Electricity and New Energy

AC Transmission Lines

Courseware Sample

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Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

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

Safety and Common Symbols

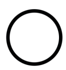
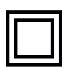
Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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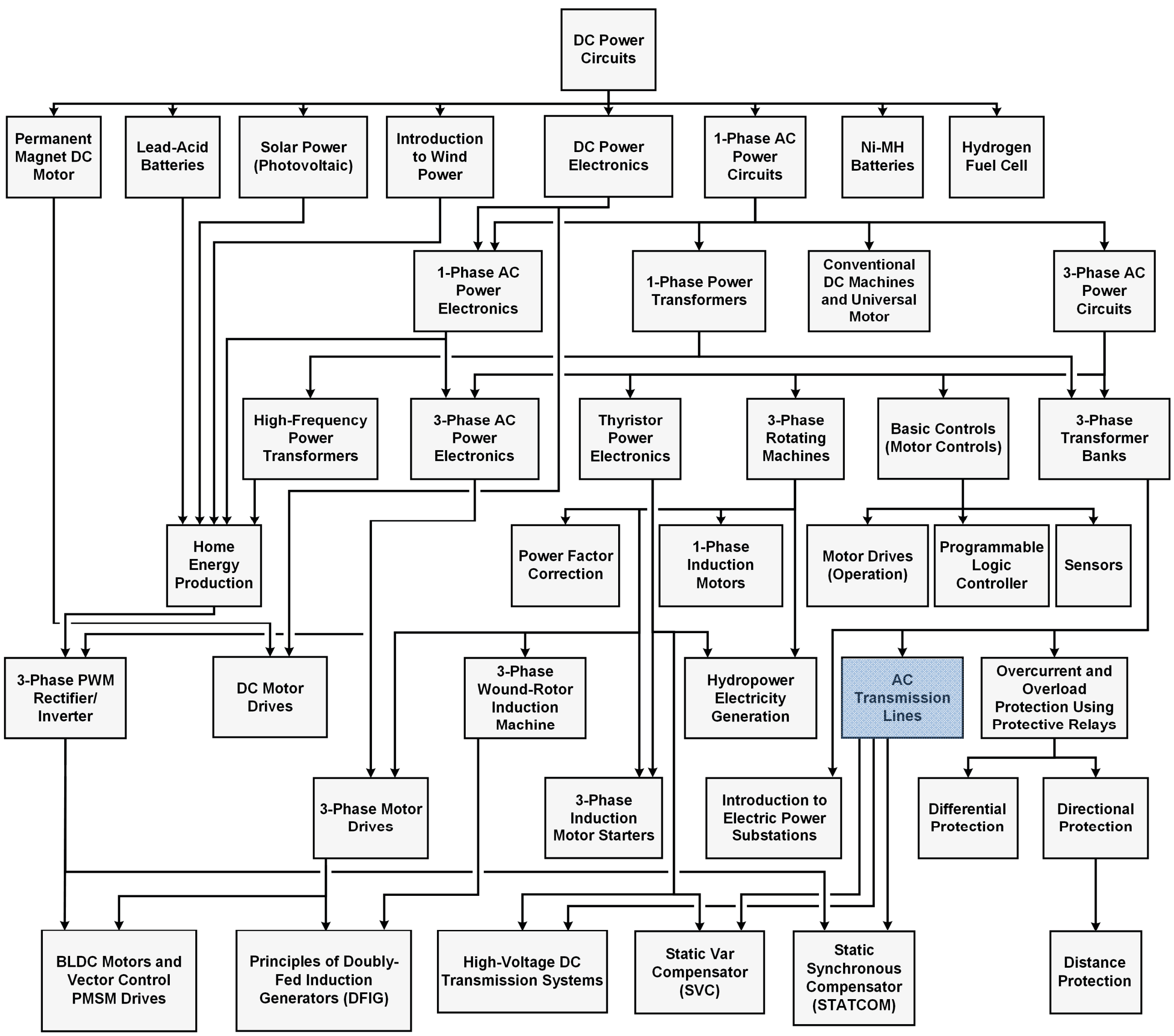
Table of Contents

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.

To the Instructor

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

Accuracy of measurements

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

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Electric Power Technology Training Equipment must have been properly installed, according to the instructions given in the user guide Electric Power Technology Training Equipment.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

Exercise 5

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.

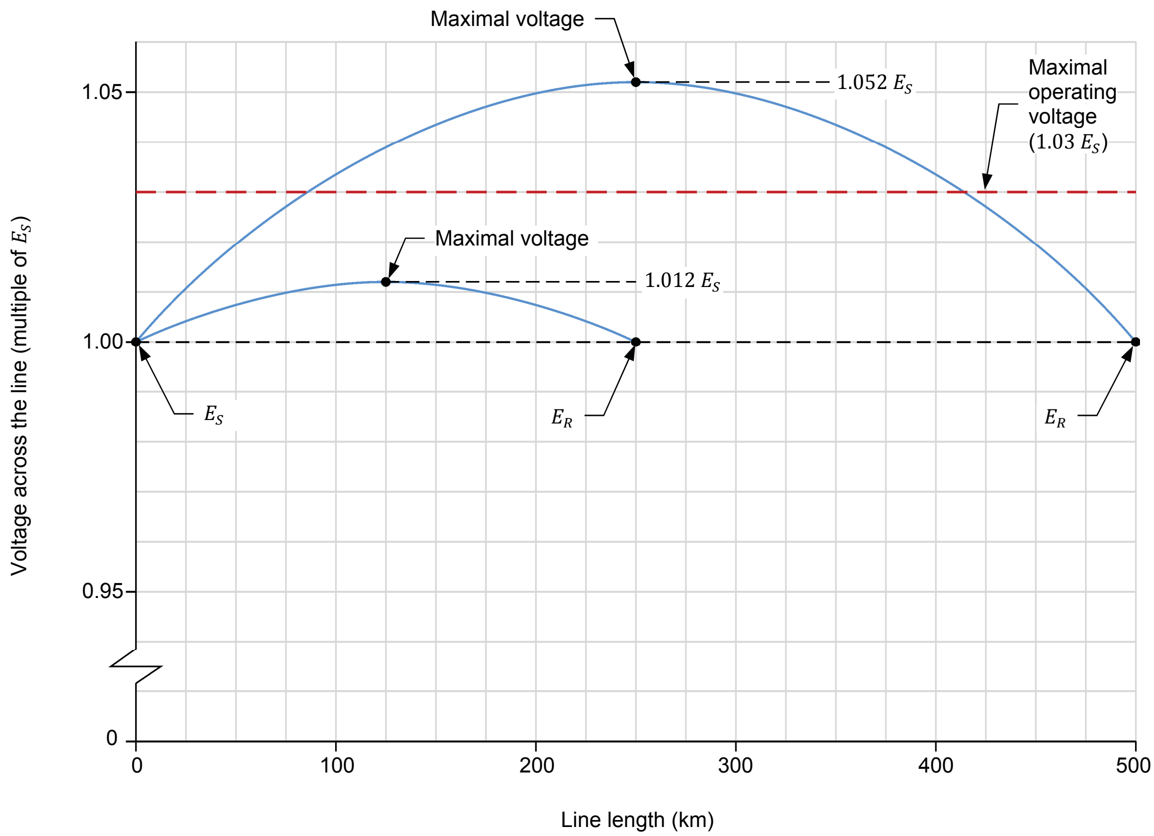


Figure 45. Voltage profiles along the 250 km (155 miles) and 500 km (310 miles) ac transmission lines shown in the discussion of Exercise 4 when they are voltage compensated using switched shunt compensation at both ends and operate without load.

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.

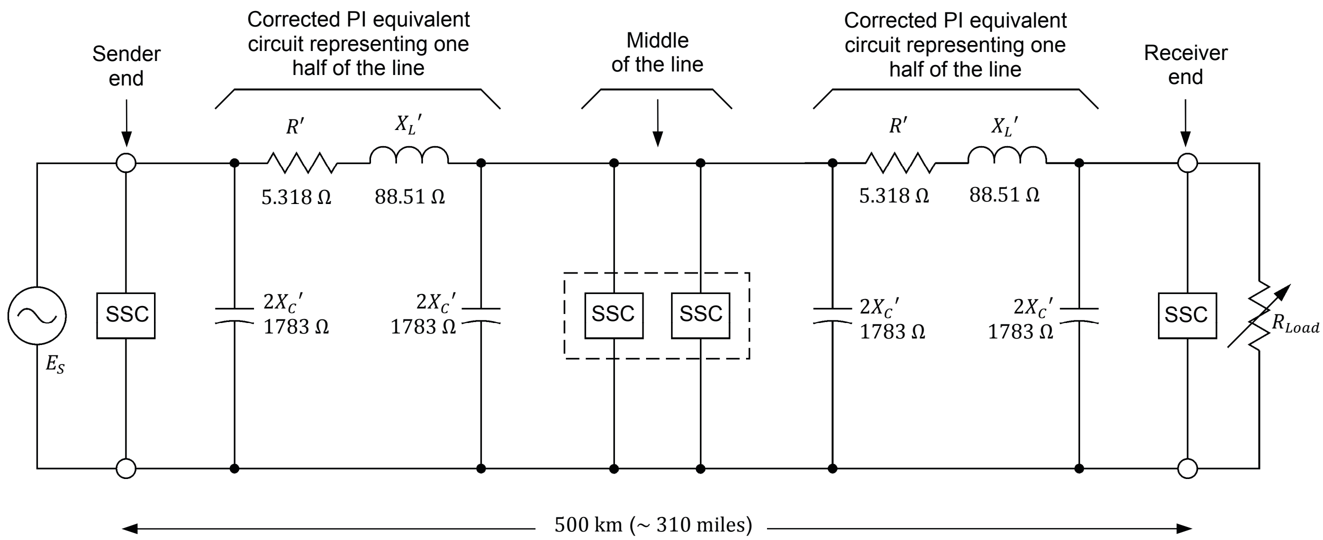


Figure 46. 500 km (about 310 miles) ac transmission line with switched shunt compensation (SSC) at both ends of the line and in the middle of the line. One phase of the ac transmission line is shown.

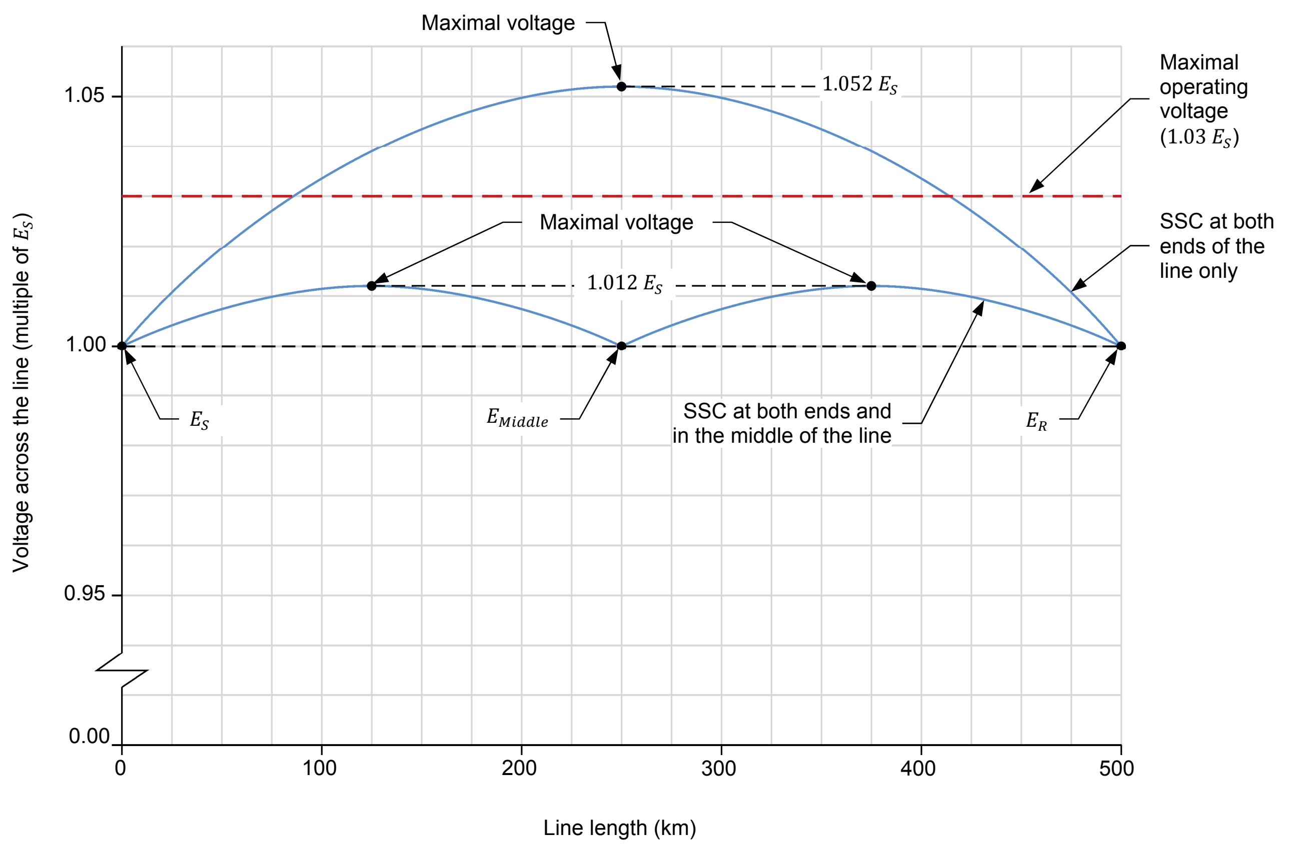


Figure 47. Voltage profiles along the 500 km (about 310 miles) ac transmission line in Figure 46 when SSC is used at both ends of the line only, and when SSC is used at both ends of the line and in the middle of the line.

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.

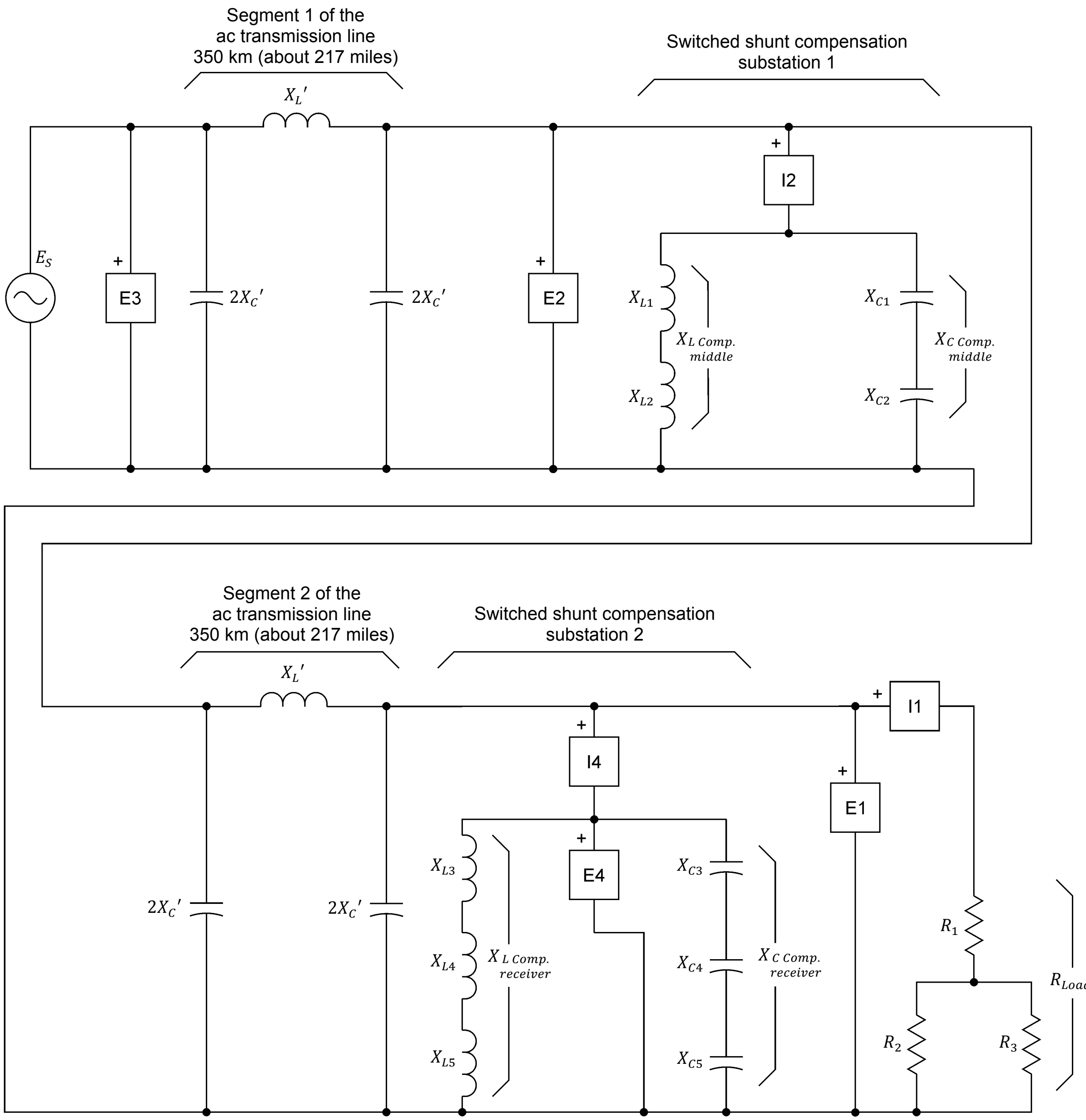
As Figure 49 shows, each of the two inductors in the ac transmission line is implemented using one phase of the Three-Phase Transmission Line module. Each of the four capacitors in the ac transmission line is implemented with one capacitor section (group of 3 parallel-connected capacitors) in one of 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.

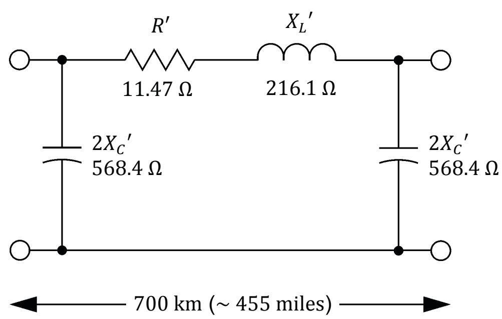
On the Resistive Load, set the load resistance R_{Load} to infinite.

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	$X_C = 213.6\ \text{k}\Omega/\text{km}$	$(132.7\ \text{k}\Omega/\text{mile})$

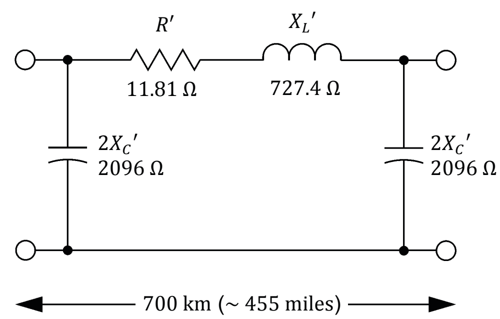
Corrected PI equivalent circuit



(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	$X_C = 782.2\ \text{k}\Omega/\text{km}$	$(486.0\ \text{k}\Omega/\text{mile})$

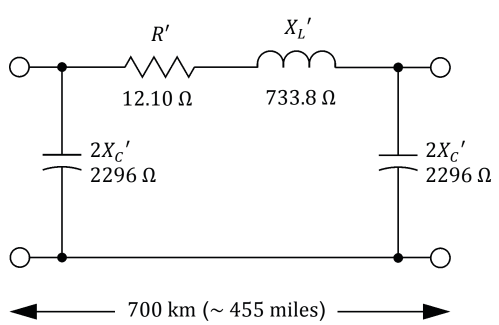
Corrected PI equivalent circuit



(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	$X_C = 852.1\ \text{k}\Omega/\text{km}$	$(529.4\ \text{k}\Omega/\text{mile})$

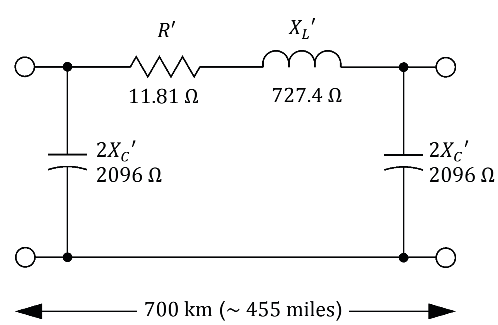
Corrected PI equivalent circuit



(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.

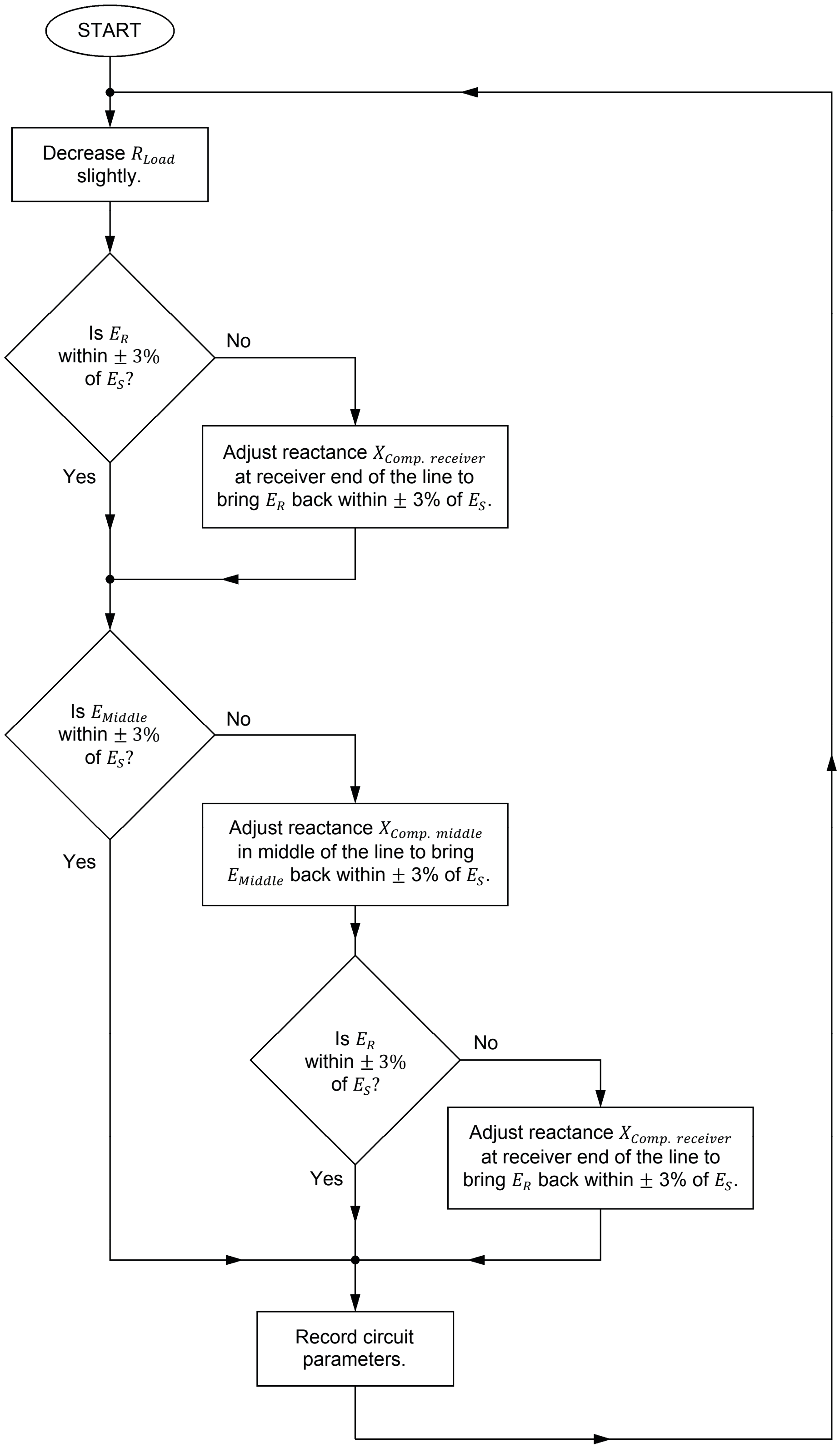


Figure 51. Algorithm used to control the distributed, switched shunt compensation.

The results recorded to the Data Table are presented below.

Measured parameters of the 700 km (about 435 miles) ac transmission line (one phase only) when switched shunt compensation is used at the receiver end and in the middle of the line for voltage compensation.

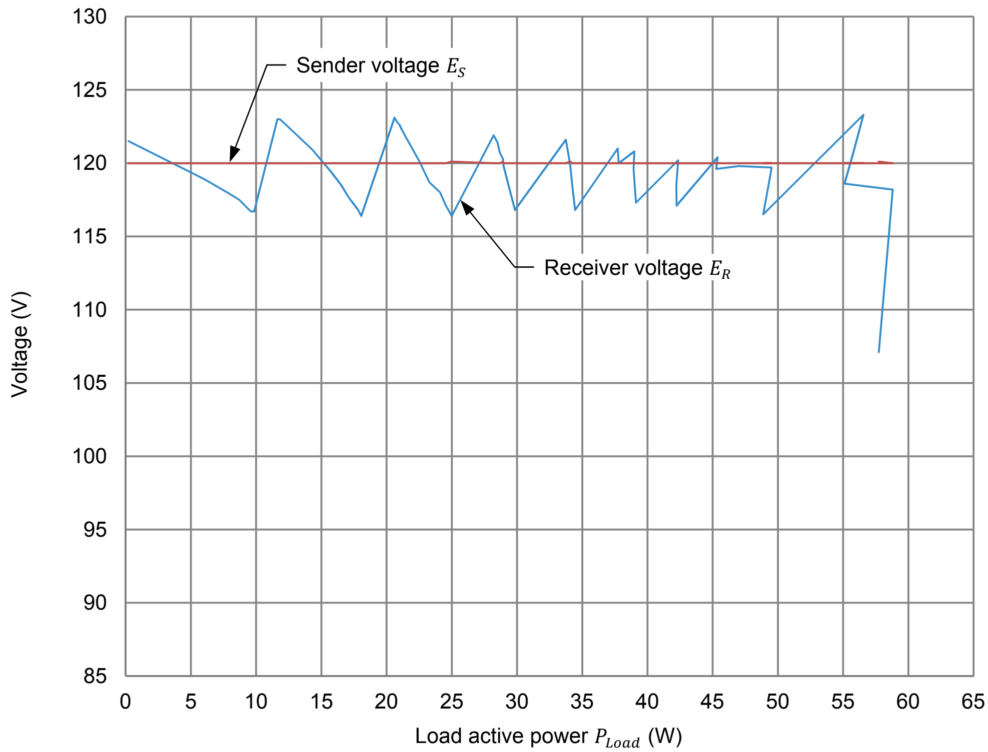
Shunt compensation applied	Sender voltage E_S (V)	Middle voltage E_{Middle} (V)	Receiver voltage E_R (V)	Load current I_{Load} (A)	Load active power P_{Load} (W)	Phase shift δ_{Middle} between $E_{Mid.}$ and E_S (°)	Phase shift δ between E_R and E_S (°)	Comp. reactance $X_{Comp.\ middle}$ (Ω)	Comp. reactance $X_{Comp.\ receiver}$ (Ω)
$X_{Comp.\ middle}$ = 600 Ω $X_{Comp.\ receiver}$ = 1200 Ω	120.0	121.1	121.5	0.007	0.219	1.998	2.960	626.2	1247
	120.0	120.0	118.9	0.051	6.033	4.777	8.572	626.7	1247
	120.0	119.4	118.0	0.066	7.791	5.564	10.29	627.4	1253
	120.0	119.0	117.5	0.074	8.707	6.030	11.26	627.7	1251
	120.0	118.5	116.7	0.082	9.589	6.538	12.23	626.8	1244
	120.0	118.6	116.7	0.085	9.849	6.575	12.37	628.3	1254
$X_{Comp.\ middle}$ = 600 Ω $X_{Comp.\ receiver}$ = 1800 Ω	120.0	121.4	123.0	0.095	11.63	7.484	13.90	627.3	1811
	120.0	121.4	123.0	0.096	11.82	7.636	14.15	627.6	1811
	120.0	121.1	122.6	0.101	12.30	7.814	14.56	626.7	1817
	120.0	120.0	120.9	0.119	14.33	8.835	16.79	627.4	1823
	120.0	119.0	119.4	0.132	15.75	9.621	18.43	626.0	1811
	120.0	118.4	118.5	0.140	16.52	10.08	19.37	626.0	1816
	120.0	117.9	117.7	0.145	17.06	10.31	20.00	627.5	1806
	120.0	117.5	117.2	0.149	17.48	10.54	20.57	625.8	1814
	120.0	117.3	116.8	0.153	17.82	10.74	20.95	629.3	1804
	120.0	117.2	116.4	0.155	18.06	10.87	21.30	627.9	1810
$X_{Comp.\ middle}$ = 600 Ω $X_{Comp.\ receiver}$ = 3600 Ω	120.0	120.0	123.1	0.168	20.61	11.91	22.86	626.9	3467
	120.0	119.8	122.8	0.170	20.81	12.05	23.04	626.5	3460
	120.0	119.7	122.6	0.171	21.00	12.19	23.33	626.6	3463
	120.0	119.5	122.4	0.173	21.10	12.23	23.48	627.3	3490
	120.0	119.3	122.1	0.174	21.27	12.38	23.71	626.8	3488
	120.0	118.0	120.1	0.188	22.52	13.02	25.32	627.2	3487
	120.0	117.1	118.7	0.196	23.27	13.54	26.48	625.2	3465

Shunt compensation applied	Sender voltage E_S (V)	Middle voltage E_{Middle} (V)	Receiver voltage E_R (V)	Load current I_{Load} (A)	Load active power P_{Load} (W)	Phase shift δ_{Middle} between $E_{Mid.}$ and E_S (°)	Phase shift δ between E_R and E_S (°)	Comp. reactance $X_{Comp.\ middle}$ (Ω)	Comp. reactance $X_{Comp.\ receiver}$ (Ω)
$X_{Comp.\ middle}$ = 900 Ω, $X_{Comp.\ receiver}$ = 1800 Ω	120.0	120.6	118.0	0.204	24.11	13.74	26.84	943.3	1807
	120.0	120.0	117.1	0.210	24.55	14.04	27.57	938.6	1811
	120.1	119.6	116.4	0.215	24.99	14.22	28.10	938.2	1820
$X_{Comp.\ middle}$ = 900 Ω, $X_{Comp.\ receiver}$ = 3600 Ω	120.0	121.8	121.9	0.232	28.21	15.63	30.24	942.3	3460
	120.0	121.4	121.4	0.235	28.50	15.84	30.67	940.9	3466
	120.0	120.9	120.7	0.238	28.69	15.94	31.05	940.4	3414
	120.1	120.6	120.3	0.241	28.92	16.08	31.38	939.1	3452
	120.0	120.2	119.8	0.242	28.97	16.20	31.67	941.7	3485
	120.0	118.3	116.8	0.256	29.84	16.79	33.37	943.1	3463
$X_{Comp.\ middle}$ = 900 Ω, $X_{Comp.\ receiver}$ = ∞	120.0	119.6	121.6	0.278	33.74	18.68	36.29	939.4	∞
	120.1	118.7	119.9	0.284	34.07	18.98	37.10	942.9	∞
	120.0	117.3	118.1	0.290	34.28	19.18	37.93	942.7	∞
	120.0	116.6	116.8	0.295	34.45	19.41	38.53	940.1	∞
$X_{Comp.\ middle}$ = 900 Ω, $X_{Comp.\ receiver}$ = -3600 Ω	120.0	117.2	121	0.312	37.72	21.34	41.56	942.2	-3638
	120.0	116.6	120	0.315	37.79	21.47	42	939.4	-3613
$X_{Comp.\ middle}$ = 1800 Ω, $X_{Comp.\ receiver}$ = ∞	120.0	121.6	120.8	0.323	38.99	20.88	41.00	1813	∞
	120.0	120.7	119.6	0.326	38.93	21.03	41.47	1820	∞
	120.0	119.2	117.3	0.334	39.12	21.36	42.55	1831	∞
$X_{Comp.\ middle}$ = 1800 Ω, $X_{Comp.\ receiver}$ = -3600 Ω	120.0	119.1	120.2	0.352	42.36	23.33	45.84	1830	-3618
	120.0	118.0	118.5	0.356	42.21	23.47	46.44	1816	-3642
	120.0	117.1	117.1	0.361	42.23	23.52	46.91	1815	-3645
$X_{Comp.\ middle}$ = 1800 Ω, $X_{Comp.\ receiver}$ = -1800 Ω	120.0	117.1	120.4	0.377	45.37	25.62	50.37	1819	-1790
	120.0	116.6	119.6	0.379	45.27	25.66	50.60	1819	-1790
$X_{Comp.\ middle}$ = ∞, $X_{Comp.\ receiver}$ = -1800 Ω	120.0	121.3	119.8	0.392	46.99	25.43	50.02	∞	-1784.0
	120.0	119.1	119.7	0.414	49.51	27.46	54.15	∞	-1785
	120.0	118.8	119.4	0.414	49.46	27.51	54.29	∞	-1786
	120.0	117.0	116.5	0.420	48.87	27.56	55.07	∞	-1798

Shunt compensation applied	Sender voltage E_S (V)	Middle voltage E_{Middle} (V)	Receiver voltage E_R (V)	Load current I_{Load} (A)	Load active power P_{Load} (W)	Phase shift δ_{Middle} between $E_{Mid.}$ and E_S (°)	Phase shift δ between E_R and E_S (°)	Comp. reactance $X_{Comp.\ middle}$ (Ω)	Comp. reactance $X_{Comp.\ receiver}$ (Ω)
$X_{Comp.\ middle}$ = -1800 Ω $X_{Comp.\ receiver}$ = -1200 Ω	120.0	121.5	123.3	0.459	56.55	31.74	60.99	-1791	-1214
	120.0	120.1	120.8	0.462	55.81	31.64	61.40	-1795	-1206
	120.0	118.7	118.6	0.465	55.11	31.56	61.95	-1783	-1208
$X_{Comp.\ middle}$ = -900 Ω $X_{Comp.\ receiver}$ = -1200 Ω	120.0	120.8	118.2	0.498	58.8	33.55	65.34	-901.6	-1205
$X_{Comp.\ middle}$ = -600 Ω $X_{Comp.\ receiver}$ = -1200 Ω	120.1	116.7	107.1	0.539	57.73	34.28	70.19	-612.8	-1212

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.

The resulting graph is shown below.



Power-voltage curve of the 700 km (about 435 miles) ac transmission line (for one phase) when distributed SSC (inductive and capacitive) is used for voltage compensation.

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.

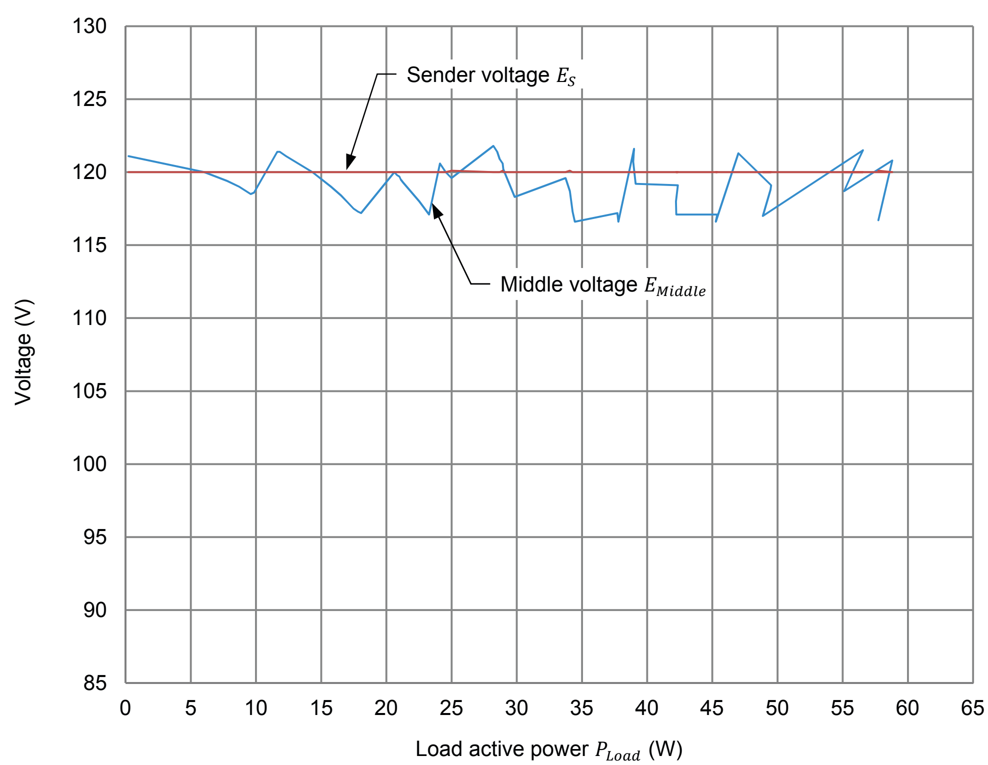
Yes. The amount of active power (about 59 W) that the 700 km (about 435 miles) ac transmission line with distributed SSC is able to convey while maintaining the receiver voltage E_R within the voltage limits (i.e., $\pm$ 3% of voltage E_S in this situation) is virtually the same as the amount of power (about 60 W) that the 350 km (about 217 miles) ac transmission line with SSC at the receiver end only is able to convey while maintaining the receiver voltage E_R within the voltage limits (i.e., $\pm$ 1.7% of voltage E_S in this situation).

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

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. Consequently, the voltage range within which the receiver voltage E_R can be maintained using a given switched shunt compensation arrangement (i.e., the number and values of the shunt reactive components used for voltage compensation of the line) increases as the line length increases. For instance, this voltage range is $\pm$1.7% of voltage E_S for the 350 km (about 217 miles) ac transmission line used in Exercise 3, while this voltage range is $\pm$3% of voltage E_S for the 700 km (about 435 miles) ac transmission line used in the present exercise.

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.

The resulting graph is shown below.



Power-voltage curve in the middle of the 700 km (about 435 miles) ac transmission line (for one phase only) when distributed SSC (inductive and capacitive) is used for voltage compensation.

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.

Yes. The no-load voltage (about 121 V) in the middle of the 700 km (about 435 miles) ac transmission line with distributed SSC is much closer to the sender voltage E_S (about 120.0 V) than the no-load voltage (about 133 V) in the middle of the 700 km ac transmission line with SSC at the receiver end only.

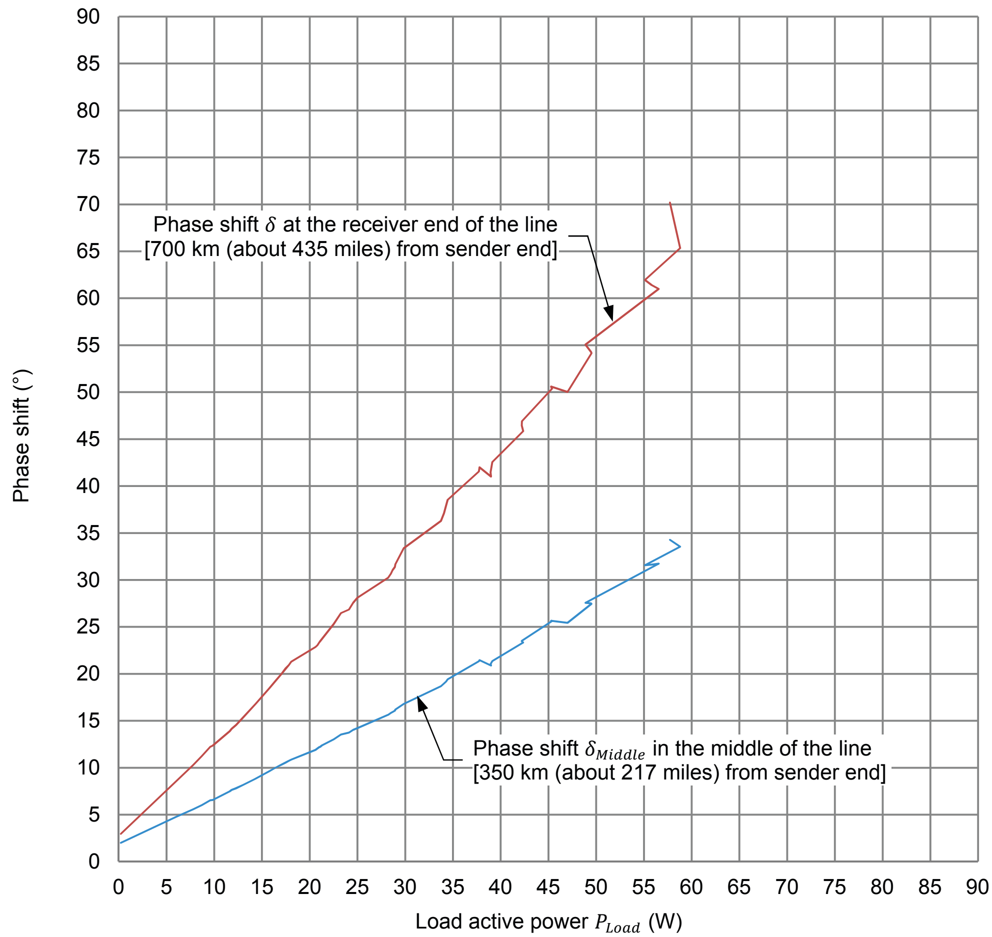
Does using distributed SSC allow the voltage in the middle of the 700 km (about 435 miles) ac transmission line to be maintained close to the sender voltage E_S no matter the amount of active power the line conveys?

❑ Yes ❑ No

Yes

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}.

The resulting graph is shown below.



Phase shift δ between voltages E_R and E_S and phase shift δ_{Middle} between voltages E_{Middle} and E_S as a function of the active power P_{Load} when the 700 km (about 435 miles) ac transmission line is voltage compensated using distributed SSC (inductive and capacitive).

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.

Yes. The phase shift δ between the voltage E_R at the receiver end of the line and the sender voltage E_S is virtually equal to twice the phase shift δ_{Middle} between the voltage E_{Middle} in the middle of the line and the sender voltage E_S. For instance, when the active power P_{Load} is 34.28 W, the phase shift δ between voltages E_R and E_S (distance of 700 km, or about 435 miles) is 37.93°, while the phase shift δ_{Middle} between the voltages E_{Middle} and sender voltage E_S (distance of 350 km, or about 217 miles) is 19.18°.

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.

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

Yes. For instance, when the active power P_{Load} is 45.37 W, the sender voltage E_S (i.e., the sender voltage E_S of the line), receiver voltage E_R (i.e., voltage E_{Middle}), and phase shift δ (i.e., phase shift δ_{Middle}) related to the sender-end half of the ac transmission line are equal to 120.0 V, 117.1 V and 25.62°, respectively. The power $P_{(Comp.)}$ calculated using these values and the inductive reactance $X_L{}'$ (120 Ω) of the sender-end half of the ac transmission line is 151.9 W, which is relatively close to three times the measured active power P_{Load} which is for one phase only. Similarly, when the active power P_{Load} is 45.37 W, the sender voltage E_S (i.e., voltage E_{Middle}), receiver voltage E_R (i.e., receiver voltage E_R of the line), and phase shift δ (i.e., phase shift δ – phase shift δ_{Middle}) related to the receiver-end half of the ac transmission line, are equal to 117.1 V, 120.4 V, and 24.75° (i.e., 50.37°- 25.62°), respectively. The power $P_{(Comp.)}$ calculated using these values and the inductive reactance $X_L{}'$ (120 Ω) of the receiver-end half of the ac transmission line is 147.6 W, which is relatively close to three times the measured active power P_{Load}, which is for one phase only.

The values of power $P_{(Comp.)}$ calculated using the equation are a little higher than 3 times the measured value of active power P_{Load}, which is for one phase only, because there are significant power losses in the ac transmission line, as well as in the shunt inductors.

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.

   This problem can be solved by adding switched shunt compensation (SSC) in the middle of the ac transmission line. This is equivalent to 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.

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

   Distributed, switched shunt compensation (distributed SSC) of a long ac transmission line consists of dividing the line into as many segments as required, and applying SSC at both ends of the line and between each line segment, to obtain a voltage profile which remains within the maximal voltage at which the line can operate.

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?

   The longest segment of an ac transmission line that is voltage compensated using distributed SSC has the lowest maximal transmissible power. This means that the longest segment of the ac transmission line is the most restrictive, and thus the one which determines the maximal transmissible power $P_{Max.\ (Comp.)}$ of the entire ac transmission line.

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.

   The phase shift δ between the receiver voltage E_R and sender voltage E_S of a voltage-compensated ac transmission line, for any given value of active power $P_{(Comp.)}$, increases with the line length. This occurs because each segment of the line phase shifts (delays) the incoming voltage when the line conveys active power. Thus, the phase shift δ between the receiver voltage E_R and sender voltage E_S of the line is equal to the sum of the phase shifts produced by each line segment. Therefore, the longer the line, the greater the phase shift δ.

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.

Increasing the line length of an ac transmission line that is voltage compensated using SSC or distributed SSC causes the operation of the line to become less stable. This is because the variation of the receiver voltage E_R produced by a given change in the amount of active power conveyed by the line increases with the line length even when SSC or distributed SSC is used for voltage compensation. 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, thus causing the operation of the line to become less stable.

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