Module-4

Subject: Flexible AC Transmission System (FACTS)

Content: Thyristor Controlled Series Capacitor

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4.0 SERIES COMPENSATION

Fixed-Series Compensation

Series capacitors offer certain major advantages over their shunt counterparts. With series capacitors, the reactive power increases as the square of line current, whereas with shunt capacitors, the reactive power is generated proportional to the square of bus voltage. For achieving the same system benefits as those of series capacitors, shunt capacitors that are three to six times more reactive power rated than series capacitors need to be employed. Furthermore, shunt capacitors typically must be connected at the line midpoint, whereas no such requirement exists for series capacitors.

Let Q_{se} and Q_{sh} be the ratings of a series and shunt capacitor, respectively, to achieve the same level of power transfer through a line that has a maximum angular difference of δmax across its two ends. Then

$$\frac{Q_{se}}{Q_{sh}} = \tan^2\left(\frac{\delta_{max}}{2}\right) \tag{4.1}$$

Specifically, for δ_{max} of 358, Q_{se} will be approximately 10% of Q_{sh}. Even though series capacitors are almost twice as costly as shunt capacitors (per-unit var) because of their higher operating voltages, the overall cost of series compensation is lower than shunt compensation.

4.1 The Need for Variable-Series Compensation

Compensation of transmission lines by series capacitors is likely to result in the following benefits:

- enhanced base-power flow and loadability of the series-compensated line;
- additional losses in the compensated line from the enhanced power flow;
- increased responsiveness of power flow in the series-compensated line from the outage of other lines in the system.

Studies have revealed that with increasing level of fixed-series compensation, even though the losses in remaining transmission lines decrease, the overall system losses are exacerbated from the enhanced losses in the series compensated line. Also, the increased sensitivity or responsiveness of the compensated line to other network outages may cause a line loading that exceeds the enhanced loadability level of the line itself. These undesirable effects can be avoided by employing variable levels of series compensation instead of fixed compensation. Series compensation can be varied, depending on the enhancement of power transfer desired at that time, without affecting other system-performance criteria.

4.1.1 Advantages of the TCSC

Use of thyristor control in series capacitors potentially offers the following little-mentioned advantages:

1. Rapid, continuous control of the transmission-line series-compensation level.
2. Dynamic control of power flow in selected transmission lines within the network to enable optimal power-flow conditions and prevent the loop flow of power.
3. Damping of the power swings from local and inter-area oscillations.
4. Suppression of subsynchronous oscillations. At subsynchronous frequencies, the TCSC presents an inherently resistive–inductive reactance. The subsynchronous oscillations cannot be sustained in this situation and consequently get damped.
5. Decreasing dc-offset voltages. The dc-offset voltages, invariably resulting from the insertion of series capacitors, can be made to decay very quickly (within a few cycles) from the firing control of the TCSC thyristors.

6. Enhanced level of protection for series capacitors. A fast bypass of the series capacitors can be achieved through thyristor control when large overvoltages develop across capacitors following faults. Likewise, the capacitors can be quickly reinserted by thyristor action after fault clearing to aid in system stabilization.
7. The TCSC, in conjunction with series capacitors, can generate reactive power that increases with line loading, thereby aiding the regulation of local network voltages and, in addition, the alleviation of any voltage instability.
8. Reduction of the short-circuit current: During events of high short-circuit current, the TCSC can switch from the controllable-capacitance to the controllable-inductance mode, thereby restricting the short-circuit currents.

4.2 THE TCSC CONTROLLER

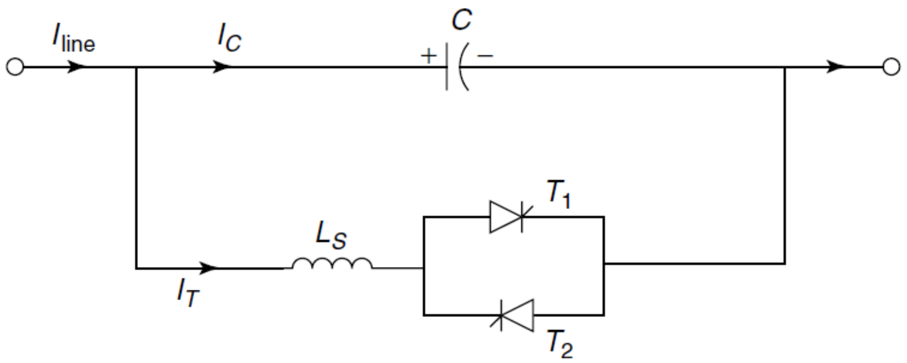
The basic conceptual TCSC module comprises a series capacitor, *C*, in parallel with a thyristor-controlled reactor, *LS*, as shown in Fig. 4.1(a). However, a practical TCSC module also includes protective equipment normally installed with series capacitors, as shown in Fig. 4.1(b).

A metal-oxide varistor (MOV), essentially a nonlinear resistor, is connected across the series capacitor to prevent the occurrence of high-capacitor overvoltages. Not only does the MOV limit the voltage across the capacitor, but it allows the capacitor to remain in circuit even during fault conditions and helps improve the transient stability.

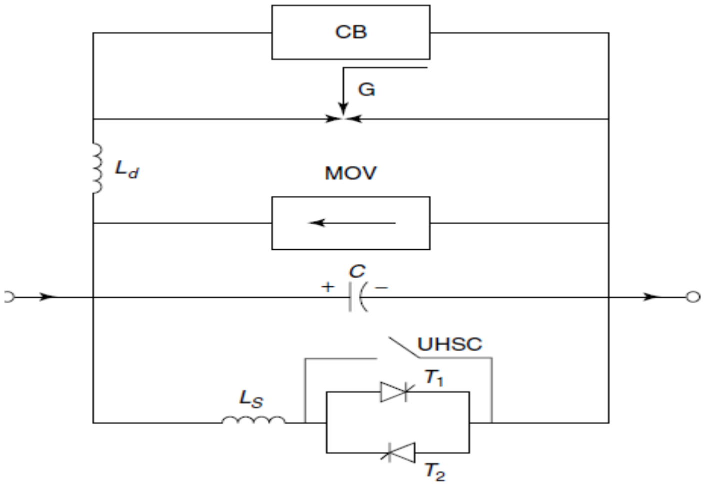
Also installed across the capacitor is a circuit breaker, CB, for controlling its insertion in the line. In addition, the CB bypasses the capacitor if severe fault or equipment-malfunction events occur. A current-limiting inductor, L_d, is incorporated in the circuit to restrict both the magnitude and the frequency of the capacitor current during the capacitor-bypass operation.

If the TCSC valves are required to operate in the fully “on” mode for prolonged durations, the conduction losses are minimized by installing an ultra–high-speed contact (UHSC) across the valve. This metallic contact offers a virtually lossless feature similar to that of circuit breakers and is capable of handling many switching operations. The metallic contact is closed shortly after the thyristor valve is turned on, and it is opened shortly before the valve is turned off. During a sudden overload of the valve, and also during fault conditions, the metallic contact is closed to alleviate the stress on the valve.

An actual TCSC system usually comprises a cascaded combination of many such TCSC modules, together with a fixed-series capacitor, C_F. This fixed series capacitor is provided primarily to minimize costs. A conceptual TCSC system with basic TCSC modules is shown in Fig. 7.2. The capacitors—C_1, C_2,. . . , C_n—in the different TCSC modules may have different values to provide a wider range of reactance control. The inductor in series with the antiparallel thyristors is split into two halves to protect the thyristor valves in case of inductor short circuits.



(a)



(b)

Figure 4.1 A TCSC module: (a) a basic module and (b) a practical module.

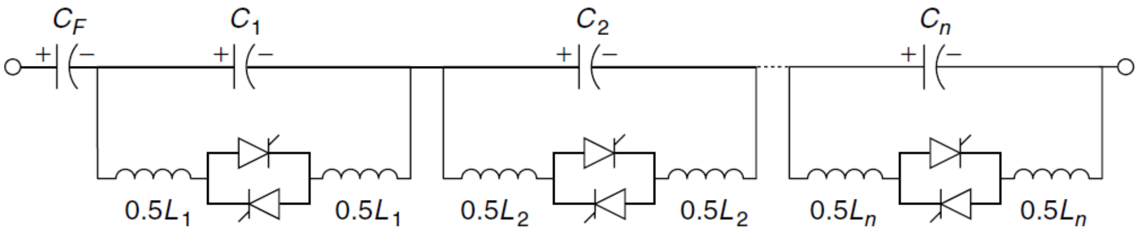


Figure 4.2 A typical TCSC system.

4.2.1 OPERATION OF THE TCSC

Basic Principle

A TCSC is a series-controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. From the system viewpoint, the principle of variable-series compensation is simply to increase the fundamental-frequency voltage across an fixed capacitor (FC) in a series compensated line through appropriate variation of the firing angle, α . This enhanced voltage changes the effective value of the series-capacitive reactance. A simple understanding of TCSC functioning can be obtained by analyzing the behavior of a variable inductor connected in parallel with an FC, as shown in Fig. 4.3. The equivalent impedance, Z_{eq}, of this *LC* combination is expressed as follows:

$$Z_{eq} = \left(j \frac{1}{\omega c}\right) \bigg|\bigg| (j\omega L) = -j \frac{1}{\omega C - \dfrac{1}{\omega L}} \tag{4.2}$$

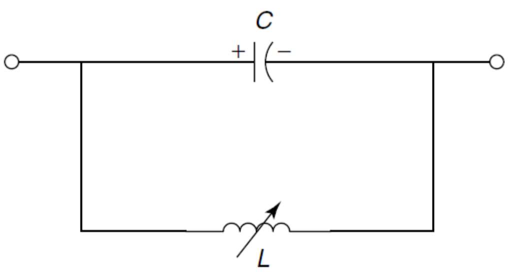


Figure 4.3 A variable inductor connected in shunt with an FC.

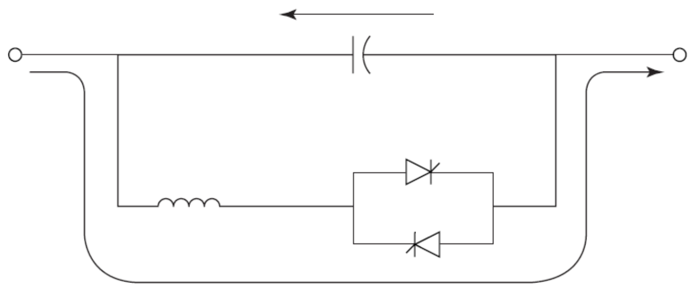
The impedance of the FC alone, however, is given by $-j(1/\omega C)$. If $\omega C - (1/\omega L) =$□$0$ or, in other words, $\omega L =$ □$(1/$□$\omega C)$, the reactance of the FC is less than that of the parallel-connected variable reactor and that this combination provides a variable-capacitive reactance are both implied. Moreover, this inductor increases the equivalent-capacitive reactance of the *LC* combination above that of the FC.

If $\omega C - (1/\omega L) = 0$, a resonance develops that results in an infinite-capacitive impedance—an obviously unacceptable condition. If, however, $\omega C - (1/$□$\omega L) < 0$, the *LC* combination provides inductance above the value of the fixed inductor. This situation corresponds to the inductive-vernier mode of the TCSC operation. In the variable-capacitance mode of the TCSC, as the inductive reactance of the variable inductor is increased, the equivalent-capacitive reactance is gradually decreased. The minimum equivalent-capacitive reactance is obtained for extremely large inductive reactance or when the variable inductor is open-circuited, in which the value is equal to the reactance of the FC itself.

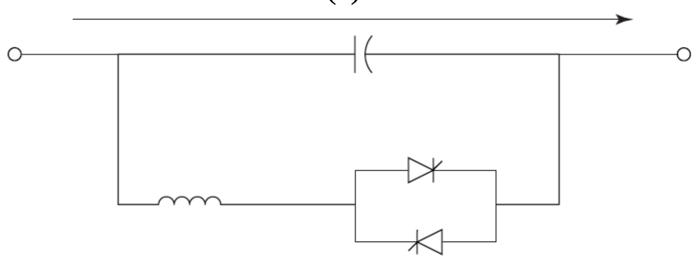
The behavior of the TCSC is similar to that of the parallel *LC* combination. The difference is that the *LC*-combination analysis is based on the presence of pure sinusoidal voltage and current in the circuit, whereas in the TCSC, because of the voltage and current in the FC and thyristor-controlled reactor (TCR) are not sinusoidal because of thyristor switchings.

4.2.2 Modes of TCSC Operation

There are essentially three modes of TCSC operation ; these are illustrated in Fig. 4.4 and described in the following text.



(a)



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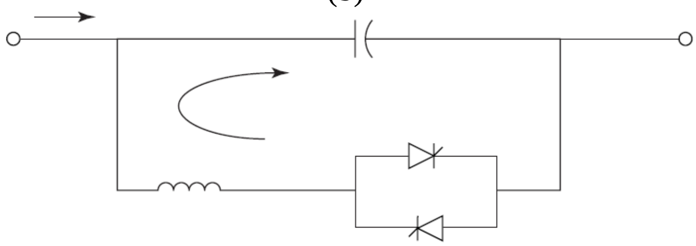
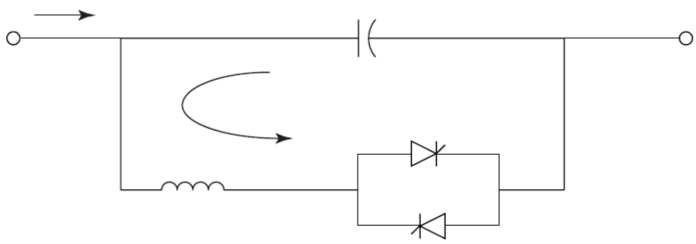


(c)



(d)

Figure 4.4 Different operating modes of a TCSC: (a) the bypassed-thyristor mode; (b) the blocked-thyristor mode; (c) the partially conducting thyristor (capacitive-vernier) mode; and (d) the partially conducting thyristor (inductive-vernier) mode.

Bypassed-Thyristor Mode In this bypassed mode, the thyristors are made to fully conduct with a conduction angle of 180^0. Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous sinusoidal of flow current through the thyristor valves. The TCSC module behaves like a parallel capacitor–inductor combination. However, the net current through the module is inductive, for the susceptance of the reactor is chosen to be greater than that of the capacitor.

Also known as the *thyristor-switched-reactor* (TSR) mode, the bypassed thyristor mode is distinct from the *bypassed-breaker* mode, in which the circuit breaker provided across the series capacitor is closed to remove the capacitor or the TCSC module in the event of TCSC faults or transient overvoltages across the TCSC. This mode is employed for control purposes and also for initiating certain protective functions. Whenever a TCSC module is bypassed from the violation of the current limit, a finite-time delay, T_{delay}, must elapse before the module can be reinserted after the line current falls below the specified limit.

Blocked-Thyristor Mode In this mode, also known as the *waiting* mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing. The TCSC module is thus reduced to a fixed-series capacitor, and the net TCSC reactance is capacitive.
In this mode, the dc-offset voltages of the capacitors are monitored and quickly discharged using a dc-offset control without causing any harm to the transmission-system transformers.

Partially Conducting Thyristor, or Vernier, Mode This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range. However, a smooth transition from the capacitive to inductive mode is not permitted because of the resonant region between the two modes. A variant of this mode is the *capacitive-vernier-control* mode, in which the thyristors are fired when the capacitor voltage and capacitor current have opposite polarity. This condition causes a TCR current that has a direction opposite that of the capacitor current, thereby resulting in a loop-current flow in the TCSC controller. The loop current increases the voltage across the FC, effectively enhancing the equivalent-capacitive reactance and the series-compensation level for the same value of line current. To preclude resonance, the firing angle α of the forward-facing thyristor, as measured from the positive reaching a zero crossing of the capacitor voltage, is constrained in the range $\alpha_{min} \le \alpha \le 180°$. This constraint provides a continuous vernier control of the TCSC module reactance. The loop current increases as α is decreased from 180° to α_{min}. The maximum TCSC reactance permissible with a α_{min} is typically two-and-a-half to three times the capacitor reactance at fundamental frequency.

Another variant is the *inductive-vernier mode*, in which the TCSC can be operated by having a high level of thyristor conduction. In this mode, the direction of the circulating current is reversed and the controller presents a net inductive impedance.
Based on the three modes of thyristor-valve operation, two variants of the TCSC emerge:

- *Thyristor-switched series capacitor* (TSSC), which permits a discrete control of the capacitive reactance.
- *Thyristor-controlled series capacitor* (TCSC), which offers a continuous control of capacitive or inductive reactance. (The TSSC, however, is more commonly employed.)

4.3 THE TSSC

A TSSC scheme consists of a series connection of multiple TCSC modules together with a fixed-series capacitor, as shown in Fig. 4.2. The thyristor pairs operate either in the blocked mode or the bypassed mode, thus acting as switches that are off or on, respectively. The inductors L_1, L_2, . . . , L_n in Fig. 4.2 are replaced by small current-limiting inductors for suppressing any transient current flow through the thyristor valves during switching. With each valve switching, the corresponding series capacitor is either inserted or removed from the transmission-line circuit.

Many capacitive-reactance steps are made possible by installing capacitors of different reactances. One such scheme has $n-1$ capacitors, each having a reactance of $(0.5X_{C\square n})$ and one capacitor of reactance $0.5X_C$. Appropriate switchings can result in the following combinations of effective reactances:

$$X_{\text{eff}} = \frac{0.5X_C}{n}\,p, \qquad p = 0, 1, 2, \ldots, 2n \tag{4.3}$$

The TSSC offers the following benefits compared to mechanically switched series capacitors:

- The thyristor switches allow an unlimited number of operations without any wear. This capability is used to alter the degree of line compensation more frequently and to achieve a greater control over the power flow.
- Exact switching instants (point-of-voltage waveforms) can be selected with thyristors, which significantly minimizes the switching transients. In contrast, the switching of mechanical breakers is unsynchronized.
- A very rapid speed of response, in which the time between the initiation of a control signal and a capacitor insertion, or bypass, is typically less than a half-cycle (8 ms for 60 Hz). Thus, in case a major tie-line suffers an outage, the power-transfer capability of an alterative line can be increased rapidly through the TSSC.
- No generation of harmonics.
- A possibility that minimizing thyristor-valve losses in a TSSC can be accomplished by using UHSCs.

The TSSC scheme is quite satisfactory when only stepwise control of transmission-line reactance is considered adequate. However, when continuous control is desired, the other variant—the TCSC—is employed.

4.4 The Single-Module TCSC

The capability characteristics of a single-module TCSC in the voltage line–current plane is depicted in Fig. 4.5. These characteristics are illustrated for continuous-time applications, short-duration implementations (30 min), and 1–10 s. In both capacitive and inductive zones, the operation is generally constrained between the minimum and maximum reactance limits. Certain other voltage-, current-, and harmonic-related limits also exist that constrain the operating range, as described in the following text.

In the capacitive region, the maximum apparent capacitive reactance is chosen based on the TCSC design so that the TCSC does not venture close to or into the inherently unstable resonant point. The maximum X_{TCSC} is typically 2–3 pu, as expressed in per units of X_C. This restriction is imposed in the form of a maximum advance angle, b, limit. The minimum TCSC capacitive reactance is obtained when the thyristors are blocked, corresponding to α =180 and the absence of thyristor-current flows and relating to X_{TCSC} = 1 pu. As the line current increases, the TCSC voltage increases until the maximum voltage limit of the TCSC is reached, as indicated in Fig. 4.5. This limit is dependent on the duraction of the voltage application.

In the inductive-reactance zone, the maximum reactance limit is also selected to prevent the TCSC from operating in the resonant region. This limit is attained at low line currents and is expressed in terms of the maximum firing-delay angle. A maximum inductive reactance of 2 pu is typical; the minimum inductive reactance limit is reached when the thyristors are fully conducting, corresponding to α =90°. With increasing line current, harmonics are generated that cause not only the heating of the reactor and thyristors but also peak voltages close to the voltage limits of the capacitors and MOV, which is indicated by a time duration–dependent constant-voltage limit in the capability curve. At

high line currents, the maximum thyristor current in the inductive-vernier mode constrains the TCSC operation.

Alternatively, the TCSC capability can be expressed in a reactance–line-current plane, as shown in Fig. 4.6. The dynamic range of the TCSC reactance is reduced with increasing line current. As discussed previously, a smooth transition from the inductive to capacitive region is not possible. The TCSC usually operates in the first quadrant of both the *V-I* and *X-I* characteristics.

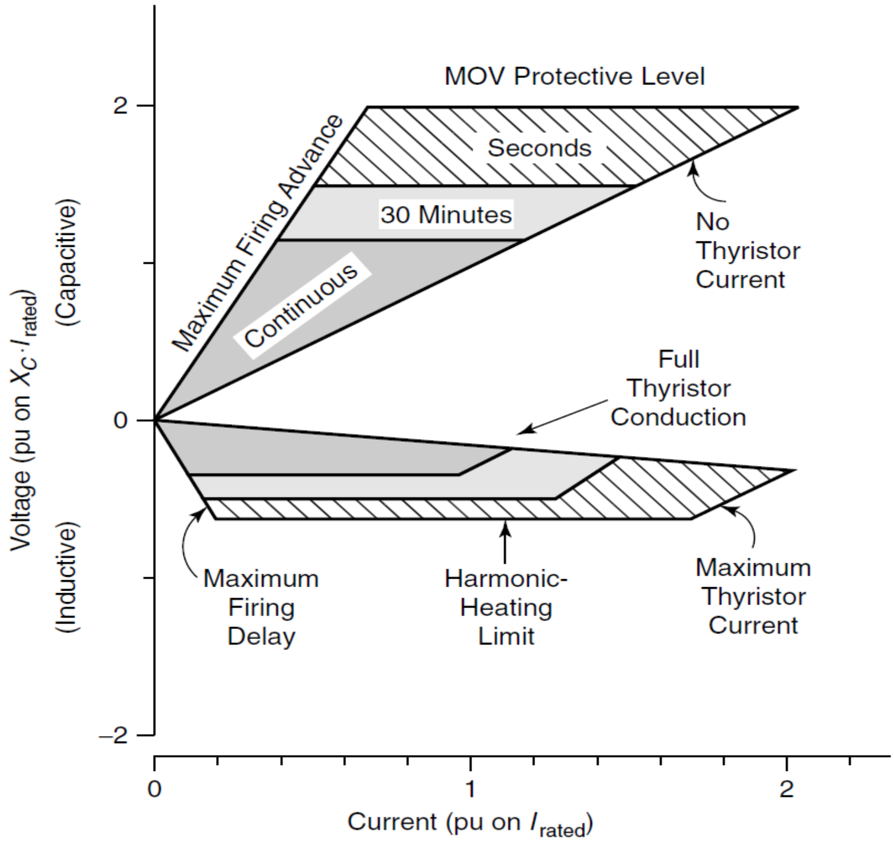


Figure 4.5 The *V-I* capability characteristics for a single-module TCSC.

4.5 The Multimodule TCSC

In several power-system applications, such as power-flow control and damping enhancement, a smooth variation in the line reactance is desirable that can be achieved by splitting a single TCSC into multiple modules and operating them independently in the inductive and capacitive modes. Splitting a single TCSC into two modules, each with a half-MVA rating, results in a *V-I* capability curve with both similar and dissimilar operation. Similar operation of both modules in either the capacitive or inductive mode produces a capability curve identical to that of a single module TCSC, as expected, whereas dissimilar operation results in an intermediate characteristic. It is evident that the greater the number of TCSC modules, the more expansive the controllable range of the TCSC for the same total MVA rating of the TCSC, (although achieved at a greater cost). In the multimodule case, the modules are only switched in or out if the desired TCSC reactance is lower than the nominal capacitive reactance of the bank. The vernier operation is resorted to only when the reactance order is greater than the rated capacitive reactance of the bank.

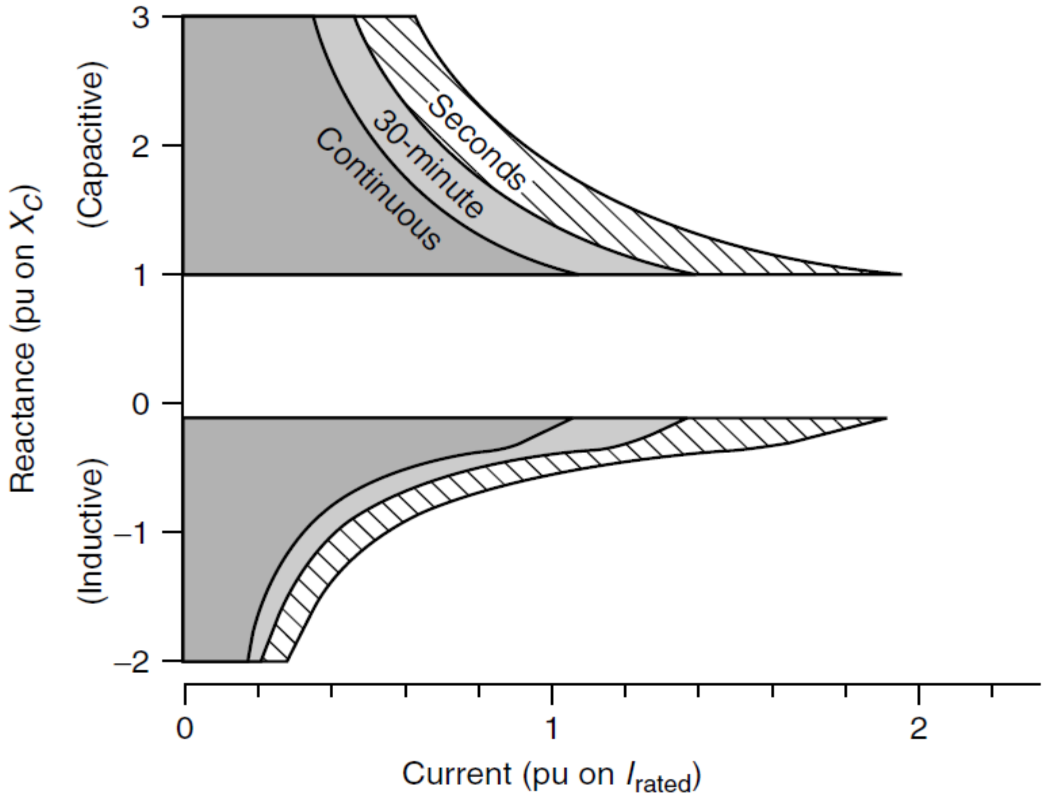


Figure 4.6 The *X-I* capability characteristic for a single-module TCSC.

4.6 MODELING OF THE TCSC

A TCSC involves continuous-time dynamics, relating to voltages and currents in the capacitor and reactor, and nonlinear, discrete switching behavior of thyristors. Deriving an appropriate model for such a controller is an intricate task.

4.6.1 Variable-Reactance Model

A TCSC model for transient- and oscillatory-stability studies, used widely for its simplicity, is the variable-reactance model depicted in Fig. 4.7. In this quasi-static approximation model, the TCSC dynamics during power-swing frequencies are modeled by a variable reactance at fundamental frequency. The other dynamics of the TCSC model—the variation of the TCSC response with different firing angles, for example—are neglected . It is assumed that the transmission system operates in a sinusoidal steady state, with the only dynamics associated with generators and PSS. This assumption is valid, because the line dynamics are much faster than the generator dynamics in the frequency range of 0.1–2 Hz that are associated with angular stability studies.

As described previously, the reactance-capability curve of a single-module TCSC, as depicted in Fig. 4.6, exhibits a discontinuity between the inductive and capacitive regions. However, this gap is lessened by using a multimode TCSC. The variable-reactance TCSC model assumes the availability of a continuous-reactance range and is therefore applicable for multimodule TCSC configurations. This model is generally used for inter-area mode analysis, and it provides high accuracy when the reactance-boost factor (=X_{TCSC}.□X_C) is less than 1.5.

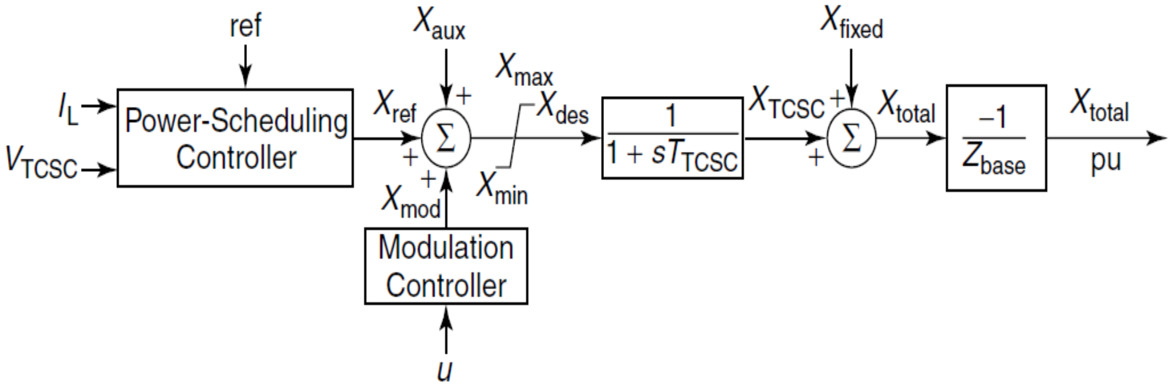


Figure 4.7 A block diagram of the variable-reactance model of the TCSC.

4.7 IMPROVEMENT OF THE SYSTEM-STABILITY LIMIT

During the outage of a critical line in a meshed system, a large volume of power tends to flow in parallel transmission paths, which may become severely overloaded. Providing fixed-series compensation on the parallel path to augment the power-transfer capability appears to be a feasible solution, but it may increase the total system losses. Therefore, it is advantageous to install a TCSC in key transmission paths, which can adapt its series-compensation level to the instantaneous system requirements and provide a lower loss alternative to fixed-series compensation.

The series compensation provided by the TCSC can be adjusted rapidly to ensure specified magnitudes of power flow along designated transmission lines. This condition is evident from the TCSC's efficiency, that is, ability to change its power flow as a function of its capacitive-reactance setting:

$$P_{12} = \frac{V_1 V_2}{(X_L - X_C)} \sin \delta \tag{4.4}$$

where

P_{12} = the power flow from bus 1 to bus 2

V_1□□V_2 = the voltage magnitudes of buses 1 and 2, respectively

X_L = the line-inductive reactance

X_C = the controlled TCSC reactance combined with fixed-series capacitor reactance

δ = the difference in the voltage angles of buses 1 and 2

This change in transmitted power is further accomplished with minimal influence on the voltage of interconnecting buses, as it introduces voltage in quadrature. In contrast, the SVC improves power transfer by substantially modifying the interconnecting bus voltage, which may change the power into any connected passive loads. The freedom to locate a TCSC almost anywhere in a line is a significant advantage.

Power-flow control does not necessitate the high-speed operation of powerflow control devices. Hence discrete control through a TSSC may also be adequate in certain situations. However, the TCSC cannot reverse the power flow in a line, unlike HVDC controllers and phase shifters.

4.8 ENHANCEMENT OF SYSTEM DAMPING

The TCSC can be made to vary the series-compensation level dynamically in response to controller-input signals so that the resulting changes in the power flow enhance the system damping. The power modulation results in a corresponding variation in the torques of the connected synchronous generators—particularly if the generators operate on constant torque and if passive bus loads are not installed.
The damping control of a TCSC or any other FACTS controller should generally do the following:

- stabilize both postdisturbance oscillations and spontaneously growing oscillations during normal operation;
- obviate the adverse interaction with high-frequency phenomena in power systems, such as network resonances; and
- preclude local instabilities within the controller bandwidth.

In addition, the damping control should

- be robust in that it imparts the desired damping over a wide range of system operating conditions, and
- be reliable.

4.8.1 Principle of Damping

The concept of damping enhancement by line-power modulation can be illustrated with the two-machine system depicted in Fig. 4.8. The machine SM_1 supplies power to the other machine, SM_2, over a lossless transmission line. Let the speed and rotor angle of machine SM_1 be denoted by η_1 and φ_1, respectively; of machine SM_2, denoted by η_2 and φ_2, respectively. During a power swing, the machines oscillate at a relative angle $\Delta\varphi$ ($=\varphi_2 - \varphi_1$). If the line power is modulated by the TCSC to create an additional machine torque that is opposite in sign to the derivative of the rotor-angle deviation, the oscillations will get damped. This control strategy translates into the following actions: When the receiving end–machine speed is lower than the sending end–machine speed, that is, $\Delta\eta$ ($= \eta_2 - \eta_1$) is negative, the TCSC should increase power flow in the line. In other words, while the sending-end machine accelerates, the TCSC control should attempt to draw more power from the machine, thereby reducing the kinetic energy responsible for its acceleration. On the other hand, when $\Delta\eta$ is positive, the TCSC must decrease the power transmission in the line. This damping control strategy is depicted in Fig. 4.8 through plots of the relative machine angle $\Delta\varphi$, the relative machine speed $\Delta\eta$,
and the incremental power variation ΔP_{mod}. It may be recalled from Chapter 6 that the damping-control action of the SVC is also similar to that described in the preceding text.

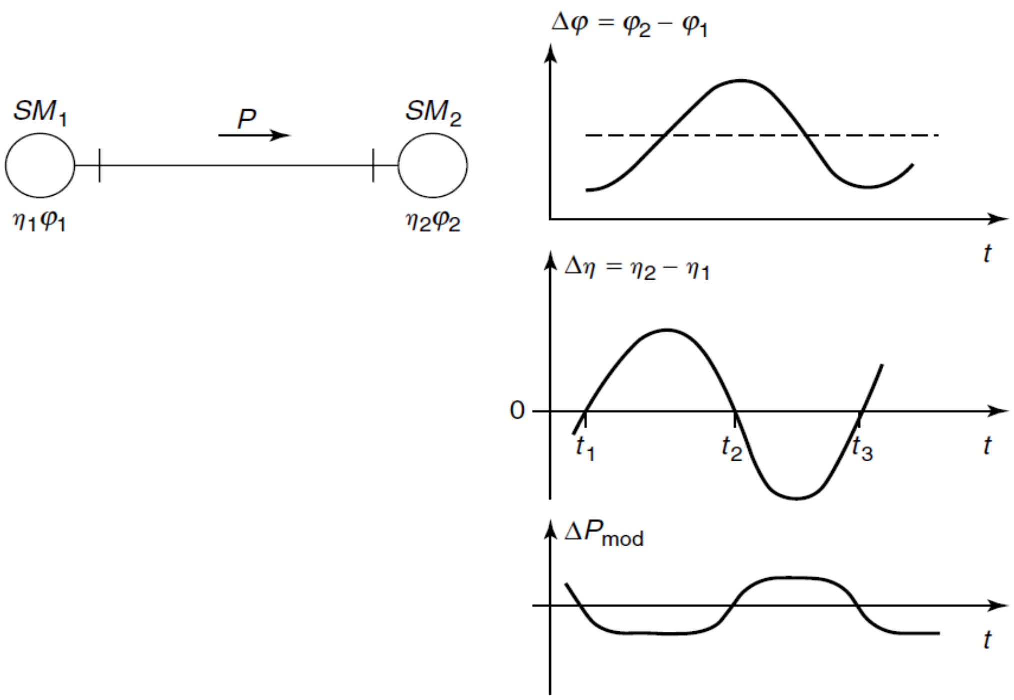


Figure 4.8 The TCSC line-power modulation for damping enhancement.

The incremental variation of the line-power flow ΔP, given in megawatts (MW), with respect to ΔQ_{TCSC}, given in MVAR, is as follows:

$$\frac{\Delta P}{\Delta Q_{\mathrm{TCSC}}} = \frac{1}{2\tan\,\delta/2}\left(\frac{I}{I_N}\right)^2 \tag{4.5}$$

where δ= the angular difference between the line-terminal voltages

I = the operating-point steady-state current

I_N = the rated current of the TCSC

Thus the TCSC action is based on the variation of line-current magnitude and is irrespective of its location. Typically, the change in line-power transfer caused by the introduction of the full TCSC is in the range of 1–2, corresponding to an angular difference (δ) of 30°–40° across the line.

The influence of any bus load on the torque□ power control of the synchronous generator is derived for the case of a resistive load and completely inductive generator impedance. The ratio of change in generator power to the ratio of change in the power injected from the line into the generator bus is expressed as

$$\frac{\Delta P_m}{\Delta P} = \frac{\cos(\delta/2 \pm \alpha)}{\cos(\delta/2)} \tag{4.6}$$

where the + sign corresponds to the sending end; the − sign, the receiving end.

Also,

where ΔPm = the variation in generator power

ΔP = the variation in power injected from the transmission line into the machine bus

$\alpha = \tan-1\ (X_{\text{source}} /\square\ R_{\text{load}})$

The effect of all practical passive loads is generally moderate, and the sign of generator power is not changed. In the absence of any bus load, $\Delta P_m = \Delta P$. It is not necessary to make the entire series compensation in a line controllable; in fact, the effectiveness of a TCSC is shown to increase in presence of fixed series compensation. The required series compensation in a line is therefore usually split into a fixed-capacitor component and a controllable TCSC component. The controlled-to-fixed ratio of capacitive reactance in most applications is in the 0.05–0.2 range, the exact value determined by the requirements of the specific application.

4.9 SUBSYNCHRONOUS RESONANCE (SSR) MITIGATION

Series compensation of long transmission lines may cause the following kinds of oscillations:

- *Subsynchronous oscillations*, caused by interaction between the electrical network and the generator torsional system.
- *Low-frequency (≈10 Hz) oscillations*, caused by interaction between the series capacitors and the shunt inductors, especially during line switchings and faults. These oscillations have large magnitudes and last for long periods because of high shunt-reactor *Q*-factors.
- *Switching oscillations*, caused by the switching of lines.

The TCSCs can be employed successfully to mitigate the listed oscillations. The principle of SSR mitigation by TCSCs has been obtained from the pioneering work done by Dr. N. G. Hingorani, for whom the NGH scheme of damping SSR was named. This scheme involves a thyristor-controlled discharge resistor connected in shunt with the series capacitor and is installed in practical systems. The NGH scheme is described in great length in refs, for which reason this book focuses on the impact the TCSC controller in suppressing the SSR.

4.9.1 TCSC Impedance at Subsynchronous Frequencies

The TCSC impedance is purely capacitive at a nominal synchronous frequency and can be raised above the rated capacitance of the series capacitor by a factor of 2.5–3 through the appropriate firing-angle control. However, at subsynchronous frequencies, the TCSC under constant-reactance control presents a very different impedance characteristic, which greatly aids the damping of subsynchronous oscillations.

A frequency-domain EMTP study of the TCSC equivalent impedance is described. The simulation is performed on a test system shown in Fig. 4.9 that comprises a single-segment TCSC placed in a transmission line having resistance *R* and inductance *L*. The system is energized by the combination of a synchronous 60-Hz voltage source and a subsynchronous 10-Hz

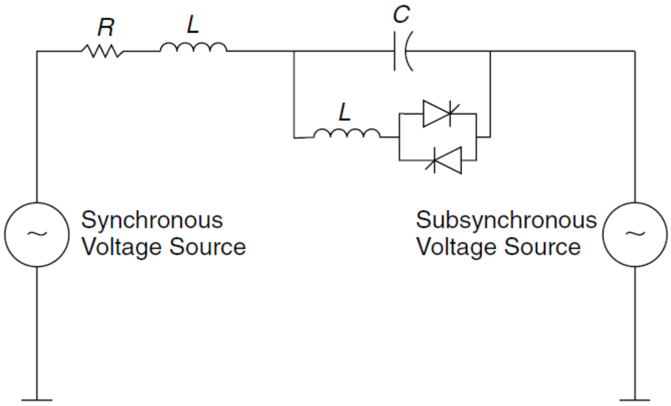


Figure 4.9 Network for the simulation study of the TCSC equivalent impedance.

voltage source, with the voltage magnitude of the latter much smaller than that of the former. The reactance of the TCSC fixed capacitor is 1.33 Ω . The simulated TCSC voltage corresponding to a 70^0 conduction angle is shown in Fig. 4.10, and the square root of its power-density spectrum (PDS) is shown in Fig. 4.11. Two main frequency components—one at 60 Hz, the other at 10 Hz—are visible in the TCSC voltage signal. These individual-frequency components of TCSC voltage, as well as the TCSC current, are filtered through a second-order Chebyshev filter, as illustrated in Fig. 4.9. The equivalent TCSC impedance is then obtained by dividing the TCSC voltage by the TCSC current for the corresponding frequency. The equivalent impedance is calculated as $1.65\angle -90^\circ\ \Omega$ at 60 Hz that, as expected, is 1.33 times the X_{order}, which has been specified as 1.2 pu. However, the TCSC equivalent impedance at 10 Hz is $3.4\angle -8.5^\circ\ \Omega$. The equivalent impedance is similarly obtained for different frequencies corresponding to a given set of excitation-voltage magnitudes and the desired TCSC reactance Xorder. It may be noted that because TCSC operation is nonlinear, the equivalent impedances will be functions of excitation voltages. The equivalent TCSC impedance, $Z_e(\omega)$, at different subsynchronous frequencies can be expressed as

$$Z_e(\omega) = R_e(\omega) + jX_e(\omega)$$

where $R_e(\omega)$ =the equivalent resistance of the TCSC

$X_e(\omega)$ =the equivalent reactance of the TCSC

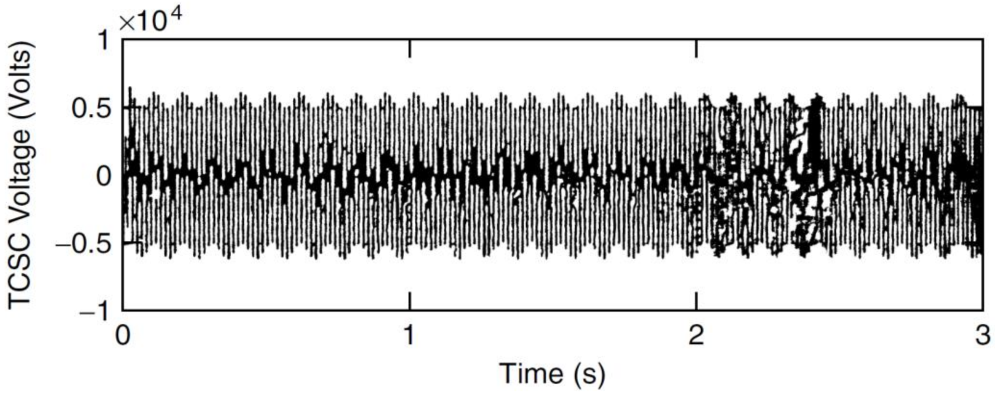
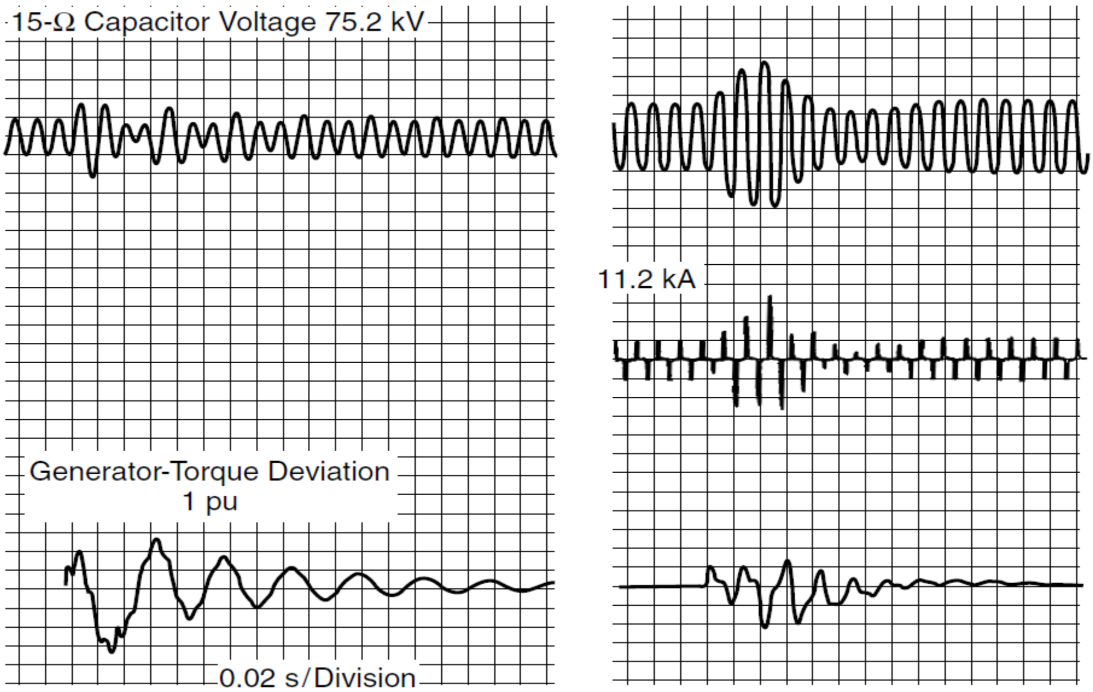


Figure 4.10 Simulated TCSC voltage

The TCSC presents an increasingly resistive effect as the frequency decreases below the synchronous level, implying that the TCSC offers resistive damping to subsynchronous oscillations. On the other hand, it is seen that while TCSC amplifies the capacitive reactance at the fundamental frequency according to the specified X_{order}, the equivalent TCSC capacitive reactance is reduced as the frequency is decreased below the subsynchronous frequency. In other words, the TCSC introduces an inductive effect at subsynchronous frequencies. The TCSC equivalent reactance corresponds to the reactance of the TCSC fixed capacitor at neither the nominal frequency nor the subsynchronous frequency. Thus, in the vernier mode of operation, the TCSC detunes the electrical resonant frequency with respect to the torsional mode by changing its equivalent-capacitive reactance at subsynchronous frequency. It further provides a positive, resistive damping to the subsynchronous oscillations. In the subsynchronous-frequency range of 28–60 Hz, the equivalent resistance increases with the X_{order}. Because the electrical frequency shown in the figure is complementary to the torsional-mode frequency (60 Hz), it can be argued that a higher X_{order}

will impart a larger resistive damping to the low-frequency torsional modes in the range of 0–32 Hz. For a specified *X*order, the equivalent-capacitive reactance deviates most from the fixed-capacitor reactance (or offers a maximum inductive effect) at lower electrical frequencies. This deviation implies that the TCSC will be more effective in suppressing the complementary higher-frequency torsional modes.



(a) (b)

Figure 4.11 The transient torques: (a) conventional and (b) with TCSC.

The preceding study is indicative only of TCSC behavior. The exact performance may vary with differing system configurations, system parameters, TCSC operating conditions, and so forth. A series-compensated electrical network that carries power from
a fossil generator to an infinite bus is considered. The total series reactance, X_L, is 203 Ω , whereas the capacitive reactance, *Xc*, of the conventional fixed capacitor equals 90 Ω , resulting in an electrical natural frequency of 40 Hz.

A comparison is made between the performance of the conventional capacitor bank and a TCSC of same rating at synchronous frequency. The 90-Ω series-capacitive reactance is realized through two 15-Ω conventional-capacitorsegments and two 15-Ω TCSC segments operating at twice the nominal reactance by the appropriate firing control (90 Ω = 2 □□15 Ω+ 2 □□15 Ω □□2). It is interesting to note that the TCSC with constant-reactance control is able to reduce the magnitude of generator transient-torque oscillation and also change the frequency of torque oscillation from 20 Hz to approximately 37 Hz. The electrical frequency corresponding to 37 Hz is 23 Hz (60 − 37 Hz), which is determined by the capacitance of the conventional capacitor 30 Ω (2 □□15 Ω) and a TCSC reactance of 2 □30 Ω . The TCSC thus minimizes the transient torque by detuning a resonant condition.

Usually, generation and transmission projects are financially and, to a great extent, technically decoupled, so it is highly desirable to implement SSR countermeasures in the offending series-compensation equipment. Thus, in a series-compensated system in which a small percent of series compensation is provided by the TCSC, the SSR effects can be mitigated successfully by enhanced control of the TCSC.

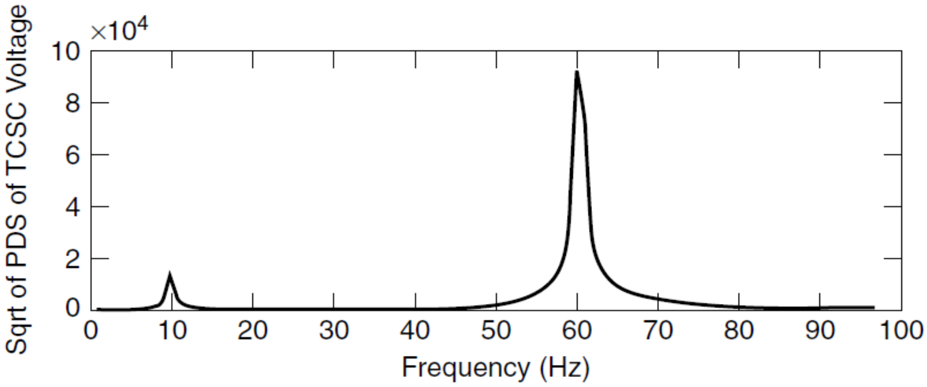


Figure 4.11 The square root (sqrt) of the power-density spectrum (PDS) of the simulated TCSC voltage.

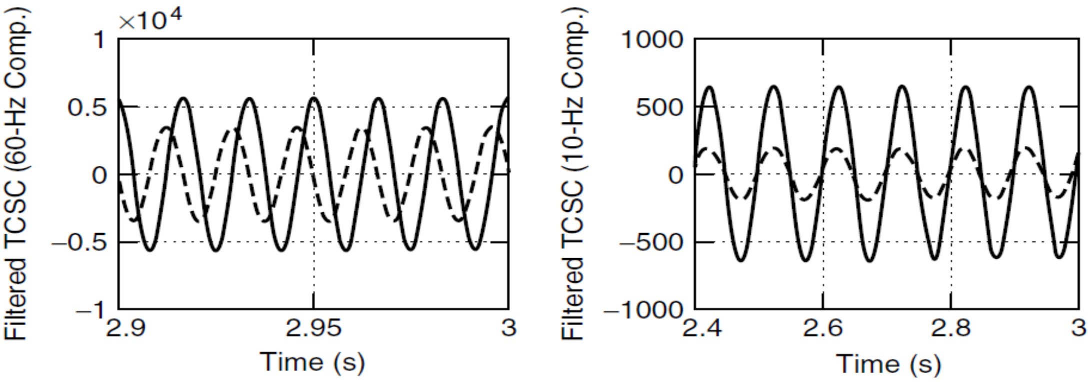


Figure 4.12 Filtered frequency components of the system responses: solid line denotes voltage in volts and dashed line denotes current in amps.

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