Course Name: Power Electronics Applications in Power Systems

Course Instructor: Dr. Sanjib Ganguly

Department of Electronics and Electrical Engineering,
Indian Institute of Technology Guwahati

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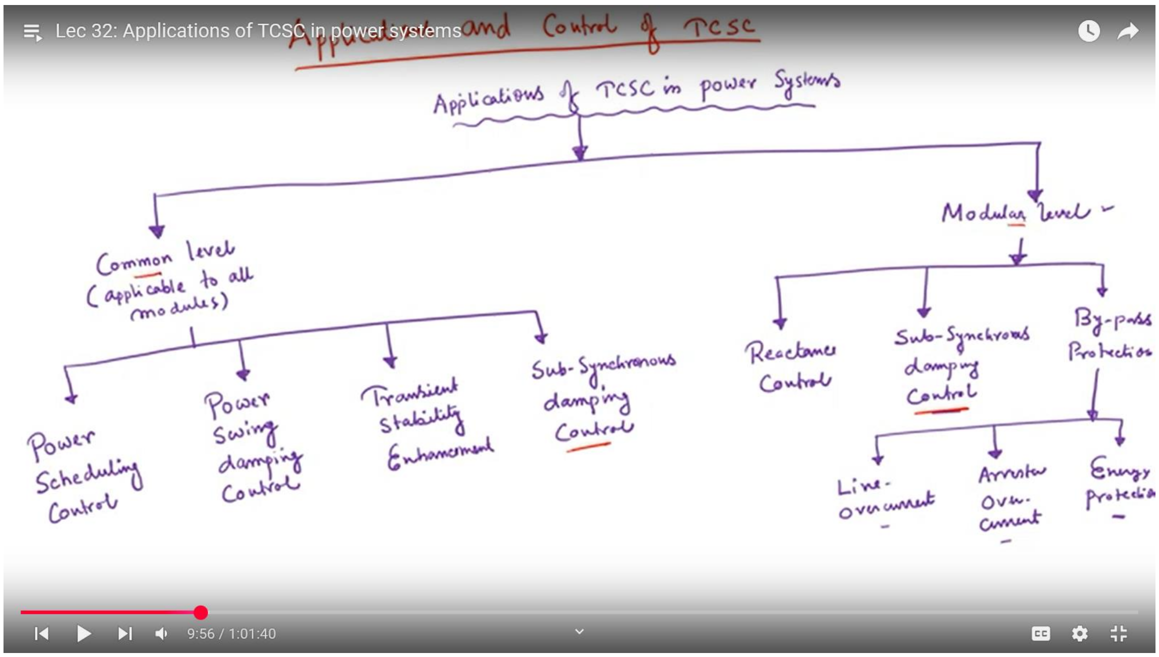
Lecture: 02

Lec 32: Applications of TCSC in power systems

Welcome again to my course Power Electronics Applications in Power Systems. In the last few lectures, I discussed a specific type of series compensation that is TCSC. Its full form is thyristor control series capacitor, right. So, I discussed the basic operating principle, I also discussed the mathematical model of TCSC and also I discussed the analysis of TCSC performance all together in the previous lecture. So, this lecture is the last part of the TCSC module. In this particular lecture, I will discuss the application and control of TCSC.

So, let us proceed. So, application and control of TCSC. So, in this particular lecture, I will discuss different applications of TCSC. Also, I will discuss different control approaches for TCSC. Now, where is their application? Of course, this application of TCSC is in power system. So, now if we write this applications of TCSC in power system, then we can categorize various applications into two different parts. One is called common level, common level application, another is called modular level. So, if you can remember my first lecture on TCSC, I discussed that TCSC is not a single module. Rather multiple TCSC modules are connected in series to form a single TCSC. This I discussed at the very beginning of this basic schematic diagram of TCSC. Now, so therefore we have two different applications of control levels, one is called common level. So, this common level is applicable to all modules and in modular level means it is applicable to individual modular. So, now in common-level control, we have multiple applications.

Specifically, we have four different applications. One is called power scheduling control. Next is called power swing damping control or damping of power system oscillations. You know power swing damping control, one is called transient stability enhancement. Another application is Sub-Synchronous Damping Control. These are all common level control and I will discuss each of these different control approaches or each of these different applications of TCSC in very detail in this particular lecture.



Now let us see what are the control or applications available for modular level of a TCSC. There are three different controls or applications of TCSC at the modular level available one is called reactance control. As you have seen that basically this Vernier mode of operation of TCSC is done with the reactance control. And I already derived the expression mathematical expression for TCSC reactance in the last lecture. And you can see that that reactance can be controllable with the appropriate setting of this angle of advance that is beta.

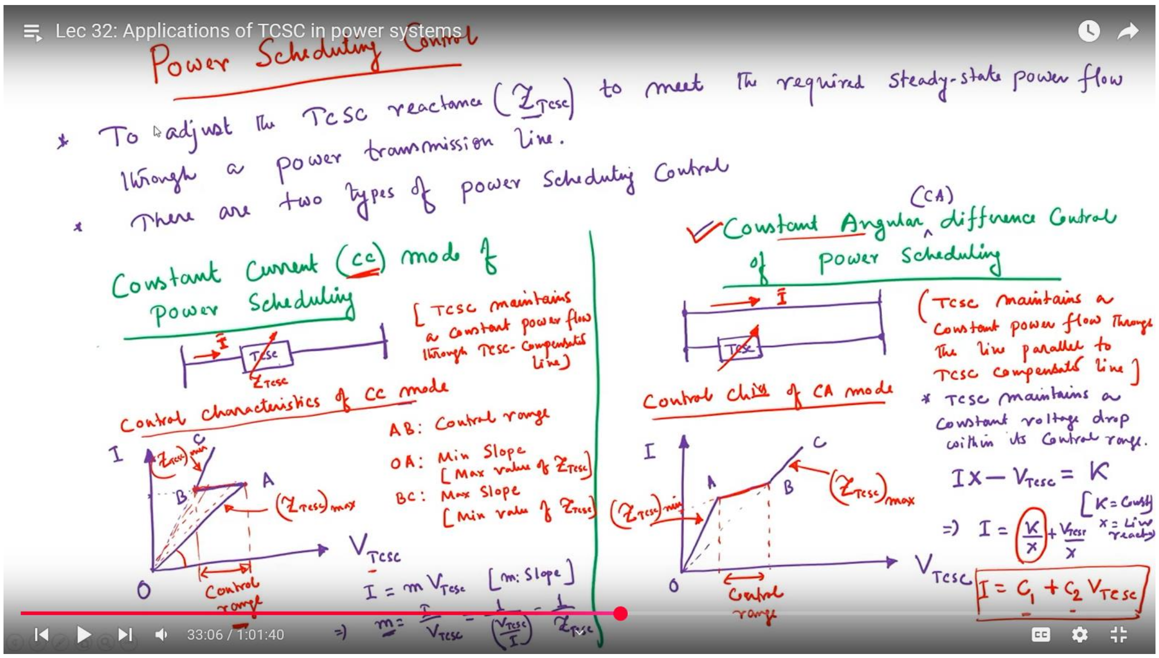
So, according to the requirement. Now, next is subsynchronous damping control, which is very important control application. Now why this happens? Sub-synchronous, what do you mean by sub-synchronous damping? this I will discuss in this particular lecture also. And why it is so important in TCSC, that thing also I will discuss. Now apart from that, there is another modular level control that exists which is called bypass protection. So, when we need to bypass this TCSC, we need to initiate this modular level control approach which is called bypass protection. Now, this bypass protection is of different types, one is called when a line over current will happen due to some reason, due to faults, etc. Then modular level control application would be initiated to bypass the whole unit from the system. So, this is just a protective measure you can say. So, there is a lightening arrester. So, arrester overcurrent is another mode of control application which is modular level applications.

So, when there is a lightening and there is a over current due to lightening in the line, then this TCSC should be able to protect itself by initiating this modular level control action. Now there is another control bypass protection control which is called energy protection which is similar to this previous two protection I discussed. But whenever there is over current or abnormalities if these two control action did not initiate then it will this energy protection will be initiated. Calculate the energy for a short duration and if it goes above the threshold value it will disconnect or it will initiate this bypass protection mode of TCSC. So altogether these applications of this TCSC in power systems are of these different control actions or these different control applications to power system.

Now I will discuss all this one by one, all these different techniques one by one. So, in fact, you can understand that some of the control actions are similar like the sub-synchronous damping control is common to common level control as well as modular level control. So, I will discuss this once. And this bypass mode, bypass protection mode, I need not to discuss. It is, you should understand by your common sense. And this reactance control is eventually required for all these different other common level control like power scheduling control, power swing damping control, transient stability enhancements and so on. So, I will start with this power scheduling control. Now, this power scheduling control is a unique application of TCSC, similar to this power flow enhancement is done in case of static var compensator. Now, how this power scheduling control happens or what are the different types of power scheduling control actions usually followed by TCSC, those things I will discuss. Now, first of all, what is power scheduling control? Power scheduling control is to adjust the TCSC reactance which is nothing but ZTCSC, I discussed in the last lecture to adjust this TCSC reactance to meet the required steady state power flow, steady state power flow through a transmission line.

. So, this is the goal of this, you know, power scheduling control of TCSC and this is what the main purpose or main applications of TCSC in power system. This is something one needs to understand. So, what it actually does, it adjusts the TCSC reactance that means ZTCSC. I already derived the mathematical expression for ZTCSC in my previous lecture and thereby it will help to meet the required power flow through a particular transmission line. Sometimes, when we have multiple transmission lines working in a parallel, one of them may have this TCSC placed and this transmission line we may call as a TCSC compensated power transmission line and it can do this same thing that this it can help to meet this steady state power flow through a particular transmission line or through a group of transmission line which are operated in parallel.

This I will discuss. Now, there are two types of there are two types of power scheduling control. One is called constant current mode, or CC mode of power scheduling. Another is called constant angular difference control or constant angular difference control of power scheduling. So, these are the two different modes of power scheduling. And how this power scheduling is done? This is done by using a feedback control or closed-loop control action by, it will adjust this reactance according to the required amount of power flow through a particular transmission line where TCSC is placed. So, in the constant current mode of power scheduling, it is something like this. We have a transmission line. Somewhere in the transmission line, we have TCSC. Here, for example, we have TCSC. Now, this is what the transmission line.



So, what it does actually, it helps, the action of the TCSC is to control the reactance. So, it will adjust this ZTCSC, so that the same amount of current will flow through this particular transmission line, irrespective of the other operating conditions in that particular line. But the question is, can it be possible to all these different loading scenarios or all these different operating scenarios of a power system? Of course, it is not possible. It can be possible to have, to maintain a certain amount of current or power flow through a transmission line when this TCSC acts according to this, its capacity. Now, I will see what it is actually. So, its, this control characteristics is something like that. This control characteristic of CC mode is something like that. We have this axis, we have a horizontal axis, and we have a vertical axis. In the horizontal axis, let us keep V tcsc, that is voltage across this tcsc, and in the vertical axis or y axis, let us keep this line flow. Now, this control characteristic of TCSC in CC mode is that, it can able to maintain this current for a particular current, this is what the current might be, up to a certain level of voltages across this TCSC. And this control characteristic is something like this. This is supposed the point O which is the origin, this is supposed point A and this is what this control range is let us say this is point B and this is what where it operates as an overload region. Now, here you can see or I should draw this like this, so that this will meet in the origin. Now, here this A to B, A to B, this is the control range of the TCSC, this is the control range within this range of the voltage across this TCSC, this TCSC can change its reactance to maintain this current flow or power flow through this transmission line constant. Now that is what the control range is that I have already discussed in case of SVC.

In case of SVC what actually it was within the control range it could maintain a certain constant or maybe it could maintain the voltage within a given band according to the slope of the control characteristics. That is what the main purpose of placing the SVC. Whereas, the placement of TCSC is to maintain the current within the control range constant flowing through it. Since it is connected to a particular transmission line in series, so when it helps to maintain the constant current across it, it means that it will eventually be helpful to maintain a constant current through the particular transmission line and thereby it will be able to maintain a constant power flow through this particular transmission line. So, that is what the main task in the CC mode of operation of TCSC.

Now, here this AB is the control range within which this TCSC would be able to maintain a constant current flow through it or through the transmission line. And OA is one limit of this TCSC and BC is another limit. Now the question is this what are the limits actually. Now you see that if we use this equation, form of this control characteristics, then you can see i is equal to, that is y axis we have i, i is equal to some constant or some slope m, m multiplied by this VTCSC, where m is the slope, slope of the M is the slope of the straight line. Now, you can see this M is equal to I by V T C Now, what is I by V tcsc? It is nothing but 1 upon V TCSC divided by I.

Now, what is V tcsc divided by I? We know this voltage across this tcsc divided by the current flowing through it is nothing but 1 upon Z tcsc. So, therefore, the slope of this OA is inversely proportional to the reactance of the TCSC or impedance of the TCSC. So the slope of this, so therefore you can understand that wherever is the higher slope that corresponds to minimum amount of TCSC or minimum TCSC limit. And, wherever we have the lower slope that corresponds to the maximum value of the TCSC. So, therefore, this OA corresponds to minimum slope, that it is having minimum slope. So, therefore, it is the maximum value of ZTCSC. So, therefore, we can call this OA corresponds to ZTCSC max. Similarly, this BC will corresponds to ZTCSC mean. So, this corresponds to maximum slope. So, therefore, minimum value of ZTCSC. So that means, this is, this O to B or BC corresponds to the minimum ZTCSC and OA corresponds to maximum ZTCSC. And you know that TCSC reactants can be controlled within its many minimum and maximum values based upon its rating. So therefore, this, within this particular control range, it can adjust this ZTCSC to any value like this, to any value, so that irrespective of the value of this VTCSC, it could be able to maintain a constant current flow or constant power flow through this particular transmission line. So, this is what the constant current mode of power scheduling control of TCSC. Now we move on this constant angular difference control of power scheduling in short it is called as CA mode of control of TCSC.

So what is actually done when we have suppose two parallel transmission line one is this another is this where we have this TCSC. So, in constant current mode of operation what you have seen is it can this TCSC maintains a constant power flow through TCSC compensated line. So, that is what you have seen. Whereas, here in constant angular difference mode of control or power scheduling in TCSC, TCSC maintains a constant power flow through the line parallel to TCSC compensated line. Now look at the difference between these two modes of operation. In one case TCSC, wherever the TCSC place in that particular line, the current or power flow is maintained with the TCSC action. Here this TCSC will operate to show that the power or current flow through this particular line which is in parallel to that TCSC compensated line constant. So, here the goal of this TCSC was to maintain a constant current flow or power flow through the TCSC compensated line. Here, in case of constant angular control, the goal is to maintain a constant current flow or power flow through the line which is in parallel to the TCSC compensated line.

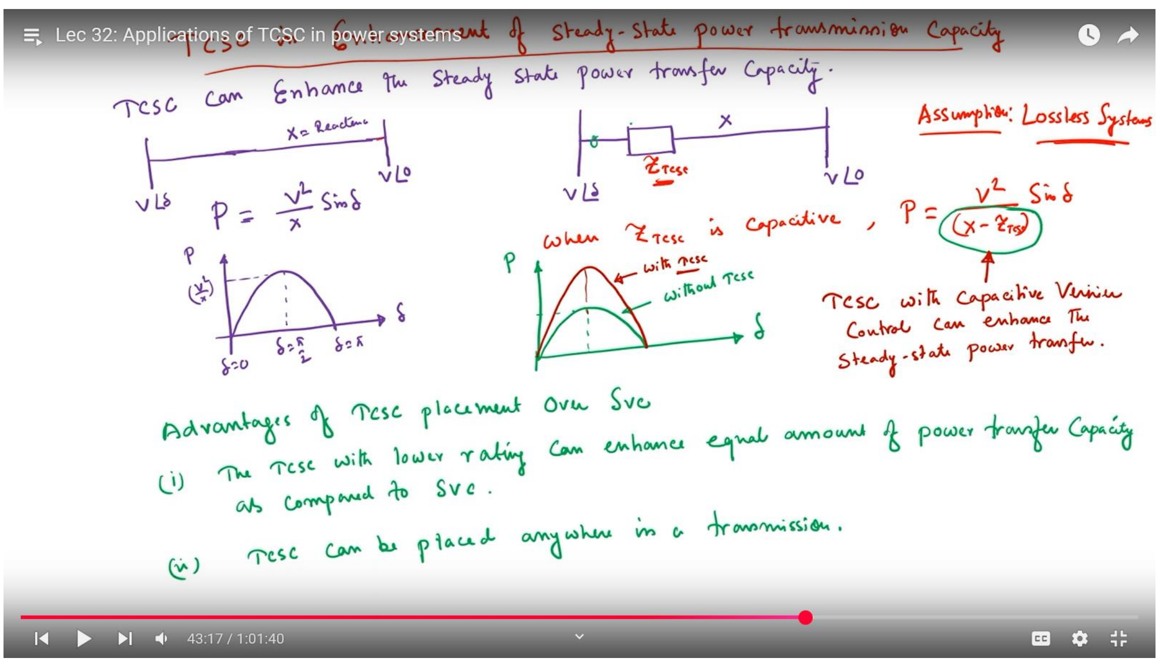
So, that is what the difference is. Now, let us see the control characteristics. I am writing characteristics in short of CA mode. In control characteristics in CA mode, it would be something like this. Again, we will be having Y axis or vertical axis as the line flow or current flow and this horizontal axis will be VTCS. Now in this particular this control the characteristics is something like this. We have this is O, this is point A in the control mode, then this is what the control range A to B and this is what this B to C. Now here this control range is this, control range is this, this is what the control range. Now the question is why this control range is like a straight line having an intercept. You can look at this AB. The difference of this control range and this control range when we have CC mode of control is that here AB is having sub slope with some intercept with the vertical axis. Here AB is in parallel to the horizontal axis or x axis. So, that is what the difference. Now, the question is why it is so? How can we mathematically justify this? In order to justify this mathematically, so you have to understand when it is possible that you can keep the power flow or line flow constant through the parallel line of the TCSC compensated line. This is only possible if you have, if you can maintain a constant voltage drop across these two lines. So, here TCSC maintains a constant voltage drop within its control range.

So, therefore, if it is so, then we can write I x, this x is not x dc sc, that is what the x of this parallel line. So, I x minus this v dc sc. It is equal to constant and k. So, k is our constant. So, what is this Ix minus VTCSC? This is what the drop, voltage drop through this particular line, and the same voltage drop will be applicable to the parallel line as well because they are in parallel. So, therefore, from this equation, I can find out I is equal to K by X. Now, here X is equal to this line reactance. I is equal to K plus divided by X plus VTCSC divided by X. Now, you know that this K is constant and X is also constant. So, this part is constant. So, let us consider another constant C1 and this part X is constant. So, we have some another constant C2, then VTCSC. So, therefore the equation will be like this, i is equal to c1, which is a constant plus addition to c2, which is another constant multiplied by VTCSE. This gives the same characteristics shown by AB. So, we have some positive intercept, which corresponds to c1 and we have some slope c2, positive slope multiplied by V TCSE.

And you know this OA corresponds to this slope which is higher. So, therefore, this will correspond to ZTCSC minimum and this BC will have a slope corresponds to ZTCSC maximum. So, this is what this power scheduling control. And, this is what the applications of TCSC in power scheduling control and you can understand this control characteristics of CC mode and CA mode as well. So, this is how TCSC is operated to schedule the power flow through a transmission line. Now, we will come to the second application which is of course a part of this power scheduling control also that is TCSC also can enhance the power flow through a particular transmission line. So, we will write TCSC in the enhancement of steady-state power transmission capacity. So, this is also a part of this power scheduling control only, but this is one of the applications of TCS in power systems. You can see, if you can go back and look back at my previous lecture, in particular when I discussed SVC applications in power systems, I said that SVC can increase or enhance the power flow or the steady-state power transmission capacity of a typical transmission line. Similarly, TCSC can also do the same thing, but there is a difference in the way they do. So, TCSC can enhance the steady-state power transfer capacity.

So, TCSC can enhance the steady-state power transfer capacity similar to SVC, but there is a difference in how they do this thing. In SVC you can remember that SVC also the placement of SVC also enhance the steady state power transfer capacity. How it is done? By changing the midpoint voltage or the voltage wherever this HVC is connected. So, HVC can change the voltage wherever it is connected and thereby it can also enhance the power flow or the power transfer capacity. Whereas, TCSC basically adjusts the denominator of the power flow equation. Now, what is the power flow equation? We know the power, suppose we have a transmission line over here, and let us consider that at some point we have TCSC. We have T C S C. Now, we know that suppose this voltage at this end is V at an angle delta, the voltage at this end is V at an angle 0 and x is the reactance. Of course, let us consider that there is no TCSC over here. So, it is like a simple transmission line.

So, the Re x is the reactance of the line. Then the power flow of this, you know, the power flow equation that is the active power flow is V square divided by x sine delta and we can plot this also. So, if this is p, this is delta. So, this plot is something like this, where this is the maximum power flow, which is representing v square by x and this corresponds to the delta being equal to 0, this is corresponds to the delta being equal to pi. So, this happens when delta is equal to pi by 2. This is something is well known to us. However, suppose if we have a TCSC over here. For the same transmission line having this voltage are V delta, this voltage is V naught, and we have this X, the reactance of the line. Now, here because of this ZTCSC, because of this reactance here, which is represented by ZTCSC and ZTCSC can be positive, can be negative. Now, when Z TCSC is capacitive. Now, for both the analysis we assume that our assumption is lossless system. So, this assumptions I have taken consistently throughout this lecture. So, you can always assume that there is no loss in the transmission line, there is no power loss inside this ZTCSC as well. So, therefore, when this ZTCSC is capacitive, the power flow expression would be V square divided by X minus ZTCSC sin delta. So, therefore, this TCSC, presence of TCSC is, it is impacting on this denominator of the power flow equation. So, therefore, for the same line, if your power flow characteristic was like this without TCSC, so this is supposed without TCSC.



This power flow characteristic or P delta characteristic is similar to this. Then with this TCSC, the characteristic would be changed to something like this. So, this will be the power flow characteristics with TCSC. This is something you know already. Now, how it is done? This is done by changing this denominator of the power flow equation. So, TCSC with its capacitive vernier mode of control can enhance the steady-state power transfer capacity of the line. So, TCSC with capacitive Vernier control can enhance the steady-state power transfer of a transmission line. So, this is something that is easy to understand. Now, there is an advantage of TCSC as already I discussed with the mathematical derivation that the rating requirement of the series compensator to enhance the power transfer capacity is much lesser than the rating requirement of the shunt compensator. So, in that sense, TCSC with a smaller capacity or TCSC with a smaller rating can enhance the similar power transfer capacity of a transmission line as compared to an SVC.

So, this is something already I have established with mathematical derivations. There is another advantage that TCSC can be placed anywhere in the network depending upon the or anywhere in the transmission line depending upon the availability of the space and this operator perspective. Whereas, this SVC we have already seen it is the impact of this SVC placement would be higher if we place it at the midpoint. So, there are two advantages of TCSC placement over SVC. Number one is the TCSC with a lower rating can enhance similar or equal amount of power transfer capacity as compared to SVC.

The second is that TCSC can be placed anywhere in a transmission line. So, at any means TCSC can be placed either near to this sending end site or receiving end site or at the midpoint or however to have a same impact unlike this SVC placement. This is something I want to discuss. Now, the application of TCSC, application of TCSC in transient stability enhancement: So, the application of TCSC in transient stability enhancement; So, similar to SVC, TCSC can also improve the transient stability. So, how it can improve? Let us see. Now, you can see that without TCSC, if this power delta characteristic is something like this, P delta characteristic is something like this, where this is P max, then you have seen that with TCSC, these power flow characteristics would be something like this. This is P, this is delta. So, now these characteristics will be something like this. So, here we will have this P max. Now, you can see suppose this is what the mechanical power P mech. And there is a fault in this transient fault in a typical transmission line.

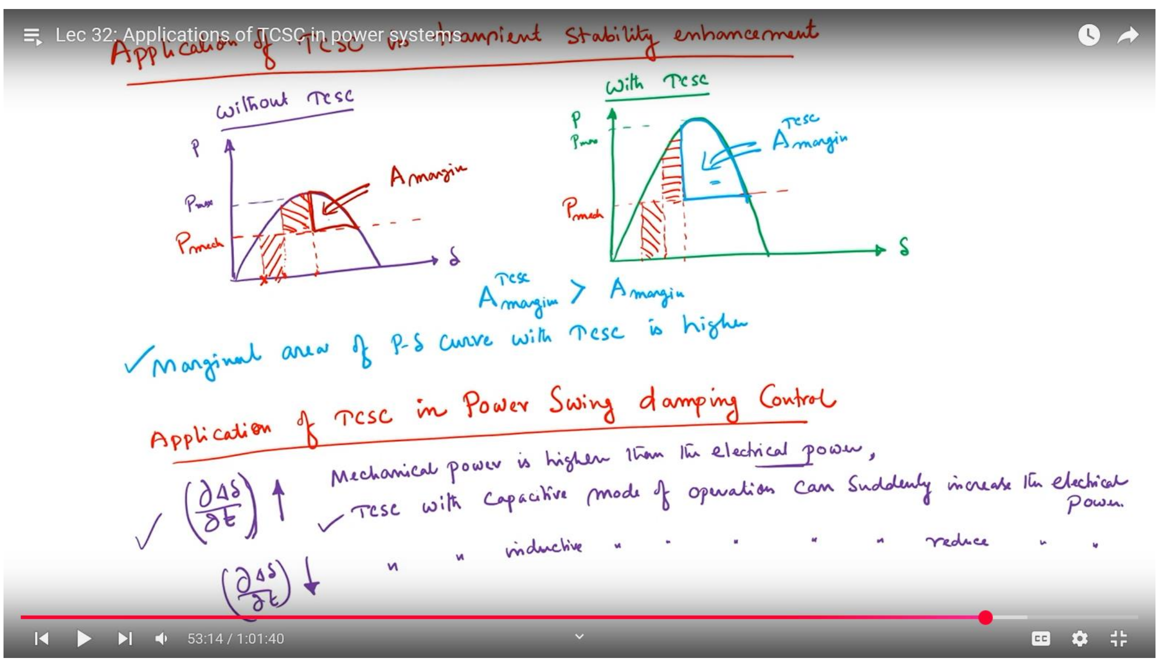
You see that this is the point where this fault happens. Then what will happen? At the instant the fault happens, P will come down to 0, but mechanical power will be there. So, it will cause a increase in the speed of the generator. So, then suppose at this point fault is cleared. And then this delta will swing up to this point and it will get settled before it gets settled. So, therefore, you know that this is what this accelerating power and this is what the decelerating power which is to be equal to have a stable operation of the system, and this I already discussed and then whatever the amount of area left in this P delta curve, we call it, we call it this the margin area. So, this is called this area, this area is called A margin. So, this is what the marginal area which is left to help the system stable and if this fault clears beyond this marginal area it will the system will lose stability and it will be unstable. So, those things I already discussed. Now, similar to this suppose here also for SVC TCSC compensated line here, similar kind of fault is initiated. So, again this fault is cleared at this point. So, at this point it will be stable. Here also we will have the same criteria accelerating power should be equal to the decelerating power that is equal area criteria. However, here you can see this marginal area would be that much. And obviously this marginal area, so this is the marginal area, A margin with TCSC. Now you can see if you compare this marginal area with that marginal area, so one can understand that A margin TCSC will be much higher than a margin without TCSC. So, it means that this marginal area for stability, transient stability of this P delta curve with TCSC is higher.

So, this concludes that this marginal area of the P delta curve with TCSC. So that is how it is it can improve the transient stability of a particular system wherever it is placed. So, this is similar to this what we call this SVC application in power system. Now, I will discuss the next application of TCSC, which is TCSC, the application of TCSC in power swing damping control. Now, how a TCSC can improve the power swing damping control? You know that power angle the delta will undergo some sort of swings due to some disturbance or some events after a certain event in a power system and it is very important to this control this swing by providing appropriate damping. And this is possible by using this TCSC control. Now, how do we realize this damping control? It may so happen that we will realize this power swing with the change of del del delta with del t, which is similar to this change of the frequency which is similar to change in the frequency. Suppose this parameter, this del delta to del t increases at this particular instant of time after a major this event or major disturbance in a power system. So, what it is to be done? So, in that case, when this frequency is increased that means this mechanical out power, mechanical power is higher than the electrical power, than the electrical power. So, if it happens, then what we need to do, is the electrical power needs to be increased so that we can erase this change of del del t to del t. So, therefore, if it happens, then TCSC with the capacitive mode of operation can suddenly increase the electrical power.

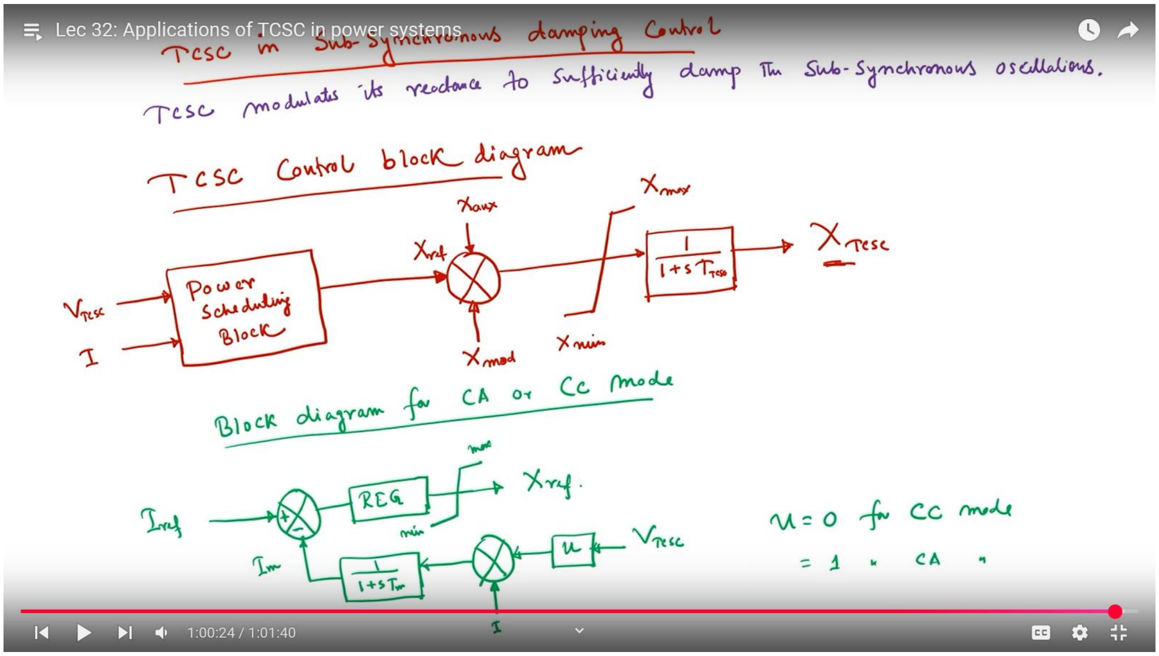
So this is how TCSC can do. So in order to damp the first swing, so it will, this TCSC what it will do, it will just operate its maximum capacity mode. So thereby it suddenly increase the, this power flow through the line. And just by modulating its reactance and again when this del del t to del t goes below this to a certain threshold, then it resists operation from this modulation. So, similarly, if this del del t to del t is declining, then TCSC with the inductive mode, mode of operation can suddenly reduce the electrical power. And this is how it can provide the appropriate damping just by modulating the reactance of the TCSC from this maximum capacitive mode to the maximum inductive mode. And with a very short duration it is usually done and thereby it can provide appropriate damping to the system. Now, one is the last application that I will discuss TCSC in Sub-synchronous Damping Control. Now, what do you mean by sub-synchronous damping? In power systems, in power systems, typically power swings below the power frequency, the power frequency in India you know is 50 Hertz. So, below this 50 Hertz sometimes this the power swing happens and this is this happens basically due to this resonance or series resonance of the, this series reactance and the series, series capacitance which is provided by the series compensation.

This sometimes would be detrimental. This sometimes would have much effort, and impact on this power system. And in 1970s it has been seen that some of the generator a result of the sub-synchronous oscillation causes so vibration that there are breaking of their shafts. So, therefore, this sub-synchronous damping is very essential in power systems. And in TCSC can provide this modulation of its reactance, so TCSC modulates its reactance to sufficiently dampen the subsynchronous swing of subsynchronous oscillation. There are various research papers are developing this control approach to damp the subsynchronous oscillation with the TCSC control.

You may go through if you are interested further. So, this is what it is. Now, we will go for this last part of this lecture that this TCSC control block diagram. So TCSC control block diagram has several blocks. One is the main block is the power scheduling block, which is the main purpose of the TCSC power scheduling block. These inputs are VTCSC and I, you already have seen and the output is ZTCSC or this I said X reference. And then there is a comparator where there is some auxiliary signal and there is a modulating reactance.



Whenever there is a transient or we require to modulate this, then whatever this reactance is fed, it is compared with the x max and xmin that means minimum and maximum value of ZTCSC and then there is a transfer function which is specifically for this delay in this TCSC operation. This t is the time period and it is fed to the XTCSC symbol and then from this XTCSC appropriate this appropriate this gating pulse is generated and is fed to the gating operation of the thyristors. So, from this we have this gating pulse and GPU unit get and which is fed this thing I am not shown over here. Now, in case of this block diagram for CA or CC control this block diagram for CA or CC mode of operation.

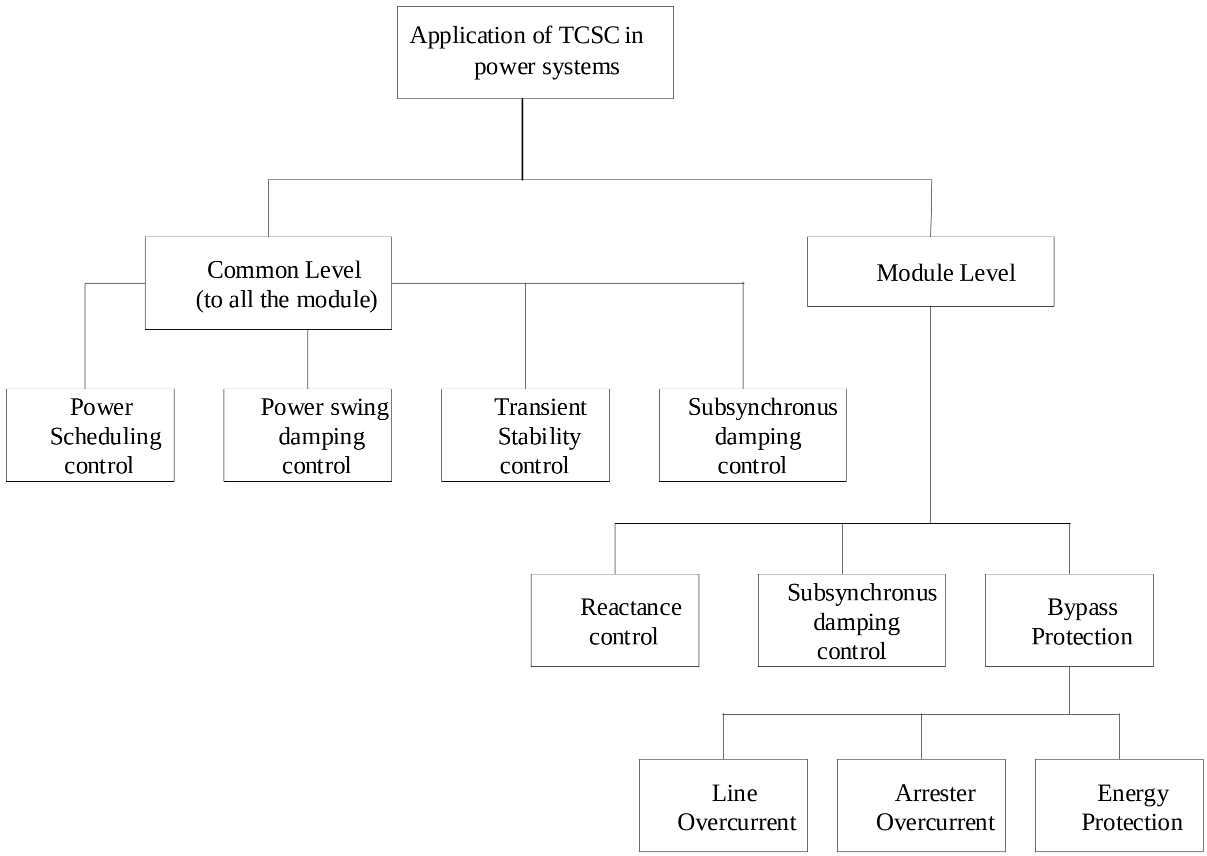


It would be something like this. We have a reference signal generated and it is fed. Then there is a comparator like this. We have this measured signal of IM. IM is here measured signal. We have a control block for this time for this measurement. And then we also have another comparator which compare this current and there is a control block by U and here we have VTCS. Now, U is 0 for SISC mode of operation because we do not need this, it is only required to have a maintain, a current there and U is equal to 1 for CM mode of operation. Now, here in this particular comparator, this reference signal and measure signals are compared. Then we have this regulator unit. And then we have a comparator to check the minimum and maximum of this reactance. And here we provide this X reference. This is what the block diagram for CA and CC mode of power scheduling control for TCSC. So, this is all about this control and applications for TCSC and as I promised I discuss all these different types of control actions which include power scheduling control, power swing damping control, transient stability, sub synchronous damping, then reactance control and subsynchronous damping control for all these different control actions for TCSC. And with this, I will stop today and we will proceed further for the next module of this course.

Thank you very much for joining this lecture. I look forward to seeing you in the next lecture. Thank you. Thank you.

❖ Applications and Control of TCSC

The control of TCSC is explained by the following tree diagram.



➢ Power Scheduling control

- To adjust the TCSC reactance (Z_{TCSC}) to meet the required steady-state power flow through the power transmission line.
- There are two types of power scheduling control i.e.,

1. Constant current control
2. Constant angular difference control

1. Constant current control mode:

- TCSC maintains a constant power flow through TCSC-compensated line.
- It is not modular level control rather it is a common level control.

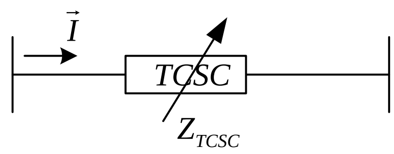


Fig.1. Single line diagram of TCSC connected in transmission line

Consider a system with a TCSC connected in series with the transmission line, as shown in Fig. 1.

Control characteristics of CC mode

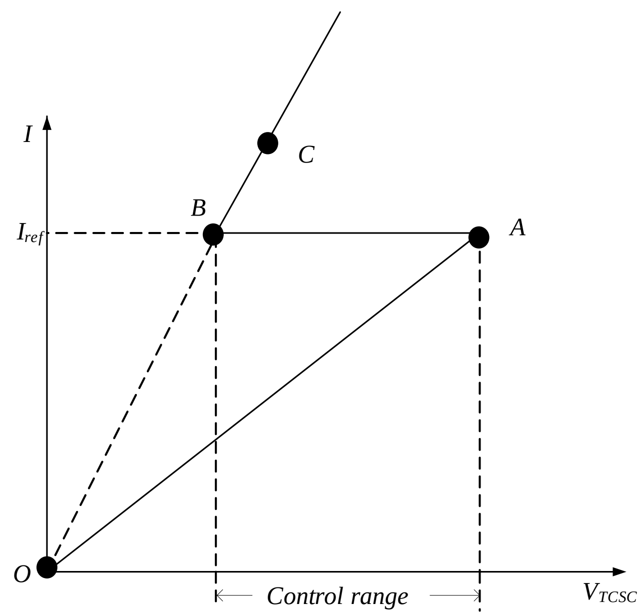


Fig.2. Constant current control mode

In Fig.2, AB: Control range within which the TCSC would be able to maintain a constant current flow through the transmission line

OA: Minimum slope [Maximum value of Z_{TCSC}]

BC: Maximum slope [Minimum value of Z_{TCSC}]

$I = mV_{TCSC}$ [m: slope of the straight line]

$$\Rightarrow m = \frac{I}{V_{TCSC}} = \frac{1}{\left(\frac{V_{TCSC}}{I}\right)} = \frac{1}{Z_{TCSC}}$$

2. Constant angular difference control mode:

- TCSC maintains a constant power flow through the line parallel to the TCSC compensated line as shown in Fig. 8.
- TCSC maintains a constant voltage drop within its control range.
- During a transient, the line in which TCSC is situated carries the required power so that the power flow in parallel paths is kept constant.

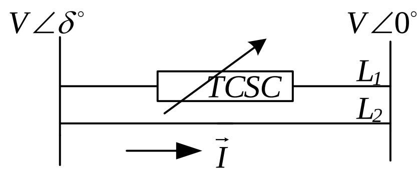


Fig.3. TCSC in constant angular difference control mode

- This equivalent to maintaining the angular difference across the line a constant. This is called as constant angle control.
- If δ becomes constant, constant P and I could be obtained.

$X_{TCSC} = \frac{Vtcsc}{IL}$

The max and minimum limits decided by OA and BC

$$IX - V_{TCSC} = V_{ref} = K \quad [K = \text{constant and } X = \text{line reactance}]$$

$$\Rightarrow V_{TCSC} = IX - K$$

$$\Rightarrow IX = V_{TCSC} + K$$

$$\Rightarrow I = \frac{V_{TCSC}}{X} + \frac{K}{X}$$

$$\Rightarrow I = C_1 + C_2 V_{TCSC}$$

Control characteristics of CA mode

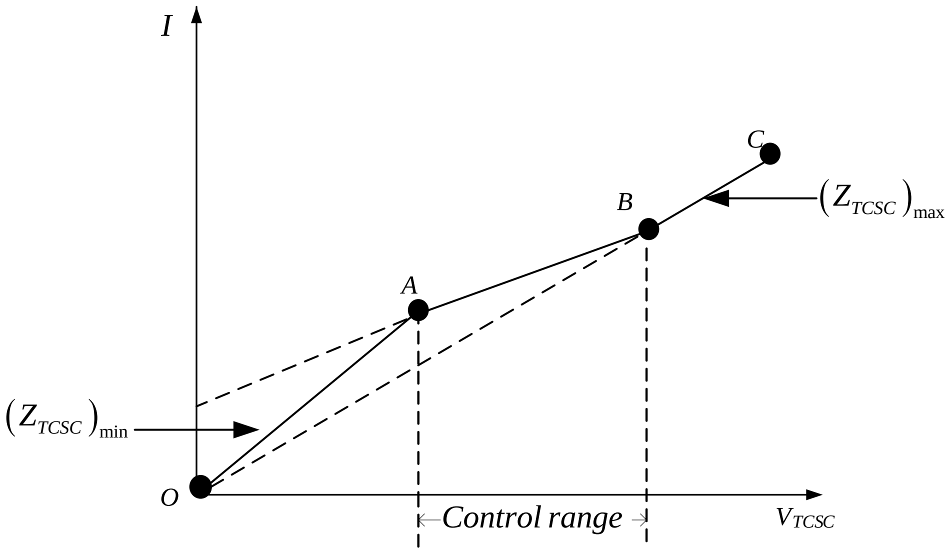


Fig.4. Constant angular difference (CA) control

In Fig.4, AB: Control range within which the TCSC would be able to maintain constant power flow through the line parallel to the TCSC compensated line

OA: Maximum slope [Minimum value of Z_{TCSC}]

BC: Minimum slope [Maximum value of Z_{TCSC}]

TCSC in enhancement of steady-state power transmission capacity

TCSC can enhance the steady state power transfer capacity. To understand this let us consider two systems; one without TCSC and one with TCSC as shown in Fig. 5.

Assumption: Lossless system

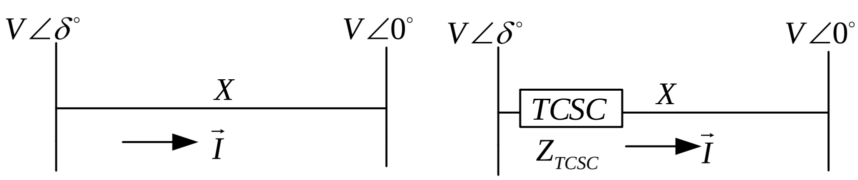


Fig.5. Single line diagram of transmission line without and with TCSC

Without TCSC the steady state power flow through the line can be given as:

$P = \frac{V^2}{(X - Z_{TCSC})} sin\delta$

With TCSC, when Z_{TCSC} is capacitive, $P = \frac{V^2}{(X - Z_{TCSC})} sin\delta$

TCSC with capacitive Vernier control can enhance the steady state power transfer capacity of a power transmission line which can be observed from the $P - \delta$ characteristics as shown in Fig. 6.

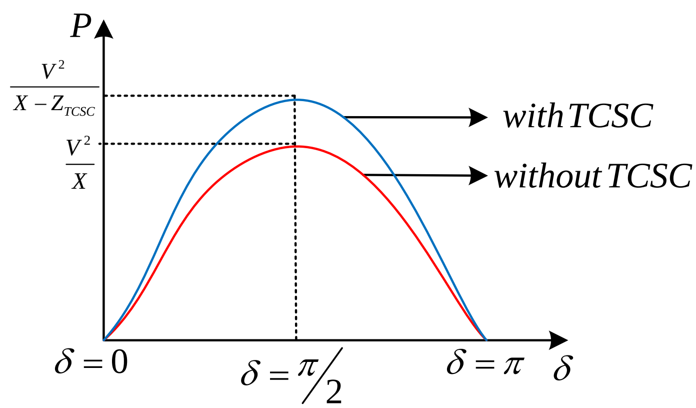


Fig.6. $P - \delta$ characteristics of system with and without TCSC

Advantages of TCSC placement over SVC

(i) TCSC with lower rating can enhance equal amount of power transfer capacity as compared to SVC.

(ii) TCSC can be placed anywhere in a transmission line and will have the same impact unlike the placement of SVC.

Application of TCSC in transient stability enhancement

- Transient stability problem majorly occurs due to the faults and it is a large signal stability problem.
- Transient stability control is generally a discrete control in response to the detection of a major system disturbance.
- The controller is activated immediately after a major disturbance such as clearing of a fault and is deactivated when the magnitude of frequency deviation is below threshold.
- This type of control is beneficial not only in reducing the first swing but also for damping subsequent swings.

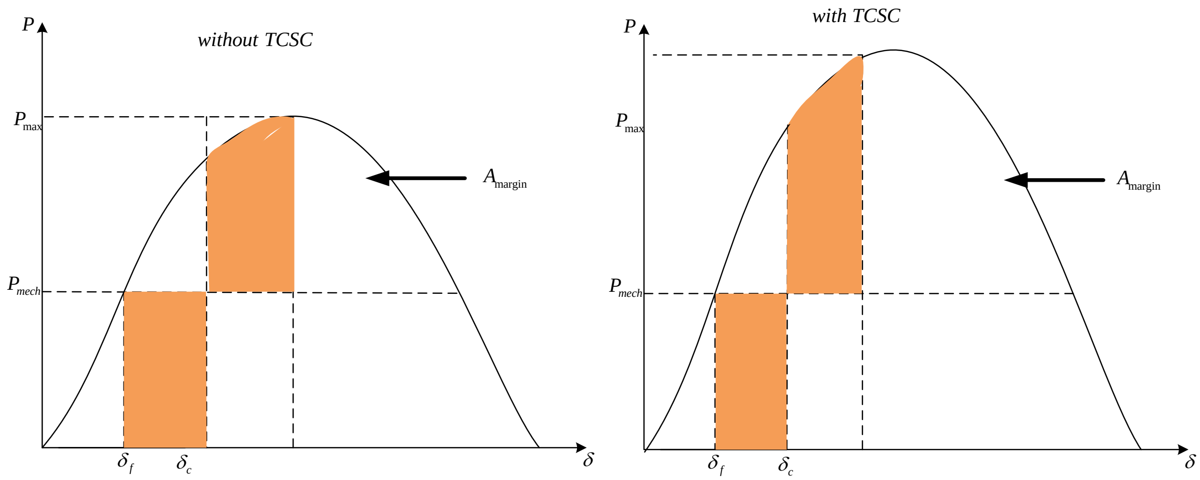


Fig.7. $P - \delta$ characteristics of the system with and without TCSC

From Fig.7, it is observed that $\left(A_{margin}\right)_{with\ TCSC} > \left(A_{margin}\right)_{without\ TCSC}$

i.e., Marginal area of $P - \delta$ curve with TCSC is higher.

Application of TCSC power swing damping control:

- Power system oscillations create disturbance in the operation of power system.
- These oscillations are small signal stability problem.
- These oscillations are of three types
    - Local mode of oscillations
    - Intra area mode of oscillations
    - Inter area mode of oscillations
- Power swing damping control is designed to modulate the TCSC reactance in response to an appropriately chosen control signal derived from local measurements.
- The objective is to damp low frequency swing modes (corresponding to oscillation of generator rotors) of frequencies in the range of 0.2 to 2.0 Hz.
- One of the signals that is easily accessible is the line current magnitude. Alternatively, the signal corresponding to the frequency of Thevenin voltage of the system across the TCSC can be used.
- This signal can be synthesized from the knowledge of voltage and current measurements.

$\left(\frac{\partial \Delta\delta}{\partial t}\right) \uparrow \Rightarrow$ Mechanical power is higher than the electrical power, TCSC with capacitive mode of operation can suddenly increase the electrical power.

$\left(\frac{\partial \Delta\delta}{\partial t}\right) \downarrow \Rightarrow$ Mechanical power is lower than the electrical power, TCSC with inductive mode of operation can suddenly reduce the electrical power.

Sub-synchronous damping control:

- Any frequency that is less than the synchronous frequency (usually 20 to 30Hz) is called sub-synchronous frequency.
- Sub-synchronous resonance appears due to the line reactance of several devices and capacitance. Due to this vibration can be observed in generation unit (shaft of generator).
- TCSC modulates its reactance to sufficiently damp the sub-synchronous oscillations.
- The use of Vernier control mode at the module level by setting the reactance setpoint at the requisite(minimum) level is often adequate to damp sub-synchronous oscillations caused by series resonance in the line and sustained due to torsional interaction.
- However, in some cases, the constant reactance control may not be adequate. In such cases, a damping control is added.
- The control signal is based on the synthesis of speed of remote turbo-generators. The control signal can be derived from the locally measured current and voltage signals.

Modelling of TCSC in power scheduling control:

The block diagram of TCSC is shown in Fig.8.

- X_{ref} is determined by the power scheduling controller or in its absence, by manual control based on order from load dispatch.
- X_{mod} is required to improve the transient stability.

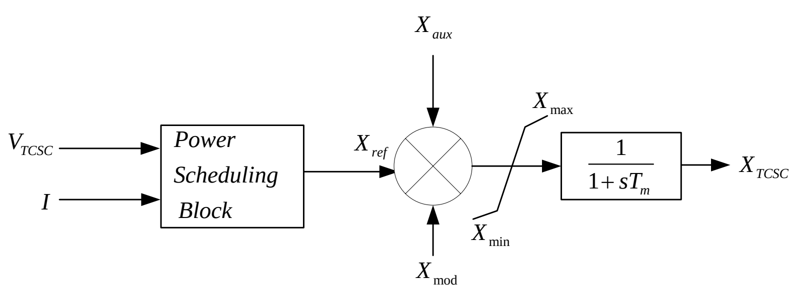
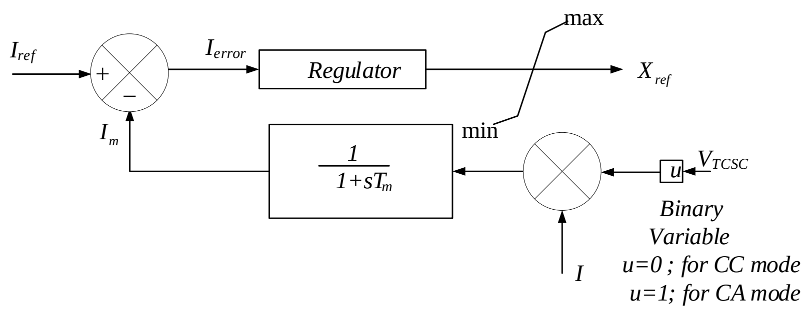


Fig.8. Block diagram of TCSC

Block diagram for CC and CA control

The block diagram of constant current (CC) or constant angle (CA) controller is shown in Fig.9.

- T_m is the time constant of first order low pass filter associated with the measurement of line current I and the TCSC voltage.
- For constant current control, $u = 0$.
- For constant angle control, $u = 1$



[Here I_m: Measured signal]

Fig.9. Block diagram of Constant current or constant angular control mode of operation

Regulator block diagram (PI control)

- The regulator block diagram is given in Fig.10. This consists mainly PI controller and phase lead circuit if required.
- The proportional gain K_P, can be set to zero if only integral control is used.
- The gain K_I is positive in case of the current control and negative in case of constant angle control.
- In case of constant angle control, I_{ref} is actually the voltage reference divided by . Hence positive error signal implies the net voltage drop in the line is less than the reference and X_{TCSC}(assumed to be positive in capacitive region) is to be reduced.
- In case of constant current control, if the error is positive, the controller has to increase X_{TCSC} to raise the line current to reduce the error.

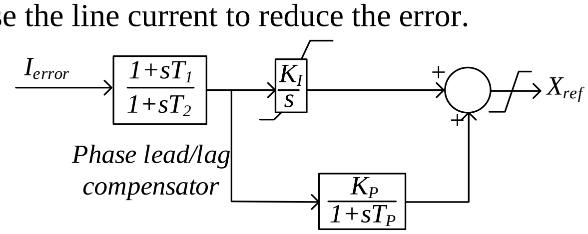


Fig.10. Block diagram of the regulator