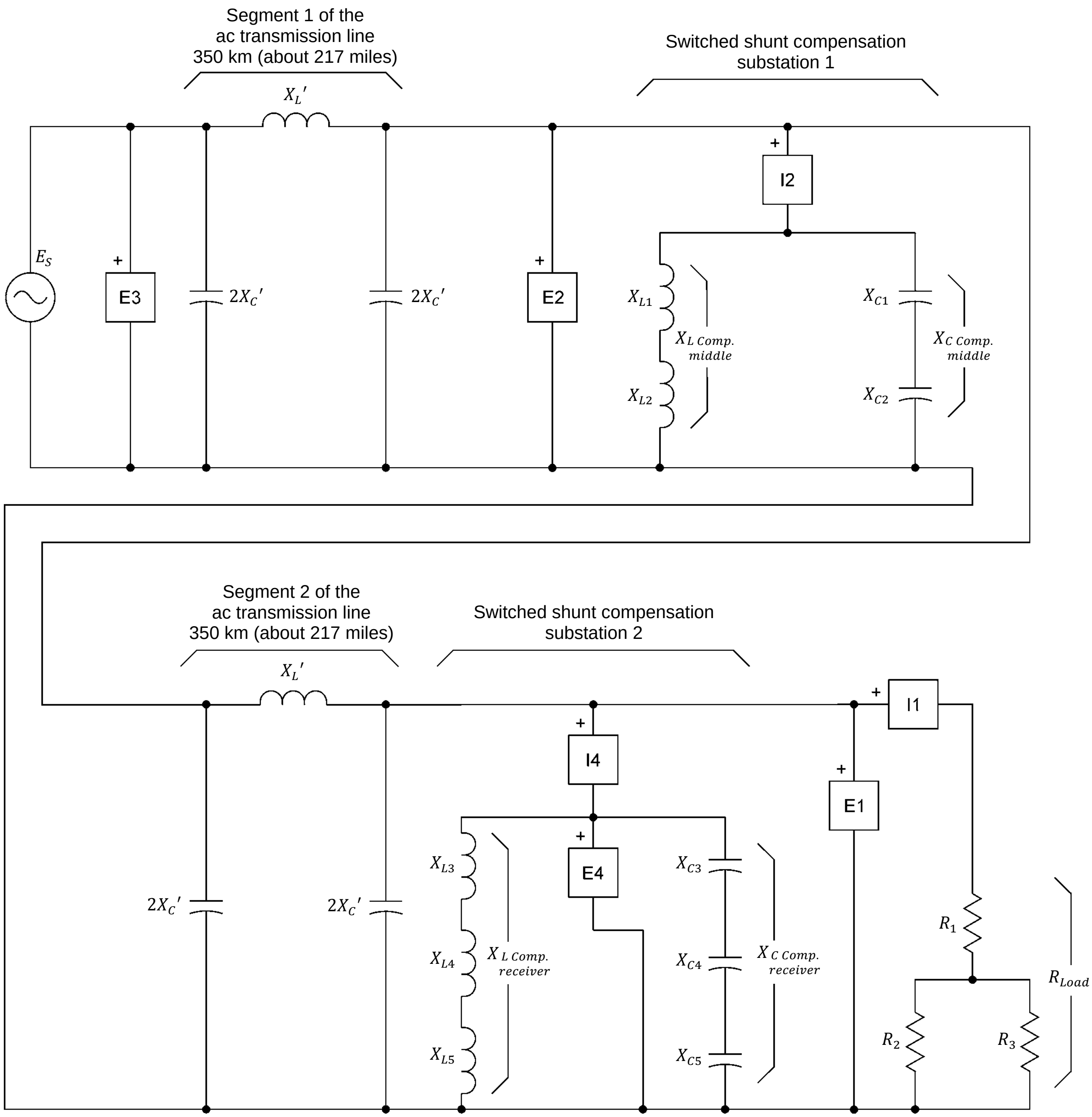
As Figure 49 shows, each of the two inductors in the ac transmission line is implemented using one phase of the Three-Phase Transmission Line module. Each of the four capacitors in the ac transmission line is implemented with one capacitor section (group of 3 parallel-connected capacitors) in one of the three Capacitive Load modules. The load consists of a series-parallel arrangement of three resistors. Each of these resistors is implemented with one resistor section (group of 3 parallel-connected resistors) in the Resistive Load module.

Two inductor sections (groups of 3 parallel-connected inductors) of an Inductive Load module are connected in series to implement inductors X_{L1} and X_{L2} in the bank of switched shunt inductors in the middle of the line. Two capacitor sections (groups of 3 parallel-connected capacitors) of a Capacitive Load module are connected in series to implement capacitors X_{C1} and X_{C2} in the bank of switched shunt capacitors in the middle of the line. The inductive reactance $X_{L\ Comp.\ middle}$ of the bank of switched shunt inductors and the capacitive reactance $X_{C\ Comp.\ middle}$ of the bank of switched shunt capacitors in the middle of the line can be changed to implement SSC.

To obtain the maximal value of inductive reactance ($1.5 \times 2X_C'$) required for SSC in the middle of the line using the sections of inductors available in the Inductive Load module, the inductors are connected in series instead of being connected in parallel as is usual when compensating an actual ac transmission line. However, the inductive reactance $X_{L\ Comp.\ middle}$ implemented with the series-connected inductors can be varied in the same way as if a bank of three parallel-connected switched shunt inductors (each inductor having a reactance value of $1.5 \times 2X_C'$) were used. The same approach is used to implement the shunt capacitors.

Three inductor sections (groups of 3 parallel-connected inductors) of an Inductive Load module are connected in series to implement inductors X_{L3}, X_{L4}, and X_{L5} of the bank of switched shunt inductors at the receiver end of the line. Three capacitor sections (groups of 3 parallel-connected capacitors) of a Capacitive Load module are connected in series to implement capacitors X_{C3}, X_{C4}, and X_{C5} in the bank of switched shunt capacitors at the receiver end of the line. The inductive reactance $X_{L\ Comp.\ receiver}$ of the bank of switched shunt inductors and the capacitive reactance $X_{C\ Comp.\ receiver}$ of the bank of switched shunt capacitors at the receiver end of the line can be changed to implement SSC.

To obtain the maximal value of inductive reactance ($3 \times 2X_C'$) required for SSC at the receiver end of the line using the sections of inductors available in the Inductive Load module, the inductors are connected in series instead of being connected in parallel as is usual when compensating an actual ac transmission line. However, the inductive reactance $X_{L\ Comp.\ receiver}$ implemented with the series-connected inductors can be varied in the same way as if a bank of three parallel-connected switched shunt inductors (each inductor having a reactance value of $3 \times 2X_C'$) were used. The same approach is used to implement the shunt capacitors.



Local ac power network		X_L' (Ω)	$2X_C'$ (Ω)	$X_{L\ Comp.\ middle}$ (Ω)	$X_{C\ Comp.\ middle}$ (Ω)	$X_{L\ Comp.\ receiver}$ (Ω)	$X_{C\ Comp.\ receiver}$ (Ω)	R_{Load} (Ω)
Voltage (V)	Frequency (Hz)							
120	60	120	1200	600	∞	1200	∞	∞
220	50	400	4400	2200	∞	4400	∞	∞
240	50	400	4800	2400	∞	4800	∞	∞
220	60	400	4400	2200	∞	4400	∞	∞

Figure 49. 700 km (about 435 miles) ac transmission line with switched shunt compensation in the middle of the line and at the receiver end (one phase only).

6. On the Three-Phase Transmission Line, make sure that the I/O toggle switch is set to the I position, then set the reactance $X_L{}'$ of the line inductors to the value indicated in the table of Figure 49.

On the Capacitive Load modules used to implement the capacitors (4) in the line, set the reactance $2X_C{}'$ of these capacitors to the value indicated in the table of Figure 49.

On the Inductive Load module used to implement the bank of switched shunt inductors in the middle of the line, set the reactance $X_{L\,Comp.\,middle}$ to the value indicated in the table of Figure 49.

On the Capacitive Load module used to implement the bank of switched shunt capacitors in the middle of the line, set the reactance $X_{C\,Comp.\,middle}$ to infinite.

On the Inductive Load module used to implement the bank of switched shunt inductors at the receiver end of the line, set the reactance $X_{L\,Comp.\,receiver}$ to the value indicated in the table of Figure 49.

On the Capacitive Load module used to implement the bank of switched shunt capacitors at the receiver end of the line, set the reactance $X_{C\,Comp.\,receiver}$ to infinite.

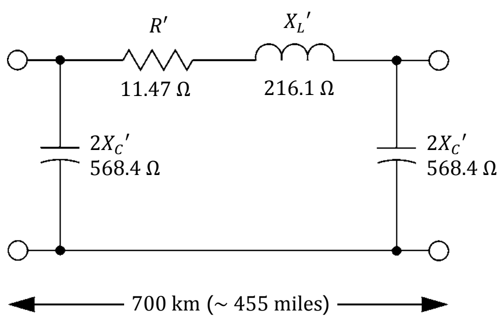
On the Resistive Load, set the load resistance R_{Load} to infinite.

7. Figure 50 shows the fundamental characteristics and corrected PI equivalent circuit of the 700 km (about 435 miles) ac transmission line in Figure 49, for the various voltage-frequency combinations of the local ac power network.

The fundamental characteristics of the 700 km (about 455 miles) ac transmission line in Figure 49 at ac power network voltage values of 220 V and 240 V, have been specifically adjusted to take into account the nominal operating power (0.2 kW) of the equipment supplied. Consequently, the fundamental characteristics X_L and X_C of the ac transmission line at ac power network voltage values of 220 V and 240 V differ significantly from those of actual ac transmission lines. However, this does not affect the behavior of the ac transmission line implemented with the equipment supplied, which is very similar to that of actual ac transmission lines.

LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 0.355\ \Omega/\text{km}$	$(0.571\ \Omega/\text{mile})$
Capacitive reactance $X_C = 213.6\ \text{k}\Omega/\text{km}$	$(132.7\ \text{k}\Omega/\text{mile})$

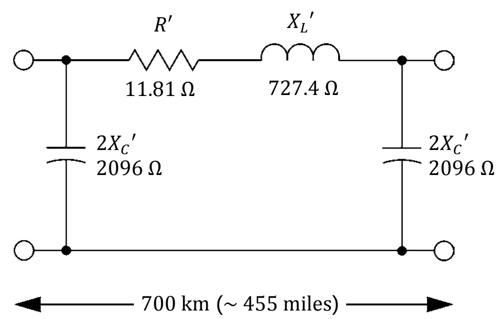
Corrected PI equivalent circuit



(a) 120 V, 60 Hz

LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 1.179\ \Omega/\text{km}$	$(1.898\ \Omega/\text{mile})$
Capacitive reactance $X_C = 782.2\ \text{k}\Omega/\text{km}$	$(486.0\ \text{k}\Omega/\text{mile})$

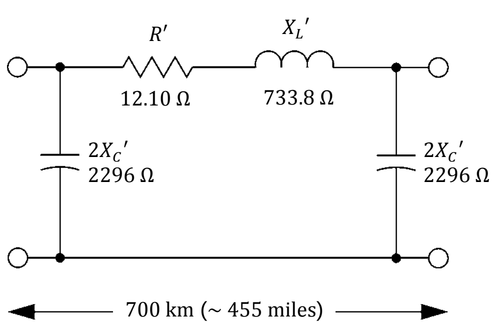
Corrected PI equivalent circuit



(b) 220 V, 50 Hz

LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 1.177\ \Omega/\text{km}$	$(1.894\ \Omega/\text{mile})$
Capacitive reactance $X_C = 852.1\ \text{k}\Omega/\text{km}$	$(529.4\ \text{k}\Omega/\text{mile})$

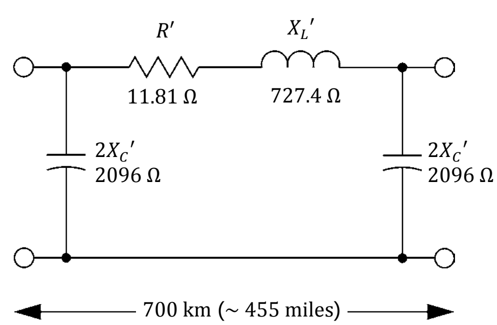
Corrected PI equivalent circuit



(c) 240 V, 50 Hz

LINE FUNDAMENTAL CHARACTERISTICS	
Resistance $R = 0.022\ \Omega/\text{km}$	$(0.035\ \Omega/\text{mile})$
Inductive reactance $X_L = 1.179\ \Omega/\text{km}$	$(1.898\ \Omega/\text{mile})$
Capacitive reactance $X_C = 782.2\ \text{k}\Omega/\text{km}$	$(486.0\ \text{k}\Omega/\text{mile})$

Corrected PI equivalent circuit



(d) 220 V, 60 Hz

Figure 50. Fundamental characteristics and corrected PI equivalent circuit (one phase only) of the 700 km (about 435 miles) ac transmission line shown in Figure 49 for the various voltage-frequency combinations of the local ac power network.

8. In LVDAC-EMS, open the Metering window, then open the Acquisition Settings dialog box. Set the *Sampling Window* to 8 cycles, then click *OK* to close the dialog box. This provides better accuracy when measuring certain parameters of the ac transmission line.

   In the Metering window, make the required settings in order to measure the sender voltage E_S (input *E3*), the voltage E_{Middle} in the middle of the line (input *E2*), the receiver voltage E_R (input *E1*), the load current I_{Load} (input *I1*), the active power P_{Load} supplied to the load [*PQS1(E1,I1)*], the phase shift δ_{Middle} between the voltage E_{Middle} in the middle of the line and sender voltage E_S [*PS(E2,E3)*], the phase shift δ between the receiver voltage E_R and sender voltage E_S [*PS(E1,E3)*], the compensation reactance ($X_{Comp.\ middle}$) in the middle of the line [*RXZ(E2,I2)*], and the compensation reactance ($X_{Comp.\ receiver}$) at the receiver end of the line [*RXZ(E4,I4)*]. Set the meters to continuous refresh mode.

Voltage compensation of an ac transmission line using distributed, switched shunt compensation

In this section, you will gradually decrease the resistance of the resistive load connected to the receiver end of the line by steps, and adjust the switched shunt compensation at the receiver end and in the middle of the line so that the receiver voltage E_R and voltage E_{Middle} in the middle of the line both remain close to the sender voltage E_S. While doing so, you will record the circuit parameters for each load resistance value. You will use the results to plot the power-voltage curve of the line, as well as the power-voltage curve obtained in the middle of the line. You will also plot a curve of the phase shift δ between voltages E_R and E_S versus the load power P_{Load}, and a curve of the phase shift δ_{Middle} between voltages E_{Middle} and E_S versus the load power P_{Load}. You will analyze your results.

9. On the Power Supply, turn the three-phase ac power source on. The receiver voltage E_R and the voltage E_{Middle} in the middle of the line both should be within $\pm$ 3% of the sender voltage E_S.

10. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the circuit parameters, i.e., the sender voltage E_S, the voltage E_{Middle} in the middle of the line, the receiver voltage E_R, the load current I_{Load}, the active power P_{Load} supplied to the load, the phase shift δ_{Middle} between the voltage E_{Middle} in the middle of the line and sender voltage E_S, the phase shift δ between the receiver voltage E_R and sender voltage E_S, the compensation reactance ($X_{Comp.\ middle}$) in the middle of the line, and the compensation reactance ($X_{Comp.\ receiver}$) at the receiver end of the line.

    Record the circuit parameters in the Data Table.

11. Increase the load at the receiver end of the line in small steps while adjusting the switched shunt compensation so that the receiver voltage E_R and the voltage E_{Middle} in the middle of the line both remain within $\pm 3\%$ of the sender voltage E_S. Increase the load as long as you are able to maintain the receiver voltage E_R and the voltage E_{Middle} in the middle of the line within $\pm 3\%$ of the sender voltage E_S. To do so, perform the sub-procedure below.

(a) Change the switch settings on the Resistive Load to slightly decrease the resistance of the load (R_{Load}) at the receiver end of the line.

At a certain point, you may have to short-circuit resistor R_1 using a safety banana plug lead to decrease the resistance of the load (R_{Load}) to the value required.

(b) Verify that the receiver voltage E_R is still within $\pm 3\%$ of the sender voltage E_S. If so, go to step (c) of this sub-procedure. Otherwise, adjust the reactance ($X_{Comp.\ receiver}$) of the switched shunt compensation at the receiver end of the line to bring the receiver voltage E_R back within $\pm 3\%$ of the sender voltage E_S, then go to step (c) of this sub-procedure. Table 16 shows the sequence of reactance ($X_{Comp.\ receiver}$) values to be followed when adjusting the switched shunt compensation at the receiver end of the line. It is the same sequence as that used in Exercise 3 for voltage compensation of the 350 km (about 217 miles) ac transmission line.

If voltage E_R becomes 3% lower than voltage E_S while maximal capacitive shunt compensation is applied at the receiver end of the line, continue with step (c) of this sub-procedure to complete the voltage compensation.

Table 16. Sequence of reactance ($X_{Comp.\ receiver}$) values to be followed when adjusting the switched shunt compensation at the receiver end of the line.

Local ac power network		Sequence of values for reactance $X_{Comp.\ receiver}$ (Ω)						
Voltage (V)	Frequency (Hz)	Inductive			4	Capacitive		
		1 (No load)	2	3		5	6	7 (Max. load)
120	60	1200	1800	3600	∞	-3600	-1800	-1200
220	50	4400	6600	13 200	∞	-13 200	-6600	-4400
240	50	4800	7200	14 400	∞	-14 400	-7200	-4800
220	60	4400	6600	13 200	∞	-13 200	-6600	-4400

Positive values indicate that reactance $X_{Comp.\ receiver}$ is inductive. Negative values indicate that reactance $X_{Comp.\ receiver}$ is capacitive.

(c) Verify that the voltage E_{Middle} in the middle of the line is still within $\pm 3\%$ of the sender voltage E_S. If so, go to step (e) of this sub-procedure. Otherwise, adjust the reactance ($X_{Comp.\ middle}$) of the switched shunt compensation in the middle of the line to bring the voltage E_{Middle} back within $\pm 3\%$ of the sender voltage E_S, then go to step (d) of this sub-procedure. Table 17 shows the sequence of reactance ($X_{Comp.\ middle}$) values to be followed when adjusting the switched shunt compensation in the middle of the line.

Table 17. Sequence of reactance ($X_{Comp.\ middle}$) values to be followed when adjusting the switched shunt compensation in the middle of the line.

Local ac power network		Sequence of values for reactance $X_{Comp.\ middle}$ (Ω)						
Voltage (V)	Frequency (Hz)	Inductive			4	Capacitive		
		1 (No load)	2	3		5	6	7 (Max. load)
120	60	600	900	1800	∞	-1800	-900	-600
220	50	2200	3300	6600	∞	-6600	-3300	-2200
240	50	2400	3600	7200	∞	-7200	-3600	-2400
220	60	2200	3300	6600	∞	-6600	-3300	-2200

Positive values indicate that reactance $X_{Comp.\ middle}$ is inductive. Negative values indicate that reactance $X_{Comp.\ middle}$ is capacitive.

(d) Verify once again that the receiver voltage E_R is within $\pm 3\%$ of the sender voltage E_S. If so, go to step (e) of this sub-procedure. Otherwise, adjust the reactance ($X_{Comp.\ receiver}$) of the switched shunt compensation at the receiver end of the line to bring the receiver voltage E_R back within $\pm 3\%$ of the sender voltage E_S, then go to step (e) of this sub-procedure. Table 16 shows the sequence of reactance ($X_{Comp.\ receiver}$) values to be followed when adjusting the switched shunt compensation at the receiver end of the line.

(e) Record the circuit parameters in the Data Table then go back to step (a) of this sub-procedure.

Figure 51 shows the above sub-procedure as an algorithm.

12. Once you have reached the maximal load for which the receiver voltage E_R and the voltage E_{Middle} in the middle of the line can be maintained within $\pm 3\%$ of the sender voltage E_S, turn the three-phase ac power source of the Power Supply off.

In the Data Table window, save the recorded data.

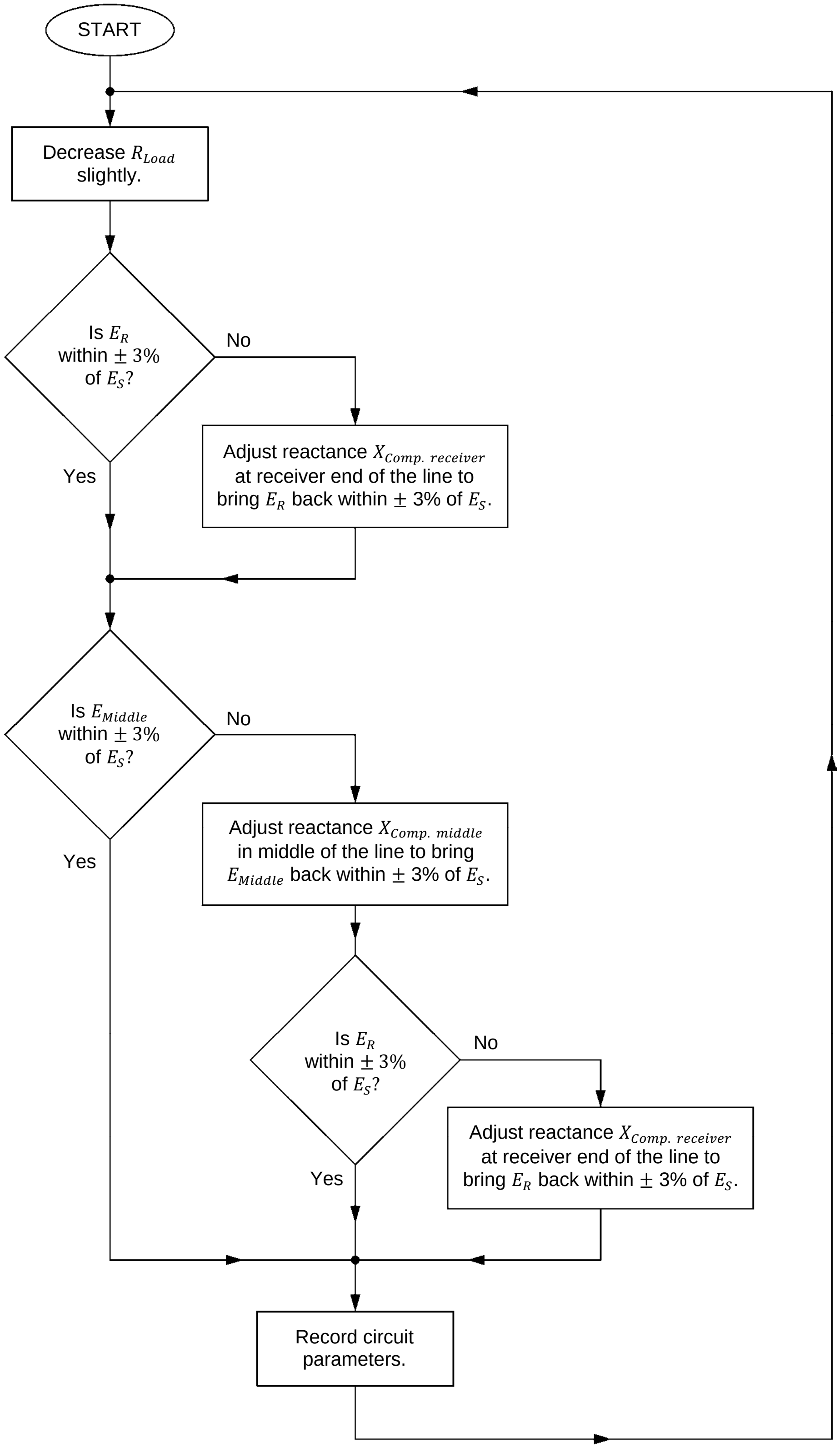


Figure 51. Algorithm used to control the distributed, switched shunt compensation.

13. Use the values of the receiver voltage E_R and active power P_{Load} recorded in the Data Table to plot the power-voltage curve of the ac transmission line obtained when distributed (i.e., in the middle of the line and at the receiver end of the line), switched shunt compensation (inductive and capacitive) is used for voltage compensation. Also, use the values recorded in the Data Table to plot, in the same graph, a curve of the sender voltage E_S as a function of the active power P_{Load}. This graph makes it easy to relate the receiver voltage E_R to the sender voltage E_S.

14. Compare the power-voltage curve of the 700 km (about 435 miles) ac transmission line obtained with distributed SSC (inductive and capacitive) plotted in the previous step to the power-voltage curve of the 350 km (about 217 miles) ac transmission line with SSC (inductive and capacitive) at the receiver end only plotted in step 37 of Exercise 3.

Is the 700 km (about 435 miles) ac transmission line with distributed SSC able to convey an amount of active power similar to that conveyed by the 350 km (about 217 miles) ac transmission line with SSC at the receiver end only, while maintaining the receiver voltage E_R within the voltage limits? Explain.

How does the line length affect voltage compensation of an ac transmission line?

15. Use the values of the voltage E_{Middle} in the middle of the line and active power P_{Load} recorded in the Data Table to plot the power-voltage curve in the middle of the ac transmission line that is obtained when distributed (in the middle of the line and at the receiver end of the line), switched shunt compensation (inductive and capacitive) is used for voltage compensation. Also, use the values recorded in the Data Table to plot, in the same graph, a curve of the sender voltage E_S as a function of the active power P_{Load}. This graph makes it easy to relate the voltage E_{Middle} to the sender voltage E_S.

16. Compare the no-load voltage in the middle of the 700 km (about 435 miles) ac transmission line with distributed SSC to the no-load voltage in the middle of the 700 km ac transmission line with SSC at the receiver end of the line only (measured and recorded in step 20 of Exercise 4). Does using distributed SSC prevent the no-load voltage in the middle of the line from significantly exceeding the sender voltage E_S? Explain.

____

____

____

____

____

Does using distributed SSC allow the voltage in the middle of the 700 km (about 435 miles) ac transmission line to be maintained close to the sender voltage E_S no matter the amount of active power the line conveys?

❑ Yes ❑ No

17. Use the values recorded in the Data Table to plot a curve of the phase shift δ between the receiver voltage E_R and the sender voltage E_S as a function of the active power P_{Load} that is obtained when the ac transmission line is voltage compensated using distributed (in the middle of the line and at the receiver end of the line), switched shunt compensation (inductive and capacitive). Also, use the values recorded in the Data Table to plot in the same graph, a curve of the phase shift δ_{Middle} between the voltage E_{Middle} in the middle of the line and the sender voltage E_S as a function of the active power P_{Load}.

18. Is the phase shift δ between the receiver voltage E_R and the sender voltage E_S directly proportional to the length of the ac transmission line? Explain briefly.

____

____

____

____

19. Do the values of the sender voltage E_S, voltage E_{Middle} in the middle of the line, receiver voltage E_R, active power P_{Load}, phase shift δ, and phase shift δ_{Middle} recorded in the Data Table confirm the equation below (already given in the discussion)? Explain.

$$P_{(Comp.)} = 3\left(\frac{E_S\,E_R}{X_L{}'}\sin\delta\right)$$

____

____

____

____

____

____

____

____

____

20. 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 that adding switched shunt compensation (SSC) in the middle of a high-voltage ac transmission line maintains the voltage at this point of the line close to the sender voltage E_S and modifies the whole voltage profile of the line markedly. You saw that long ac transmission lines can be divided into as many segments as required, and SSC can be applied at both ends of the line and between each line segment to obtain a satisfactory voltage profile. You learned that the maximal transmissible power $P_{Max.\,(Comp.)}$ of an ac transmission line that is voltage compensated using distributed SSC is equal to that of the longest segment of the line. Finally, you learned that the phase shift δ between the receiver voltage E_R and sender voltage E_S in a voltage-compensated ac transmission line, for any given value of active power $P_{(Comp.)}$, increases with the line length.

REVIEW QUESTIONS

1. Assume a long ac transmission line with switched shunt compensation (SSC) at both ends of the line only. What can be done when the voltage in the middle of this line exceeds the maximal voltage at which the line can operate? Explain.

____

____

____

____

____

2. Briefly explain what is distributed, switched shunt compensation (distributed SSC) of a long ac transmission line.

3. Which segment of a long ac transmission line that is voltage compensated using distributed SSC has the lowest maximal transmissible power? What does this imply?

4. How does the length of a voltage-compensated ac transmission line that is voltage compensated using distributed SSC affect the phase shift δ between the receiver voltage E_R and sender voltage E_S? Explain why.

5. Describe the effect which increasing the line length has on the stability of operation of an ac transmission line that is voltage compensated using SSC or distributed SSC. Explain briefly.

Control of the Active Power Flowing Through Voltage-Compensated AC Transmission Lines

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 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
- Introduction to the regulating autotransformer

DISCUSSION

Control of active power flow in interconnected power networks

In Exercise 3, you saw that the receiver voltage E_R lags behind the sender voltage E_S when active power is conveyed from the sender end to the receiver end of a voltage-compensated ac transmission line. The higher the active power $P_{(Comp.)}$ conveyed by the ac transmission line, the greater the phase shift δ between the receiver voltage E_R and the sender voltage E_S. This is consistent with the equation given in the discussion of Exercise 3 (repeated below) that relates the active power $P_{(Comp.)}$ to the sender voltage E_S, the receiver voltage E_R, the inductive reactance $X_L{}'$ in the corrected PI equivalent circuit of the line, and the phase shift δ between voltages E_S and E_R.

$$P_{(Comp.)} = 3\left(\frac{E_S\,E_R}{X_L{}'}\,\sin\delta\right) \tag{10}$$

Controlling the active power $P_{(Comp.)}$ conveyed by a voltage-compensated 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 line is always the sender and the other end is always the receiver. It is basically a matter of limiting the power demand (i.e., the load at the receiver end of the line) so that the maximal transmissible power $P_{Max.\ (Comp.)}$ is not exceeded. It is even common practice in ac power networks to limit the power demand to half the value of $P_{Max.\ (Comp.)}$. This limits the phase shift δ to values less than 30° and provides a safety margin of 100%, as mentioned in the discussion of Exercise 3.

Controlling the active power $P_{(Comp.)}$ conveyed by a voltage-compensated ac transmission line, however, is not always so simple. This is because ac power networks often have a more complex configuration, i.e., they often consist of several regions interconnected by several ac transmission lines instead of only two regions interconnected by a single ac transmission line. In such interconnected power networks, certain ac transmission lines do not have definite sender and receiver ends since the active power conveyed by these lines does not flow in the same direction at all times, depending on the power demand in the corresponding regions. In these conditions, it becomes increasingly difficult to coordinate the phase shift between the voltages at each region (node) of the power network with the amount of active power that needs to be exchanged between the various nodes of the power network.

For example, consider the diagram of the interconnected power network shown in Figure 52. In this figure, each dot represents a region that can consume or supply active power, and each line represents an ac transmission line.

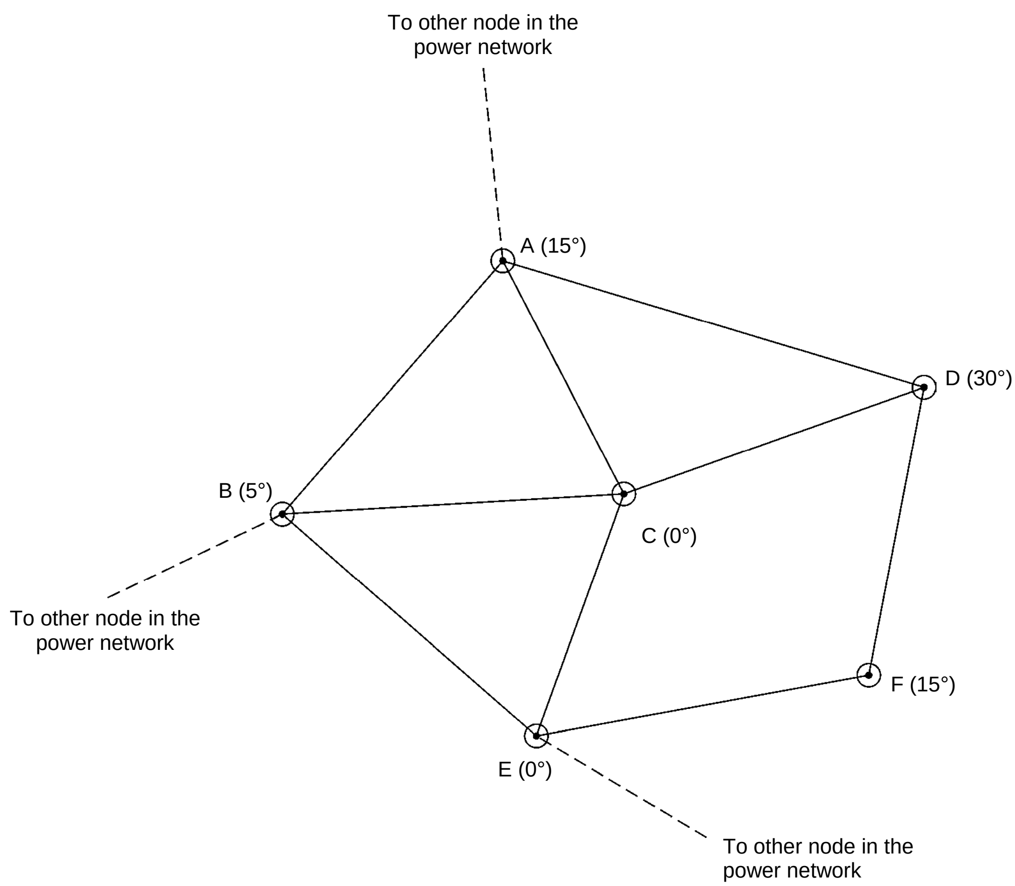
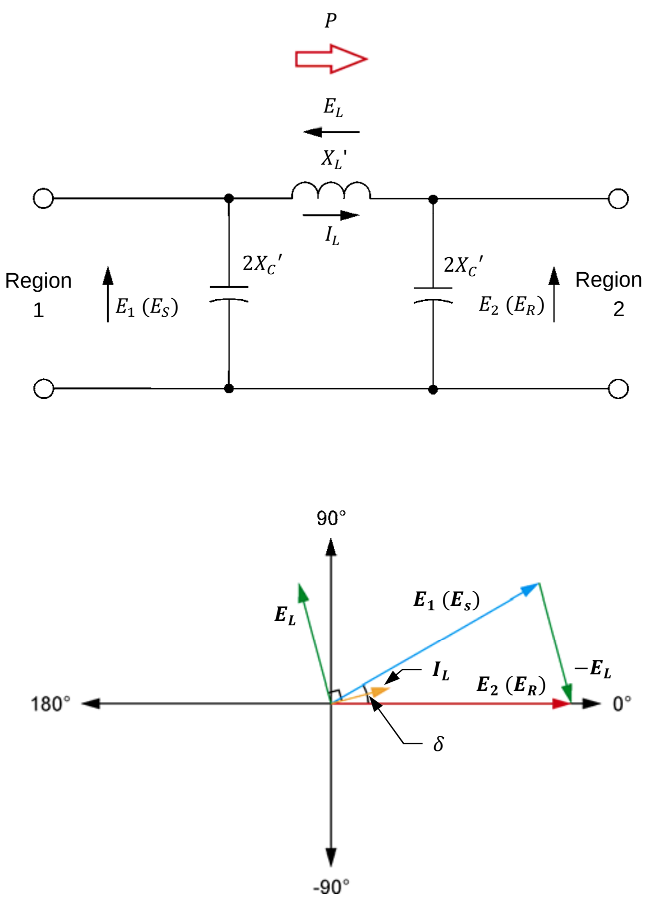


Figure 52. Diagram of an interconnected power network.

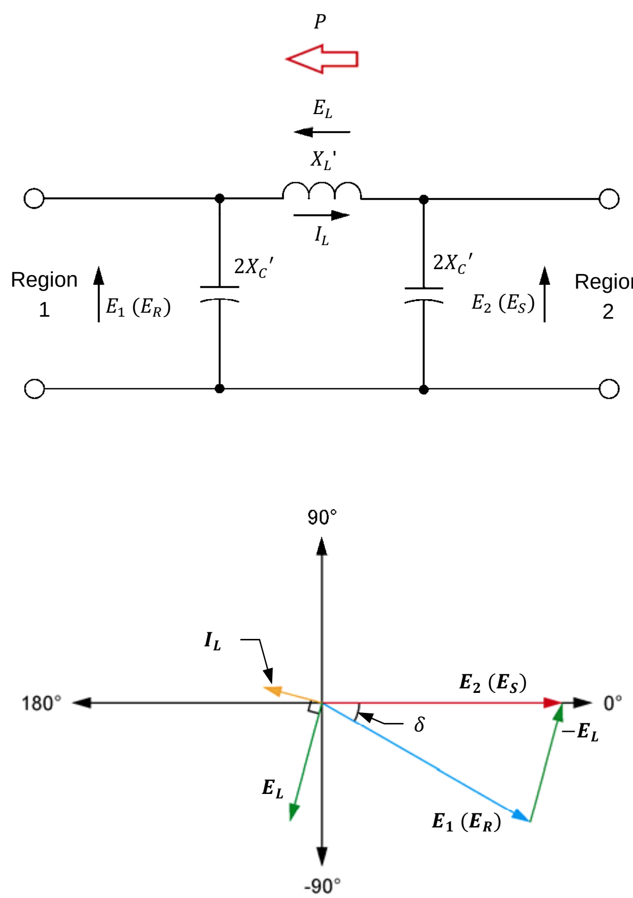
The portion of the interconnected power network illustrated in Figure 52 shows 6 regions that can be either a receiver (the region consumes active power) or a sender (the region supplies active power). Since the active power $P_{(Comp.)}$ transferred via a voltage-compensated ac transmission line is proportional to the phase shift δ between the voltages at both ends, only the regions between which there is a non-null phase shift can exchange active power. This is the case for all regions in the interconnected power network shown in Figure 52, except regions C and E which both have a phase angle of 0°, leading to a phase shift δ 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 δ 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 δ 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 between two regions and the corresponding phasor diagrams are illustrated in Figure 53.

In Figure 53, the switched shunt inductors and capacitors used for voltage compensation of the ac transmission line are not shown for clarity purposes.



(a) E_2 lagging behind E_1 (positive phase shift)



(b) E_2 leading E_1 (negative phase shift)

Figure 53. The direction of active power flow in a voltage-compensated ac transmission line of an interconnected power network depends on the polarity of the phase shift δ between the voltages at both ends of the line.

As Figure 53 shows, the direction of the flow of active power 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 corrected PI equivalent circuits of the ac transmission line in Figure 53, the phase shift δ 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 53a, the flow of active power is from region 1 to region 2 since voltage E_1 is leading voltage E_2, resulting in a phase shift that is positive when voltage E_2 is taken as the reference phasor. Conversely, in the circuit of Figure 53b, the flow of active power is from region 2 to region 1 since voltage E_1 is lagging behind voltage E_2, resulting in a phase shift that is negative when voltage E_2 is taken as the reference phasor.

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 between all regions of the power network. Figure 54 shows the diagram of the interconnected power network in Figure 52 with the direction of the flow of active power between each region.

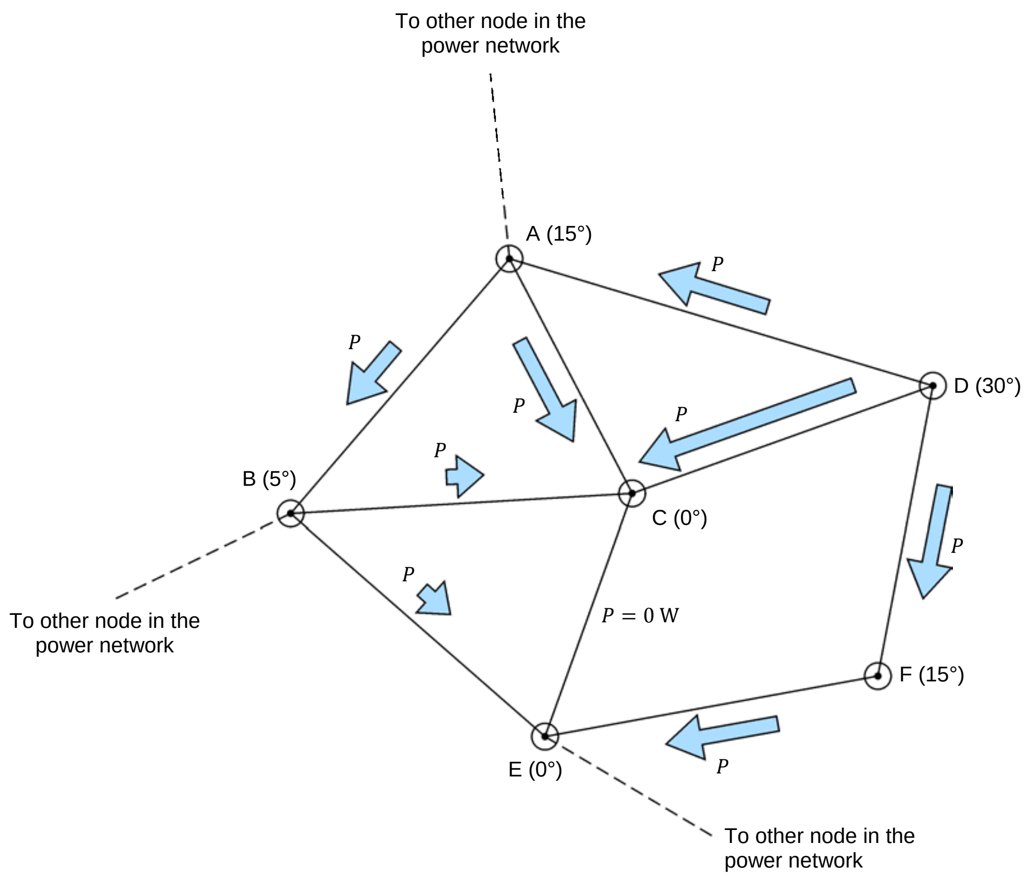


Figure 54. Diagram of the interconnected power network of Figure 52 with the direction of the flow of active power between each region.

Notice that the length of each arrow indicating the direction of active power flow, in Figure 54, 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 54 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 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 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 in the ac transmission lines is required 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. In this way, it is possible to control the flow of active power between two regions of an interconnected power network without modifying the phase angle at any of the regions.

Figure 55. Phase-shifting transformer used to control active power flow through an ac transmission line in an interconnected power network (©Siemens AG 2014, all rights reserved).

Figure 56 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 54. 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 Figure 56, without modifying the phase angle of the voltage at regions E and C. Conversely, if the phase-shifting transformer were adjusted so as to delay the phase angle of the voltage applied to the ac transmission line, this would cause active power to flow from region C to region E.

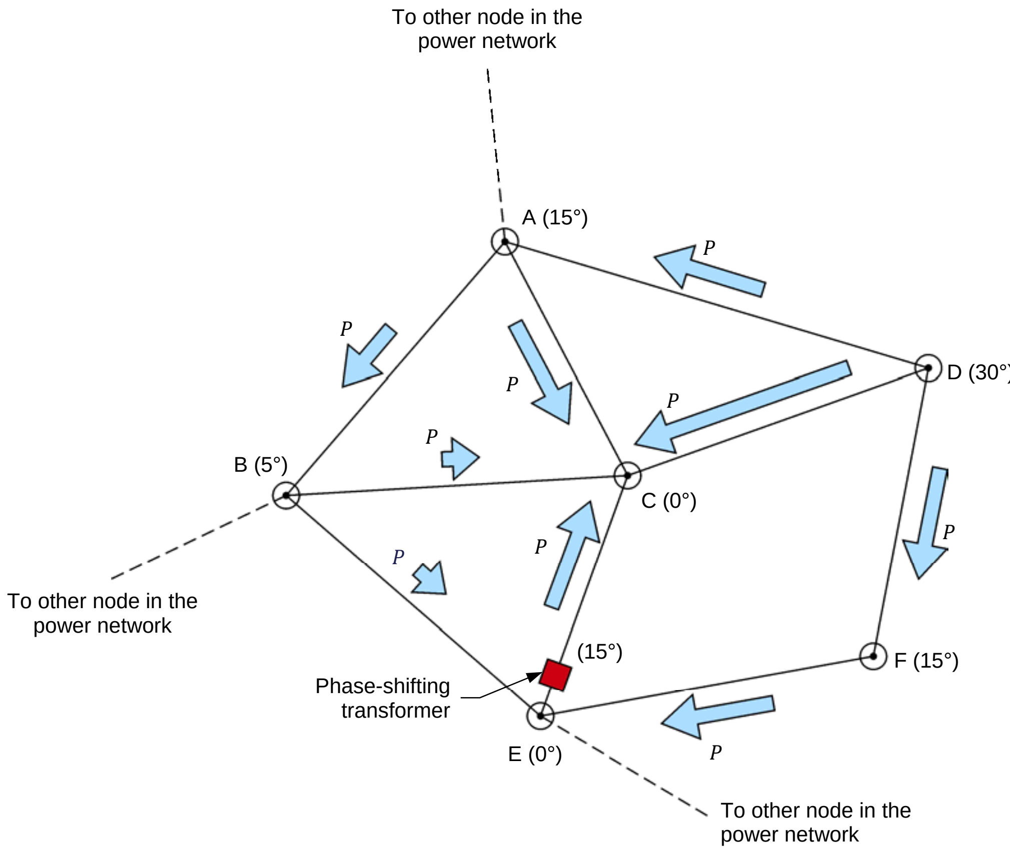


Figure 56. Diagram of the interconnected power network of Figure 54 when a phase-shifting transformer is added between region E and the ac transmission line going to region C.

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 in an ac transmission line. The active power can be controlled by decreasing or increasing the phase angle of 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 57.

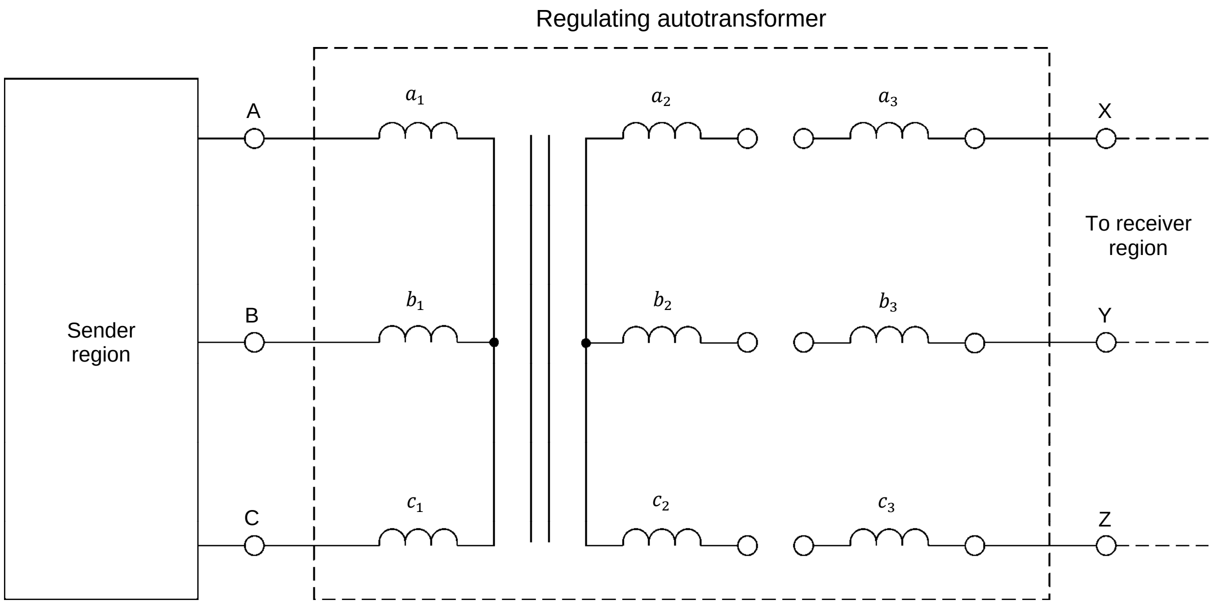
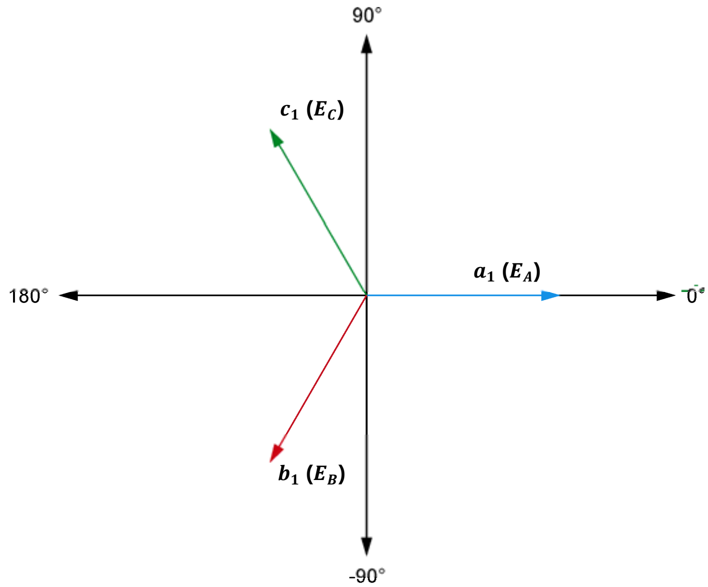


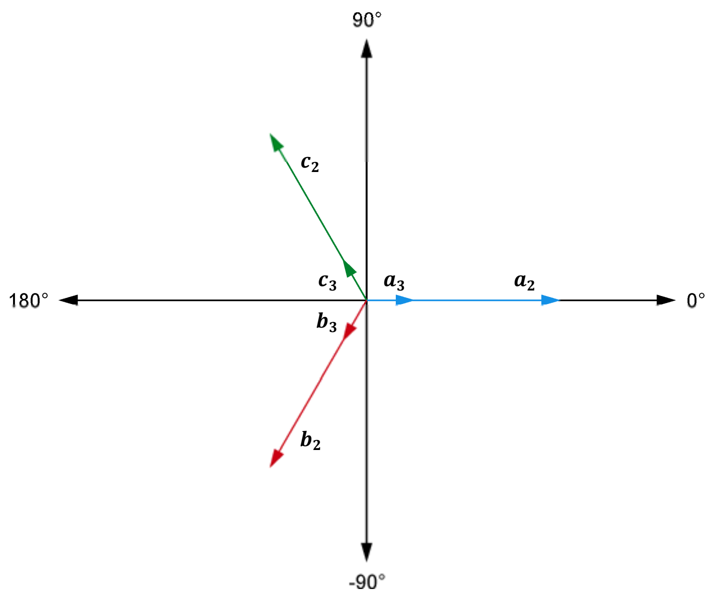
Figure 57. Equivalent circuit of a regulating autotransformer.

As Figure 57 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 58.

As Figure 58 shows, 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 59.



(a) Phasor diagram of the voltages at the primary windings



(b) Phasor diagram of the voltages at the secondary and tertiary windings

Figure 58. Phasor diagrams of the voltages at the primary, secondary, and tertiary windings of the regulating autotransformer in Figure 57.

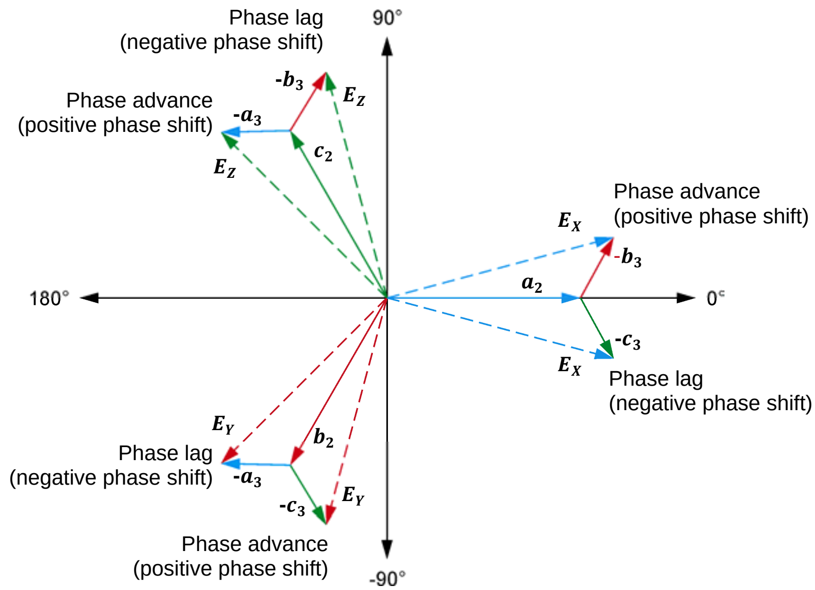


Figure 59. Phasor diagrams of the regulating autotransformer when it acts as a phase-shifting transformer.

Figure 59 shows that, 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 59 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 to keep it 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 regulating 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 autotransformer.

Figure 60 shows a phasor diagram of the various outgoing voltages possible at one phase of a regulating autotransformer acting as both a phase-shifting transformer and a buck-boost transformer.

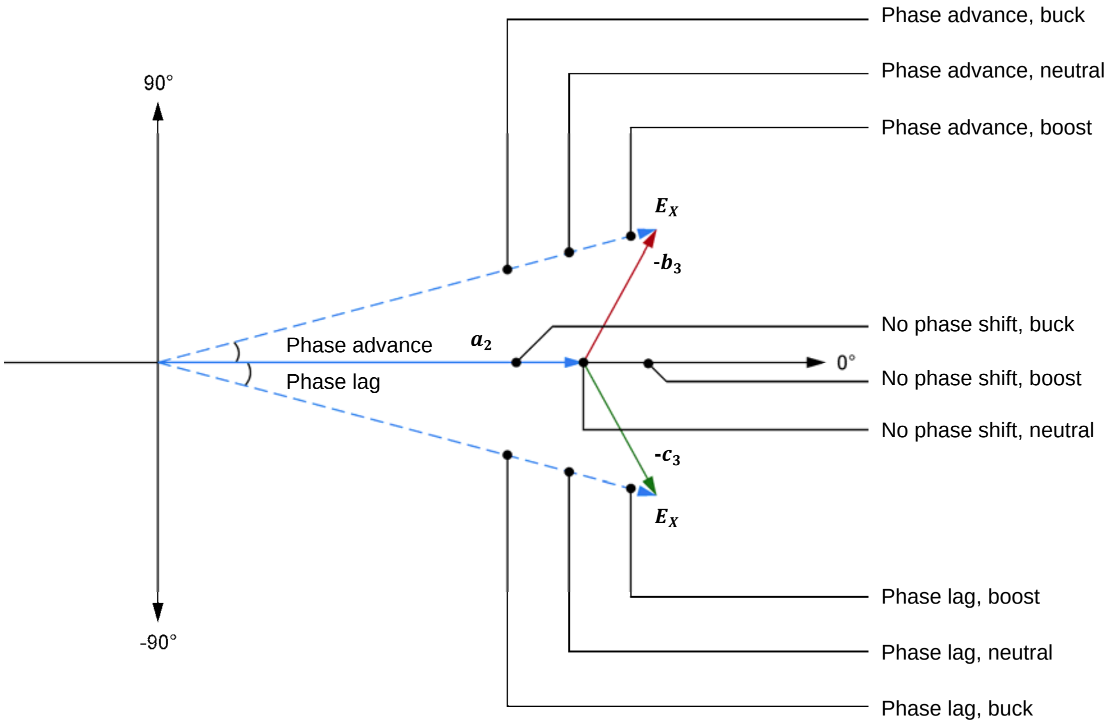


Figure 60. Phasor diagram of the outgoing voltages possible at one phase of a regulating autotransformer acting as both a phase-shifting transformer and a buck-boost transformer.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Controlling the active power flow in an interconnected power network

PROCEDURE

⚠ WARNING

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 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 set the measuring equipment to measure the parameters of 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.

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. 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 circuit shown in Figure 61, which represents an ac transmission line interconnecting two regions (A and B) in an interconnected ac power network. Each of the three inductors in the ac transmission line is implemented using one phase of the Three-Phase Transmission Line. Each of the three capacitors at each end of the ac transmission line is implemented with one capacitor section (group of 3 parallel-connected capacitors) in a Capacitive Load module.

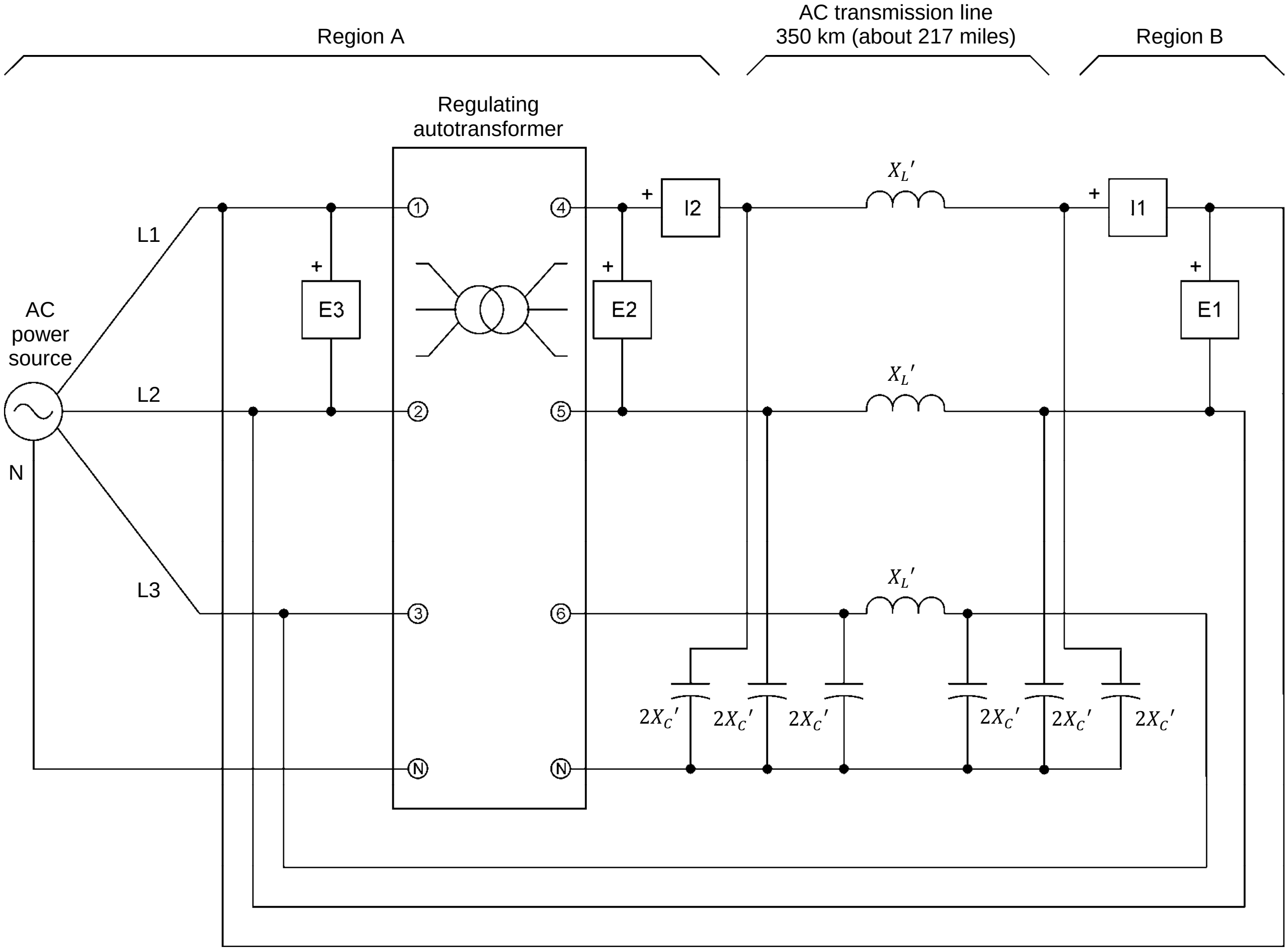
   No switched shunt compensation (SSC) is required at both ends of the ac transmission line for voltage compensation. This is because the reactive power required at the sender and receiver ends of the line for voltage compensation is provided by the three-phase ac power source. In other words, the ac transmission line in the figure below is voltage compensated even if no SSC is used.

   Region A and region B are identified on the circuit diagram of Figure 61. 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 δ 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 *E2* and *I2* measure the voltage $E'_{Reg.\ A}$ at region A after modification by the Regulating Autotransformer and the line current $I_{Reg.\ A}$ at region A, respectively. Inputs *E1* and *I1* measure the voltage $E_{Reg.\ B}$ and the line current $I_{Reg.\ B}$ at region B, respectively.

6. On the Three-Phase Transmission Line, make sure that the I/O toggle switch is set to the I position, then set the reactance X_L' of the line inductors to the value indicated in the table of Figure 61.

   On the Capacitive Load modules, set the reactance $2X_C'$ of the capacitors at both ends of the line to the value indicated in the table of Figure 61.

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



Local ac power network		X_L' (Ω)	$2X_C'$ (Ω)
Voltage (V)	Frequency (Hz)		
120	60	120	1200
220	50	400	4400
240	50	400	4800
220	60	400	4400

Figure 61. Circuit used to observe active power flow control in an ac transmission line (voltage-compensated) of an interconnected power network.

7. In LVDAC-EMS, open the Metering window, then open the Acquisition Settings dialog box. Set the *Sampling Window* to 8 cycles, then click *OK* to close the dialog box. This provides better accuracy when measuring certain parameters of the ac transmission line.

   In the Metering window, set three meters to measure the rms values of the voltage $E_{Reg.\ A}$ at region A (input *E3*), the voltage $E'_{Reg.\ A}$ at region A after modification by the Regulating Autotransformer (input *E2*), and the voltage $E_{Reg.\ B}$ at region B (input *E1*). Set another meter to measure the phase shift δ between the voltages $E'_{Reg.\ A}$ and $E_{Reg.\ B}$ at both ends of the ac transmission line [*PS(E1,E2)*].

   The phase shift δ indicated by the phase shift meter is with respect to the voltage $E_{Reg.\ B}$, i.e., it is equal to the phase angle of voltage $E'_{Reg.\ A}$ minus the phase angle of voltage $E_{Reg.\ B}$. Therefore, positive values of phase shift δ indicate that voltage $E'_{Reg.\ A}$ leads voltage $E_{Reg.\ B}$.

   Finally, set two other meters to measure the three-phase active power $P_{Reg.\ A}$ at region A [*PQS2 (E2,I2) 3~*] and the three-phase active power $P_{Reg.\ B}$ at region B [*PQS1 (E1,I1) 3~*].

   Metering functions PQS2 (E2,I2) 3~ and PQS1 (E1,I1) 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.

   Set the meters to continuous refresh mode.

8. In LVDAC-EMS, open the Phasor Analyzer. Make the required settings to observe the phasors of the voltage $E_{Reg.\ A}$ at region A (input *E3*), the voltage $E'_{Reg.\ A}$ at region A after modification by the Regulating Autotransformer (input *E2*), and the voltage $E_{Reg.\ B}$ at region B (input *E1*). Set the phasor of voltage $E_{Reg.\ B}$ as the reference phasor. Set the Phasor Analyzer to continuous refresh mode.

Controlling the active power flow in an interconnected power network

In this section, you will change the phase shift δ between the voltages at both ends of the ac transmission line and observe the effect that this has on the active power flow in the line.

9. On the Power Supply, turn the three-phase ac power source on.

   On the Phasor Analyzer, adjust the voltage sensitivity as required.

10. Observe the values indicated by the various meters in the Metering window. Also, observe the phasors of voltages $E_{Reg.\ A}$, $E'_{Reg.\ A}$, and $E_{Reg.\ B}$ displayed on the Phasor Analyzer. Record the circuit parameters below.

Voltage $E_{Reg.\ A}$ = _______ V

Phase angle of voltage $E_{Reg.\ A}$ = _______ °

Voltage $E'_{Reg.\ A}$ = _______ V

Phase angle of voltage $E'_{Reg.\ A}$ = _______ °

Voltage $E_{Reg.\ B}$ = _______ V

Phase angle of voltage $E_{Reg.\ B}$ = _______ °

Phase shift δ = _______ °

Three-phase active power $P_{Reg.\ A}$ = _______ W

Three-phase active power $P_{Reg.\ B}$ = _______ W

Does active power flow from one region to the other via the ac transmission line? Explain briefly.

Positive values of active power indicate that active power flows from region A to region B, while negative values of active power indicate that active power flows from region B to region A.

____

____

____

11. On the Regulating Autotransformer, set the *Phase Shift* selector to +15°.

12. Observe the values indicated by the various meters in the Metering window. Also, observe the phasors of voltages $E_{Reg.\ A}$, $E'_{Reg.\ A}$, and $E_{Reg.\ B}$ displayed on the Phasor Analyzer. Record the circuit parameters below.

Voltage $E_{Reg.\ A}$ = _______ V

Phase angle of voltage $E_{Reg.\ A}$ = _______ °

Voltage $E'_{Reg.\ A}$ = _______ V

Phase angle of voltage $E'_{Reg.\ A}$ = _______ °

Voltage $E_{Reg.\ B}$ = _______ V

Phase angle of voltage $E_{Reg.\ B}$ = _______ °

Phase shift δ = _______ °

Three-phase active power $P_{Reg.\ A}$ = _______ W

Three-phase active power $P_{Reg.\ B}$ = _______ W

Does active power flow from one region to the other via the ac transmission line? Explain briefly.

____

____

____

Does phase shifting the voltage at one end of the ac transmission line using the Regulating Autotransformer affect the phase angle of the voltage $E_{Reg.\,A}$ at region A or the phase angle of the voltage $E_{Reg.\,B}$ at region B?

____

____

____

13. On the Regulating Autotransformer, set the *Phase Shift* selector to -15°.

14. Observe the values indicated by the various meters in the Metering window. Also, observe the phasors of voltages $E_{Reg.\ A}$, $E'_{Reg.\ A}$, and $E_{Reg.\ B}$ displayed on the Phasor Analyzer. Record the circuit parameters below.

Voltage $E_{Reg.\ A}$ = _______ V

Phase angle of voltage $E_{Reg.\ A}$ = _______ °

Voltage $E'_{Reg.\ A}$ = _______ V

Phase angle of voltage $E'_{Reg.\ A}$ = _______ °

Voltage $E_{Reg.\ B}$ = _______ V

Phase angle of voltage $E_{Reg.\ B}$ = _______ °

Phase shift δ = _______ °

Three-phase active power $P_{Reg.\ A}$ = _______ W

Three-phase active power $P_{Reg.\ B}$ = _______ W

Does active power flow from one region to the other via the ac transmission line? Explain briefly.

---

15. Are the results you obtained in steps 12 and 14 coherent with the equation (shown below) that relates the active power $P_{(Comp.)}$ conveyed by a voltage-compensated ac transmission line to the sender voltage E_S, the receiver voltage E_R, the inductive reactance $X_L{}'$ in the corrected PI equivalent circuit of the line, and the phase shift δ between voltages E_S and E_R? Explain briefly.

The line-to-line voltage values recorded in steps 12 and 14 must be divided by $\sqrt{3}$ before using them in the equation below.

$$P_{(Comp.)} = 3\left(\frac{E_S\,E_R}{X_L{}'}\sin\delta\right)$$

---

16. 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 that in ac power networks consisting of several regions interconnected by voltage-compensated ac transmission lines, only the regions where there is a non-null phase shift δ between the voltages at both ends of the line exchange active power. You learned that the direction of active power flow in a voltage-compensated ac transmission line of an interconnected power network depends on the polarity of the phase shift δ between the voltages at both ends of the line. You learned that phase-shifting transformers provide a means to control active power flow through ac transmission lines in interconnected power networks. You became familiar with the operation of regulating autotransformers, which can act as either phase-shifting transformers or buck-boost transformers, and thus can be used to control active power flow in interconnected power networks.

Review Questions

1. In a voltage-compensated ac transmission line of an interconnected power network, what determines the amount of active power $P_{(Comp.)}$ transferred through this line? Explain.

2. In a voltage-compensated ac transmission line of an interconnected power network, what determines the direction of active power flow?

3. Determine the direction of active power flow between regions A and B in an interconnected power network when the voltage at region A is leading the voltage at region B.

4. Briefly describe what a phase-shifting transformer is.

5. What can be done to control the flow of active power in ac transmission lines of a complex interconnected power network? Explain.

Equipment Utilization Chart

The following equipment is required to perform the exercises in this manual.

Equipment							
Model	**Description**	**1**	**2**	**3**	**4**	**5**	**6**
8134[1]	Workstation	1	1	1	1	1	1
8311[2]	Resistive Load	1	1	1	1	1	
8321	Inductive Load	1		1	1	2	
8329	Three-Phase Transmission Line	1	1	1	1	1	1
8331	Capacitive Load	1	1	2	2	3	2
8349	Regulating Autotransformer						1
8823	Power Supply	1	1	1	1	1	1
8951-L	Connection Leads	1	1	1	1	1	1
8951-N	Connection Leads	1	1	1	1	1	1
8990	Host Computer	1	1	1	1	1	1
9063-B[3]	Data Acquisition and Control Interface	1	1	1	1	1	1
30004-2	24 V AC Power Supply	1	1	1	1	1	1

(1) The Mobile Workstation, Model 8110 can also be used.

(2) Resistive Load unit with voltage rating corresponding to your local ac power network voltage. Use model variant -00, -01, -02, -05, -06, -07, or -0A.

(3) Model 9063-B consists of the Data Acquisition and Control Interface, Model 9063, with the Computer-Based Instrumentation function set, Model 9069-1.

Glossary of New Terms

buck-boost transformer

A buck-boost transformer is a special type of power transformer that has the ability to decrease (buck) or increase (boost) the value of incoming voltages.

characteristic impedance Z_0

The value of the load impedance (i.e., the resistance in the case of a purely resistive load) required at the receiver end of an ac transmission line to make the receiver voltage E_R equal to the sender voltage E_S. The characteristic impedance Z_0 of an ac transmission line is also referred to as the surge impedance. The value of the characteristic impedance Z_0 depends on the fundamental electrical characteristics (i.e., the inductive and capacitive reactance per unit of length) of the ac transmission line.

corrected PI (π) equivalent circuit

The corrected PI equivalent circuit of a high-voltage ac transmission line is a reduction, obtained through mathematical calculations, of the distributed-parameter equivalent circuit of this line. It takes the form of a lumped-parameter equivalent circuit having the same configuration (reminiscent of the Greek letter π) as the equivalent circuit of a short segment of the high-voltage ac transmission line. The characteristics and behavior observed with the corrected PI equivalent circuit of an ac transmission line are very similar to those of actual high-voltage ac transmission lines.

distributed, switched shunt compensation (distributed SSC)

Technique used for voltage compensation of long high-voltage ac transmission lines. This method consists in dividing a long high-voltage ac transmission line into as many segments as required, and applying SSC at both the sender and receiver ends of the line and between each line segment, to obtain a satisfactory voltage profile.

distributed-parameter equivalent circuit

Equivalent electric circuit of a short segment (e.g., 1 km or 1 mile) of a high-voltage ac transmission line (one phase only) repeated as many times as required to obtain the equivalent electric circuit of the complete ac transmission line. This equivalent circuit is not well suited for the study of ac transmission lines because resolving this circuit is complex and time consuming.

natural load P_0

The natural load P_0 is the active power delivered to a resistive load whose resistance is equal to the characteristic impedance Z_0 of an ac transmission line. The natural load P_0 of an ac transmission line is also referred to as the surge impedance load (SIL).

phase-shifting transformer

A phase-shifting transformer is a special type of three-phase power transformer that has the ability to introduce a phase shift (usually ranging between about +30° to about -30°) between the incoming voltages and the outgoing voltages. Because of this ability, phase-shifting transformers can be used to control the flow of active power in ac transmission lines of an interconnected power network.

receiver end In an ac transmission line, the receiver end of the line is the end that receives active power from the other end (sender end) of the line.

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. The active power P can be controlled by decreasing or increasing the phase angle of the incoming voltages.

sender end In an ac transmission line, the sender end of the line is the end that supplies active power to the other end (receiver end) of the line.

surge impedance See "Characteristic impedance Z_0".

surge impedance load See "Natural load P_0".

switched shunt compensation (SSC) Voltage compensation of a high-voltage ac transmission lines using banks of switched shunt inductors, and also banks of switched shunt capacitors when the line has to operate at load levels well beyond the natural load P_0. Switched shunt compensation modifies the capacitive reactance X_C of the line so that the characteristic impedance ($Z_{0\ Comp.}$) of the compensated line is as close as possible to the load resistance. In other words, switched shunt compensation makes an ac transmission line virtually balanced, and keeps the receiver voltage E_R close to the sender voltage E_S, at any load value. Because of this, switched shunt compensation is also referred to as characteristic impedance compensation or surge impedance compensation.

transmission line Transmission lines are the element in a power network that transfers electrical power from the power generating stations to the electrical distribution system. Electrical power is generally transferred over a long distance in transmission lines that operate at a very high voltage to keep the line conductors to a reasonable size and limit the power losses in the line conductors. Most transmission lines carry three-phase alternating current (ac) and are aerial (i.e., supported by large towers) rather than underground.

voltage regulation The voltage regulation of an ac transmission line indicates the extent of the variation in the receiver voltage E_R that occurs when the load connected to the ac transmission line varies. The voltage regulation characteristic of an ac transmission line mainly depends on the type of load at the receiver end of the ac transmission line, and on the value of the inductive reactance X_L of the ac transmission line.

Impedance Table for the Load Modules

The following table gives impedance values which can be obtained using either the Resistive Load, Model 8311, the Inductive Load, Model 8321, or the Capacitive Load, Model 8331. Figure 62 shows the load elements and connections. Other parallel combinations can be used to obtain the same impedance values listed.

Table 18. Impedance table for the load modules.

Impedance (Ω)			Position of the switches								
120 V 60 Hz	**220/230 V 50 Hz/60 Hz**	**240 V 50 Hz**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1200	4400	4800	I								
600	2200	2400		I							
300	1100	1200			I						
400	1467	1600	I	I							
240	880	960	I		I						
200	733	800		I	I						
171	629	686	I	I	I						
150	550	600	I			I	I	I			
133	489	533		I		I	I	I			
120	440	480			I		I	I			
109	400	436			I	I	I	I			
100	367	400	I		I	I	I	I			
92	338	369		I	I	I	I	I			
86	314	343	I	I	I	I	I	I			
80	293	320	I			I	I	I	I	I	I
75	275	300		I		I	I	I	I	I	I
71	259	282			I		I	I	I	I	I
67	244	267			I	I	I	I	I	I	I
63	232	253	I		I	I	I	I	I	I	I
60	220	240		I	I	I	I	I	I	I	I
57	210	229	I	I	I	I	I	I	I	I	I

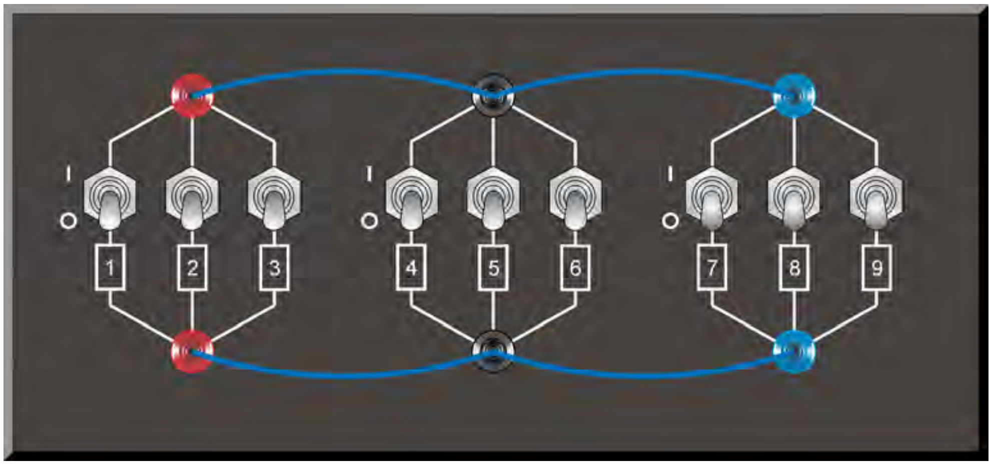


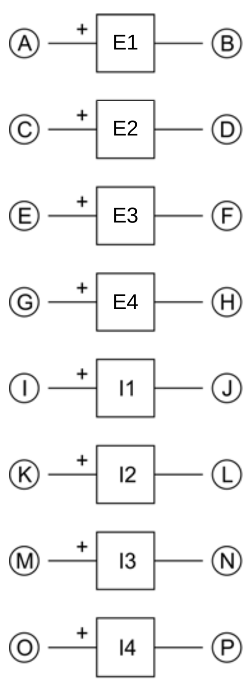
Figure 62. Location of the load elements on the Resistive Load, Inductive Load, and Capacitive Load, Models 8311, 8321, and 8331, respectively.

Circuit Diagram Symbols

Various symbols are used in the circuit diagrams of this manual. Each symbol is a functional representation of a particular electrical device that can be implemented using the equipment. The use of these symbols greatly simplifies the number of interconnections that need to be shown on the circuit diagram, and thus, makes it easier to understand the circuit operation.

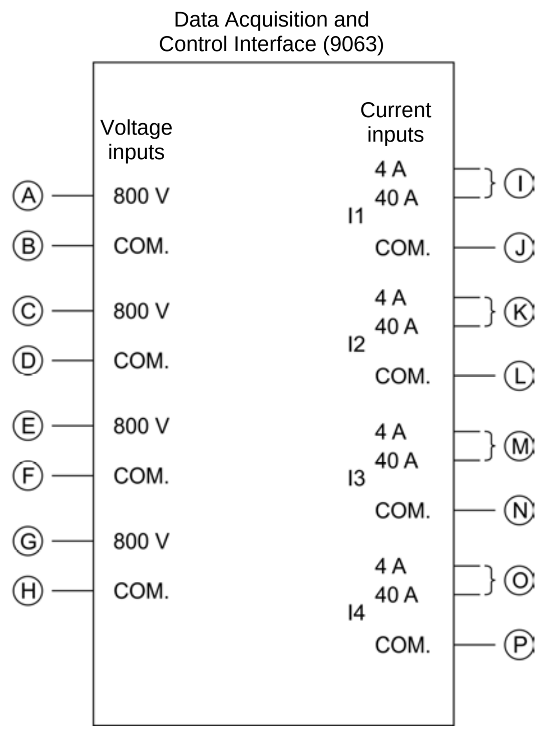
For each symbol other than those of power sources, resistors, inductors, and capacitors, this appendix gives the name of the device which the symbol represents, as well as the equipment and the connections required to properly connect the device to a circuit. Notice that the terminals of each symbol are identified using circled letters. The same circled letters identify the corresponding terminals in the Equipment and Connections diagram. Also notice that the numbers (when present) in the Equipment and Connections diagrams correspond to terminal numbering used on the actual equipment.

Symbol



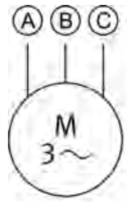
Isolated voltage and current measurement inputs

Equipment and Connections



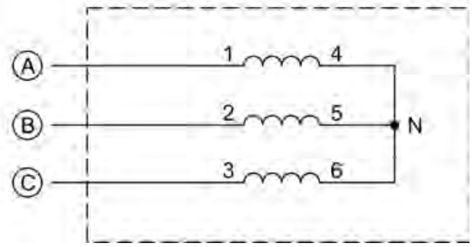
When a current at inputs I1, I2, I3, or I4 exceeds 4 A (either permanently or momentarily), use the corresponding 40 A input terminal and set the Range parameter of the corresponding input to High in the Data Acquisition and Control Settings window of LVDAC-EMS.

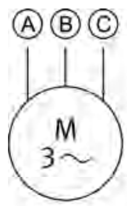
Symbol	**Equipment and Connections**



Three-phase
induction machine

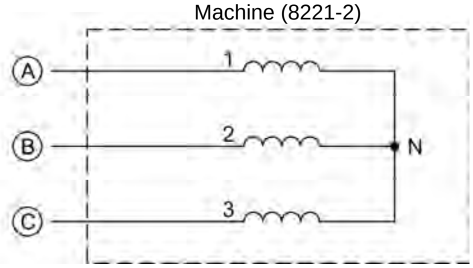
Four-Pole Squirrel Cage Induction
Motor (8221-0)

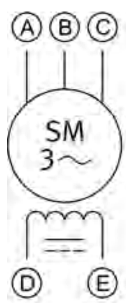




Three-phase
induction machine

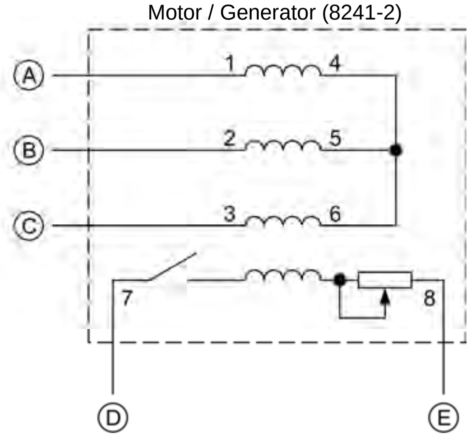
Three-Phase Induction
Machine (8221-2)

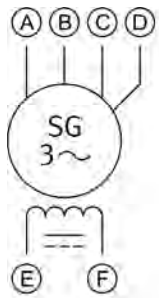
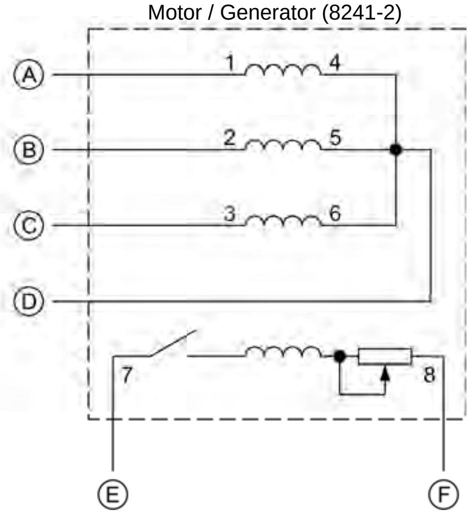
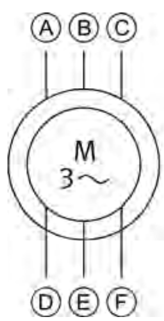
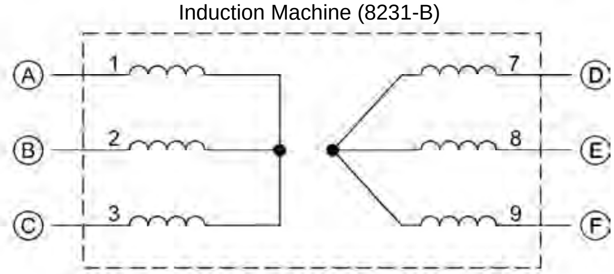




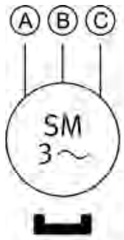
Three-phase synchronous
motor

Synchronous
Motor / Generator (8241-2)



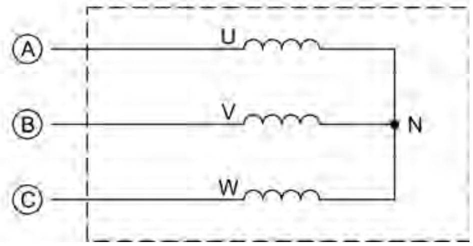
Symbol	**Equipment and Connections**
 Three-phase synchronous generator	Synchronous Motor / Generator (8241-2) 
 Three-phase wound-rotor induction machine	Three-Phase Wound-Rotor Induction Machine (8231-B) 

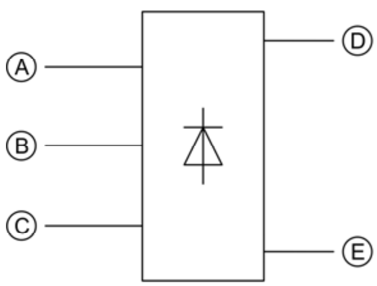
Symbol	Equipment and Connections



Permanent Magnet
Synchronous Machine

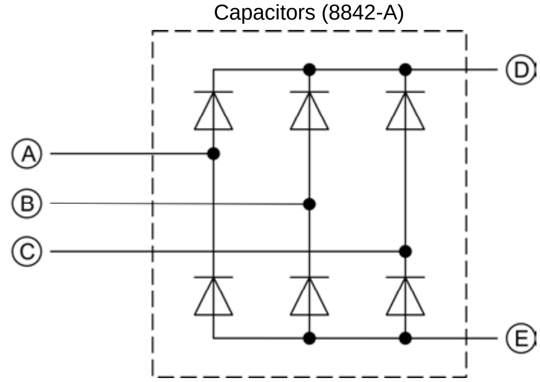
Permanent Magnet
Synchronous Machine (8245)

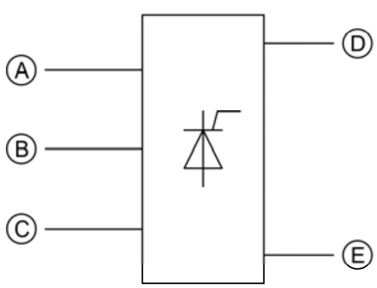




Power diode three-phase
full-wave rectifier

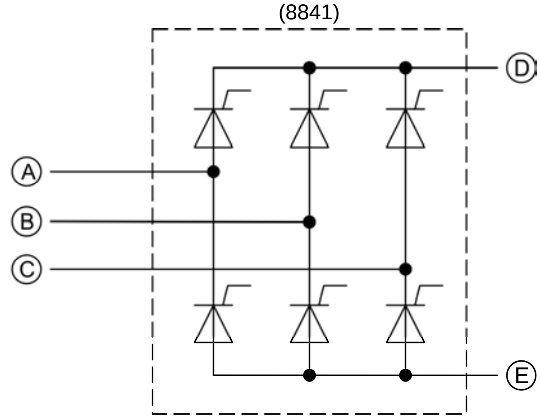
Rectifier and Filtering
Capacitors (8842-A)

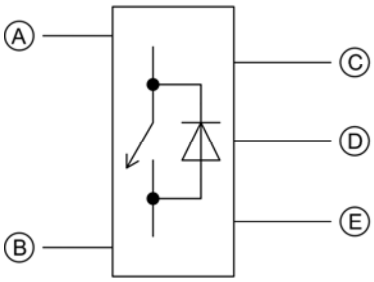
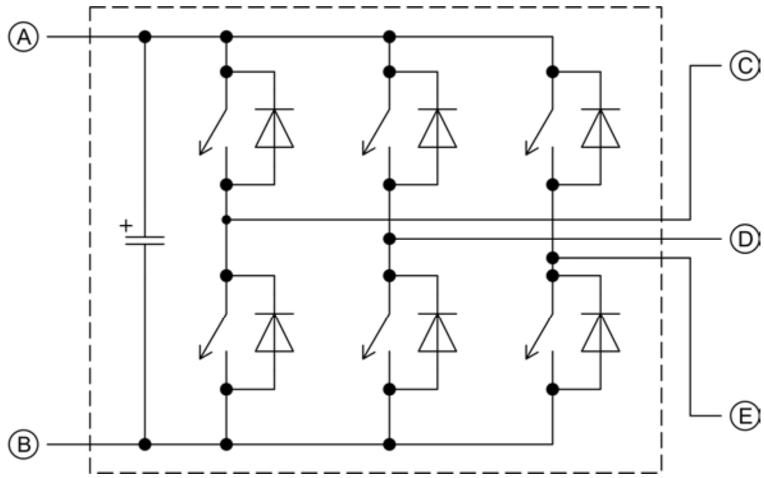




Power thyristor
three-phase bridge

Power Thyristors
(8841)



Symbol	**Equipment and Connections**
 Three-phase inverter	IGBT Chopper / Inverter (8837-B) 

The electronic switch symbol in the three-phase inverter above replaces MOSFET or IGBT symbols. It is not an IEC or ANSI symbol.

Index of New Terms

The bold page number indicates the main entry. Refer to the Glossary of New Terms for definitions of new terms.

Bibliography

Acha E., Agelidis V.G., Anaya-Lara O., Miller T.J.E., *Power Electronic Control in Electrical Systems*, Oxford: Newnes, 2002, ISBN 0-7506-5126-1

Boylestad, Robert L., *Introductory Circuit Analysis*, 11th ed., Upper Saddle River: Prentice Hall, 2006, ISBN 978-0131730441.

Duncan Glover, J. and Sarma, Mulukutla S. and Overbye, Thomas J., *Power Systems Analysis and Design*, 5th ed., Stamford: Cengage Learning, 2012, ISBN 978-1-111-42577-7.

Wildi, Theodore, *Electrical Machines, Drives, and Power Systems*, 6th ed., Upper Saddle River: Prentice Hall, 2005, ISBN 978-0131776913.