Electricity and New Energy

Static Var Compensator (SVC)

Courseware Sample

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By the staff of Festo Didactic

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

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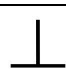
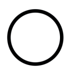
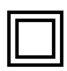
Safety and Common Symbols

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

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

Safety and Common Symbols

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

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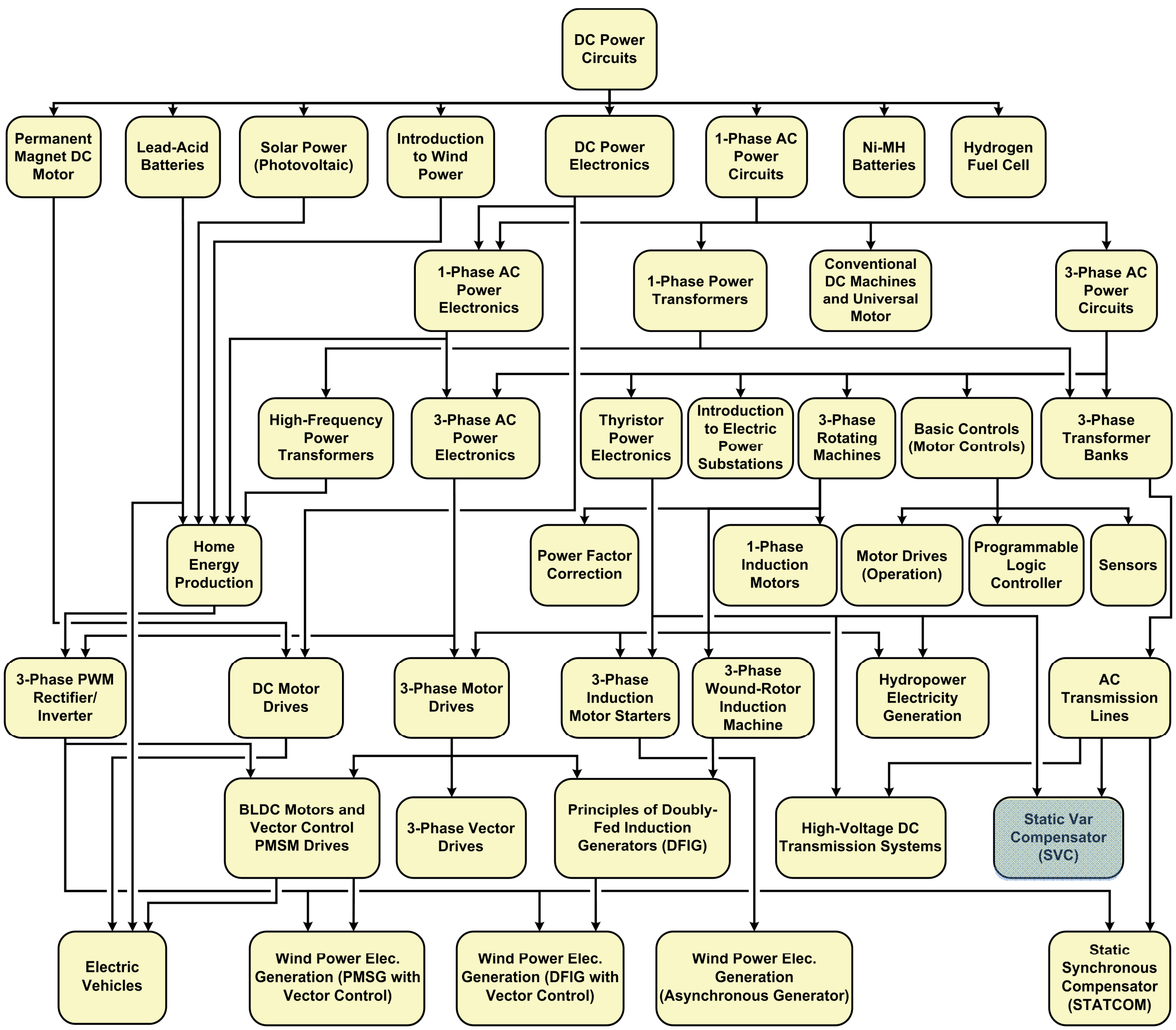
Preface

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 var compensators (SVCs) 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 system to which they are connected. SVCs achieve this by switching in or out one or more thyristor-switched capacitors (TSCs), and by adjusting the firing angle of a thyristor-controlled reactor (TCR). Some SVCs also comprise a number of fixed capacitors (FCs) which supply a steady amount of reactive power.

SVCs can be used for voltage compensation at the receiver end of ac transmission lines, thus replacing banks of shunt capacitors. When used for this purpose, SVCs offer a number of advantages over banks of shunt capacitors, 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.

SVCs 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. SVCs 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 Var Compensators (SVCs), teaches the basic concepts of voltage compensation in ac transmission lines and power factor correction in large industrial plants using SVCs. Students are introduced to the operation of SVCs and their different components. They also learn about different types of SVCs, and how each type of SVC operates. Students also verify the theory presented in the manual by performing circuit measurements and calculations.

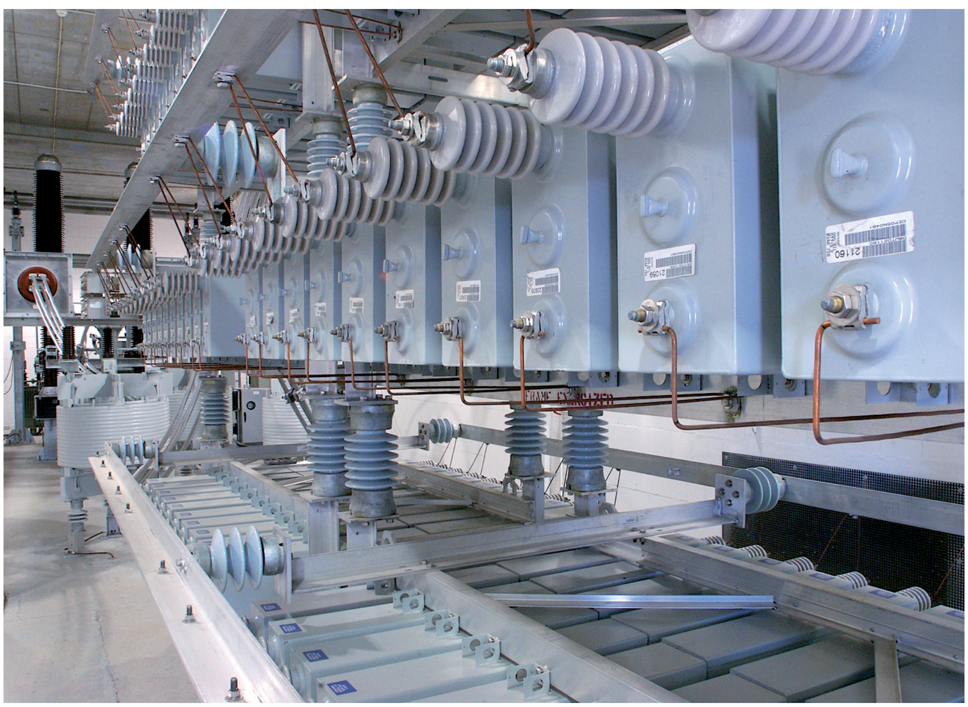


Figure 1. Indoor view of a static var compensator (SVC) substation in Denmark. (© Siemens AG 2012, all rights reserved).

About This Manual

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*, p.n. 86350, *Single-Phase AC Power Circuits*, p.n. 86358, *Single-Phase Power Transformers*, p.n. 86377, *Three-Phase AC Power Circuits*, p.n. 86360, *Thyristor Power Electronics*, p.n. 86363, *Three-Phase Transformer Banks*, p.n. 86379, and *AC Transmission Lines*, p.n. 86365.

Systems of units

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

To the Instructor

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

Accuracy of measurements

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

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, part number 38486-E.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

Voltage Compensation of AC Transmission Lines Using an SVC

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the operating principles of SVCs used for voltage compensation of ac transmission lines. You will also be familiar with the two basic types of SVCs: TCR-FC and TCR-TSC. You will know which components are used in each type of SVC, as well as how each type of SVC operates. You will also know how an SVC controller designed for automatic voltage control compensates the voltage across the ac power system to which the SVC is connected.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Voltage compensation of ac transmission lines using an SVC
- Types of SVCs: TCR-FC and TCR-TSC
  SVC of the TCR-FC type. SVC of the TCR-TSC type.
- Automatic voltage compensation
  Precision of the voltage compensation achieved by the SVC during load variations. Speed of the voltage compensation achieved by the SVC during load variations.

DISCUSSION

Voltage compensation of ac transmission lines using an SVC

In the Introduction to this manual, you learned that a significant voltage drop occurs at the receiver end of ac transmission lines. The magnitude of this voltage drop increases with the length of the line, as well as with the load at the receiver end of the line. Such a voltage drop cannot be tolerated 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 (close to the voltage for which they are rated).

One way to compensate for the voltage drop occurring across an ac transmission line is to add substations containing shunt capacitors along the line. Adding shunt-capacitor substations in such a way produces the effect of dividing an ac transmission line into many segments of shorter length. Each substation serves the purpose of compensating the voltage drops across the ac transmission line (i.e., maintaining a constant voltage across each segment of the ac transmission line).

Figure 29 illustrates 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).

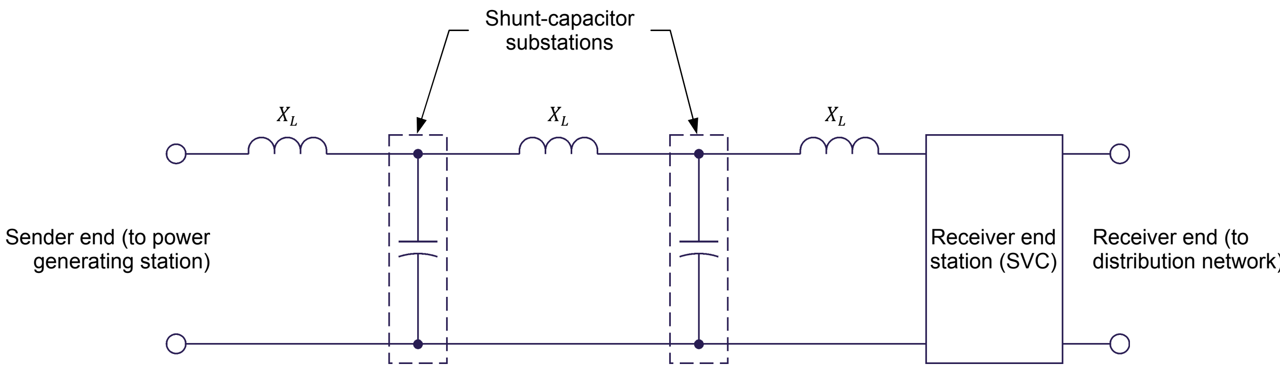


Figure 29. Typical ac transmission line used to transfer large amounts of electrical power over a long distance from a power generating station to the distribution network.

As Figure 29 shows, the ac transmission line is divided into three segments of equal length by two shunt-capacitor substations used for voltage compensation. The voltage at each substation is compensated by switching shunt capacitors 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 to this manual, shunt-capacitor substations have certain drawbacks, such as the difficulty in coordinating all substations and perfectly compensating the voltage across each segment of the ac transmission line. However, since the shunt-capacitor substations are located along the ac transmission line, and thus, do not directly supply power to consumers, it is not necessary for the voltage at the shunt-capacitor substations to be perfectly compensated at all times.

On the other hand, the voltage at the end of the third segment (i.e., the receiver end) of the ac transmission line in Figure 29 is compensated using an SVC substation, instead of a shunt-capacitor substation. This is due to the numerous advantages SVCs offer over shunt capacitor substations, most notably a tight and fast compensation of the voltage across the line. Since the receiver end station is located at the end of the ac transmission line, it is important for the voltage at this station to be as perfectly compensated as possible before the electrical power is distributed to consumers; hence, a SVC substation is used here instead of a shunt-capacitor substation.

Due to its fast and precise compensation of the voltage at the receiver end of an ac transmission line, an SVC substation is able to compensate for the voltage fluctuations occurring across the line (generated by switching shunt capacitors in and out in the substations), and compensate for the voltage fluctuations caused by the variation of the load (i.e., the electrical power demand of the consumers).

To obtain a level of precision in the voltage compensation comparable to an SVC while using a shunt-capacitor substation at the receiver end of an ac transmission line, a large number of capacitors of different reactance values would need to be installed in the shunt-capacitor substation. This would give the shunt-capacitor substation a large variety of possible shunt capacitor combinations, and therefore would enable the shunt-capacitor substation to precisely compensate the voltage at the receiver end of the ac transmission line. Such a shunt-capacitor substation, however, would be just as costly as an SVC substation (if not more so), while having a response time that is much slower than an SVC substation. This is why, for fast and precise voltage compensation at the receiver end of an ac transmission line, SVC substations are much more efficient than shunt-capacitor substations.

It would be possible to replace all the shunt-capacitor substations in the ac transmission line of Figure 29 with SVC substations to achieve even more effective voltage compensation. However, even though SVCs are more efficient than shunt-capacitor substations in every aspect, it is not common practice to systematically replace shunt-capacitor substations with SVC substations. This is primarily due to an SVC substation being much more costly (about 5 times more) than a shunt-capacitor substation with a comparable power rating. Since the use of shunt-capacitor substations to compensate the voltage along ac transmission lines already yields acceptable results, replacing all shunt-capacitor substations in an ac transmission line with SVC substations is usually not cost effective.

Figure 30. SVC substation in Pingguo, China (© Siemens AG 2012, all rights reserved).

Types of SVCs: TCR-FC and TCR-TSC

There are two basic types of SVCs, each having a different combination of the components described in Exercise 1 of this manual: the SVC of the TCR-FC type and the SVC of the TCR-TSC type. Both types of SVCs are covered in detail in the following two subsections.

SVC of the TCR-FC type

As its name indicates, the SVC of the TCR-FC type consists of a TCR, which absorbs reactive power from the ac power system to which the SVC is connected, and several FCs, which supply reactive power to the system connected to the SVC. The simplified single-wire circuit diagram of an SVC of the TCR-FC type is illustrated in Figure 31.

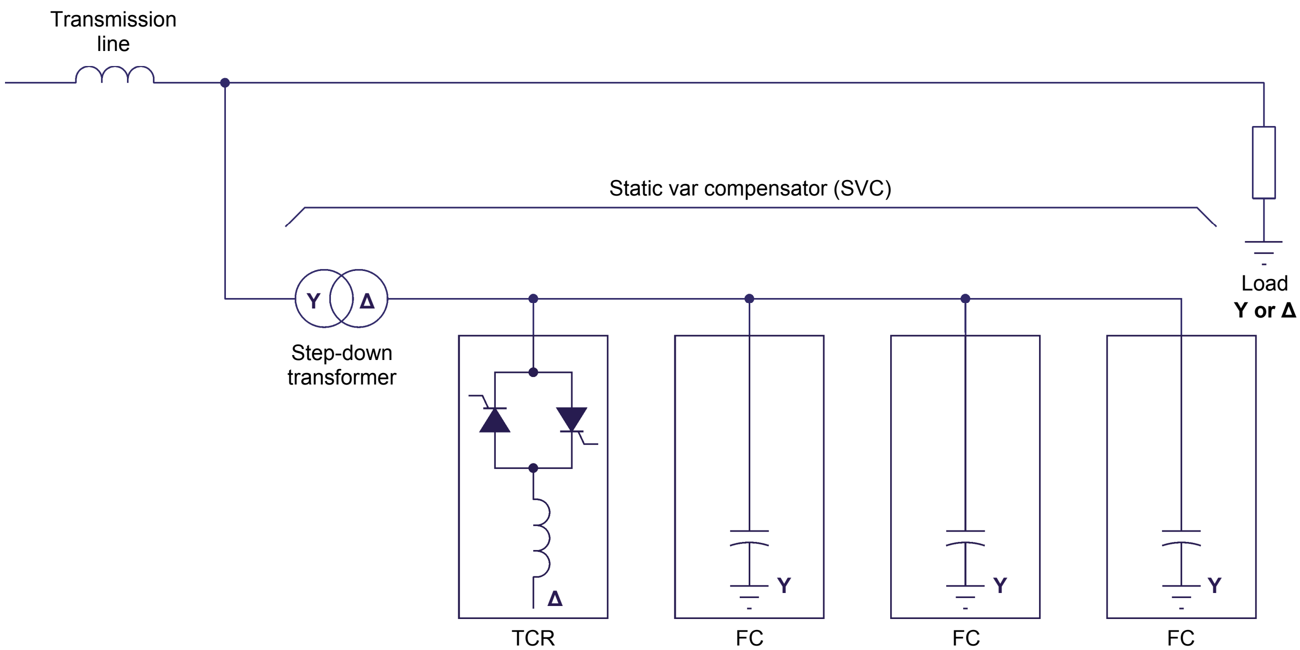


Figure 31. Simplified single-wire circuit diagram of an SVC of the TCR-FC type.

As seen in Exercise 1, FCs have a fixed reactance value (i.e., they supply a fixed amount of reactive power) and cannot be switched in or out. The amount of reactive power absorbed by the TCR, on the other hand, can be adjusted as needed from a maximal value (TCR firing angle $= 90°$) to zero (TCR firing angle $= 180°$). The main voltage, current, and reactive power parameters related to one leg (phase) of an SVC of the TCR-FC type are shown on the circuit diagram in Figure 32. Note that to simplify the circuit diagram, only one FC is used to represent all FCs of the SVC.

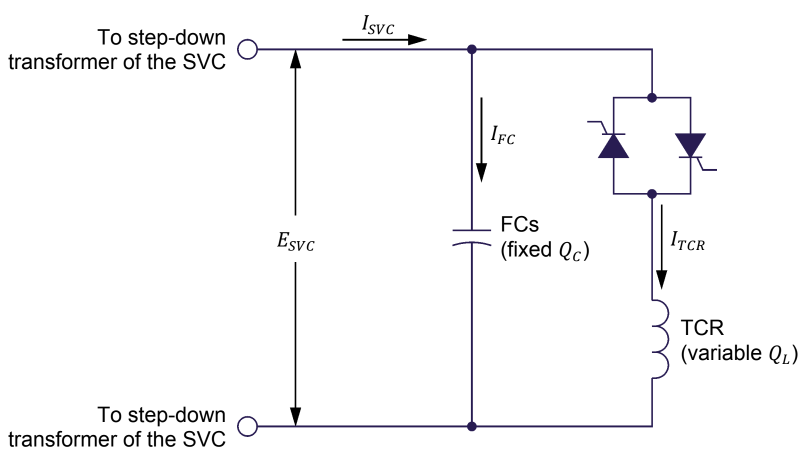


Figure 32. Simplified circuit diagram of one leg (phase) of an SVC of the TCR-FC-type showing the main voltage, current, and reactive power parameters.

When the amount of reactive power required to compensate the voltage in the ac power system connected to an SVC of the TCR-FC type is null, the TCR firing angle is adjusted so that the reactive power absorbed by the TCR fully offsets the fixed amount of reactive power (Q_C) supplied by the FCs. When the SVC has to supply reactive power to compensate the voltage in the ac power system (i.e., when the system absorbs reactive power), the TCR firing angle is increased so that the amount of reactive power absorbed by the TCR decreases. The lower the reactive power which the TCR absorbs, the higher the reactive power which the SVC supplies. When the TCR is set to the non-conducting state, the amount of reactive power supplied by the SVC is maximal. The maximal amount of reactive power which an SVC of the TCR-FC type can supply is equal to the reactive power rating (i.e., Q_C) of the FCs.

Conversely, when the SVC has to absorb reactive power to compensate the voltage in the ac power system (i.e., when the system supplies reactive power), the TCR must absorb enough reactive power to, firstly, fully offset the fixed amount of reactive power supplied by the FCs, and, secondly, absorb enough extra reactive power to compensate for the reactive power supplied by the ac power system connected to the SVC. This means that the power rating of the TCR in an SVC of the TCR-FC type needs to be higher than that of the FCs, otherwise, the SVC would not be able to absorb reactive power from the ac power system to which it is connected. The reactive power exchange characteristic of an SVC of the TCR-FC type is illustrated in Figure 33.

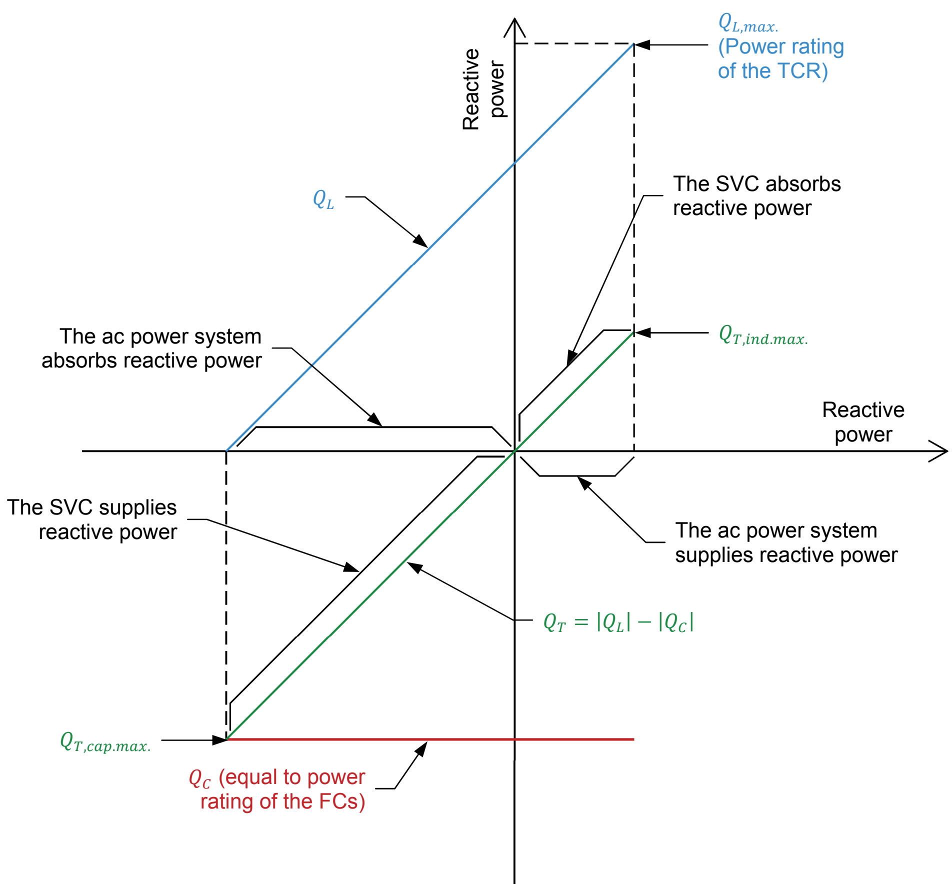


Figure 33. Reactive power exchange characteristic of an SVC of the TCR-FC-type.

As the figure shows, the total reactive power Q_T which an SVC of the TCR-FC type exchanges with the ac power system to which it is connected is equal to the variable reactive power Q_L absorbed by the TCR minus the fixed reactive power Q_C supplied by the FCs. The total reactive power Q_T of an SVC of the TCR-FC type thus ranges from the maximal capacitive reactive power $Q_{T,cap.max.}$, which is equal to the reactive power rating Q_C of the FCs, to the maximal inductive reactive power $Q_{T,ind.max.}$, which is equal to the reactive power rating $Q_{L,max.}$ of the TCR minus the reactive power rating Q_C of the FCs. When the total reactive power Q_T in the SVC is negative, the SVC supplies reactive power. Conversely, when the total reactive power Q_T in the SVC is positive, the SVC absorbs reactive power.

In order for an SVC of the TCR-FC type to operate properly, it is necessary for the control and monitoring components of the SVC to be implemented effectively. The two main tasks that the SVC controller must perform to meet the reactive power requirement of the ac power system connected to the SVC are summarized below.

- To determine the amount of reactive power that must be absorbed by the TCR to precisely meet the amount of reactive power needed for accurate compensation of the voltage in the ac power system connected to the SVC, taking into account the amount of reactive power supplied by the FCs.

- To control the TCR firing angle (and, consequently, the rms value of the current flowing in the TCR) so that the amount of reactive power absorbed by the TCR corresponds to the value determined above.

The major drawback of any SVC of the TCR-FC type is that the TCR needs to have a power rating $Q_{L,max.}$ that is equal to the reactive power (Q_T) range of the SVC, thereby resulting in a large TCR. For example, when the reactive power Q_T of an SVC can vary from -100 Mvar to +25 Mvar, the power rating $Q_{L,max.}$ of the TCR required is 125 Mvar. This is due to the fact that the TCR must absorb enough reactive power to fully offset the reactive power supplied by the FCs and still be able to absorb any additional reactive power that the ac power system connected to the SVC could supply. This generally results in significant power losses (RI^2 losses) in the TCR because during normal operation the reactive power Q_L in the TCR is often comparable to, or even exceeds, the reactive power Q_T which the SVC exchanges with the ac power system to which it is connected (in other words, the current I_{TCR} flowing in the TCR is often comparable to, or even exceeds, the current I_{SVC} flowing between the SVC and the ac power system). Furthermore, due to its large size, the TCR generates a large amount of harmonics, which means that the harmonic filters in the TCR also need to be larger to properly filter all harmonics.

SVC of the TCR-TSC type

As its name indicates, the SVC of the TCR-TSC type consists of a TCR, which absorbs reactive power from the ac power system connected to the SVC, and several TSCs, which supply reactive power to the ac power system connected to the SVC. The simplified single-wire circuit diagram of an SVC of the TCR-TSC type is illustrated in Figure 34. Note that, in certain cases, SVCs of the TCR-TSC type may also contain FCs, mainly for harmonic filtering purposes. In this section of the discussion, however, it is assumed that SVCs of the TCR-TSC type only contain a TCR and several TSCs.

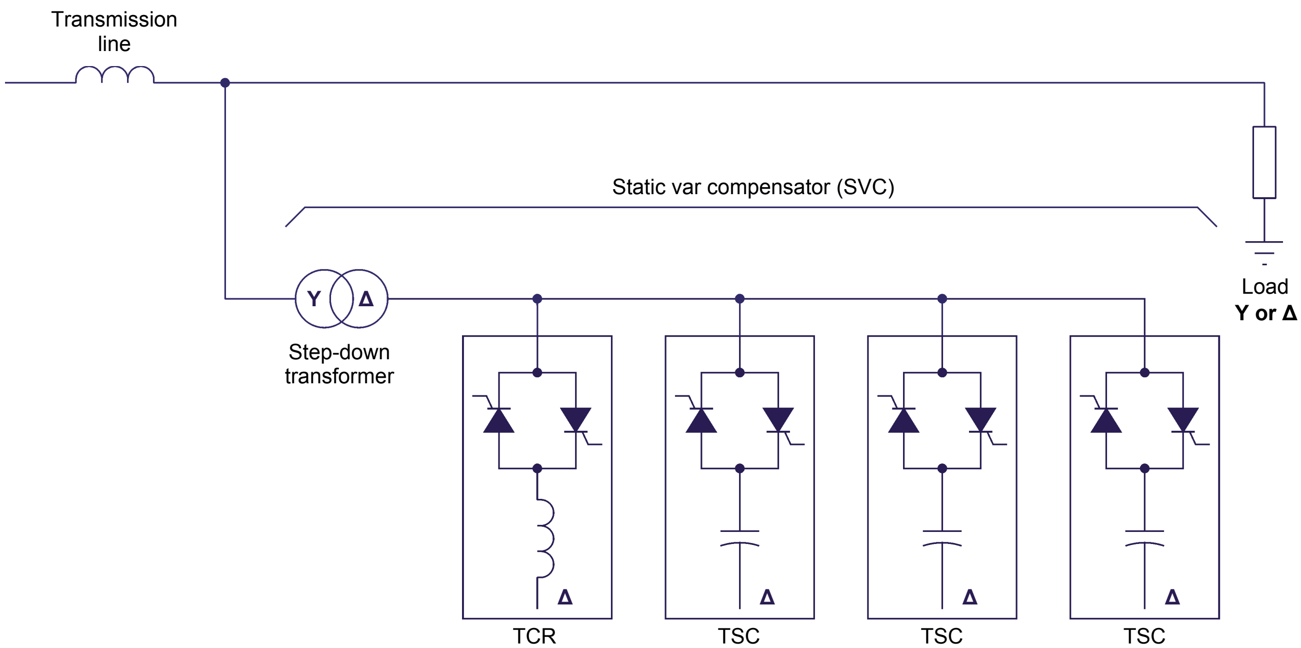


Figure 34. Simplified single-wire circuit diagram of an SVC of the TCR-TSC type.

As seen in Exercise 1, the TSCs of an SVC can only be switched in or switched out. Because of this, the amount of reactive power supplied by the TSCs can only be adjusted by steps by changing the number of TSCs that are switched in at the same time. The higher the number of TSCs that are switched in, the higher the amount of reactive power supplied by the TSCs. The TCR, on the other hand, can be adjusted as needed from a full-conducting state (TCR firing angle = 90°) to a non-conducting state (TCR firing angle = 180°), thereby allowing precise and continuous adjustment of the amount of reactive power which the SVC exchanges with the ac power system to which it is connected. The main voltage, current, and reactive power parameters related to one leg (phase) of an SVC of the TCR-TSC type are shown on the circuit diagram in Figure 35. Note that, to simplify the circuit diagram, only one TSC is used to represent all TSCs of the SVC.

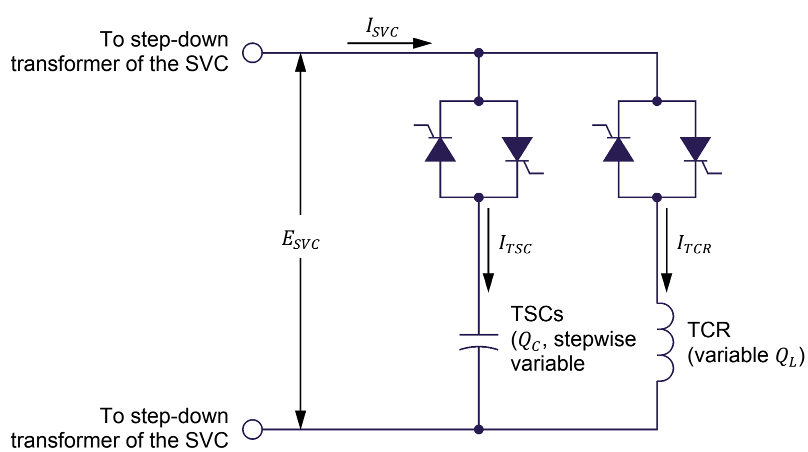


Figure 35. Simplified circuit diagram of one leg (phase) of an SVC of the TCR-TSC type showing the main voltage, current, and reactive power parameters.

When the amount of reactive power required to compensate the voltage in the ac power system connected to an SVC of the TCR-TSC type is null, all TSCs are switched out and the TCR is set to the non-conducting state (TCR firing angle = 180°). When the SVC has to supply reactive power to compensate the voltage in the ac power system, a number of TSCs are switched in so that the reactive power they supply exceeds the amount of reactive power the SVC has to supply to properly compensate the ac power system voltage. The TCR firing angle is then adjusted so that the amount of reactive power absorbed by the TCR precisely offsets the excess of reactive power supplied by the TSCs. As the amount of reactive power the SVC has to supply to properly compensate the ac power system voltage increases or decreases, the TCR firing angle is adjusted so that the TCR absorbs just the right amount of the reactive power supplied by the TSCs.

When the amount of reactive power which the SVC has to supply to compensate the voltage in the ac power system increases and exceeds the reactive power rating of the TSCs that are currently switched in (the TCR firing angle is set to 180° in this case), another TSC must be switched in. On the other hand, when the amount of reactive power which the SVC has to supply to compensate the voltage decreases below the amount of reactive power that the SVC supplies when the TCR absorbs the maximum amount of reactive power (i.e., when the TCR firing angle is 90°), a TSC must be switched out. In both cases, the TCR firing angle is then readjusted so that the TCR absorbs just the right amount of the reactive power supplied by the TSCs to meet the reactive power requirement of the ac power system to which the SVC is connected. The maximal amount of reactive power that an SVC of the TCR-TSC type can supply is obtained when all TSCs are switched in and the TCR is set to a non-conducting state (TCR firing angle = 180°).

Conversely, when the SVC has to absorb reactive power to properly compensate the voltage in the ac power system (i.e., when the system supplies reactive power), all TSCs in the SVC are switched out. Then, the TCR firing angle is adjusted so that the TCR absorbs all the reactive power supplied by the ac power system to which the SVC is connected. The reactive power exchange characteristic of an SVC of the TCR-TSC type is illustrated in Figure 36.

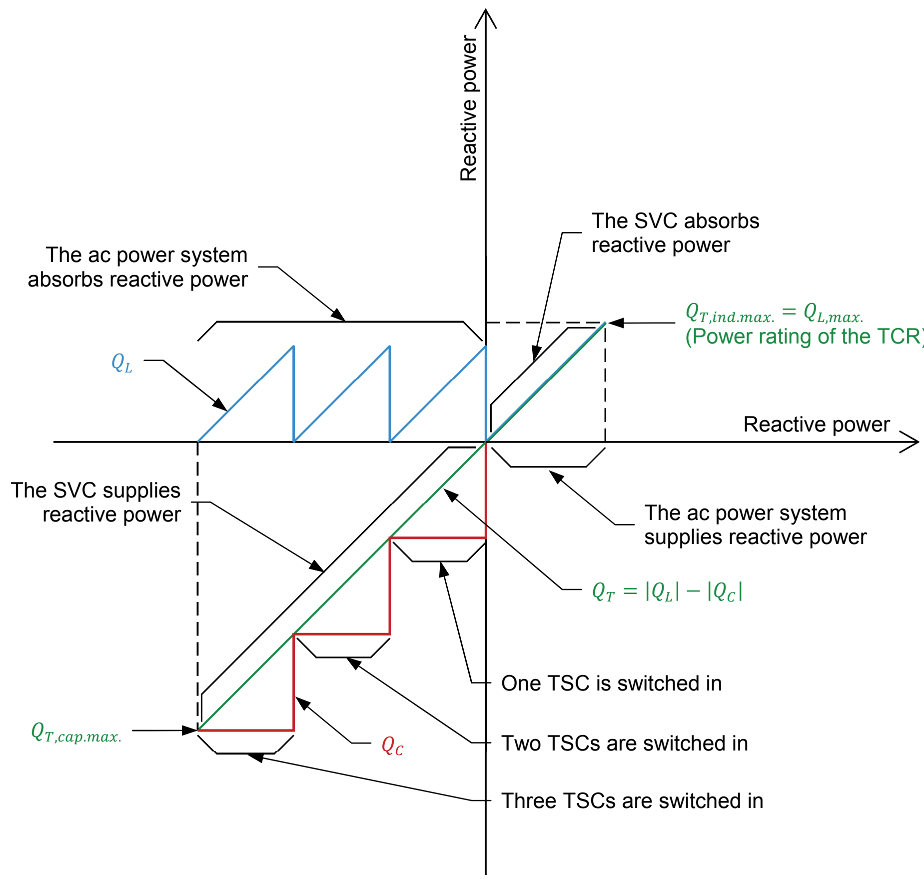


Figure 36. Reactive power exchange characteristic of an SVC of the TCR-TSC-type.

As the figure shows, the total reactive power Q_T which an SVC of the TCR-TSC type exchanges with the ac power system to which it is connected is equal to the variable reactive power Q_L absorbed by the TCR minus the reactive power Q_C (stepwise variable) supplied by the TSCs. The total reactive power Q_T of an SVC of the TCR-TSC type thus ranges from the maximal capacitive reactive power $Q_{T,cap.max.}$, which is equal to the total reactive power rating of the TSCs, to the maximal inductive reactive power $Q_{T,ind.max.}$, which is equal to the reactive power rating ($Q_{L,max.}$) of the TCR. When the total reactive power Q_T in an SVC is negative, the SVC supplies reactive power. Conversely, when the total reactive power Q_T in an SVC is positive, the SVC absorbs reactive power.

In order for an SVC of the TCR-TSC type to operate properly, it is necessary for the control and monitoring components of the SVC to be implemented effectively. The four main tasks that the controller must perform to meet the reactive power requirement of the ac power system connected to the SVC are summarized below.

- To determine the number of TSCs required and the amount of reactive power that the TCR must absorb to precisely meet the reactive power requirement of the ac power system to which the SVC is connected.

- To switch TSCs in and out so as to match the required number of TSCs determined above.
- To control the TCR firing angle (and, consequently, the rms value of the current flowing in the TCR) so that the amount of reactive power absorbed by the TCR corresponds to the value determined above.
- To properly coordinate the TSC switching control and TCR firing angle control so as to ensure transient-free operation (i.e., so as to minimize voltage transients in the ac power system to which the SVC is connected).

The primary advantage of SVCs of the TCR-TSC type over SVCs of the TCR-FC type is the smaller size of the TCR. This is due to the fact that the TCR in an SVC of the TCR-TSC type only needs to have a power rating that is slightly higher than that of any of the TSCs in order to provide a certain flexibility when switching TSCs in and out. The TCR in an SVC of the TCR-FC type, on the other hand, needs to be able to fully offset the reactive power Q_C supplied by all TSCs, as well as being able to absorb any extra amount of reactive power which the system to which the SVC is connected could supply.

Due to its much smaller size, the TCR in SVCs of the TCR-TSC type is less costly and more efficient (i.e., it has less power losses) than the larger TCR in SVCs of the TCR-FC type. The smaller size of the TCR in SVCs of the TCR-TSC type also decreases the amount of harmonics generated by the TCR which, in turn, means that the harmonic filters in the SVC can be reduced in size.

Figure 37. SVC substation in Maryland, USA. This substation was installed primarily to enhance the reliability of the heavily loaded power transmission lines in the area (photo courtesy of ABB).

Automatic voltage compensation

When an SVC is used for compensating the voltage across an ac power system (typically ac transmission lines), the voltage across the SVC is regulated using a voltage control loop implemented in the SVC controller. This controller monitors the voltage across the SVC and determines the number of TSCs (if any) that must be switched in and the TCR firing angle required in order to maintain the voltage measured across the SVC at the desired value (usually the nominal voltage of the ac power system to which the SVC is connected). The block diagram of an SVC designed for voltage compensation (i.e., automatic voltage control) is shown in Figure 38.

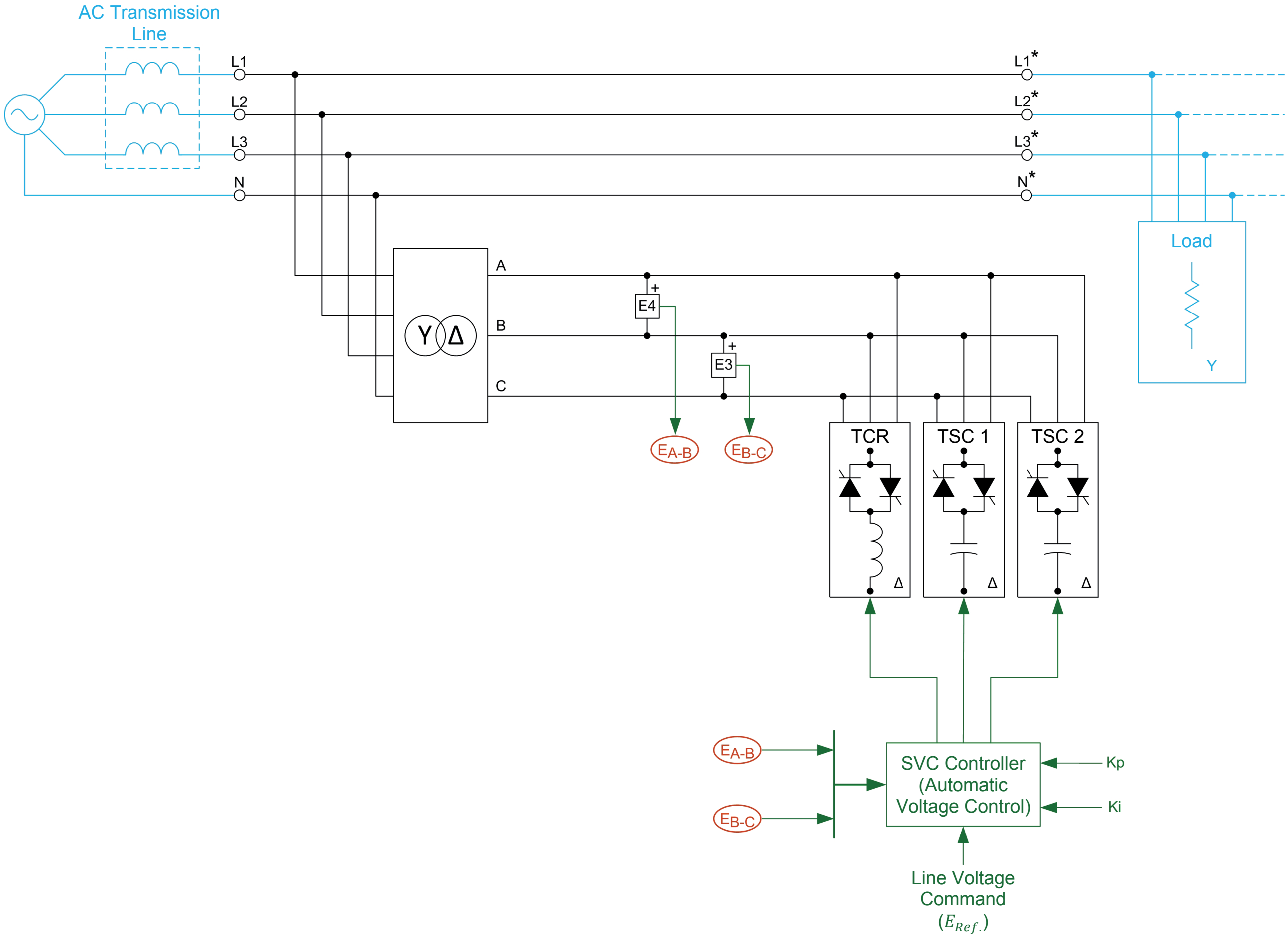


Figure 38. Block diagram of an SVC designed for voltage compensation.

As Figure 38 shows, two voltage sensors measure line voltages E_{A-B} and E_{B-C} across the SVC side of the step-down transformer and send these voltages to the SVC controller (which is set for automatic voltage control). The SVC controller compares the measured line voltages to the line voltage command $E_{Ref.}$ of the SVC, and determines the error in the measured line voltage across the SVC side of the step-down transformer. Using the determined error, the SVC controller switches TSCs in and out, and adjusts the TCR firing angle, so that the amount of reactive power which the SVC exchanges with the ac power system precisely compensates the voltage measured across the SVC side of the step-down transformer. This maintains the measured voltage as close as possible to the line voltage command $E_{Ref.}$ of the SVC. Note that line voltage E_{A-B} is also used to properly synchronize the firing of the thyristors in the TCR, as well as to provide the phase angle (θ) information required to perform mathematical calculations in the controller. The operation of an SVC controller designed for automatic voltage control is covered in more detail in Appendix D.

Figure 39. Parkdale SVC substation in the Dallas-Fort Worth metropolitan area, in Texas, USA. This substation is one of the world's largest and fastest-acting concentrations of SVCs (photo courtesy of ABB).

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Reactive power capacity of the SVC
- Voltage compensation at the receiver end of an ac transmission line using an SVC
- Voltage compensation using an SVC at the receiver end of an ac transmission line containing a shunt-capacitor substation

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 an SVC consisting of one TCR and two TSCs. You will then set up the measuring equipment required to study the operation of the SVC.

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.

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

Connect the *Low Power Input* of the Power Thyristors module to the *Power Input* of the Data Acquisition and Control Interface. 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 the Data Acquisition and Control Interface is detected. Make sure the *Computer-Based Instrumentation* and *SVC Control* functions for the Data Acquisition and Control Interface are available. Also, select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

5. Connect the equipment as shown in Figure 40 and Figure 41. Use the reactors and thyristor switched capacitors in the SVC Reactors/Thyristor Switched Capacitors module to implement the TCR and the TSCs, respectively. Note that points A1, A2, A3, and A4 in Figure 40 are connected to the corresponding points in Figure 41.

Before connecting the TCR, make sure that switch S_1 on the Power Thyristors module is set to the O (open) position, then set switch S_2 to the I (closed) position. Doing so connects thyristor Q_1 in series with thyristor Q_4, thyristor Q_2 in series with thyristor Q_5, and thyristor Q_3 in series with thyristor Q_6. This reduces the number of leads required to connect the TCR.

When connecting TSC 1, make sure to close the open branch by short-circuiting the terminals linked by a dotted line.

Also, note that, in the circuit of Figure 40 and Figure 41, the inputs (*E1* and *I1*) used to measure the reactive power which the SVC exchanges with the ac power source (i.e., the ac power network) are connected at the secondary windings of the three-phase, step-down transformer, instead of directly to the ac power network. This ensures that the reactive power measured is due to the TCR and TSCs in the SVC exclusively, and not to the three-phase, step-down transformer (which absorbs a small amount of reactive power).

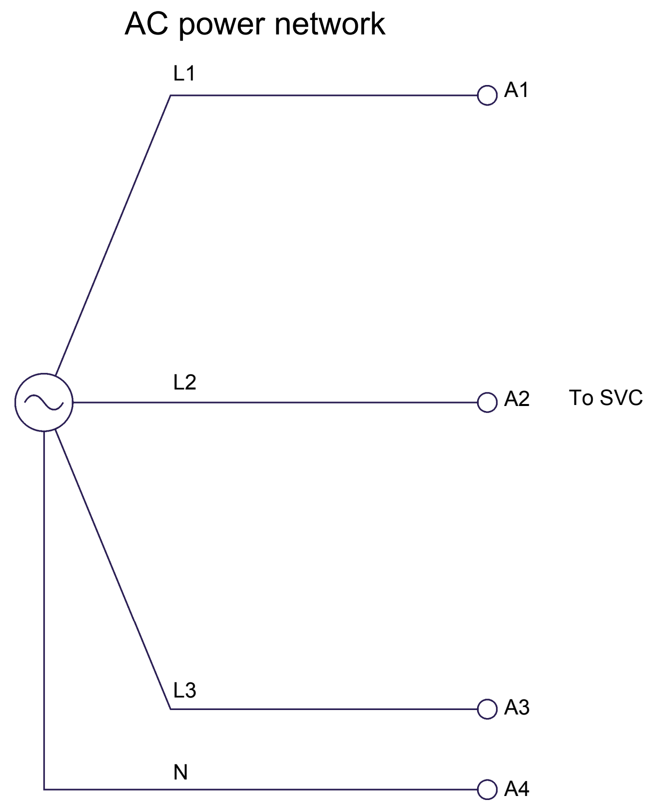


Figure 40. Circuit for measuring the reactive power capacity of an SVC consisting of one TCR and two TSCs.

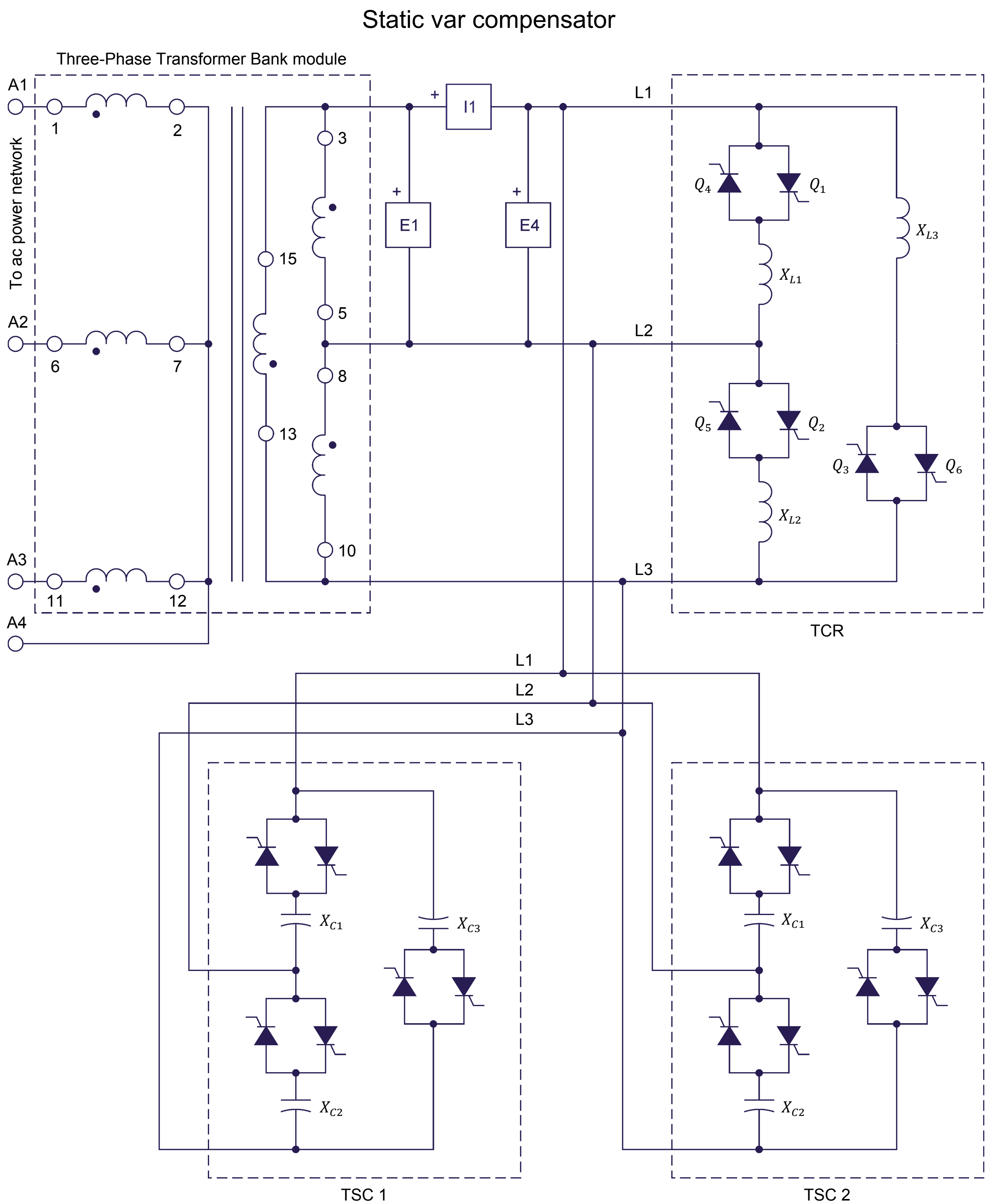


Figure 41. Circuit for measuring the reactive power capacity of an SVC consisting of one TCR and two TSCs.

In the circuit of Figure 40 and Figure 41, input E4 of the Data Acquisition and Control Interface is used for synchronization of the firing signals of the thyristors in the Power Thyristors module. Because of this, input E4 cannot be used for voltage measurements using the LVDAC-EMS instrumentation.

6. Connect the *Digital Outputs* of the Data Acquisition and Control Interface to the *Firing Control Inputs* of the Power Thyristors module using the provided cable with DB9 connectors.

Connect *Digital Output 1* and *Digital Output 2* of the Data Acquisition and Control Interface to the *TSC 1 Switching Control Input* and *TSC 2 Switching Control Input*, respectively, on the SVC Reactors/Thyristor Switched Capacitors module using miniature banana plug leads.

Connect a common digital (*D*) terminal (white) of the *Digital Outputs* on the Data Acquisition and Control Interface to the common terminal of the *TSC Switching Control Inputs* on the SVC Reactors/Thyristor Switched Capacitors module using a miniature banana plug lead.

7. Determine the type of SVC you just set up, and note it below.

The SVC you just set up is an SVC of TCR-TSC type.

8. In LVDAC-EMS, open the SVC Control window and make the following settings:

– Make sure the *Function* parameter is set to *Static Var Compensator*.

– Set the *Control Mode* parameter to *Manual Control*.

– Make sure the *TCR Firing Angle* parameter is set to 180°.

– Make sure that *TSC 1* and *TSC 2* parameters are set to *Switched Out*.

– Start the *Static Var Compensator* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

9. In LVDAC-EMS, 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 enables a better accuracy when measuring the different parameters of the SVC.

In the Metering window, make the required settings in order to measure the three-phase reactive power Q_{SVC} in the SVC [metering function *PQS1 (E1, I1) 3~*].

Reactive power capacity of the SVC

In this section, you will successively switch the first TSC in, then the second, and observe what happens to the reactive power in the SVC as you do so. You will measure the amount of reactive power in the SVC when both TSCs are switched in (i.e., the amount of reactive power which the SVC exchanges with the ac power network that is due to the TSCs). You will then switch both TSCs out, and decrease the TCR firing angle. You will observe what happens to the reactive power in the SVC as you do so. You will measure the amount of reactive power in the SVC when the TCR is set to a full-conducting state (i.e., the amount of reactive power which the SVC exchanges with the ac power network that is due to the TCR). Using the reactive power values you measured, you will then determine the reactive power capacity (range) of the SVC.

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

11. In the SVC Control window, set the *TSC 1* parameter to *Switched In*. While doing so, observe in the Metering window the reactive power Q_{SVC} in the SVC.

What happens to the reactive power Q_{SVC} in the SVC as you switch one of the TSCs in? Explain briefly what this indicates about the exchange of reactive power between the SVC and the ac power network.

The reactive power Q_{SVC} in the SVC increases and is of negative polarity as one of the TSCs is switched in. This indicates that the SVC supplies reactive power to the ac power source (i.e., the ac power network).

12. Record the value of the reactive power Q_{SVC} in the SVC when one of the TSCs is switched in and the TCR is set to a non-conducting state.

Reactive power Q_{SVC} = _______ var

Reactive power $Q_{SVC} = -74.8\ \text{var}$

13. In the SVC Control window, set the *TSC 2* parameter to *Switched In*. While doing so, observe in the Metering window the reactive power Q_{SVC} in the SVC.

What happens to the reactive power Q_{SVC} in the SVC as you switch the second TSC in?

The reactive power Q_{SVC} in the SVC approximately doubles as the second TSC is switched in.

14. Record the value of the reactive power Q_{SVC} in the SVC when all TSCs are switched in and the TCR is set to a non-conducting state.

Reactive power Q_{SVC} = _______ var

Reactive power $Q_{SVC} = -148$ var

What does this reactive power value correspond to, in relation to the power rating of the SVC?

This reactive power value corresponds to the maximal amount of reactive power that the SVC can supply to the ac power system to which it is connected. In other words, it corresponds to the capacitive reactive power rating ($Q_{T,cap.max.}$) of the SVC.

15. In the SVC Control window, set *TSC 1* and *TSC 2* parameters to *Switched Out*.

Slowly decrease the *TCR Firing Angle* parameter to 85°. While doing so, observe in the Metering window what happens to the reactive power Q_{SVC}.

What happens to the reactive power Q_{SVC} in the SVC as you decrease the TCR firing angle down to 85°? Explain briefly what this indicates about the exchange of reactive power between the SVC and the ac power network.

The reactive power Q_{SVC} in the SVC increases and is of positive polarity as the TCR firing angle is decreased. This indicates that the SVC absorbs more and more reactive power from the ac power source (i.e., the ac power network).

16. Record the value of the reactive power Q_{SVC} in the SVC when the TCR is set to a full-conducting state and all TSCs are switched out.

Reactive power Q_{SVC} = _______ var

Reactive power $Q_{SVC} = 95.8$ var

What does this reactive power value correspond to, in relation to the power rating of the SVC?

This reactive power value corresponds to the maximal amount of reactive power that the SVC can absorb from the ac power system to which it is connected. In other words, it corresponds to the inductive reactive power rating ($Q_{T,ind.max.}$) of the SVC.

17. Based on your observations in this part of the exercise, determine the reactive power rating of the SVC illustrated in the circuit of Figure 40 and Figure 41. Explain briefly.

The reactive power rating of the SVC used in this exercise is 152 var capacitive and 96.8 var inductive (i.e., -152 var to +96.8 var). This means that the SVC can supply a maximal amount of 152 var of reactive power to the ac power system to which it is connected, and can absorb a maximal amount of 96.8 var of reactive power from the ac power system.

18. Stop the *Static Var Compensator* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

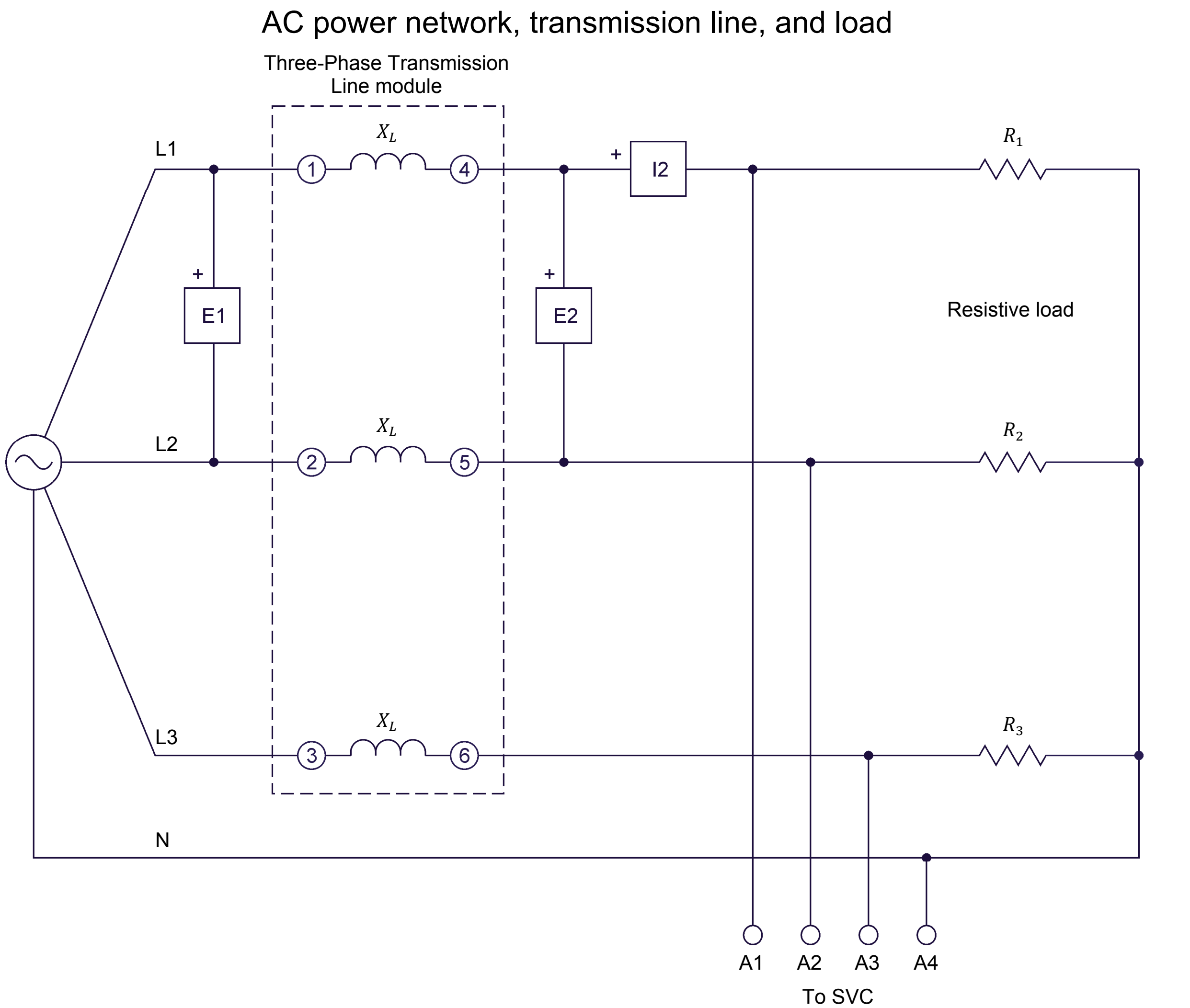
19. Turn the three-phase ac power source in the Power Supply off.

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

In this section, you will set up a circuit consisting of an ac transmission line supplying power to a resistive load, with an SVC at the receiver end of the line for voltage compensation. You will set the SVC to operate in automatic voltage control. You will vary the resistance of the resistive load, and record for each value the switch state of both TSCs, the TCR firing angle, the reactive power exchanged by the SVC, the sender voltage, and the receiver voltage. You will analyze the results and determine how precisely the SVC achieves voltage compensation during load variations. You will then use the Oscilloscope to record the transient in the receiver voltage, as well as the switching control signals sent to the TSCs, when, firstly, the resistive load decreases and when, secondly, the resistive load increases. Using the signals recorded on the Oscilloscope, you will determine how fast the SVC achieves voltage compensation during load variations.

20. Modify the equipment connections to obtain the circuit shown in Figure 42 and Figure 43. Note that, in this circuit, a three-phase transmission line and a three-phase load are added, and the connections of the voltage and current inputs differ. However, the connections of the various SVC components remain the same.

This circuit represents an ac transmission line that is voltage compensated at the receiver end of the line using an SVC substation. The resistive load in the circuit represents the electrical power demand of the electricity consumers. By adjusting the resistance of the resistive load, it is thus possible to vary the intensity of the electrical power demand.



Local ac power network		Line inductive reactance X_L (Ω)	Resistive loads R_1, R_2, R_3 (Ω)					
Voltage (V)	Frequency (Hz)		1st	2nd	3rd	4th	5th	6th
120	60	120	1200	600	400	300	240	200
220	50	400	4400	2200	1467	1100	880	733
240	50	400	4800	2400	1600	1200	960	800
220	60	400	4400	2200	1467	1100	880	733

Figure 42. Circuit for studying the operation of an SVC used for voltage compensation of an ac transmission line supplying power to a resistive load.

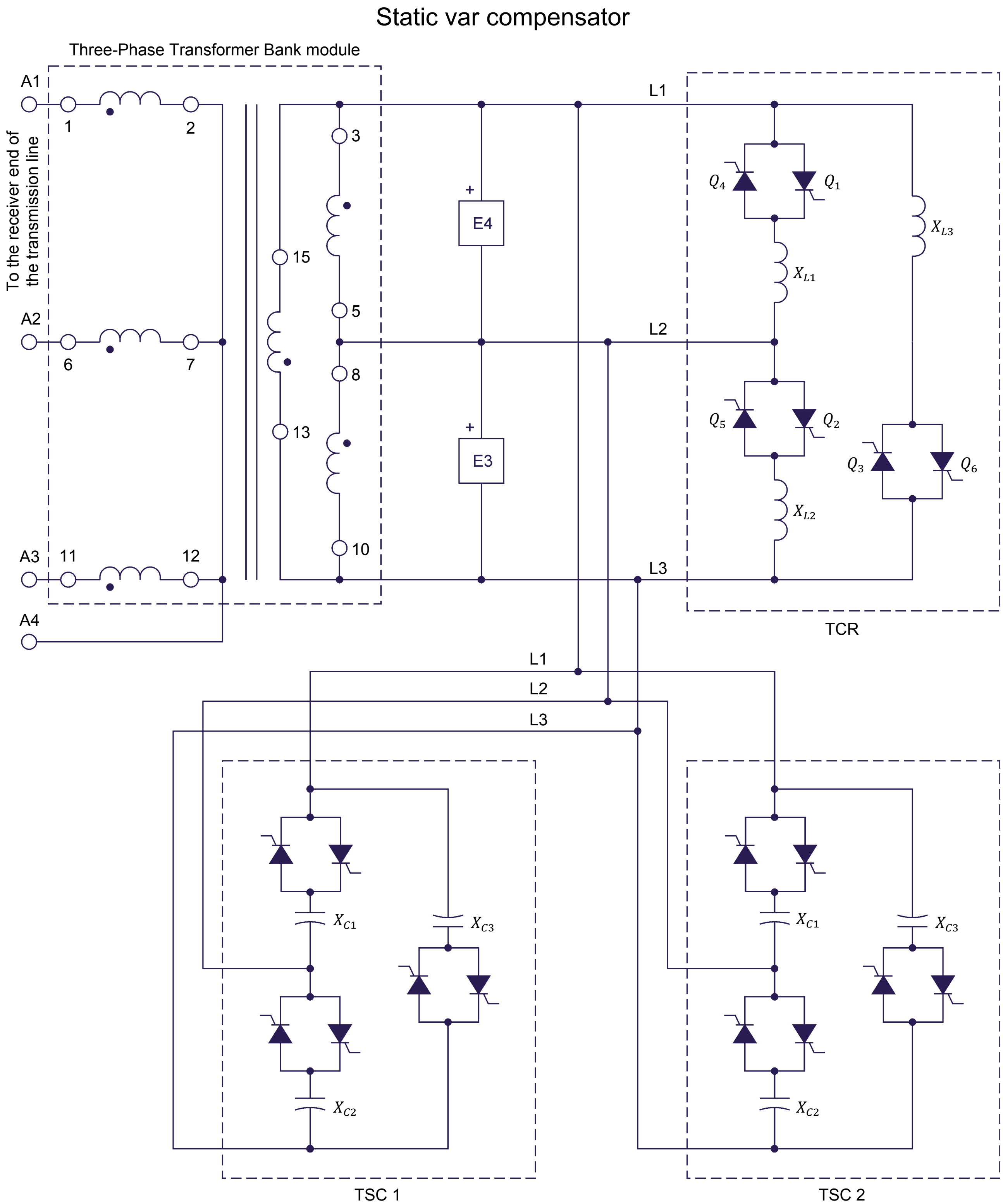


Figure 43. Circuit for studying the operation of an SVC used for voltage compensation of an ac transmission line supplying power to a resistive load.

In the circuit of Figure 42 and Figure 43, inputs E3 and E4 of the Data Acquisition and Control Interface are used to measure the circuit parameters necessary for automatic voltage control at the receiver end of the ac transmission line. Because of this, inputs E3 and E4 cannot be used for voltage measurement using the LVDAC-EMS instrumentation.

21. On the Data Acquisition and Control Interface, connect *Digital Output 1* and *Digital Output 2* to *Analog Input 1* and *Analog Input 2*, respectively, using miniature banana plug leads.

On the Data Acquisition and Control Interface, connect a common digital (*D*) terminal (white) of the Digital Outputs to a common analog (*A*) terminal (white) of the Analog Inputs using a miniature banana plug lead.

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

On the Three-Phase Transmission Line, set the inductive reactance selector to the value indicated in the table of Figure 42 corresponding to your local ac power network voltage and frequency.

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

Make the necessary switch settings on the Resistive Load to obtain the 1st resistance value indicated in the table of Figure 42 corresponding to 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.

23. In the Metering window, clear the previous settings, then 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. Set also a meter to measure the three-phase reactive power Q_{SVC} exchanged by the SVC [metering function *PQS2 (E2, I2) 3~*].

Precision of the voltage compensation achieved by the SVC during load variations

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

25. In the SVC Control window, make the following settings:

– Set the *Control Mode* parameter to *Automatic Voltage Control*. This control mode allows the voltage of the system to which the SVC 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 requires inputs *E3* and *E4* to be connected as shown in the circuit of Figure 42 and Figure 43.

– Make sure the *Line Voltage Command* parameter is set to the value indicated in Table 3 corresponding to your local ac power network voltage and frequency.

Table 3. Line voltage command.

Local ac power network		Line voltage command (V)
Voltage (V)	Frequency (Hz)	
120	60	120
220	50	220
240	50	240
220	60	220

This line voltage command value ensures that the SVC controller automatically adjusts the amount of reactive power supplied or absorbed by the SVC so that the line voltage across the SVC side of the three-phase transformer is maintained at the specified value (i.e., your local ac power network line voltage divided by $\sqrt{3}$). Since the SVC three-phase transformer then steps-up this line voltage by a factor of $\sqrt{3}$, the measured line voltage across the ac power system connected to the SVC should be equal to your local ac power network line voltage.

– Make sure the *Controller Proportional Gain Kp* is set to 1.

– Make sure the *Controller Integral Gain Ki* is set to 4.

– Start the *Static Var Compensator* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

26. Fill in the first column in Table 4 using the 1st to 6th resistance values indicated in the table of Figure 42 corresponding to your local ac power network voltage and frequency.

Table 4. TSC 1 and TSC 2 switch states, TCR firing angle, reactive power Q_{SVC}, sender voltage E_S, and receiver voltage E_R for different resistive load values when the SVC compensates the voltage at the receiver end of an ac transmission line.

Resistive loads R_1, R_2, R_3 (Ω)	TSC 1 switch state (in or out)	TSC 2 switch state (in or out)	TCR firing angle (°)	Reactive power Q_{SVC} (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.

TSC 1 and TSC 2 switch states, TCR firing angle, reactive power Q_{SVC}, sender voltage E_S, and receiver voltage E_R for different resistive load values when the SVC compensates the voltage at the receiver end of an ac transmission line.

Resistive loads R_1, R_2, R_3 (Ω)	TSC 1 switch state (in or out)	TSC 2 switch state (in or out)	TCR firing angle (°)	Reactive power Q_{SVC} (var)	Sender voltage E_S (V)	Receiver voltage E_R (V)
1st = 1200	In	Out	107	-12.7	208	208
2nd = 600	In	Out	113	-22.8	208	208
3rd = 400	In	Out	123	-38.4	208	208
4th = 300	In	Out	147	-63.4	208	208
4th = 300	In	In	97	-69.6	208	208
5th = 240	In	In	110	-96.4	208	208
6th = 200	In	In	138	-129	208	208

There are two solutions (i.e., two TSC switch state and TCR firing angle combinations) by which the SVC can compensate the voltage at the receiver end of the ac transmission line when the resistive load is set to the 4th value. The measured parameters for both solutions are presented in the above table.

27. Record in Table 4 the switch states of TSC 1 and TSC 2, as well as the TCR firing angle (indicated in the SVC Control window) in the appropriate cells of the row corresponding to the current resistance of resistive loads R_1, R_2, R_3.

Also, record in Table 4 the reactive power Q_{SVC} exchanged by the SVC, the sender voltage E_S, and the receiver voltage E_R (indicated in the Metering window) in the appropriate cells of the row corresponding to the current resistance of resistive loads R_1, R_2, R_3.

28. Make the necessary switch settings on the Resistive Load to obtain successively the 2nd to 6th resistive load values indicated in the first column of Table 4 corresponding to your local ac power network voltage and frequency. For each resistive load value, repeat step 0.

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

30. From the results recorded in Table 4, can you conclude that the SVC perfectly compensates the voltage across the ac power system to which it is connected (i.e., the receiver voltage E_R)? Explain briefly.

Yes, as the results in the above table indicate, the SVC 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). Therefore, it is possible to conclude that an SVC perfectly compensates the voltage across the ac power system to which it is connected.

Compare the precision of the voltage compensation achieved using the SVC to that achieved using a battery of shunt-capacitors. What can you conclude? Explain briefly.

As the results in the above table indicate, the SVC precisely compensates the voltage across the ac power system to which it is connected. On the other hand, a battery of shunt capacitors rarely achieves precise voltage compensation of the ac power system to which it is connected. This is because the selection of shunt capacitors available for voltage compensation is limited. Therefore, an SVC generally achieves a much more precise voltage compensation of an ac power system than a battery of shunt capacitors.

31. From the results recorded in Table 4, explain how the SVC compensates the voltage across the ac power system to which it is connected (i.e., the receiver voltage E_R).

The SVC compensates the voltage of the ac power system to which it is connected (i.e., the receiver voltage E_R) by switching TSCs in and out, as well as by varying the TCR firing angle, in order to supply just the right amount of reactive power to meet the reactive power requirement of the system. This ensures that the voltage across the ac power system connected to the SVC is maintained virtually equal to the ac power network, no matter the reactive power requirement of the system.

Speed of the voltage compensation achieved by the SVC during load variations

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

33. Make the necessary switch settings on the Resistive Load to obtain the 1st resistive load value indicated in Table 5 corresponding to your local ac power network voltage and frequency.

Table 5. Values of resistive loads R_1, R_2, and R_3 to be used for observing the speed of the voltage compensation achieved by the SVC during load variations.

Local ac power network		Resistive loads R_1, R_2, R_3 (Ω)	
Voltage (V)	Frequency (Hz)	1st	2nd
120	60	240	1200
220	50	880	4400
240	50	960	4800
220	60	880	4400

34. In LVDAC-EMS, open the Oscilloscope. Make the appropriate settings in order to observe the waveform of the receiver voltage E_R (input *E2*), as well as the switching control signal for TSC 1 and that for TSC 2 (measured using *Analog Input 1* and *Analog Input 2*, respectively).

It is recommended to set the sensitivity of the channel used to observe the receiver voltage waveform to 200 V/div, the sensitivity of the channels used to observe the switching control signals to 5 V/div, and the time base to 0.1 s/div.

On the Oscilloscope, set the trigger type to *Hardware*, the trigger source to the channel used to observe the waveform of the receiver voltage E_R, and the trigger level to about 15 V higher than the peak value of the receiver voltage. Adjust the horizontal position of the trigger point to about 4 divisions of the left-hand side of the oscilloscope screen.

These settings ensure that the Oscilloscope begins to record data only when the peak value of the receiver voltage E_R increases above its nominal peak value, i.e., when the load at the receiver end of the line decreases.

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

35. Make the necessary switch settings on the Resistive Load to obtain the 2nd resistive load value indicated in Table 5 corresponding to your local ac power network voltage and frequency.

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.

36. Save all signals recorded on the Oscilloscope by making a screen capture of the Oscilloscope window and saving it to a file.

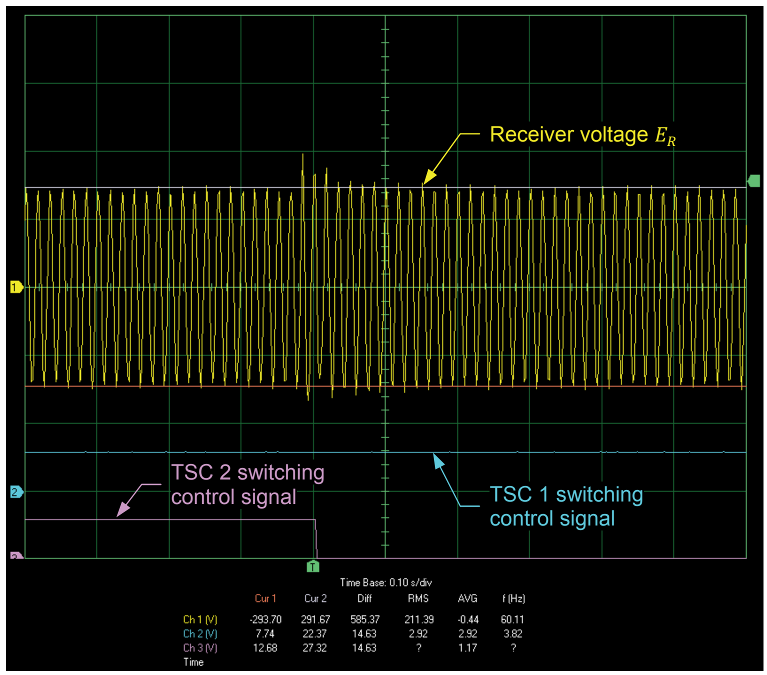
On the Oscilloscope, set the trigger source to the channel used to observe the switching control signal of TSC 2, and the trigger level to 2 V. Click the *Single Refresh* button.

These settings ensure that the Oscilloscope begins to record data only when the Data Acquisition and Control Interface sends a switching control signal to TSC 2 in order to switch it in, i.e., when the load at the receiver end of the line increases enough so that another TSC needs to be switched in.

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	AI-1
Channel-2 Scale	5 V/div
Channel-2 Coupling	DC
Channel-3 Input	AI-2
Channel-3 Scale	5 V/div
Channel-3 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, TSC 1 switching control signal, and TSC 2 switching control signal when the SVC compensates the voltage at the receiver end of an ac transmission line and the load decreases.

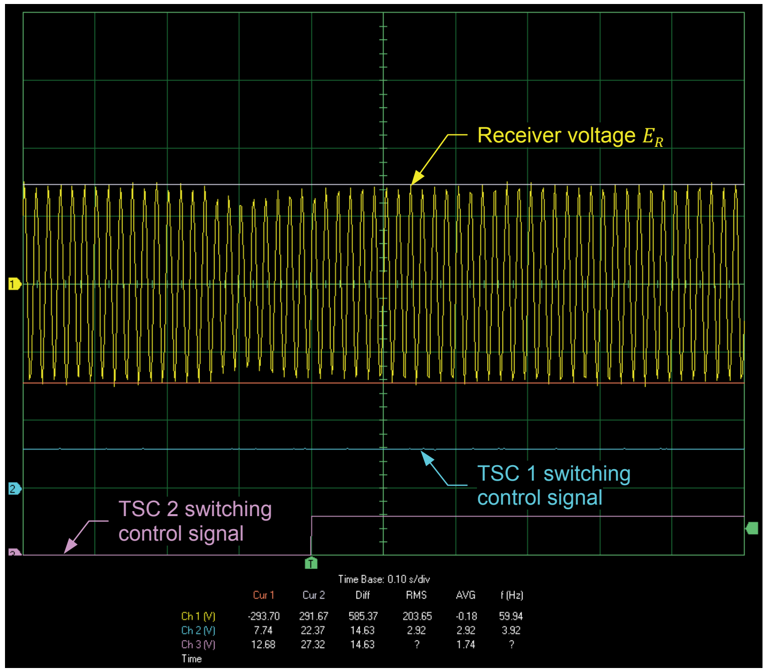
37. Make the necessary switch settings on the Resistive Load to obtain the 1st resistive load value indicated in Table 5 corresponding to your local ac power network voltage and frequency.

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.

38. Save all signals recorded on the Oscilloscope by making a screen capture of the Oscilloscope window and saving it to a file.

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 AI-1
Channel-2 Scale ....5 V/div
Channel-2 Coupling ....DC
Channel-3 Input AI-2
Channel-3 Scale ....5 V/div
Channel-3 Coupling ....DC
Show Cursors ....Horizontal
Time Base............................. 0.1 s/div
Trigger Type .... Hardware
Trigger Source Ch3
Trigger Level................................. 2 V
Trigger Slope ....Rising



Receiver voltage E_R, TSC 1 switching control signal, and TSC 2 switching control signal when the SVC compensates the voltage at the receiver end of an ac transmission line and the load increases.

39. Using the screen captures of the Oscilloscope window you saved to files, can you conclude that the SVC compensates almost instantaneously the voltage across the ac power system to which it is connected (i.e., the receiver voltage E_R)? Explain briefly.

Yes. The screen captures of the Oscilloscope window show that the SVC perfectly compensates the voltage fluctuations at the receiver end of the ac transmission line in less than about 7-8 cycles, no matter whether load decreases or increases. Therefore, it is possible to conclude that an SVC compensates almost instantaneously the voltage across the ac power system to which it is connected (i.e., the receiver voltage E_R).

40. In the Metering window, measure the line voltage E_S at the sender end of the ac transmission line. Record the value below as it is required in the next section of this exercise.

Sender line voltage E_S = _______ V

Sender line voltage $E_S = 208\ \text{V}$

41. In the SVC Control window, stop the *Static Var Compensator* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

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

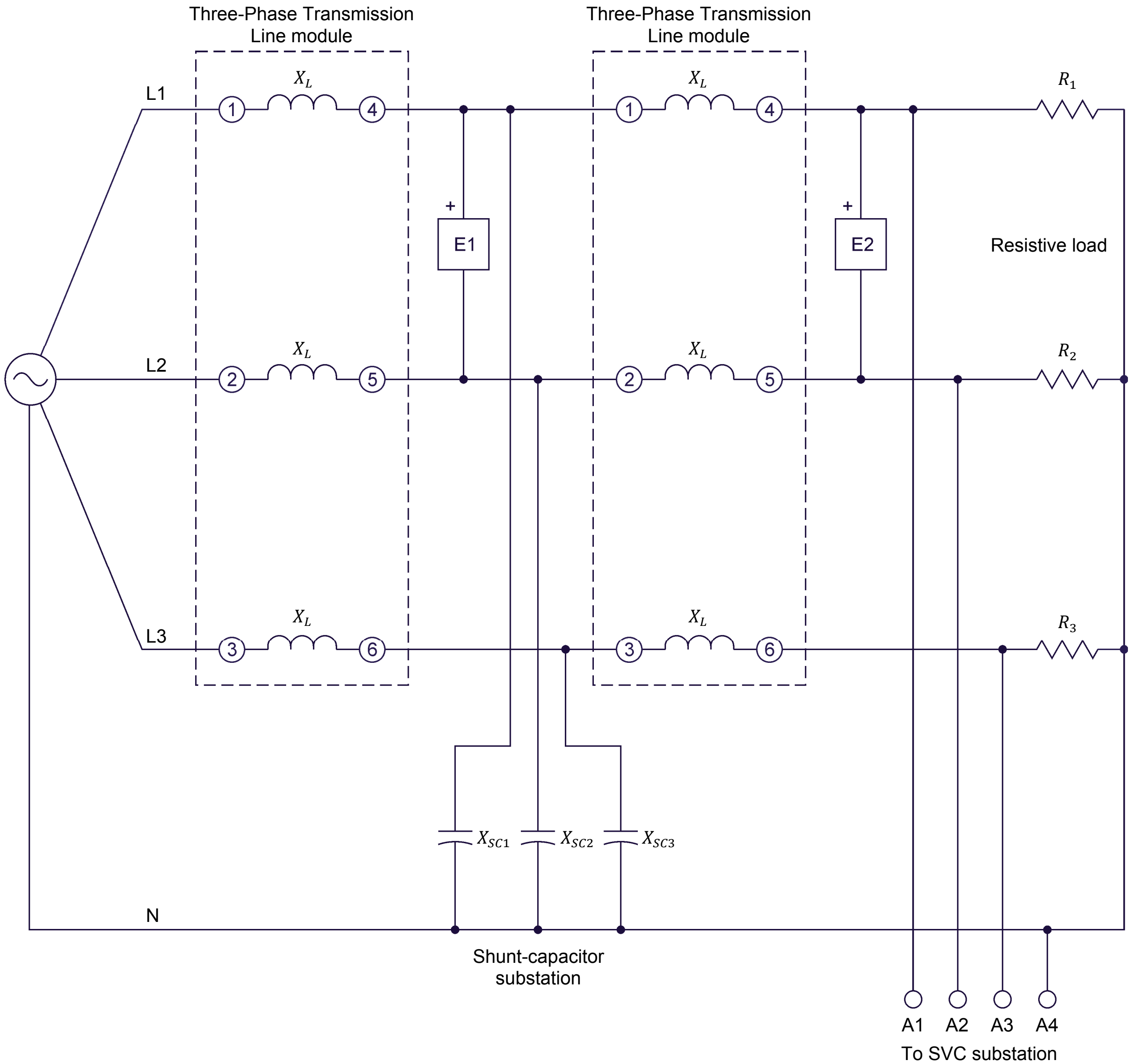
Voltage compensation using an SVC at the receiver end of an ac transmission line containing a shunt-capacitor substation

In this section, you will set up a circuit consisting of a long ac transmission line that supplies power to a resistive load, and is voltage compensated using a shunt-capacitor substation as well as an SVC located at the receiver end of the line. You will set the resistance of the resistive load and the reactance of the shunt capacitors to preliminary values. You will then use the Oscilloscope to record the transient in the receiver voltage, as well as the switching control signals sent to the TSCs, when, firstly, the resistive load decreases and when, secondly, the voltage compensation provided by the shunt capacitors decreases. Using the signals recorded on the Oscilloscope, you will determine how fast the SVC achieves voltage compensation during voltage fluctuations. For each resistance value of the resistive load and reactance value of the shunt capacitors, you will also record the voltage at the shunt-capacitor substation and that at the receiver end of the ac transmission line. Finally, you will analyse these voltage values.

43. Modify the equipment connections to obtain the circuit shown in Figure 44 and Figure 45. Note that, in this circuit, the three-phase ac transmission line consists of two segments instead of one, with a shunt-capacitor substation after the first line segment. Also, voltage input *E1* is used to measure the voltage at the shunt-capacitor substation instead of the sender voltage, while current input *I2* used to measure the current flowing in the SVC side of the three-phase step-down transformer is removed from the circuit. The connections of the various SVC components remain the same. Use the capacitors in the Capacitive Load module to implement the shunt-capacitor substation.

The circuit shown in Figure 44 and Figure 45 represents a long ac transmission line that supplies power to a resistive load and is voltage compensated using a shunt-capacitor substation (manually controlled) as well as an SVC located at the receiver end of the line. The resistive load in the circuit represents the electrical power demand of the electricity consumers. By adjusting the resistance of the resistive load, it is thus possible to vary the intensity of the electrical power demand.

AC power network, transmission line with shunt-capacitor substation, and load



Local ac power network		Line inductive reactance X_L (Ω)	R_1, R_2, R_3 (Ω)			X_{SC1}, X_{SC2}, X_{SC3} (Ω)	
Voltage (V)	**Frequency (Hz)**		**1st**	**2nd**	**3rd**	**1st**	**2nd**
120	60	120	600	400	1200	600	∞
220	50	400	2200	1467	4400	2200	∞
240	50	400	2400	1600	4800	2400	∞
220	60	400	2200	1467	4400	2200	∞

Figure 44. Circuit for studying the operation of an SVC used for voltage compensation of an ac transmission line containing a shunt-capacitor substation.

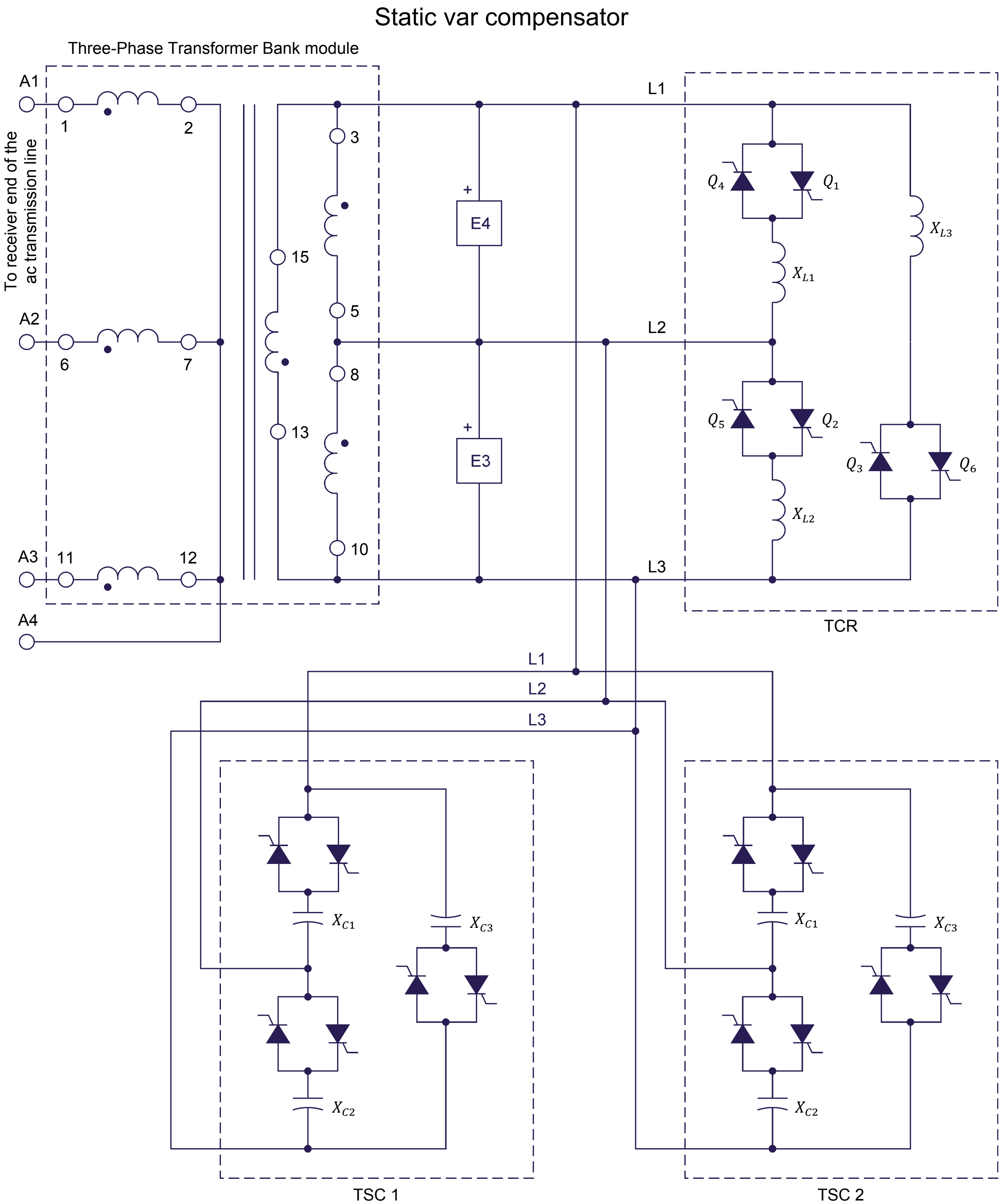


Figure 45. Circuit for studying the operation of an SVC used for voltage compensation of an ac transmission line containing a shunt-capacitor substation.

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

On the second Three-Phase Transmission Line, set the inductive reactance selector to the value indicated in the table of Figure 44 corresponding to your local ac power network voltage and frequency.

Make the necessary switch settings on the Resistive Load and on the Capacitive Load to obtain the first resistance value (for resistors R_1, R_2, and R_3) and the first reactance value (for capacitors X_{SC1}, X_{SC2}, and X_{SC3}), respectively, indicated in the table of Figure 44 corresponding to your local ac power network voltage and frequency.

45. In the Metering window, make sure that two meters are set to measure the rms values (ac) of the line voltage E_{SC} (input *E1*) at the shunt-capacitor substation and the line voltage E_R (input *E2*) at the receiver end of the ac transmission line.

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

47. In the SVC Control window, start the *Static Var Compensator* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

48. In the Metering window, measure the line voltage E_{SC} at the shunt-capacitor substation and the line voltage E_R at the receiver end of the ac transmission line. Record both values below.

Line voltage E_{SC} = _______ V

Line voltage E_R = _______ V

Line voltage E_{SC} = 226 V

Line voltage E_R = 208 V

49. Make the necessary switch settings on the Resistive Load to obtain the second resistance value indicated in the table of Figure 44 corresponding to your local ac power network voltage and frequency.

50. In the Metering window, measure the line voltage E_{SC} at the shunt-capacitor substation and the line voltage E_R at the receiver end of the ac transmission line. Record both values below.

Line voltage E_{SC} = _______ V

Line voltage E_R = _______ V

Line voltage $E_{SC} = 218$ V

Line voltage $E_R = 208$ V

51. On the Oscilloscope, set the trigger source to the channel used to observe the waveform of the receiver voltage E_R, and the trigger level to about 15 V higher than the peak value of the receiver voltage. Click the *Single Refresh* button.

These settings ensure that the Oscilloscope begins to record data only when the peak value of the receiver voltage E_R increases slightly above its nominal peak value, i.e., when the load at the receiver end of the line decreases.

52. Make the necessary switch settings on the Resistive Load to obtain the third resistance value indicated in the table of Figure 44 corresponding to your local ac power network voltage and frequency.

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.

53. In the Metering window, measure the line voltage E_{SC} at the shunt-capacitor substation and the line voltage E_R at the receiver end of the ac transmission line. Record both values below.

Line voltage $E_{SC} =$ _______ V

Line voltage $E_R =$ _______ V

Line voltage $E_{SC} = 232$ V

Line voltage $E_R = 208$ V

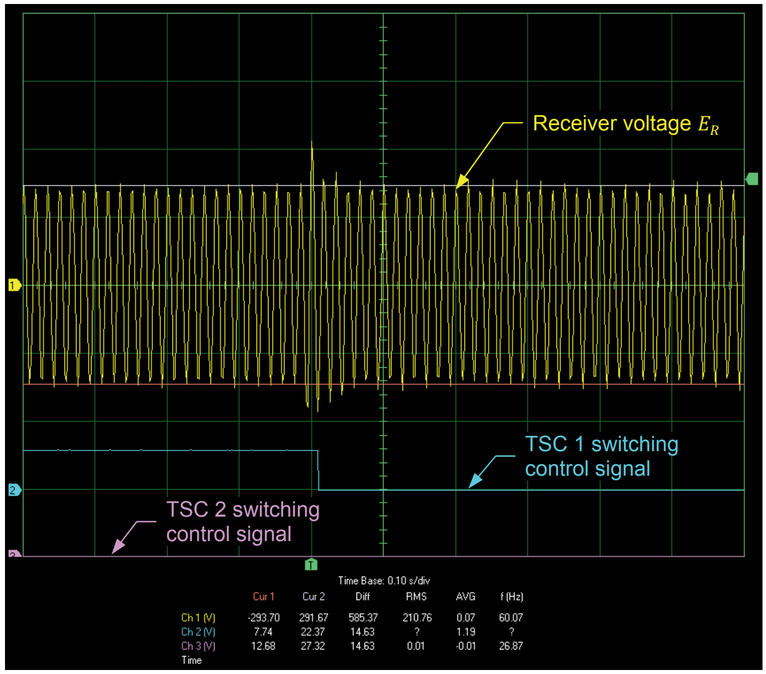
54. Save all signals recorded on the Oscilloscope by making a screen capture of the Oscilloscope window and saving it to a file.

On the Oscilloscope, set the trigger source to the channel used to observe the switching control signal of TSC 1, and the trigger level to 2 V. Click the *Single Refresh* button.

These settings ensure that the Oscilloscope begins to record data only when the Data Acquisition and Control Interface sends a switching control signal to TSC 1 in order to switch it in, i.e., when the voltage compensation provided by the shunt capacitors decreases enough so that a TSC needs to be switched in.

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 AI-1
Channel-2 Scale ....5 V/div
Channel-2 Coupling ....DC
Channel-3 Input AI-2
Channel-3 Scale ....5 V/div
Channel-3 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, TSC 1 switching control signal, and TSC 2 switching control signal when the SVC compensates the voltage at the receiver end of a long ac transmission line and the load decreases.

55. Make the necessary switch settings on the Capacitive Load to obtain the second reactance value indicated in the table of Figure 44 corresponding to your local ac power network voltage and frequency.

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

56. In the Metering window, measure the line voltage E_{SC} at the shunt-capacitor substation and the line voltage E_R at the receiver end of the ac transmission line. Record both values below.

Line voltage E_{SC} = _______ V

Line voltage E_R = _______ V

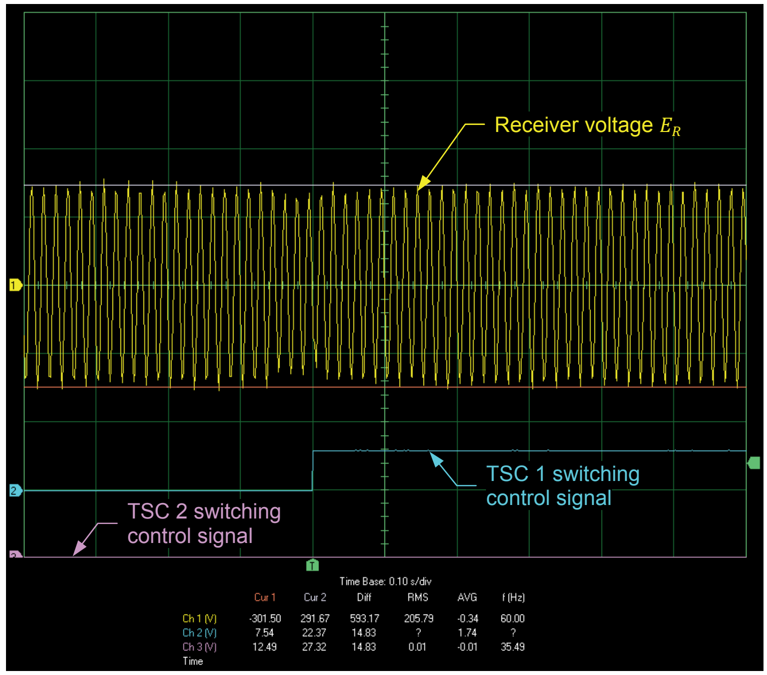
Line voltage $E_{SC} = 206$ V

Line voltage $E_R = 208$ V

57. Save all signals recorded on the Oscilloscope by making a screen capture of the Oscilloscope window and saving it to a file.

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 AI-1
Channel-2 Scale ....5 V/div
Channel-2 Coupling ....DC
Channel-3 Input AI-2
Channel-3 Scale ....5 V/div
Channel-3 Coupling ....DC
Show Cursors ....Horizontal
Time Base............................ 0.1 s/div
Trigger Type .... Hardware
Trigger Source Ch2
Trigger Level .... 2 V
Trigger Slope ....Rising



Receiver voltage E_R, TSC 1 switching control signal, and TSC 2 switching control signal when the SVC compensates the voltage at the receiver end of a long ac transmission line and the voltage compensation provided by the shunt-capacitor substation decreases.

58. From the values of voltages E_{SC} and E_R you recorded above, does varying the load at the receiver end of the ac transmission line (i.e., varying the electrical power demand) have any significant effect on the voltage E_R at the receiver end of the line?

❑ Yes ❑ No

Yes

From the values of voltages E_{SC} and E_R you recorded above, does adjusting the reactances X_{C1}, X_{C2}, and X_{C3} of the shunt capacitors in the shunt-capacitor substation have any significant effect on the voltage E_R at the receiver end of the line?

❑ Yes ❑ No

Yes

59. Using the screen captures of the Oscilloscope window you saved to files, can you conclude that the SVC compensates perfectly and almost instantaneously the voltage E_R at the receiver end of a long ac transmission line containing a shunt-capacitor substation? Explain briefly.

Yes. The screen captures of the Oscilloscope window show that the SVC perfectly compensates the voltage fluctuations at the receiver end of the long ac transmission line containing a shunt-capacitor substation in less than about 7-8 cycles. This is true whether the voltage fluctuations are due to a variation in the load at the receiver end of the line, or to a variation in the reactance value of the shunt capacitors used to compensate the voltage across the line. Therefore, it is possible to conclude that the SVC compensates perfectly and almost instantaneously the voltage across long ac transmission lines containing a shunt-capacitor substation.

60. In the SVC Control window, stop the *Static Var Compensator* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

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

62. 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 SVCs when they are used for voltage compensation of ac transmission lines. You also familiarized yourself with the two basic types of SVCs: TCR-FC and TCR-TSC. You learned which components are used in each type of SVC, as well as how each type of SVC operates. You also learned how an SVC controller designed for automatic voltage control compensates the voltage across the ac power system to which the SVC is connected.

Review Questions

1. Describe how shunt-capacitor substations and an SVC substation are distributed along a typical voltage-compensated ac transmission line covering a long distance. Explain briefly.

In a typical ac transmission line covering a long distance, the voltage along the line is compensated using shunt-capacitor substations, which provide cost-effective voltage compensation. At the receiver end of the ac transmission line, however, the voltage is compensated using an SVC. This ensures a 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.

2. Is it usual to replace all shunt-capacitor substations along an ac transmission line covering a long distance by SVC substations? Explain briefly.

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

3. Describe the main reactive components found in the two most common types of SVCs.

   The two most common types of SVCs are the TCR-FC and the TCR-TSC. SVCs of the TCR-FC type consist of a TCR, as well as one or more FCs. SVCs of the TCR-TSC type, on the other hand, consist of a TCR, as well as of one or more TSCs. Note, however, that certain SVCs of the TCR-TSC type also include one or more FCs.

4. What is the primary advantage of SVCs of the TCR-TSC type over SVCs of the TCR-FC type? Explain briefly.

   The primary advantage of SVCs of TCR-TSC type over SVCs of the TCR-FC type is the smaller size of the TCR. This is due to the fact that the TCR in an SVC of the TCR-TSC type does not need to fully offset the capacitive reactive power rating of the capacitive components, as is the case for the TCR of the TCR-FC. The TCR in an SVC of TCR-TSC type only needs to have a power rating that is slightly higher (to provide a certain latitude during capacitor switching in and out) than that of any of the TSCs in the SVC. Because of its smaller size, the TCR in an SVC of the TCR-TSC type is less costly, has lower power losses, and produces fewer harmonics than the larger TCR in SVCs of the TCR-FC type.

5. Describe briefly the four main tasks that the controller of an SVC of the TCR-TSC type must perform in order to meet the reactive power requirement of the ac power system to which it is connected.

   The four main tasks that the controller of an SVC of the TCR-TSC type must perform in order to meet the reactive power requirement of the ac power system to which it is connected are summarized below.

   - To determine the number of TSCs required and the amount of reactive power that the TCR must absorb to precisely meet the reactive power requirement of the ac power system to which the SVC is connected.

   - To switch TSCs in and out so as to match the required number of TSCs determined above.

- To control the TCR firing angle (and, consequently, the rms value of the current flowing in the TCR) so that the amount of reactive power absorbed by the TCR corresponds to the value determined above.

- To properly coordinate the TSC switching control and TCR firing angle control so as to ensure transient-free operation (i.e., so as to minimize voltage transients in the ac power system to which the SVC is connected).

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