Course Name: Power Electronics Applications in Power Systems

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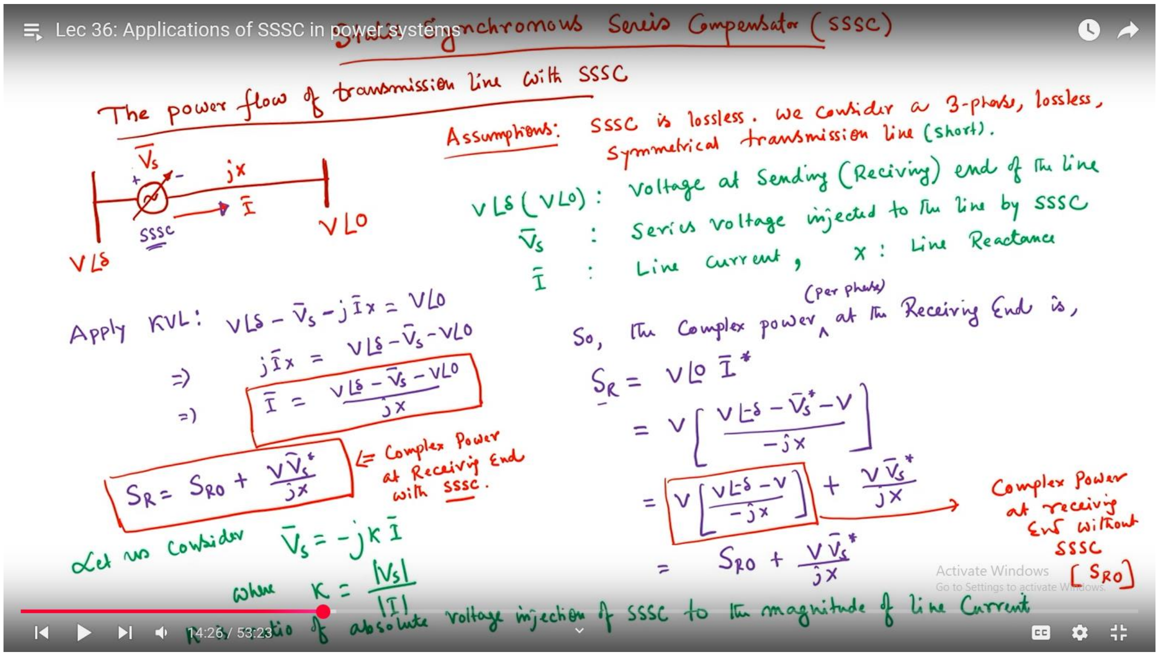
Lecture: 02

Lec 36: Applications of SSSC in power systems

So, welcome again to my course Power Electronics Applications in Power Systems. In the last lecture, I started a discussion on a specific type of converter-based power electronic compensator. It is static synchronous series compensator. So, in my last lecture, I discussed the basic operating principle of SSSC that is static synchronous series compensator. I also discussed how this SSSC placement in a typical power transmission system effects on the power flow and this reactive power of both ends of the line. So, in today's lecture, we will learn the application of SSSC. Before that, I will discuss some more aspect on power flow of a typical transmission line with SSSC. So, let us proceed. So, we are continuing our discussion on static synchronous series compensator. It is popular with its acronym SSSC that is SSSC.

Now, in today's lecture, I will discuss the power flow of the transmission line with SSSC. So, to do so, let us consider a single line diagram of a 3-page power transmission line. Here we have SSSC placed. Also for doing so, we will take some assumptions. So, our assumption is that SSSC is lossless. Also, our assumptions are we consider a three-phase lossless symmetrical transmission line. So, let us consider that this is sending end side voltage is V at an angle delta, receiving end side voltage is V at an angle 0. And this

SSSC is modeled as a controllable voltage source which is injecting a series voltage to the line. Let us consider that series voltage is Vs. And let us consider this transmission line is modeled as a short transmission line model with reactance X and the current flowing through this line is I.



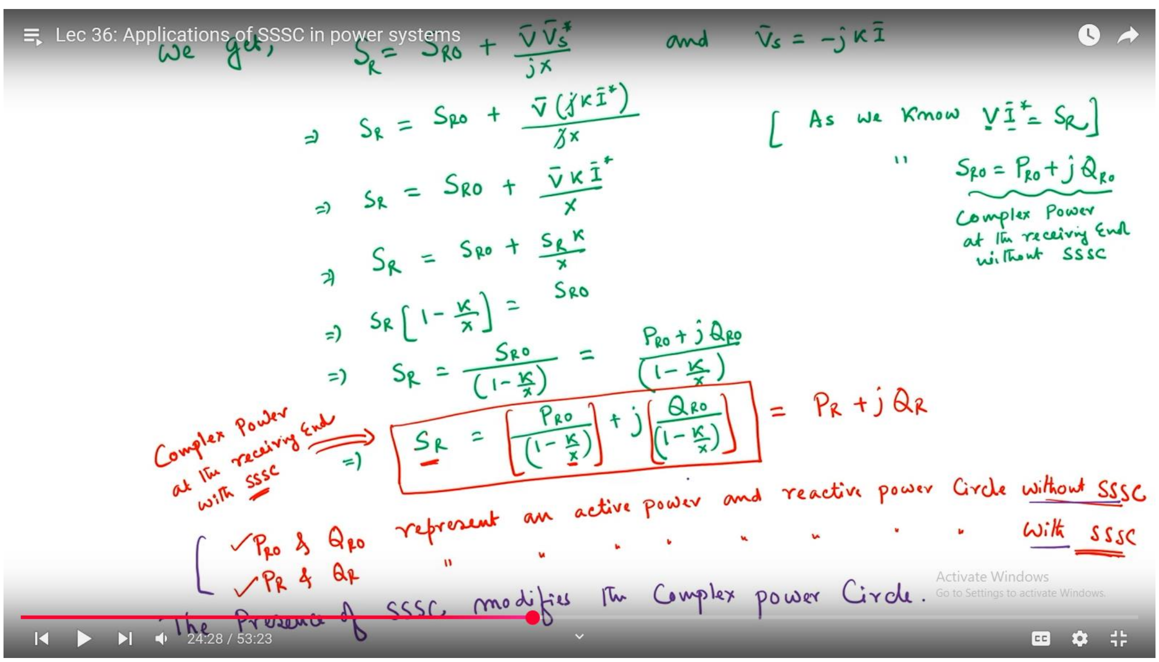
So we write this V at an angle delta and this V at an angle 0 are voltage at sending end and V at an angle 0 is voltage at receiving end of the line. Then, we consider that V s is the series voltage injected into the line. By SSSC, this I represents the line current and X represents this line reactance. So, we consider this is a short-line model. Now let us see how the effect of this SSSC impacts on the power flow of the transmission line.

In the last lecture, I have shown you with suitable control of SSSC, it is possible to reverse the flow of the power through the transmission line and this could be effective when there is a dynamic situation or when we require to change the direction of the power flow. Now, what we will do now, we will apply KVL in this particular loop. It is a single-line diagram, so you understand I believe that it represents this single line of a 3-page system and we assume that this polarity of Vs is this. Now, if it is considered then we know that by applying KVL we will get a KVL equation that is V at an angle delta that is the voltage at the sending end side minus this voltage injected by the SSSC, this is SSSC, which is modeled as a series voltage injection and minus this J i x is equal to the receiving end voltage, that is P at an angle 0. Now, from this, we can find that J i x is equal to V at an angle delta minus V s minus V at an angle zero.

So, this current is equal to V at an angle delta minus V s minus V at an angle 0 divided by j x. So, this is the expression for line current in terms of the voltages at both ends and the voltages with SSSC injection. Now, what we will do is, we will develop the expression for this power from this current. So, the complex power, power at the receiving end is S r is equal to this V at an angle 0 or rather I write it in terms of complex phasor notation multiplied by i conjugate. Now, you can understand that here let us assume that we are doing everything in power phase.

So, therefore, actual power will be 3 times of this. So, I am just omitting this 3 here, but you have to understand that this is power phase power. So, let us consider this is power phase. So, this complex power is power phase power. Now, what we will do v at an angle 0 is nothing but v and i conjugate is this v at an angle minus delta minus this v s conjugate minus v divided by minus j x. So, this is what the expression is. Now, I can write this into two part, one is v, I am just separating out this part that is voltage injection by the SSSC. So, what we will get it v at an angle minus delta minus v divided minus j x minus this v, v s conjugate divided by minus j x. So, this minus and this minus will be cancelled out and it would be j x. Now, if you look at this part.

What it is actually? It is the expression for this complex power when there is no SSSC in the line. So, this represents the complex power at the receiving end without S S S C, let us represent it by S R O. So, then this expression would be SRO where SRO is the representation of the complex part without SSSC plus this VVS conjugate. So, if I write this once again, this here S R is equal to S R O plus V, V S conjugate divided by J X. So, this is what the expressions for this complex power at the receiving end with SSSC we get.



So, this is the expression for complex power at receiving end with SSSC. Now, let us consider that, let us consider that V s is equal to minus j k i, where k represents the absolute value of the voltage injected by this to this I line current. So, K is the ratio to absolute value. So, K is ratio of absolute voltage injection of SSSC to the absolute or to the magnitude of the current flow, to the magnitude of line current. Now, if we put this over here, if we put this over here, then what we will get? Let us see. So, let us write this expression once again. So, we got s is equal to s r o, s r actually is equal to s r o plus v s conjugate divided by j x, right, yes. So, and also we got and V s we consider as minus j k i. So, if it is so, then we can write that S r is equal to S r o plus this V and V s conjugate that means, it would be minus j, so it will be plus j k i conjugate divided by j x. So, I can write it as S r o plus this V.

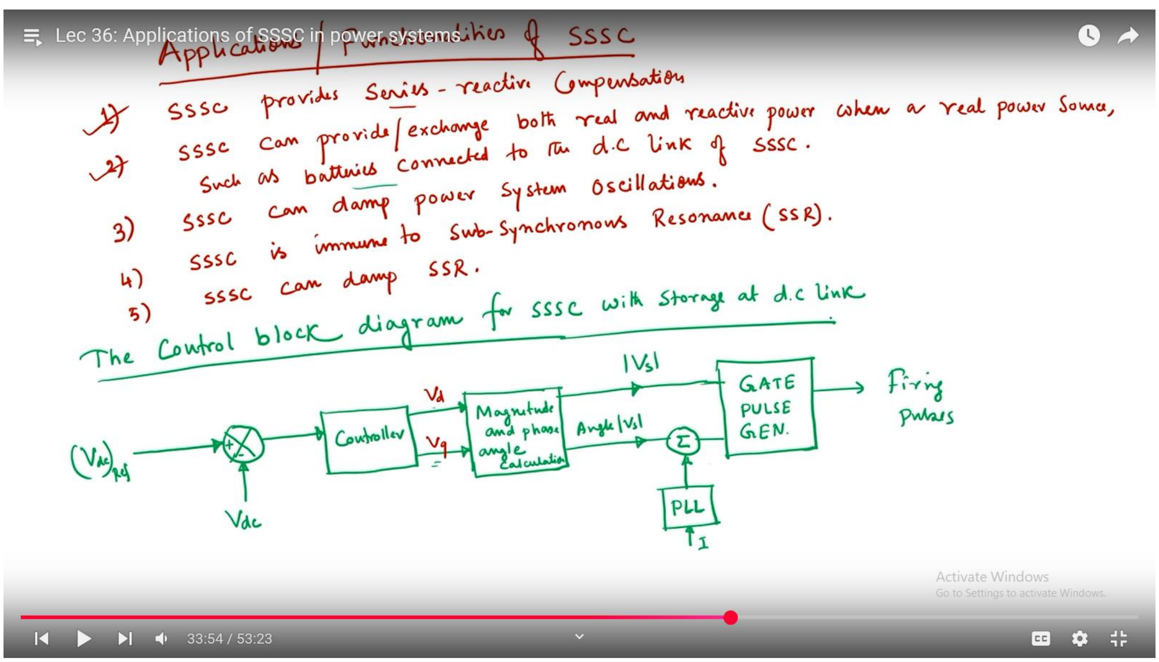
Now, you can see this j and this j would be cancelled out. So, this v multiplied by k, k is a scalar quantity multiplied by i conjugate divided by x. Now we know that this V i conjugate is what actually it is, V is the voltage at the receiving end side and when we multiply it with i conjugate then it would be nothing but S. So as we know V i conjugate is equal to S r, S r o rather, S r o. So, this represents S r o. So, therefore, this would be, can be written as S r o plus this. So, this V and I conjugate is not actually SRO. So, this basically represents SR because this V is the voltage and I is the current which is flowing in the presence of this SSSC. So, this basically represents SR multiplied by K and X. Now, you see that left-hand side we also have SR, and right-hand side we get a function which is also a function of S r.

So, what we can do is that we bring it to the left-hand side. So, what we will get 1 minus k divided by x which is equal to S r o. So, this gives S r is equal to S r o divided by 1 minus k divided by x. Now k divided by x is a scalar quantity. Now S r o can be written as p r o plus j q r o because as we know this Sro is basically representing the active power at the receiving end side when there is no SSSC plus J reactive part at the receiving end side when there is no SSSC. So, this represents complex power at the receiving end without SSSC. So, this is divided by 1 minus K by X. Now, we can write S R is equal to this P R O divided by 1 minus K divided by X plus j q r o divided by 1 minus k x. So, this is what the expression I want to arrive at. So, what we can do from this expression, or rather what we can conclude from this expression is you can see this S r is what? This S r o is nothing but complex power at the receiving end with SSSC.

Now, if you look at this expression, this complex power at the receiving end with SSSC is basically equal to this PRO, which represents the active power flow of this transmission line at the receiving end side without SSSC divided by this 1 minus k divided by x. Now, you know that what is k, k already we have defined is the ratio of absolute voltage injection of SSSC to the magnitude of the line current. Now, therefore, depending upon the values of k, depending upon the values of k and the relative value of x, Sr will represent one complex power circle. So, basically as you can understand that P R O and Q R O, they represent an active power an active power and reactive power circle without SSSC. Now, if you consider this part, this part is equal to P r and this part is equal to Q r.

That means, this whole expression is equal to P r plus j Q r. Then, this PR and QR also represent an active and reactive power circle with SSSC. So, we can write PR and QR also represent an active power and reactive power circle with SSSC. Now if you can draw these two circles, this I am leaving to you, those who are learning this course. So if you take the realistic value of x in comparison to the x, if you vary this k realistically, then you will be arriving at two circles. One is this without SSSC that constitute PRO and QRO, another is with SSSC that represents PR and QR. Then you will understand that how these two are representing different power circles. So, if you take the realistic value of x and do this simulation study, then you will be able to understand what would be the operating region as far as the power transfer is concerned when we have SSSC in the power transmission line. So, therefore, what I will conclude is I am not interested to draw this circle, I am leaving to you. So, what I can conclude from this whole analysis is that the presence of SSSC modifies the complex power circle.

One may you know draw both the circles with some realistic data then we will come to a conclusion that what is the impact of the SSSC in power flow. So, that is I am leaving to you. Now coming back to the functionalities of SSSC in mitigating several power system problems and also assisting this power system, let us discuss something about the applications or applications or functionalities of SSSC. 1) SSSC provides series reactive compensation. So this is well known because you know that any kind of series compensator or any kind of power electronic-based series compensator can exchange this reactive power to the system if it does not have any real power source connected to it.



Now also the second point that I should write is whether SSSC can provide or can exchange both real and reactive power when a real power source such as batteries or similar kinds of energy storage devices is connected to the DC link of SSSC. So, this is eventually effective, I will come to that why it is so. In fact, you have already seen that series reactive compensation is somewhat more effective as compared to the shunt reactive compensation in the sense that. If you want to enhance the steady-state power transfer capacity, the series compensator can do so with a reduced rating. So, this I already have explained with mathematical derivations in one of my previous lectures, long time ago before I start the SVC.

Now, the third application or functionality is that SSSC can damp power system oscillations. How this is possible? I will come to that. Number 4 is that SSSC is immune to sub-synchronous resonance which is an important functionality of SSSC or in short it is called SSR. So, this is an important functionalities why it is so I will come to that. Number 5 is that SSSC can damp SSR that is sub-synchronous resonance.

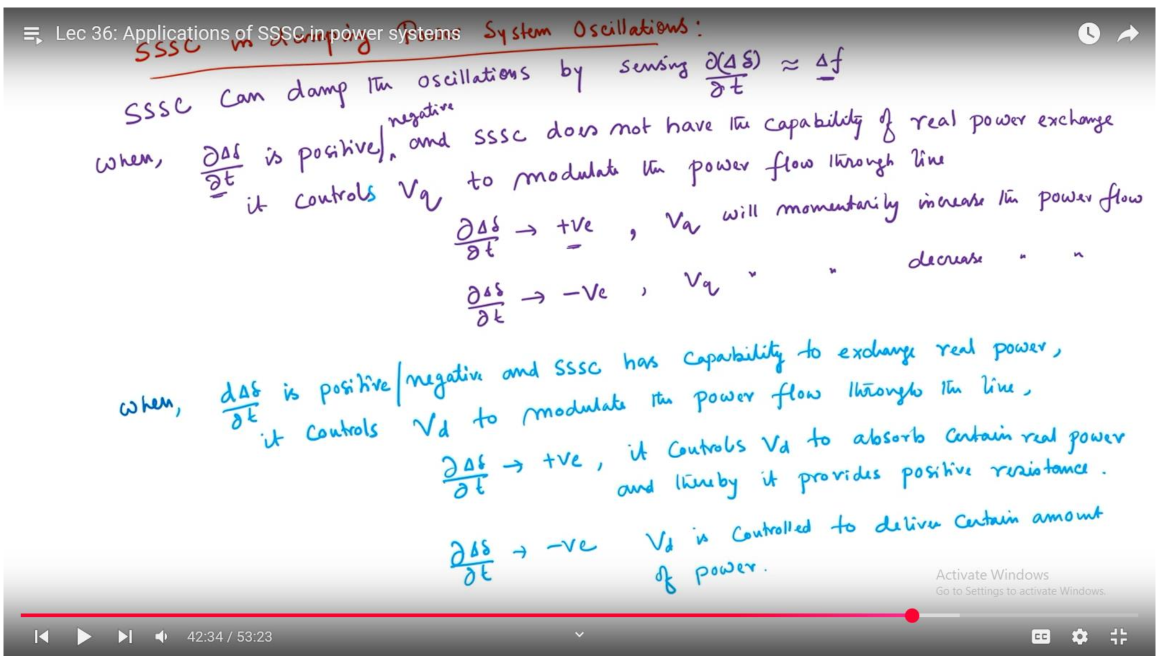
So, let me discuss all these functionalities one by one. Now, let us start with the how it provides that series reactive compensation this I will discuss along with this how it can exchange this active and reactive power when we have a active power source or an energy storage system connected to the DC link of the SSSC. So, to start with, let us draw the control block diagram for SSSC. So, to draw this control block diagram, what is there is, we have a VDC reference, which is compared with the actual VDC measured, and the error is transferred to a controller. Now this controller can be any type of controller, can be a PI controller, can be any type of improved controller, those things I am not discussing here.

Now what controller will do? It will generate two signals, one is this Vd, another is Vq, I will come to that. So, what the controller will do? It will generate a V t and V q signals and then inside this block there is a magnitude and phase angle calculation block is there, which will generate the signal of this V s magnitude and the phase of the V s that is the angle of V s. Another comparator is over here, which will take the signal from this PLL. I hope that you know what the functionality of PLL is. So, then it will be fed to the get pulse generation block and thereby it will generate the firing pulses.

Now what is the purpose of PLL? PLL is a phase lock loop you know those who are familiar with these power electronics converters and they are basically this PLL is basically responsible for keeping the operation of SSSC in synchronism with power systems. So this is what the block diagram of the SSSC. Now, we have this Vd and Vq, one is this direct axis and quadrature axis voltage component, in specifically when we have some kind of storage connected to the DC link. So, this SSSC is with some storage at DC link. Now, so this is what the control block diagram for SSSC and this is how they it will operate to provide the series reactive power compensation along with the series active power compensation to the power system.

Now, let us discuss how it can dampen this power system oscillation. So, SSSC in damping power system oscillations: How it is possible to damp power system oscillations? Now, what do you mean by power system oscillations? Again, I already discussed this in my previous lecture, when I discussed the SVC and the STATCOM actions on this power damping the power system oscillation. I will repeat it again. So, power system oscillation happens when we have this very small frequency in terms of 1 to 2 hertz which is caused by either in a particular area or maybe in internal area system dynamics. And this oscillation sometimes becomes very crucial and if this cannot be properly dampened, then this may lead to instability of the system.

Now, how this SVC or STATCOM can damp the power system oscillation? This already I discussed. So, they first sense the oscillation in terms of the rate of change of del delta. That is delta is the power angle as you know. Then they will modulate the voltages at the bus where the SVC and STATCOM were placed to increase or to modulate the power flow through the line and thereby they can damp the power system oscillations. Similar to that SSSC also can dampen the power system oscillation by sensing the rate of change of del delta.

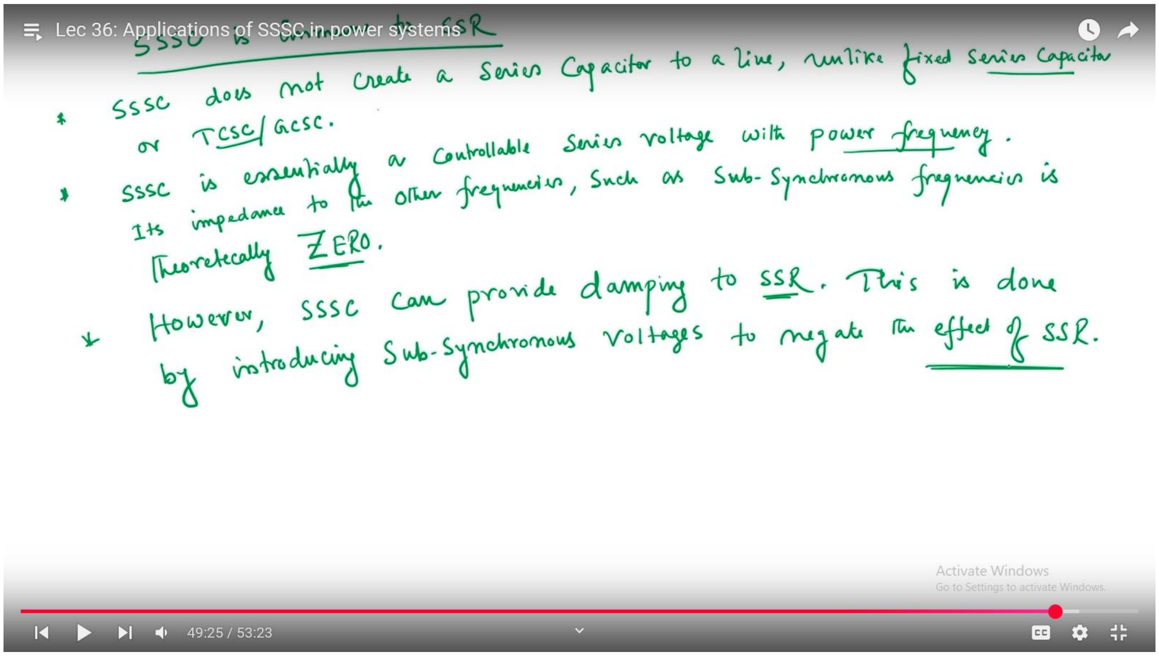


So, what SSSC does is SSSC can damp the oscillations, or low-frequency oscillations by sensing this del t, which is somewhat similar to the rate of change of frequency. So, when del delta del t is positive SSSC does not have the capability of real power exchange. So, when SSSC does not have the capability of real power exchange, that means there is no storage or no battery connected to the DC link of SSSC. Then what it does actually, it controls, it controls VQ, this quadrature voltage, already I have shown in the control block what is VQ, you can look at here, this is VQ to modulate the power flow through the line. Now, what sort of power flow modulation is requested when this del delta is positive when del delta del t is positive. Then that means the frequency is increasing that means mechanical power is higher than the electrical power. So, V q will momentarily increase the power flow. So, I should write this could be positive or negative. When this del delta del t is negative then V q will momentarily decrease the power flow ok. So, that is what this SSSC action would be or the accordingly the controller would be tuned to do this actions ok.

However, when this del delta del t is positive or negative and SSSC has capability to exchange or to exchange real power, then what it would be the, it will control, V d not V q to modulate the power flow through the line. Now, what it will do? When del del t, del t is positive what it will do is, it controls this V d, it controls V d to absorb a certain amount of power, absorb certain real power, and thereby it provides positive resistance. Similarly, when this del delta, del t is negative, V d is controlled to deliver a certain amount of power and thereby it provides the negative resistance. So, that is what it does and that is what the action of SSSC where to damp the power system oscillations or low-frequency oscillations of power systems. So, we already have explained these four functionalities of this SSSC. And, we will discuss the last functionality that is how the SSSC is immune to the sub-synchronous resonance and whether SSSC can damp the SSR or SSSC is immune to sub-synchronous resonance. How it is? Let me explain. So, this is an important aspect of SSSC that unlike a fixed capacitor or a variable susceptance or variable impedance-based compensator like TCSC, it does not provide any series capacitor to the transmission line. So, SSSC does not represent a series capacitor that is what it that advantage is. So, SSSC does not create a series capacitor to a line unlike fixed series capacitor or TCSC or GCSC.

So, what this TCSC, GCSC or fixed capacitor does that they connect a fixed capacitor to the power transmission line. And therefore, this fixed capacitor will create resonance in sub synchronous frequency that is the frequency is lower than the power frequency along with the transmission line, this inductance and inductive reactances. Whereas this SSSC, what it actually does? SSSC is essentially, SSSC is essentially a controllable AC voltage, or SSSC is essentially a controllable series voltage. It does not represent a series capacitance. No, it does not represent, it does not have this any series capacitive impedance fed to the system.

Rather, it is essentially a controllable series voltage with fundamental frequency or power frequency, with power frequency. It only injects a controllable series voltage with power frequency so that is something that needs to be understood. So, it only creates a controllable series voltage with power frequency. Therefore, its impedance to the other frequencies, its impedance to the other frequencies such as subsynchronous frequencies that is less than the power frequency is theoretically which is one of fundamental property of SSSC in comparison with TCSC and GCSC or even in comparison with a fixed capacitor. It does not create any sub-synchronous resonance because it is not representing, it is nowhere providing an impedance other than the fundamental frequency.



So, therefore there is no scope of SSR that is sub-synchronous resonance in SSSC. However, SSSC can provide damping to SSR that is sub-synchronous resonance. So, this is done by introducing sub-synchronous voltages that is voltages other than the power frequency that is sub-synchronous voltages to negate the effect of SSR. Now, how it is done, one may go through the literature. I am not discussing over here. This course is already heavy. So, I just keep this part. So, but this is something that one needs to understand. So, this is all together the different functionalities of this SSSC. Now in this lecture, I will specifically finish with some discussion on the converter-based power electronics compensators which are used in power distribution systems. So altogether all these different types of converter-based power electronics compensators which are constructed and controlled for power distribution systems are known as custom power devices, as already I mentioned.

The basic functionalities of custom power devices are closely similar to the converter-based power electronics compensators which I discussed like STATCOM, SSSC, etc. However, this distribution networks since they are very close to customers, they are directly connected to the customers. So, they are having some sort of problems, which are not experienced in power transmission systems. For example, these distribution networks often suffer from several harmonics generated by the loads. They are suffered also suffered from the voltage imbalance or voltage unbalance.

They also suffer from several power quality problems, for example, voltage quality problems like voltage sag, voltage swell, this voltage unbalance as well, this voltage flicker and all. So, the goal of developing those custom power devices is to mitigate to those power quality problems as well in addition to the functionalities of what we have in case flexible AC transmission system devices like STATCOM and SSSC. So, if somebody has a close interest in it, they can go through the literature of custom power devices. I am not going to discuss in this particular course here because already this course material is enough for this particular theme. So, therefore, these custom power devices or the power electronic-based compensators or converter-based power electronic compensators to be used in power distribution systems is another aspect of the study and you may go through the literature for it.

So, with this I will conclude this lecture and I will conclude this course as well. Thank you all, thank you all the learners for attending this course. So, thank you very much. So, I hope this course was enjoyable to you. Thank you, thank you very much. Thank you.

The power flow of a transmission line with SSSC:

Consider a balanced, 3-phase, lossless, and symmetrical short power transmission line equipped with a lossless SSSC as shown in figure below.

Applying KVL in the circuit we have,

$$V\angle\delta^{\circ} - \bar{V}_S - j\bar{I}X = V\angle 0^{\circ}$$

$$\Rightarrow j\bar{I}X = V\angle\delta^{\circ} - V\angle 0^{\circ} - \bar{V}_S$$

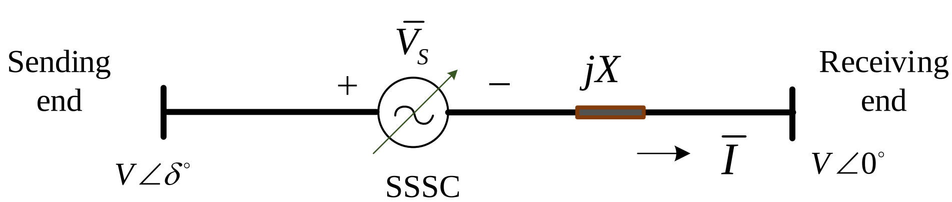


Figure: Transmission line with SSSC.

$$\Rightarrow \bar{I} = \frac{V\angle\delta^{\circ} - V\angle 0^{\circ} - \bar{V}_S}{jX}$$

So, the complex power at the receiving end can be written as:

$$S_R = V\angle 0^{\circ}\bar{I}^*$$

$$\Rightarrow S_R = V\left[\frac{V\angle{-\delta^{\circ}} - V\angle 0^{\circ} - \bar{V}_S^*}{-jX}\right]$$

$$\Rightarrow S_R = V\left[\frac{V\angle{-\delta^{\circ}} - V\angle 0^{\circ}}{-jX}\right] + V\left[\frac{\bar{V}_S^*}{jX}\right]$$

$$\Rightarrow S_R = S_{R_0} + \frac{V\bar{V}_S^*}{jX} \qquad (1)$$

Here, we can see that S_{R_0} is the complex flow in absence of the SSSC.

Let us consider, $\bar{V}_S = -jK\bar{I}$, where $K = \frac{|\bar{V}_S|}{|\bar{I}|}$ is ratio of the absolute value of SSSC voltage to the absolute value of transmission line current. Therefore, we have,

$$\Rightarrow S_R = S_{R_0} + \frac{V(jK\bar{I}^*)}{jX}$$

$$\Rightarrow S_R = S_{R_0} + \frac{K}{X}S_R \qquad \text{Here}, S_R = V\bar{I}^*$$

$$\Rightarrow S_R\left(1 - \frac{K}{X}\right) = S_{R_0}$$

If we write $S_{R_0} = P_{R_0} + jQ_{R_0}$, we have,

$$S_R = \frac{P_{R_0}}{\left(1-\frac{K}{X}\right)} + j\frac{Q_{R_0}}{\left(1-\frac{K}{X}\right)} = P_R + jQ_R \qquad (2)$$

Since, P_{R_0} andQ_{R_0} represent an active power and reactive power circle with the SSSC, P_R and Q_R represents an active and reactive power circle with SSSC. Thus, from equation 5 it can be seen that the active/ reactive power circle is modified by the presence of SSSC in the system.

Applications/ functionalities of SSSC:

An SSSC is an advanced version of controlled series compensation, that is based on VSC and the use of GTOs, unlike the use of thyristors in TCSC. SSSC has technically more advantages than TCSC. The SSSC has the following functionalities:

- SSSC provides series reactive compensation.
- SSSC can provide both reactive and active power to the system. The active power can be exchanged when a real power source, such as battery is connected to the DC link of the SSSC.
- SSSC can be used damp power system oscillations.
- SSSC is immune to sub-synchronous resonance (SSR).
- SSSC can be used to damp sub-synchronous resonance (SSR).

The control block diagram of SSSC with storage at DC link can be shown as:

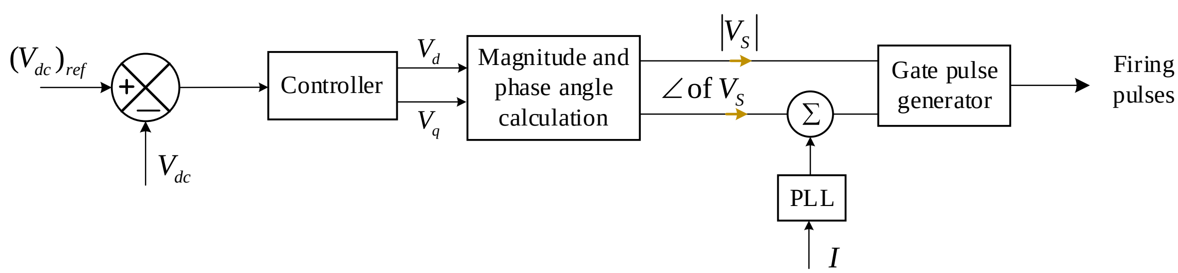


Figure: Control block diagram of SSSC.

Here, the gate pulses for the switching of VSC are generated while controlling the firing angle of the converter switches, to vary the magnitude of SSSC output voltage. A phase locked loop (PLL) is used to synchronise the SSSC voltage with the grid. When a DC energy source, such as a battery, is connected to the DC side of a Voltage Source Converter (VSC), it allows the exchange of active power with the transmission line. The active voltage component can be controlled along with the reactive voltage component. This provides two degrees of freedom, enabling the regulation of both active and reactive power flow in the transmission line. Additionally, it is possible to compensate for the line resistance (increasing X/R ratio), thereby increasing the line power transfer capacity. Instead of using an energy source, real power can be supplied by a shunt-connected VSC that interfaces with the series-connected SSSC on the DC side. This setup forms what is known as a Unified Power Flow Controller (UPFC).

SSSC in damping power system oscillations:

SSSC can damp the oscillations by sensing the rate of change of the power angle $\left(\frac{\partial(\Delta\delta)}{\partial t} \approx \Delta f\right)$. When $\frac{\partial(\Delta\delta)}{\partial t}$ is non-zero and SSSC does not have the capacity for real power exchange, it controls V_q to modulate the power flow through the transmission line.

- If $\frac{\partial(\Delta\delta)}{\partial t}$ is positive, V_q momentarily increases the power flow.
- If $\frac{\partial(\Delta\delta)}{\partial t}$ is negative, V_q momentarily decreases the power flow.

When $\frac{\partial(\Delta\delta)}{\partial t}$ is zero and SSSC has the capacity for real power exchange, it controls V_d to modulate the power flow through the transmission line.

- If $\frac{\partial(\Delta\delta)}{\partial t}$ is positive, it controls V_d to absorb certain amount of real power, and thereby it provides positive resistance.
- If $\frac{\partial(\Delta\delta)}{\partial t}$ is negative, it controls V_d to deliver certain amount of real power, and thereby it provides negative resistance.

SSR in transmission system with SSSC:

The impedance of the series capacitor is a function of frequency and thus it can cause resonances at various sub-synchronous frequencies with other reactive impedances present in the network. SSSC does not create a series capacitance with the transmission line, unlike fixed series capacitor, TCSC or GCSC. SSSC is essentially a controllable voltage source with power frequency. Its impedance to the other frequencies, such as sub-synchronous frequencies is theoretically zero. Therefore, SSSC is unable to form a series resonant circuit with the inductive line impedance to initiate sub-synchronous system oscillations. Thus, SSSC is strictly SSR neutral (if the DC capacitor has large size and the controller regulates the capacitor voltage with no perturbations caused by variations in the line current). Rather, SSSC can provide damping to SSR by introducing sub-synchronous voltages into the system to negate the effect of SSR.