Electricity and New Energy

Static Synchronous Compensator (STATCOM)

Courseware Sample

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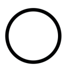
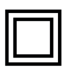
Safety and Common Symbols

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

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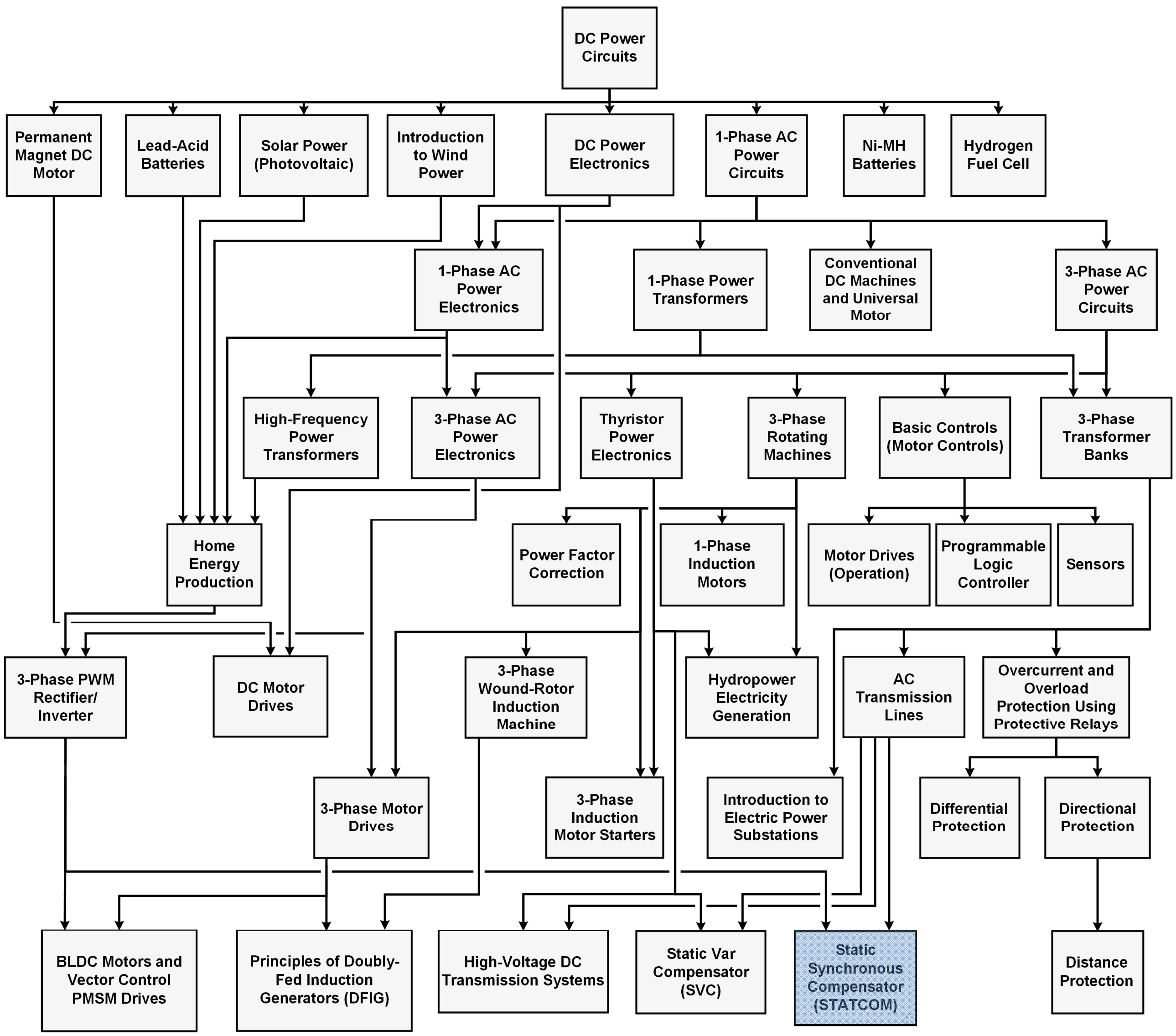
Preface

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

Static synchronous compensators (STATCOMs) are part of the flexible alternating current transmission systems (FACTS) device family. Their primary purpose is to supply a fast-acting, precise, and adjustable amount of reactive power to the ac power system to which they are connected. STATCOMs achieve this by adjusting the magnitude and polarity (phase) of the reactive component of the current flowing through their ac side. This enables STATCOMs to control the amount and direction of flow of the reactive power exchanged with the ac power system.

STATCOMs can be used for voltage compensation at the receiver end of ac transmission lines, replacing or supplementing banks of shunt inductors. When used for this purpose, STATCOMs offer a number of advantages over banks of shunt inductors, such as much tighter control of the voltage compensation at the receiver end of the ac transmission line and increased line stability during load variations.

STATCOMs are also commonly used for dynamic power factor correction (i.e., dynamic reactive power compensation) in industrial plants operating with large random peaks of reactive power demand. STATCOMs increase the power factor of the plant, minimize the voltage fluctuations at the plant input (which prevents damage to the equipment), and reduce the plant's operating costs.

This course, Static Synchronous Compensators (STATCOMs), teaches the basic concepts of voltage compensation in ac transmission lines and power factor correction in large industrial plants using STATCOMs. Students are introduced to the operation of STATCOMs, and their different components. They also learn how a STATCOM achieves automatic voltage control and automatic reactive power control. Finally, the theory presented in the manual is verified by performing circuit measurements and calculations.

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.

About This Manual

Prerequisite

As a prerequisite to this course, you should have read the following manuals: *DC Power Circuits*, part number 86350, *Lead-Acid Batteries*, part number 86351, *Solar Power*, part number 86352, *Introduction to Wind Power*, part number 86353, *DC Power Electronics*, part number 86356, *Single-Phase AC Power Circuits*, part number 86358, *Single-Phase AC Power Electronics*, part number 86359, *Single-Phase Power Transformers*, part number 86377, *High-Frequency Power Transformers*, part number 86378, *Three-Phase AC Power Circuits*, part number 86360, *Three-Phase Transformer Banks*, part number 86379, *Home Energy Production*, part number 86361, *Three-Phase PWM Rectifier/Inverter*, part number 86366, and *AC Transmission Lines*, part number 20521.

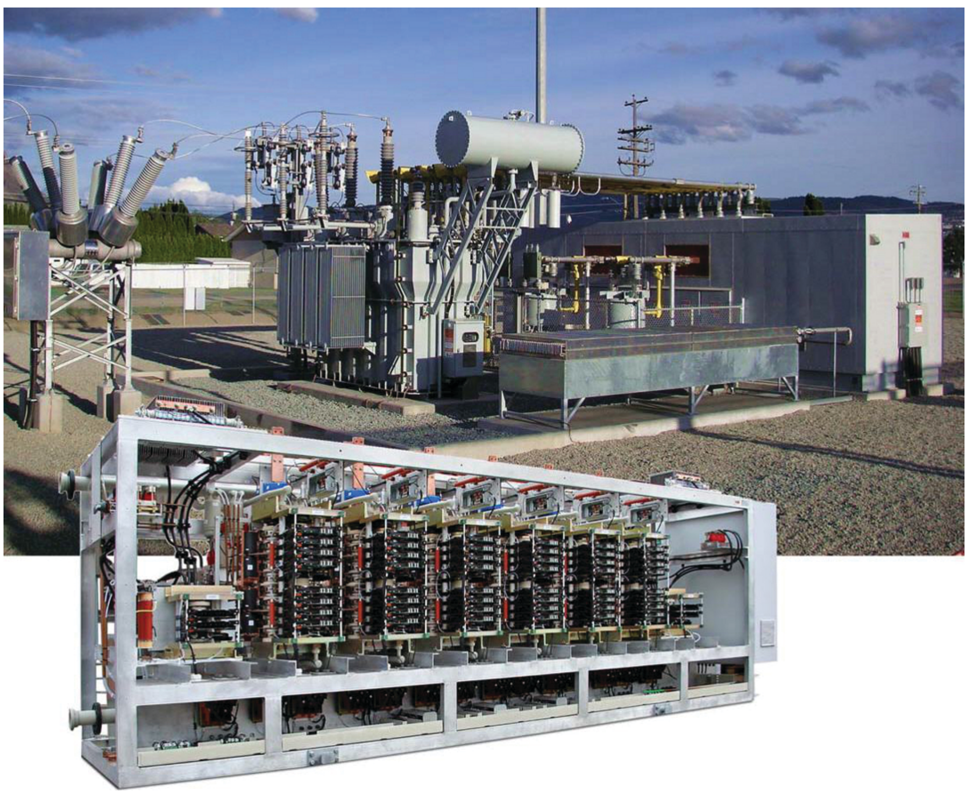


Figure 1. STATCOM substation and close-up view of the converter valves (photo courtesy of ABB).

Systems of units

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

About This Manual

Figure 2. Voltage-source converter (VSC) devices such as STATCOMs are used in offshore wind farms to ensure that the quality of the power produced by the wind farm is optimal. The above picture shows the Lillgrund wind farm in Sweden (© Siemens AG 2012, all rights reserved).

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

Voltage Compensation of AC Transmission Lines Using a STATCOM

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the operating principles of STATCOMs used for voltage compensation of ac transmission lines. You will know how a STATCOM controller designed for automatic voltage control compensates the voltage across the ac power system to which the STATCOM is connected.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Voltage compensation of ac transmission lines using a STATCOM
- Automatic voltage compensation

DISCUSSION

Voltage compensation of ac transmission lines using a STATCOM

In the Introduction of this manual, you learned that there is overvoltage at the receiver end of an ac transmission line when little or no load is applied to it. You also learned that a significant voltage variation occurs at the receiver end of an ac transmission line whenever the load varies. Such voltage variations are unacceptable in ac power networks. This is due to the fact that many electrical devices such as motors, relays, and lighting equipment work properly only under stable voltage conditions (i.e., close to the voltage for which they are rated).

One way to achieve coarse compensation of voltage variations across an ac transmission line is to add substations containing switched shunt inductors along the line. This has the effect of dividing the ac transmission line into many segments of shorter length. Each substation serves the purpose of compensating voltage variations across the ac transmission line (i.e., maintaining the voltage approximately constant across each segment of the ac transmission line).

Figure 17 shows a typical ac transmission line used to transfer large amounts of electrical power over a long distance from a power generating station to the distribution network (which, in turn, distributes the electrical power to consumers).

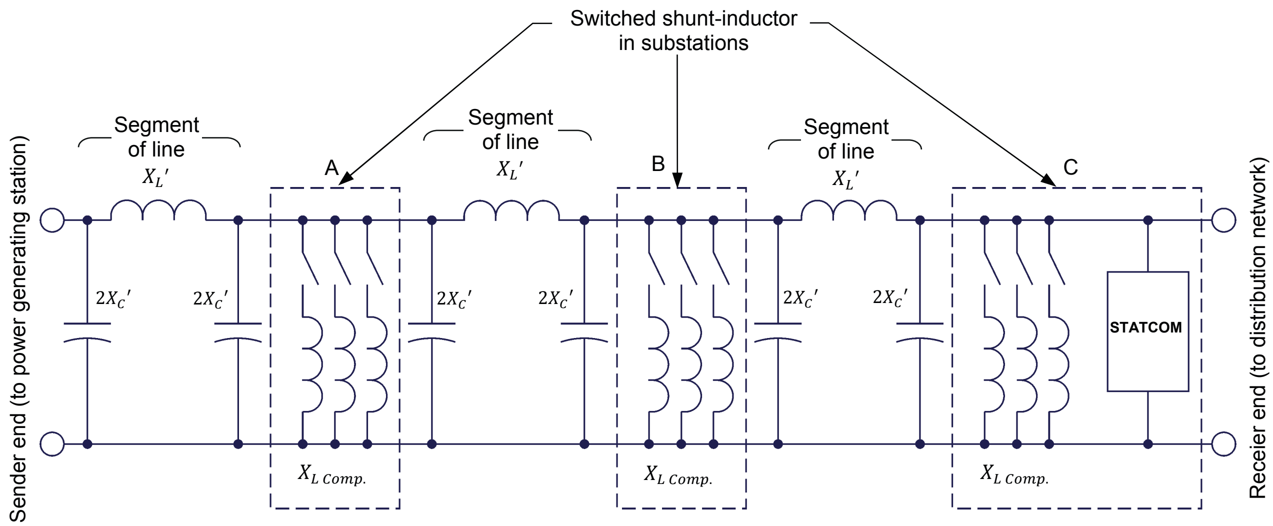


Figure 17. Typical ac transmission line used to transfer large amounts of electrical power over a long distance from a power generating station to the distribution network.

As Figure 17 shows, the ac transmission line is divided into three segments of equal length by two substations (substations A and B) containing switched shunt inductors used for voltage compensation. The voltage at each of these two substations is compensated by switching shunt inductors in and out to maintain the voltage along the ac transmission line as close as possible to the nominal value of the ac power network voltage. As mentioned in the Introduction of this manual, switched shunt-inductors in substations have certain drawbacks, such as the difficulty of coordinating all substations and perfectly compensating the voltage across each segment of the ac transmission line. However, since substations A and B are located along the ac transmission line, and thus, do not directly supply power to consumers, it is not necessary for the voltage at these substations to be perfectly compensated.

At the end of the third segment (i.e., the receiver end) of the ac transmission line in Figure 17, the voltage at the corresponding substation (substation C) is compensated using switched shunt inductors (for coarse compensation) and a STATCOM. A STATCOM offers numerous advantages over switched shunt inductors, most notably, a tight and fast compensation of the voltage across the line. Since the receiver-end substation (substation C in Figure 17) is located at the end of the ac transmission line, it is important that the voltage at this substation be compensated as perfectly as possible before distributing electrical power to consumers. Consequently, it is common to use switched shunt inductors in conjunction with a STATCOM at the receiver-end substation of an ac transmission line.

Due to its ability to perform fast and accurate compensation of the voltage at the receiver end of an ac transmission line, a STATCOM can perfectly compensate for remaining voltage fluctuations across the line (these fluctuations occur because compensation with switched shunt inductors is rarely perfect) as well as for voltage fluctuations caused by variations of the load (i.e., rapid variations of the electrical power demand of the consumers).

Instead of using a STATCOM, several inductors with different values of inductance could be used to achieve proper voltage compensation at the receiver end of an ac transmission line. However, this solution would be as costly as a STATCOM, if not costlier, and would provide a response time slower than that of a STATCOM.

It is possible to replace all switched shunt inductors in the substations of the ac transmission line of Figure 17 with STATCOMs to further increase the effectiveness of voltage compensation. However, even though STATCOMs are more efficient than switched shunt inductors in every aspect, it is not common practice to systematically replace all switched shunt inductors with STATCOMs. This is primarily because a STATCOM is much more costly (about six times more expensive) than a bank of switched shunt inductors of comparable power rating. Since the use of switched shunt inductors to compensate voltage along ac transmission lines already gives acceptable results, replacing all switched shunt inductors along these lines with STATCOMs is usually not worth the cost.

Figure 18. STATCOM substations can be used for fast-acting, precise, and adjustable voltage compensation of ac transmission lines (© Copyright 2012 Guc Kalitesi).

Automatic voltage compensation

When a STATCOM is used for compensating the voltage across an ac power system (typically ac transmission lines), the voltage across the STATCOM is regulated using a voltage control loop implemented in the STATCOM controller. This controller monitors the voltage across the STATCOM side of the step-down transformer, the current flowing through the STATCOM side of the step-down transformer, and the voltage across the dc side of the STATCOM (see Figure 19). Using the measured values, the STATCOM controller determines the switching signals to be applied to the three-phase bridge in order to ensure that the line voltages measured across the STATCOM side of the step-down transformer are equal to the ac bus line voltage command (the value of this command being set so that the resulting voltage across the STATCOM is at the required value). The switching signals applied to the three-phase bridge by the STATCOM controller also ensure that the voltage measured across the dc side of the STATCOM is equal to the dc bus voltage command. The block diagram of a STATCOM designed for voltage compensation (i.e., automatic voltage control) is shown in Figure 19.

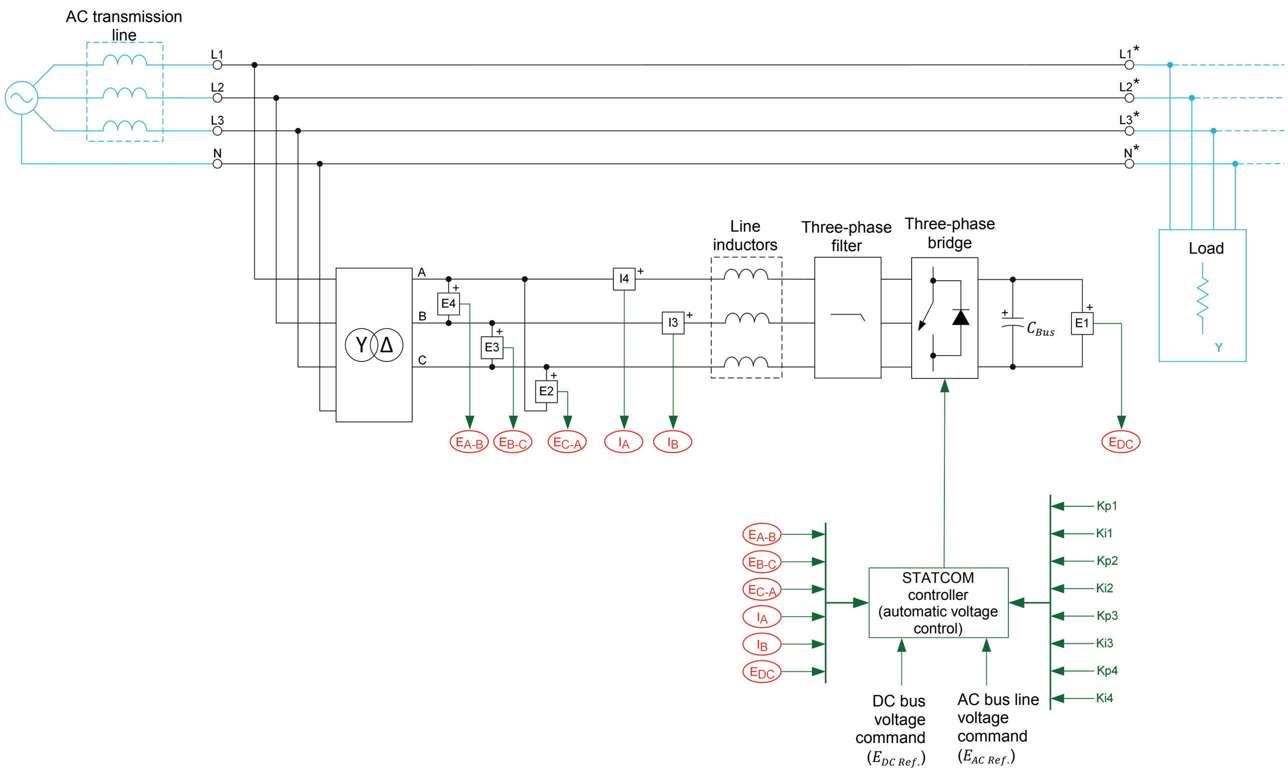


Figure 19. Block diagram of a STATCOM designed for voltage compensation.

It is assumed that the ac transmission line in the block diagram of Figure 19 is voltage compensated using switched shunt inductors. However, for the sake of simplicity, the switched shunt inductors and the capacitors normally included in the equivalent circuit of an ac transmission line have been omitted in the block diagram of Figure 19.

As Figure 19 shows, three voltage sensors measure line voltages E_{A-B}, E_{B-C}, and E_{C-A} across the STATCOM side of the step-down transformer, two current sensors (I3 and I4) measure line currents I_A and I_B flowing through the STATCOM side of the step-down transformer, and a fourth voltage sensor (E1) measures voltage E_{DC} across the dc side of the STATCOM. Signals representing these voltages and currents are sent to the STATCOM controller (which is set for automatic voltage control).

The STATCOM controller compares the measured line voltages to the ac bus line voltage command $E_{AC\ Ref.}$, and determines the error in the measured line voltages across the STATCOM side of the step-down transformer. The STATCOM controller also compares the measured dc voltage E_{DC} to the dc bus voltage command $E_{DC\ Ref.}$, and determines the error in the measured voltage across the dc side of the STATCOM. Using these calculated error values and the measured voltage and current values, the STATCOM controller determines the switching signals to be applied to the three-phase bridge so that:

1) the amount of reactive power the STATCOM exchanges with the ac power system to which it is connected ensures that the line voltages measured across the STATCOM side of the step-down transformer are equal to the ac bus line voltage command; and

2) the amount of active power flowing through the STATCOM makes the voltage measured across the dc side of the STATCOM equal to the dc bus voltage command. Note that the signal representing line voltage E_{A-B} is also used to provide the phase angle (θ) information required to perform mathematical calculations in the controller. The operation of a STATCOM controller designed for automatic voltage control is covered in further detail in Appendix D.

Figure 20. The voltage across a STATCOM designed for automatic voltage compensation is controlled using a voltage control loop. This ensures that the voltage across the STATCOM is maintained virtually constant (© Copyright 2012 Guc Kalitesi).

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Voltage compensation at the receiver end of an ac transmission line using a STATCOM

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 consisting of an ac transmission line supplying power to a resistive load, with a STATCOM at the receiver end of the line for voltage compensation. You will then set up the measuring equipment required to study the operation of the STATCOM when it is used for voltage compensation.

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 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.

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

   Connect the *Power Inputs* of both Data Acquisition and Control Interfaces together.

   Connect the *Low Power Input* of the IGBT Chopper/Inverter to the *Power Input* of any of the Data Acquisition and Control Interface modules.

   Turn the 24 V ac power supply on.

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

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

In the LVDAC-EMS Start-Up window, make sure that both Data Acquisition and Control Interface modules are detected. Make sure that the *STATCOM Control* and *Computer-Based Instrumentation* functions are available for either or both Data Acquisition and Control Interface modules. 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.

6. Before you begin connecting the equipment, record in the space below the serial number of the Data Acquisition and Control Interface (DACI) you will use to control the STATCOM, and the serial number of the DACI you will use for data acquisition.

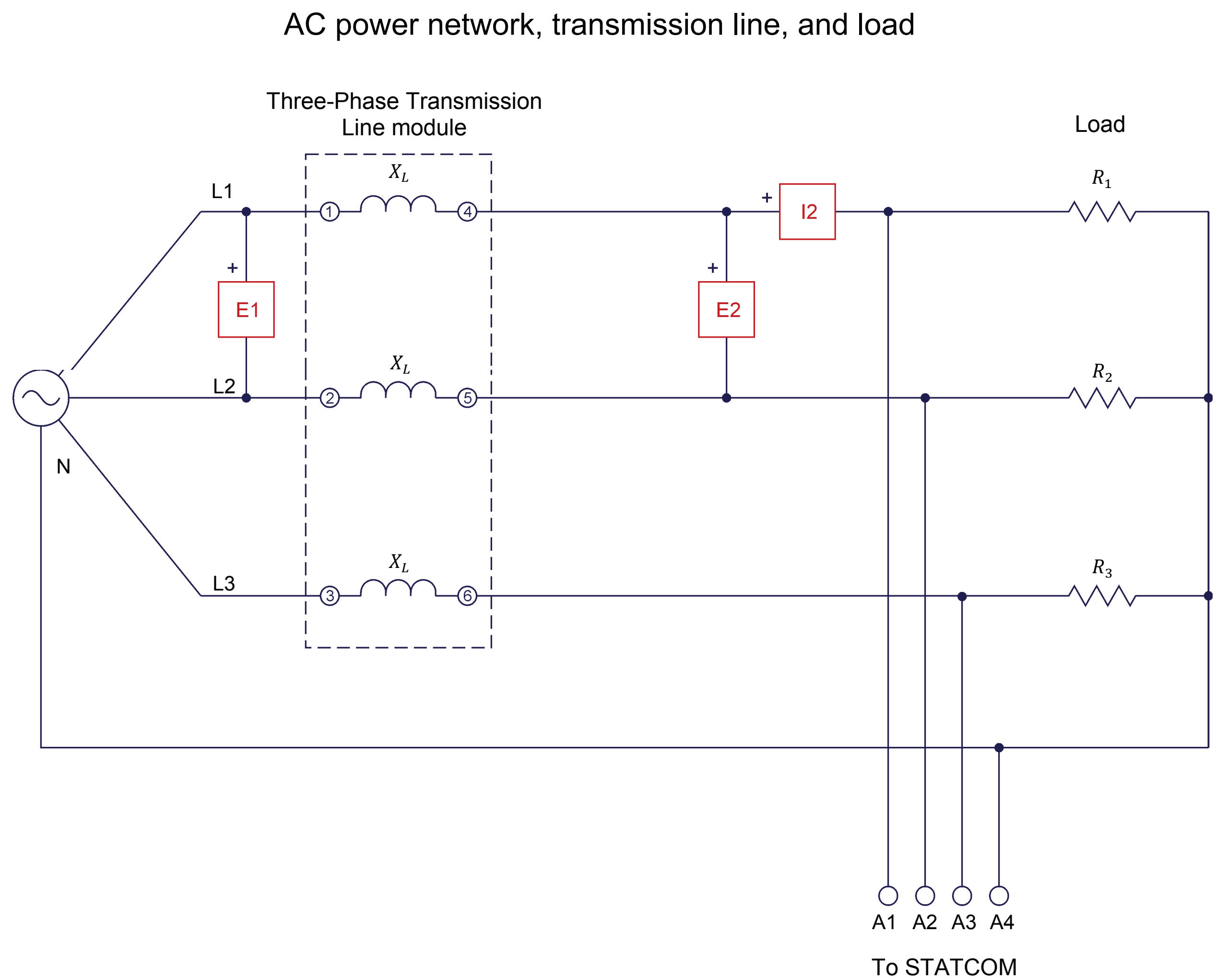
Serial number of the DACI controlling the STATCOM: __________

Serial number of the DACI used for data acquisition: __________

7. Connect the equipment as shown in Figure 21 and Figure 22. Use the Power Supply to implement the three-phase ac power source. Note that points A1, A2, A3, and A4 in Figure 21 are to be connected to the corresponding points in Figure 22.

In Figure 21 and Figure 22, voltage and current inputs shown ***in blue*** *represent inputs of the Data Acquisition and Control Interface used to control the STATCOM, while voltage and current inputs shown* ***in red*** *represent inputs of the Data Acquisition and Control Interface used for data acquisition. Note that the inputs used for STATCOM control purposes cannot be used for data acquisition, and vice versa.*

This circuit represents an ac transmission line that is voltage compensated at the receiver end of the line, using a STATCOM. The resistive load in the circuit represents the electrical power demand. By changing the resistance of the load, it is thus possible to vary the electrical power demand.



Local ac power network		Line inductive reactance X_L (Ω)	Resistance value of loads R_1, R_2, R_3 (Ω)					
Voltage (V)	**Frequency (Hz)**		**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**
120	60	120	600	400	300	240	200	171
220	50	400	2200	1467	1100	880	733	629
240	50	400	2400	1600	1200	960	800	686
220	60	400	2200	1467	1100	880	733	629

Figure 21. Circuit for studying the operation of a STATCOM used for voltage compensation of an ac transmission line supplying power to a resistive load.

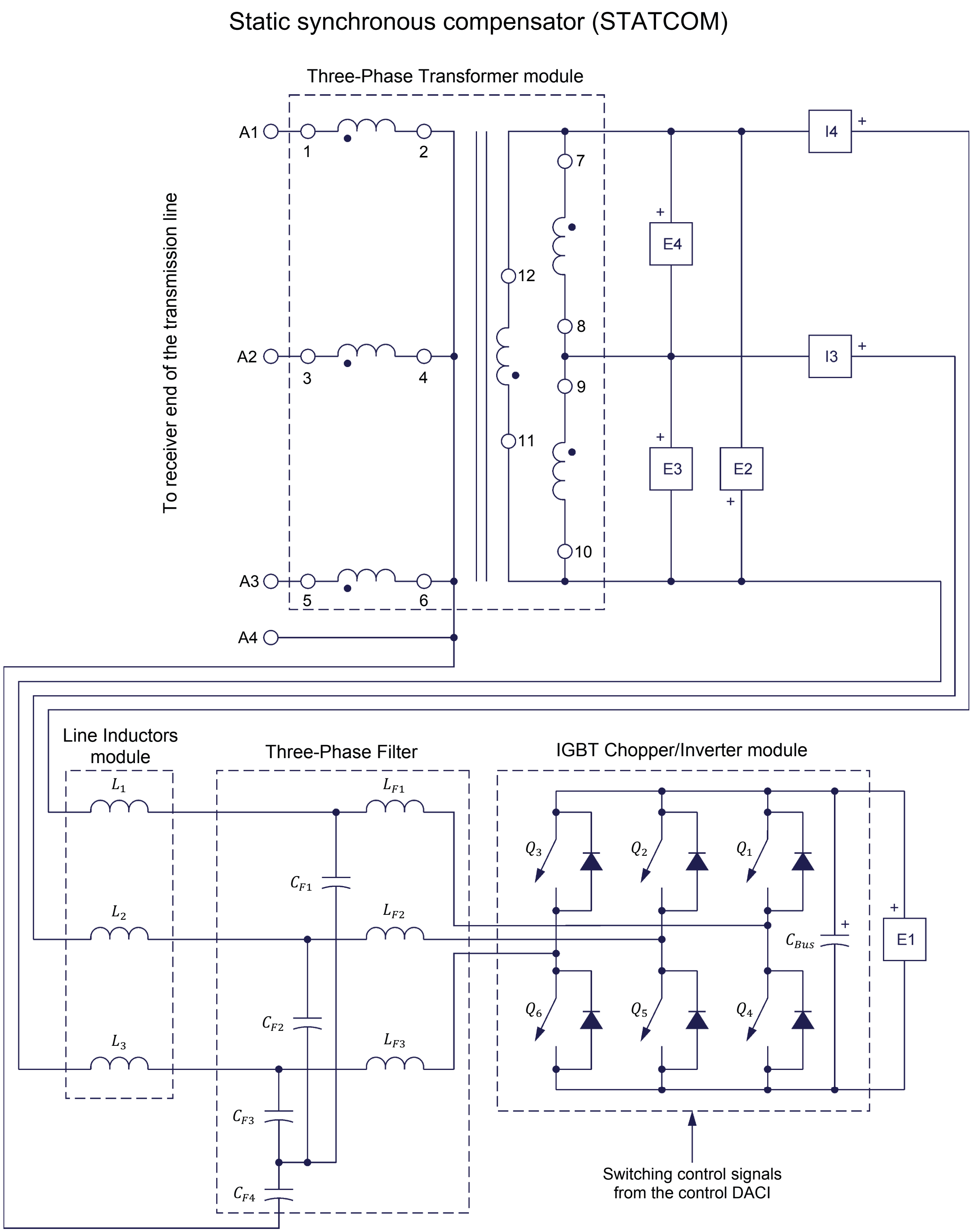


Figure 22. Circuit for studying the operation of a STATCOM used for voltage compensation of an ac transmission line supplying power to a resistive load.

8. In the circuit of Figure 21, it is assumed that the ac transmission line is also voltage compensated using fixed shunt inductors present along this line. Such an ac transmission line can be represented by a single inductor (one per phase) because the shunt inductors are sized so as to neutralize the capacitors in the equivalent circuit of the line. This is illustrated in Figure 23.

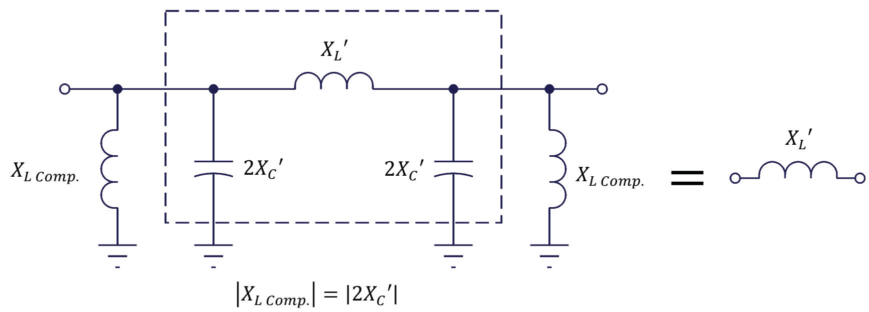


Figure 23. One phase of an ac transmission line compensated with shunt inductors.

9. On the Data Acquisition and Control Interface used for controlling the STATCOM, connect the Digital Output to the *Switching Control Inputs* of the IGBT Chopper/Inverter using a DB9 connector cable.

On the IGBT Chopper/Inverter, make sure the *Dumping* switch is set to the I position. This allows power to be dissipated in a dump resistor inside the IGBT Chopper/Inverter in the event of an overvoltage across the IGBT Chopper/Inverter. This additional protection has no effect on the STATCOM operation.

10. On the Three-Phase Transmission Line, make sure 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 21 for your local ac power network voltage and frequency.

On the Resistive Load, make the necessary switch settings to obtain the 1st resistance value indicated in the table of Figure 21 for your local ac power network voltage and frequency.

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.

11. In LVDAC-EMS, open the STATCOM Control window. A dialog box appears. Select the serial number of the Data Acquisition and Control Interface used to control the STATCOM (recorded in step 6), then click the *OK* button to close the dialog box and open the STATCOM Control window.

In the STATCOM Control window, make the following settings:

– Make sure that the *Control Mode* parameter to *Automatic Voltage Control*. This control mode allows the voltage of the ac power system to which the STATCOM is connected to be automatically compensated and maintained at a specified value (e.g., at the voltage of your local ac power network).

In order to implement this control mode, the Data Acquisition and Control Interface used for controlling the STATCOM requires that voltage inputs E1, E2, E3, and E4, as well as current inputs I3 and I4, be connected as shown in the circuit of Figure 21 and Figure 22.

– Make sure that the *DC Bus Voltage Command* parameter is set to 200.0 V. This dc voltage value is high enough to allow the STATCOM to exchange reactive power with the ac power system to which it is connected (i.e., it is high enough to allow the STATCOM to produce ac voltage at the required value).

– Make sure the *AC Bus Line Voltage Command* parameter is set to 83.0 V. With this line voltage command value, the STATCOM controller automatically adjusts the amount of reactive power supplied or absorbed by the STATCOM so that the line voltage across the STATCOM side of the three-phase transformer is maintained at 83 V. Due to the transformer voltage ratio and configuration (Y-Δ), the measured line voltage across the ac power system connected to the STATCOM should be close to your local ac power network line voltage.

– Make sure that the *Active Current Controller Prop. Gain (Kp1)* is set to 5.00.

– Make sure that the *Active Current Controller Int. Gain (Ki1)* is set to 20.00.

– Make sure that the *Reactive Current Controller Prop. Gain (Kp2)* is set to 10.00.

– Make sure that the *Reactive Current Controller Int. Gain (Ki2)* is set to 20.00

– Make sure that the *DC Bus Voltage Controller Prop. Gain (Kp3)* is set to 5.00.

– Make sure that the *DC Bus Voltage Controller Int. Gain (Ki3)* is set to 5.00.

– Make sure that the *AC Bus Line Voltage Controller Prop. Gain (Kp4)* is set to 2.50.

– Make sure that the *AC Bus Line Voltage Controller Int. Gain (Ki4)* is set to 10.00.

– Make sure that the *Status* parameter is set to *Stopped*. This ensures that the *Static Synchronous Compensator* function is stopped.

12. In LVDAC-EMS, open the Metering window. A dialog box appears. Select the serial number of the Data Acquisition and Control Interface used for data acquisition (recorded in step 6), then click the *OK* button to close the dialog box and open the Metering window.

In the *Option* menu of the Metering window, select Acquisition Settings to open the corresponding dialog box. Set the *Sampling Window* to 8 cycles, then click *OK* to close the dialog box. This provides better accuracy when measuring parameters (e. g., reactive power) of the STATCOM.

Make the required settings in order to measure the rms values (ac) of the line voltage E_S (input *E1*) at the sender end of the ac transmission line, and the line voltage E_R (input *E2*) at the receiver end of the ac transmission line. Also, set set a meter to measure the three-phase reactive power $Q_{STAT.}$ that the STATCOM exchanges with the ac power system to which it is connected [metering function *PQS2 (E2, I2) 3~*].

Voltage compensation at the receiver end of an ac transmission line using a STATCOM

In this section, you will vary the resistance of the load and, for each resistance value, you will record the three-phase PWM rectifier/inverter active current and reactive current, the reactive power exchanged by the STATCOM, the sender voltage, and the receiver voltage. You will analyze the results and determine how accurately the STATCOM achieves voltage compensation when load variations occur. You will then use the Oscilloscope to record the transient in the receiver voltage and current when the resistive load decreases suddenly, and when it increases suddenly. Using the signals recorded on the Oscilloscope, you will determine how fast the STATCOM achieves voltage compensation when load variations occur.

Accuracy of the voltage compensation achieved by a STATCOM when load variations occur

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

14. In the STATCOM Control window, start the static synchronous compensator by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

15. In the STATCOM Control window, adjust the *AC Bus Line Voltage Command* parameter so that the receiver voltage E_R indicated in the Metering window is as close as possible to the nominal value of your local ac power network voltage.

16. Fill in Table 2 as indicated below:

– On the Resistive Load, successively set the resistance of loads R_1, R_2, and R_3 to each of the values indicated in the table of Table 2 for your local ac power network voltage and frequency.

– For each load resistance value, record in the corresponding row of Table 2 the three-phase PWM rectifier/inverter active current $I_{d\ Rect./Inv.}$ and reactive current $I_{q\ Rect./Inv.}$ (indicated in the STATCOM Control window), as well as the reactive power $Q_{STAT.}$ exchanged by the STATCOM, the sender voltage E_S, and the receiver voltage E_R (indicated in the Metering window).

Table 2. Three-phase PWM rectifier/inverter active current $I_{d\ Rect./Inv.}$ and reactive current $I_{q\ Rect./Inv.}$, reactive power $Q_{STAT.}$ exchanged by the STATCOM, sender voltage E_S, and receiver voltage E_R for different resistive load values when the STATCOM compensates the voltage at the receiver end of an ac transmission line.

Resistance value of loads R_1, R_2, R_3 (Ω)	Active current $I_{d\ Rect./Inv.}$ (A)	Reactive current $I_{q\ Rect./Inv.}$ (A)	Reactive power $Q_{STAT.}$ (var)	Sender voltage E_S (V)	Receiver voltage E_R (V)
1st = _______					
2nd = _______					
3rd = _______					
4th = _______					
5th = _______					
6th = _______					

The results are presented in the following table.

Three-phase PWM rectifier/inverter active current $I_{d\ Rect./Inv.}$ and reactive current $I_{q\ Rect./Inv.}$, reactive power $Q_{STAT.}$ exchanged by the STATCOM, sender voltage E_S, and receiver voltage E_R for different resistive load values when the STATCOM compensates the voltage at the receiver end of an ac transmission line.

Resistance value of loads R_1, R_2, R_3 (Ω)	Active current $I_{d\ Rect./Inv.}$ (A)	Reactive current $I_{q\ Rect./Inv.}$ (A)	Reactive power $Q_{STAT.}$ (var)	Sender voltage E_S (V)	Receiver voltage E_R (V)
1st = 600	-0.02	-0.2	-9.55	209	209
2nd = 400	-0.04	-0.3	-23.3	209	209
3rd = 300	-0.04	-0.43	-42.9	209	209
4th = 240	-0.09	-0.59	-69.8	209	209
5th = 200	-0.11	-0.86	-103	209	209
6th = 171	-0.15	-1.18	-158	209	209

17. In the STATCOM Control window, stop the static synchronous compensator by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

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

18. From the results recorded in Table 2, does the STATCOM accurately compensate the voltage across the ac power system to which it is connected (i.e., the receiver voltage E_R)? Explain briefly.

Yes, since the results in the table indicate that the STATCOM maintains the voltage across the ac power system to which it is connected (i.e., the receiver voltage E_R) virtually equal to the ac power network voltage (i.e., the sender voltage E_S) no matter the power demand of the consumers (i.e., no matter the resistive load value). This shows that a STATCOM accurately (i.e., almost perfectly) compensates variations of the voltage across the ac power system to which it is connected.

Compare the accuracy of the voltage compensation achieved using a STATCOM to that which can be achieved using a bank of switched shunt-capacitors. What can you conclude? Explain briefly.

As the results in the table indicate, a STATCOM accurately (i.e., almost perfecty) compensates the voltage across the ac power system to which it is connected. On the other hand, a bank of switched shunt inductors can rarely achieve perfect voltage compensation of the ac power system to which it is connected. This is because the selection of shunt inductors available for voltage compensation is limited. Therefore, a STATCOM generally achieves a much more accurate voltage compensation of an ac power system than a bank of switched shunt inductors.

19. From the results recorded in Table 2, explain how the STATCOM compensates the voltage across the ac power system to which it is connected (i.e., the receiver voltage E_R).

The STATCOM compensates the voltage of the ac power system to which it is connected (i.e., the receiver voltage E_R) by adjusting the magnitude and polarity of the reactive component of the current flowing through its ac side (i.e., the reactive current component of the three-phase PWM rectifier/inverter), in order to exchange just the right amount of reactive power (in the present case, the STATCOM supplies reactive power) to meet the reactive power requirement of the system. This ensures that the voltage across the ac power system connected to the STATCOM is maintained virtually equal to the ac power network voltage, no matter the reactive power requirement of the system.

Speed of the voltage compensation achieved by a STATCOM during load variations

20. On the Resistive Load, set the resistance of loads R_1, R_2, and R_3 to the 1st value indicated in Table 3 for your local ac power network voltage and frequency.

Table 3. Resistance values of loads R_1, R_2, and R_3 to be used for observing the speed of the voltage compensation achieved by the STATCOM when a load variations occurs.

Local ac power network		Resistive loads R_1, R_2, R_3 (Ω)	
Voltage (V)	**Frequency (Hz)**	**1st**	**2nd**
120	60	200	600
220	50	733	2200
240	50	800	2400
220	60	733	2200

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

22. In the STATCOM Control window, start the static synchronous compensator by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

23. In LVDAC-EMS, open the Oscilloscope. Make the appropriate settings in order to observe the waveform of the voltage E_R (input *E2*) and current I_R (input *I2*) at the receiver end of the ac transmission line.

Set the Oscilloscope as indicated below in order to be able to perform the next manipulation:

The settings below ensure that the Oscilloscope will start recording data at the instant when the peak value of voltage E_R becomes higher than its nominal peak value, i.e., when the load resistance at the receiver end of the line increases suddenly.

– Set the sensitivity of the channel used to observe the receiver voltage E_R to 200 V/div.

– Set the sensitivity of the channel used to observe the receiver current I_R to 1 A/div.

– Set the time base to 0.1 s/div.

– Set the trigger type to *Hardware*. Set the trigger source to the channel used to observe the receiver voltage E_R, and the trigger level to about 10 V higher than the peak value of the receiver voltage.

Adjust the horizontal position of the trigger point to about 4 divisions from the left-hand side of the oscilloscope screen.

– On the Oscilloscope, click the *Single Refresh* button.

24. Create a sudden increase in load resistance at the receiver end of the line to simulate a sudden decrease in the power demand of the consumers. To do so, set the resistance of loads R_1, R_2, and R_3 on the Resistive Load to the 2nd value indicated in Table 3 for your local ac power network and voltage.

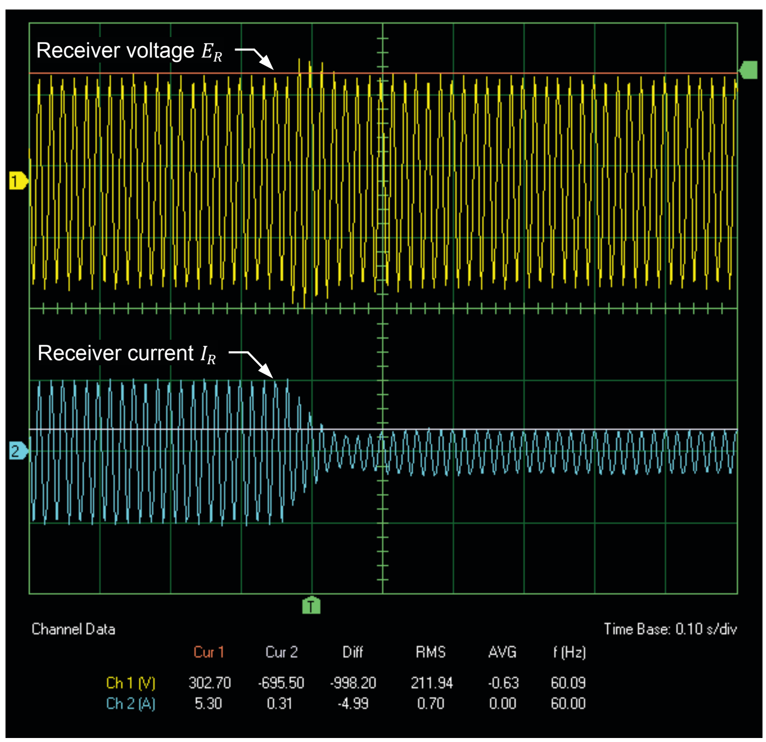
For optimal results, modify the switch settings simultaneously on the three legs of the Resistive Load in order to avoid operation with an unbalanced load as much as possible.

If no signal appear on the Oscilloscope (i.e., if the Oscilloscope does not trig) at the instant the sudden increase in load resistance occurs, set the load resistance of loads R_1, R_2, and R_3 back to the 1st value indicated in Table 3, then repeat the above manipulation until voltage and current waveforms appear on the Oscilloscope.

On the Oscilloscope, save the currently-displayed voltage and current waveforms to the first memory. These waveforms will be used later in the exercise.

The resulting waveforms are shown below.

Oscilloscope Settings
Channel-1 Input E2
Channel-1 Scale ....200 V/div
Channel-1 Coupling ....DC
Channel-2 Input I2
Channel-2 Scale ....1 A/div
Channel-2 Coupling ....DC
Show Cursors ....Horizontal
Time Base............................. 0.1 s/div
Trigger Type .... Hardware
Trigger Source Ch1
Trigger Level............................. 310 V
Trigger Slope ....Rising



Receiver voltage E_R and receiver current I_R when the STATCOM compensates the voltage after a sudden increase in load resistance at the receiver end of an ac transmission line.

25. On the Oscilloscope, make the following settings:

The settings below ensure that the Oscilloscope will start recording data when the peak value of the receiver current I_R becomes higher than its nominal peak value, i.e., when the load resistance at the receiver end of the line decreases suddenly.

– Leave the trigger type set to *Hardware*. Set the trigger source to the channel used to observe the receiver current I_R, and the trigger level to about 0.1 A higher than the peak value of the receiver current.

– Click the *Single Refresh* button.

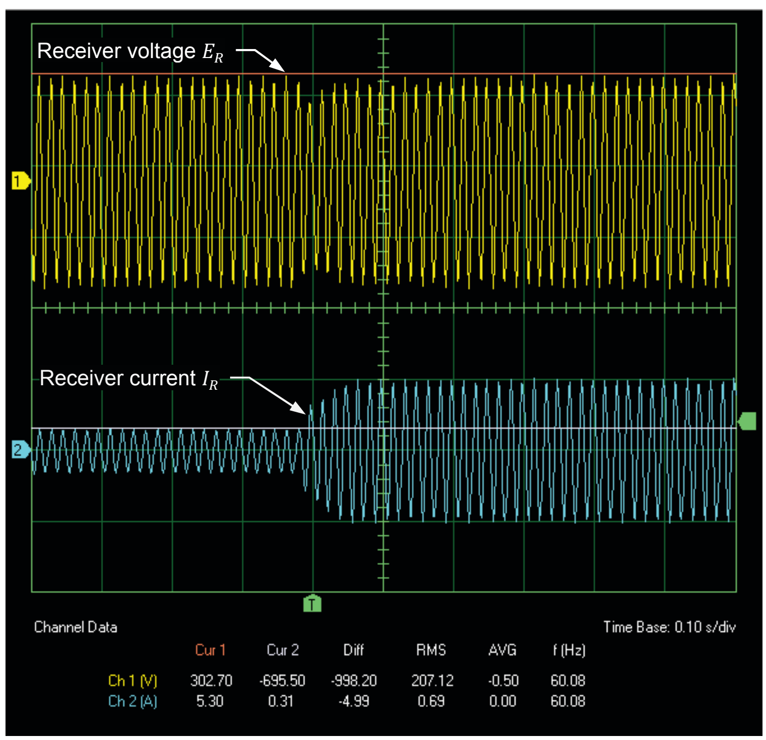
26. Create a sudden decrease in load resistance at the receiver end of the line to simulate a sudden increase in the power demand of the consumers. To do so, set the resistance of loads R_1, R_2, and R_3 on the Resistive Load to the 1st value indicated in Table 3 for your local ac power network and voltage.

For optimal results, modify the switch settings simultaneously on the three legs of the Resistive Load in order to avoid operation with an unbalanced load as much as possible.

On the Oscilloscope, save the currently-displayed voltage and current waveforms to the second memory.

The resulting waveforms are shown below.

Oscilloscope Settings
Channel-1 Input E2
Channel-1 Scale .... 200 V/div
Channel-1 Coupling .... DC
Channel-2 Input I2
Channel-2 Scale .... 1 A/div
Channel-2 Coupling .... DC
Show Cursors .... Horizontal
Time Base .... 0.1 s/div
Trigger Type .... Hardware
Trigger Source Ch2
Trigger Level .... 0.4 A
Trigger Slope .... Rising



Receiver voltage E_R and receiver current I_R when the STATCOM compensates the voltage after a sudden decrease in load resistance at the receiver end of an ac transmission line.

27. Observe the voltage and current waveforms saved to the memories of the Oscilloscope. From your observations, does the STATCOM compensate almost instantly for the voltage fluctuations across the ac power system to which it is connected (i.e., the receiver voltage E_R) due to sudden variations of the load? Explain briefly.

Yes. The voltage and current waveforms saved to the memories of the Oscilloscope show that the STATCOM compensates almost instantly (i.e., within 5 cycles or less of the receiver voltage E_R) for the voltage fluctuations at the receiver end of the ac transmission line caused by sudden variations of the load.

28. In the STATCOM Control window, stop the static synchronous compensator by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

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

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

Conclusion

In this exercise, you familiarized yourself with the operating principles of STATCOMs when they are used for voltage compensation of ac transmission lines. You learned how a STATCOM controller designed for automatic voltage control compensates the voltage across the ac power system to which the STATCOM is connected.

Review Questions

1. What are the two main advantages of STATCOMs over switched shunt inductors when they are used for voltage compensation of ac transmission lines?

When used for voltage compensation of ac transmission lines, the two main advantages of STATCOMs over switched shunt inductors substations are:

– Tighter control of the voltage compensation across the ac transmission line.

– Increased line stability during transients (i.e., during sudden changes in the load at the receiver end of the ac transmission line), due to the quickness of their STATCOM response.

2. Which component acts as the dc power source in a STATCOM? How is the voltage across that component maintained at a specific value? Explain briefly.

   A large capacitor acts as the dc power source in a STATCOM. The voltage across this capacitor is maintained at a specific value by continually adjusting the magnitude and polarity of the active component of the current at the ac side of the STATCOM. When the voltage across the capacitor needs to be increased, the STATCOM adjusts the magnitude and polarity of the active component of the current flowing through its ac side so that active power is drawn from the ac power system and converted to dc power in order to charge the capacitor. Conversely, when the voltage across the capacitor needs to be decreased, the STATCOM adjusts the magnitude and polarity of the active component of the current flowing through its ac side so that active power is returned to the ac power system, thereby discharging the capacitor.

3. What are the primary advantages of STATCOMs over SVCs?

   The primary advantages of STATCOMs over SVCs are summarized below:

   – STATCOMs are not affected significantly when operating in undervoltage conditions while SVCs are.

   – STATCOMs have a slightly faster response time than SVCs.

   – STATCOM installations are much smaller in size than SVC installations of comparable ratings.

4. Describe how banks of switched shunt inductors and a STATCOM are distributed along an ac transmission line covering a long distance. Explain briefly.

   In an ac transmission line covering a long distance, the voltage along the line is compensated using banks of switched shunt inductors along the line, which provide cost-effective voltage compensation. At the receiver end of the ac transmission line, however, the voltage is generally compensated using a bank of switched shunt inductors and a STATCOM. This ensures tighter control of the voltage at the end of the line, as well as greater line stability during transients. This is especially important at the end of the ac transmission line, where the voltage must be carefully compensated before the electrical power is distributed to consumers.

5. Is it usual to replace all switched shunt inductors along an ac transmission line covering a long distance with STATCOMs? Explain briefly.

No, it is not usual to replace all switched shunt inductors along an ac transmission line covering a long distance with STATCOMs. This is due to the fact that, even though STATCOMs are more efficient in every aspect than switched shunt inductors, they are much more costly. Since the use of switched shunt inductors to compensate voltage along ac transmission lines already yields acceptable results, replacing all switched shunt inductors with STATCOMs is usually not cost effective.

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