Course Name: Power Electronics Applications in Power Systems

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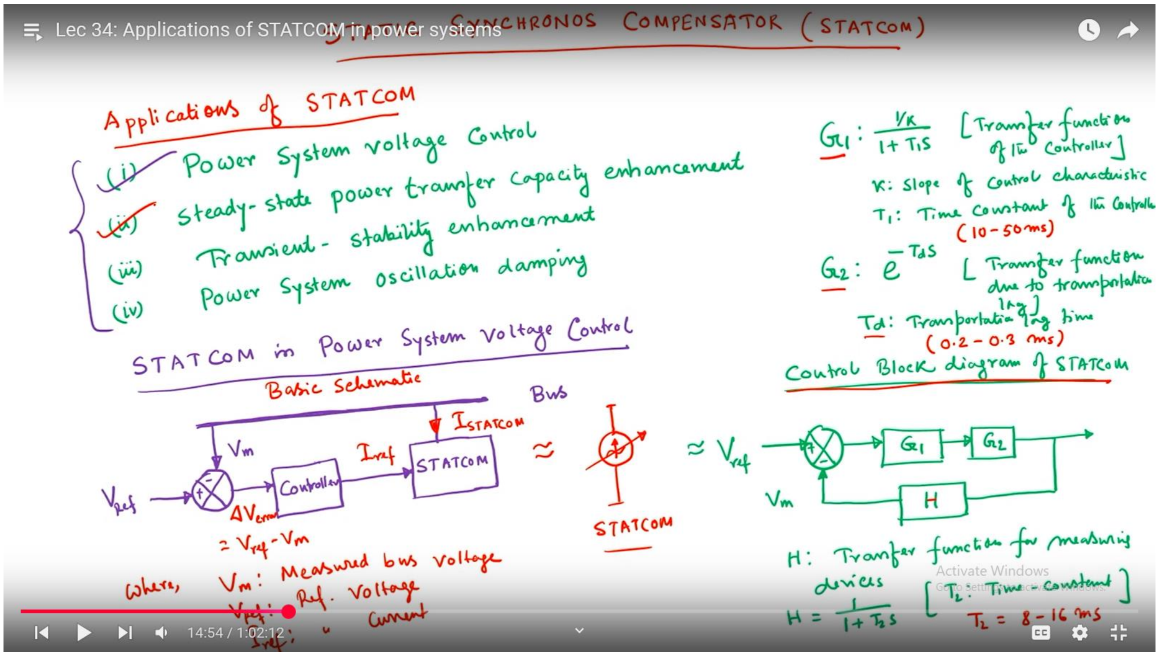
Lecture: 02

Lec 34: Applications of STATCOM in power systems

So welcome again to my course Power Electronics Applications in Power Systems. In the last lecture, I introduced the concept of converter-based compensators. So I discussed there are different types of converter-based compensators and the constructional-wise and also the operational-wise they are different than the conventional compensators I discussed such as SVC and TCSC. So, in the last lecture, I started a discussion on the shunt type of the converter-based compensator which is named as STATCOM which is static synchronous compensator. So, in this particular lecture, I will continue the discussion on STATCOM and I will discuss the various applications of STATCOM and also I will discuss the control philosophy of the STATCOM and since you have already understood the basic concept of static var compensator that is SVC. So, in my discussion, I will discuss the difference between the STATCOM and SVC.

One is converter-based compensator that is STATCOM, another is the impedance or admittance or susceptance-based compensator that is SVC. So, let us start our discussion right now. So, we are discussing on static synchronous compensator or STATCOM. And in this discussion, I will discuss the applications of STATCOM. So, similar to this SVC that is Static Var Compensator in STATCOM can be used in various applications of power systems and STATCOM can also be used to enhance the performance of the power systems. Now, how it is to be done let us discuss right now. So, similar to this

SVC STATCOM can be used in power system voltage control. Then STATCOM can also be used in steady state power transfer capacity enhancement. Then the STATCOM can also be used in transient stability enhancement.



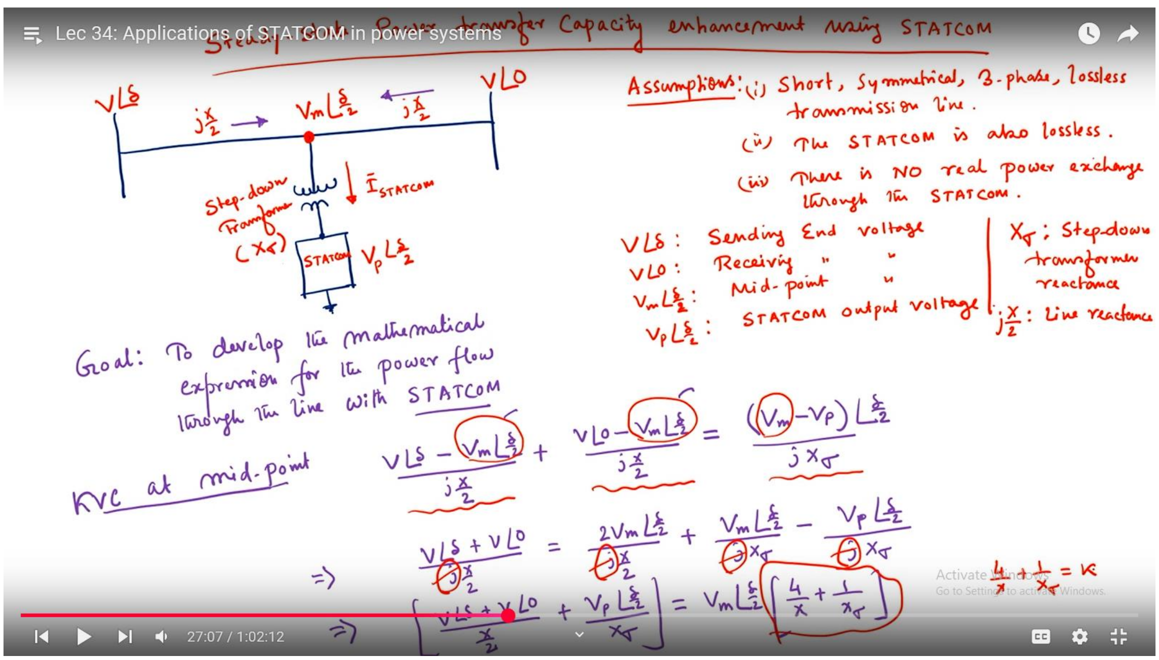
STATCOM can also be used in power system oscillation damping. Now, if you look at these four different applications, you know that these four different applications of STATCOM is quite similar to the applications of SVC. But however, there is a difference between the performance of the SVC and STATCOM. So, time to time I will discuss the comparison between the performances of SVC and STATCOM. So, let us start with this STATCOM in power system voltage control. STATCOM in power system voltage control: Now let us draw the basic schematic of block diagram of this control scheme. Suppose this is the bus at which we will place this STATCOM and this is what the STATCOM block is. This is what the STATCOM block is. So, what it is actually done is, this is a comparator. Here, V reference is fed, that is the voltage reference. And this is what the measured value of the voltage of the particular bus. Then, whatever the error would be, that will be fed to the controller. Then this controller will generate a reference current signal and it will feed to the STATCOM. So, the controller will generate a I reference from this different of this voltage error V error which is equal to V reference minus V m, where V m is measured bus voltage V reference is the reference voltage, I reference is the reference current. And with this I reference signal, this STATCOM will decide how much current it will draw from the bus that is I STATCOM.

If you remember my previous days lecture, I already discussed that STATCOM will be a model as a controllable current source. So, that is what the model of STATCOM. So, unlike this SVC which is modelled as a controllable susceptance. Now, how would be the block diagram of this diagram, this block diagram. So, this is the basic schematic diagram, basic schematic diagram of the STATCOM. Similarly, from this, we can find out the controller block. So, controller block or control block diagram of STATCOM, control block diagram of STATCOM. So, how it would be? So, we will be having a comparator over here which is comparing this V reference voltage with the measured voltage that is V m. Then the error would be fed to the controller. This controller transfer function is represented by let us say g 1. Then there is another block which represents the transfer function of the transportation lag of the STATCOM. And then finally, it is providing this desired voltage to the bus. And here in the feedback, we will also have a feedback transfer function H. Now, here where or I should write this on the top, where g 1 is representing 1 upon k 1 plus t 1 s, that is transfer function, transfer function of the controller. This k is the control characteristic slope or slope of the control characteristic.

And you know that similar to this SVC we will also maintain a very small amount of positive slope typically 1 to 5 percent in case of STATCOM also to facilitate this parallel operation of the STATCOM or the reactive power compensation sharing among the multiple STATCOM. And also for various you know reasons which I already discussed in the case of SVC. Now, T 1 is here, the time constant, the time constant of the controller. Now, typically the value of this time constant of the controller is 10 to 50 milliseconds. Now this G2 is basically representing that transfer function of transportation lag which is represented by this, where it is representing transfer function due to transportation lag. So, you know that this transportation lag is basically the time required to reach the input to that particular device to get the proper output. Now, here T d represents a transportation lag time. So, transportation lag time, which is typically in a range of 0.2 to 0.3 milliseconds. For STATCOM, this transportation lag in the case of STATCOM is much lower as compared to SVC and that is why STATCOM is much faster than SVC in operation and that is one of the advantages of STATCOM in particular during the operation of dynamic conditions. Now, this is all about G 1 and G 2. So, we have another you know transfer function which represent capital H. So, capital H represents the transfer function for measuring device, measuring So, it is typically represented at h equal to 1 upon 1 plus T 2 s, where T 2 is equal to this measuring circuit time constant. So, measuring circuit time constant and typical this value of this T 2 is equal to 8 to 16 So, this is all about the control block diagram of the STATCOM.

So, this is how the STATCOM can be used to control the voltage of a particular bus where the STATCOM can be placed. Now, this particular or strategic location of STATCOM could be the midpoint of a transmission line or somewhere at any point of the transmission line. But wherever it can be placed, it can be used to control or regulate the voltage of that particular point. This is what the similar task of STATCOM and this is what the main task of STATCOM as similar to the SVC or static bar compressor. Now, next, we will come to the second application of STATCOM which is steady-state power transfer capacity enhancement. So, the steady state power transfer capacity enhancement using STATCOM. So, this is I will discuss right now. So, to discuss this steady state power transfer capacity enhancement of STATCOM. Let us take a small transmission line model or a short transmission line model. And let us derive the mathematical expression for the power flow through the transmission line due to the presence of the STATCOM.

So, let us consider a short transmission line model where we have STATCOM placed at the midpoint. Now, before we place the STATCOM, let us assume that there is a step-down transformer as we know that we have a step-down transformer for stepping down the voltage level from the system voltage level to a much lower the voltage level to provide at the STATCOM. So, here our assumptions are, we have a short symmetrical 3-phase lossless transmission line. Now, let us consider the sending end voltage as V at an angle delta, receiving end voltage is V at an angle 0. And this is the midpoint where the STATCOM is placed.



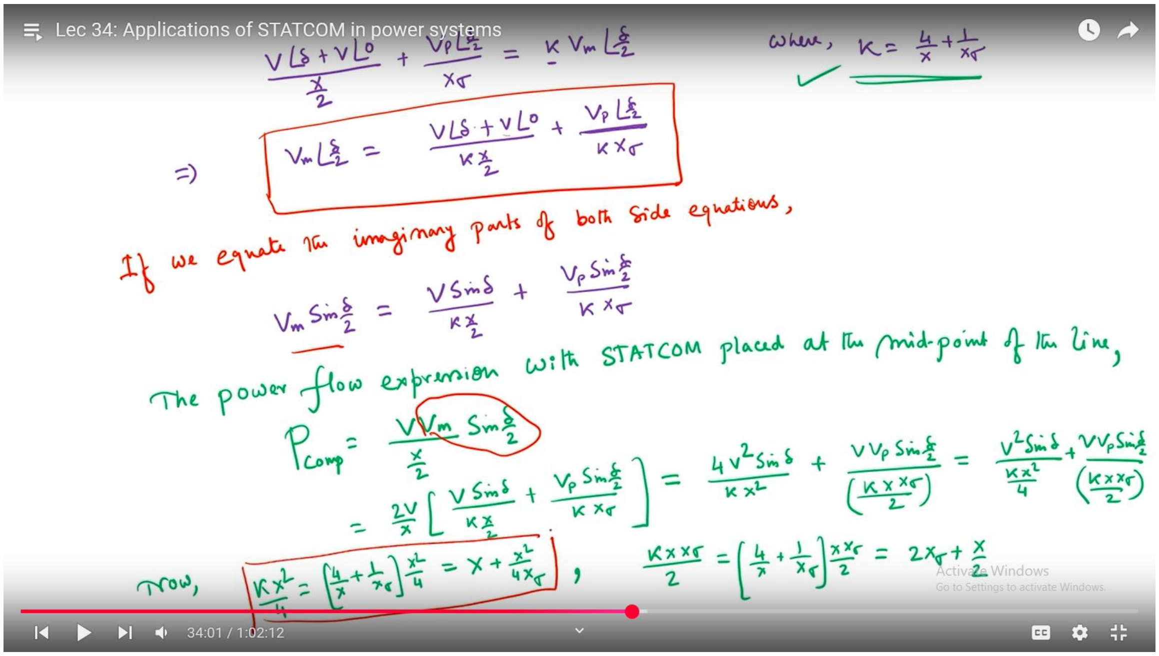
And this is what the step down transformer. So if we consider line to be symmetrical, so the voltage at the midpoint we know is equal to Vm at an angle delta by 2. Now suppose, this current drawn by this STATCOM is representing this I-STATCOM. This step-down transformer is representing is modeled with its the leakage reactance that is x sigma and this STATCOM is modeled with a controllable voltage source that represents V p at an angle delta by 2. So, here also we take the assumption that the STATCOM is also lossless. So, therefore it will there will be no real power exchange through the STATCOM.

So, there is no real power exchange through the STATCOM. Now, let us consider that this line reactance is represented by J x by 2 and J x by 2. So, you know that this here V at an angle delta sending a voltage V at an angle 0 is receiving n voltage, V m at an angle delta by 2 is midpoint voltage and this V p at an angle delta by 2 is equal to the STATCOM output voltage. And X sigma is basically the representation of step-down transformer reactance or leakage reactance as you know and this x by 2 is a representation of this line reactance. So, this is what we have. Now, we will develop the mathematical expressions for power flow through this transmission line due to the presence of the STATCOM. So, that is what our goal. So our goal is to develop the mathematical expression for the power flow through transmission line, through that line due to the STATCOM or with STATCOM. So, this is what our goal is. Now, in order to develop this mathematical expression, let us apply KCL.

KCL at midpoint. So, the current flowing from the sending end, suppose if this arrow is representing this current flow from the sending end, this arrow is representing this current flow from the receiving end. So, these two current, if you sum up, then resultant would be the current flowing through the STATCOM or current drawn by the STATCOM. So, what would be that? Let us see. So, current flowing from the sending end side would be v at an angle delta minus v m at an angle delta by 2 divided by j x by 2. And, current flowing from the receiving end would be v at an angle 0 minus v m at an angle delta by 2 divided by j x by 2.

This will be equal to the current drawn by the STATCOM which will be equal to v m minus v p at an angle delta by 2 divided by Jx sigma. So, that is what the KCL equation is. So, this expression is representing the current flowing from the sending end side. This expression is representing current flowing from the receiving end side. And this expression is representing the current drawn by the STATCOM. So, all these three currents are used in a KCL Kirchhoff current law to get this equation. Now, let us simplify this equation. So, to simplify this equation, what we will do? We have this Vm at an angle delta common here as well as here. So, we will keep it and also here.

So, we will keep it to the other side. So, what we will do is, we will keep this v at an angle delta plus v at an angle 0 divided by j x by 2, which is in the left hand side. So, therefore, this and this will bring it to the other side or right hand side. So, this we can write it as 2 v m at an angle delta by 2 divided by j x by 2. So, this is what we brought from the left-hand side to the right-hand side plus this will be as it is. So, V m at an angle delta by 2 divided by j x sigma minus V p at an angle delta by 2 divided by j x sigma. Let us keep this. See, since we have this j term all in the denominator, so we can cancel this j term here, here, here as well as here. So, let us cancel this out, ok. If we multiply j from both right hand side and left hand side, so j will be omitted from the equation. So, then what we will get? We will get right-hand side v at an angle delta plus v at an angle 0 divided by x by 2 and right-hand side what we will get is or if we bring this v p again to the left-hand side. So, then what we can write v p at an angle delta by 2 divided by x sigma is equal to So, left-hand side we will be having these equations which are not functions of V m. Right-hand side we will purposefully keep V m as a common. So, if we can write it V m as a common. So, this will be equal to or rather I will take V m at an angle delta by 2 as a common. So, what we will get? We will get 4 by x plus 1 upon x sigma.



So, this we will get. So, this is what the equation we get. So, we will continue to do derive this expression. So, what we will do is let us consider that this 4 plus 4 divided by x plus 1 divided by x sigma, let us consider some constant k. If we consider so, then our equation would be v at an angle delta plus v at an angle 0 divided by x by 2. I wrote this part as it is plus this vp at an angle delta by 2 p p at an angle delta by 2 divided by x sigma is equal to k v m at an angle delta by 2, okay. Here k is representing 4 divided by x plus 1 upon x sigma. Now, what we will do again, if we consider so, then I can write rewrite this equation as v m at an angle delta by 2 is equal to, if we divide both right hand side and left hand side with this k, then it will be equal to v at an angle delta plus v at an angle 0 divided by k x by 2 plus v p at an angle delta by 2 divided by k x So, from this expression, from this expression, I can find out this. So, this is what our expression is. And as we know that these expressions will have a real part and the imaginary part. So, if we equate, if we equate the imaginary parts of both sides equation, then what we will get? We will get this is V m sin delta by 2, this is equal to this v sin delta, because this imaginary part will be v cos delta plus j sin delta, v j sin delta. So, the imaginary part would be v sin delta. The imaginary part of this would be 0, because it is only a real quantity. So, this divided by k x by 2 plus v p sin delta by 2 that would be the imaginary part of this part divided by k x sigma. Now, the power flow expression, the power flow expression, expression with STATCOM placed at the midpoint of the line will be P is equal to or I should write P compensated because it is compensated power which is flowing through the transmission line due to the presence of the STATCOM.

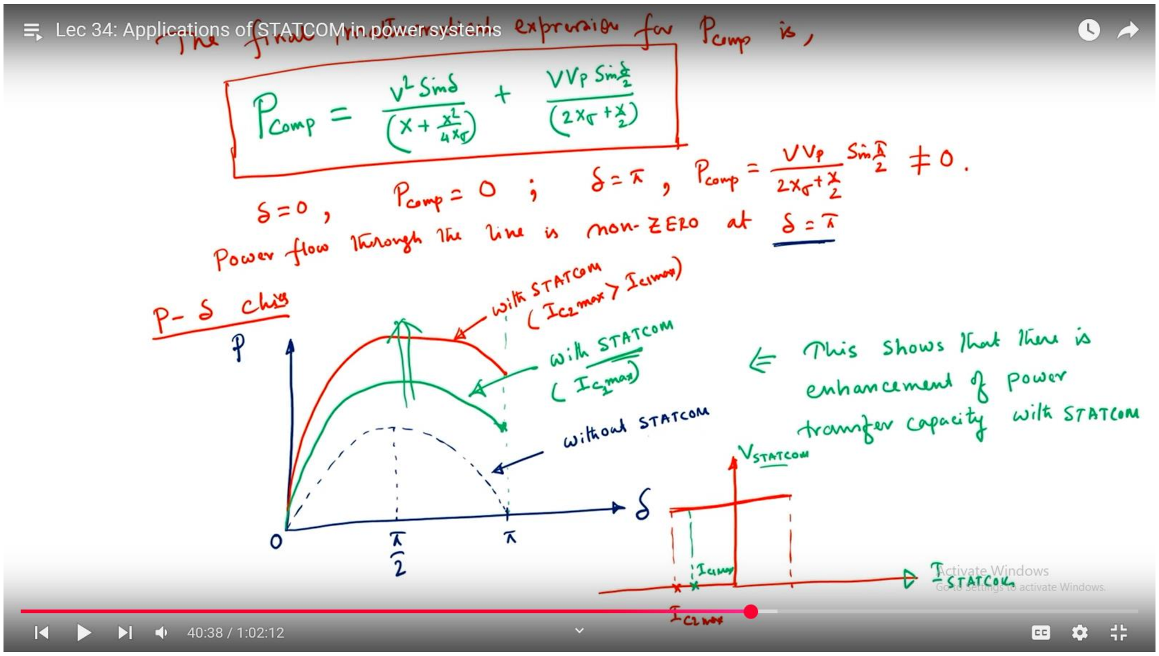
So, this will be equal to V, V m divided by x by 2 sin delta y 2. Now, already we derived the expressions for Vm sine delta by 2, so that means this Vm sine delta by 2 expression already we derived. If we replace it, then what we will get? We will get this will be equal to, so we will be having 2 V by x outside multiplied by this, that is V sine delta divided by k x by 2 plus Vp sin delta by 2 divided by k x sigma. Now, if you multiply this, then what we will get is, this will be equal to, so there will be 2 in the denominator, so there will be 4 square sin delta divided by k x square. And this portion would be v v p sin delta by 2 divided by k x x sigma divided by 2.

So, here these two I brought in the denominator. Now, we know that k is equal to this. So, if it is so, then k x, so this expression would be rather written as v square sin delta divided by k x square divided by 4 and this expression will be v v p sin delta by 2 divided by k x x sigma divided by 2. Now, this k x square divided by 4 would be equal to, if you put this k value from here, this would be equal to 4 by x plus 1 by x sigma which is equal to k multiplied by x square multiplied by 4 which is equal to x plus x square divided by 4 x sigma. This k x x sigma divided by 2 is equal to, so k again we put 4 by x plus 1 upon x sigma from here multiplied by x x sigma divided by 2, which is equal to 2 x sigma plus x by 2. So, this denominator we all further simplify with this.

Now, if we put these two denominators there, so therefore, the final expression, the final mathematical expression for P comp is P comp equal to v square sin delta and the denominator already we derived that is x plus x square divided by 4 x sigma plus this v v p sin delta by 2 divided by 2 x sigma plus x by 2. So, this is the final expression of this compensated power. Now we will analyze this expression. This expression shows that there are two components. One is sin delta component, another is sin delta by 2 component.

So therefore, if we put delta is equal to 0, so what would be the value of this P comp? So P comp will be equal to also 0. However, if we put delta is equal to pi, then you can see this part would be 0, sin delta part would be 0, but this part would not be. So, then this P comp will be equal to v v p divided by 2 x sigma plus x by 2 sin pi by 2 which is equal to 1 sin pi by 2 which is equal to 1. So, that is not equal to 0. So, this is very unlike case that at delta is equal to pi that power flow of the transmission line is not 0. So, that means power flow through the transmission line, through the line is non-zero at delta is equal to pi. Now considering so, if we plot this P delta characteristics, so how would be the P delta characteristics? So P delta characteristics if we plot, then how it would be? You know that without this STATCOM, this P delta characteristic is something like this. So this is without STATCOM. This is the power expression. So, this is p, this is delta, this is you know p is delta is equal to 0, this is delta is equal to pi, this is delta is equal to pi by 2.

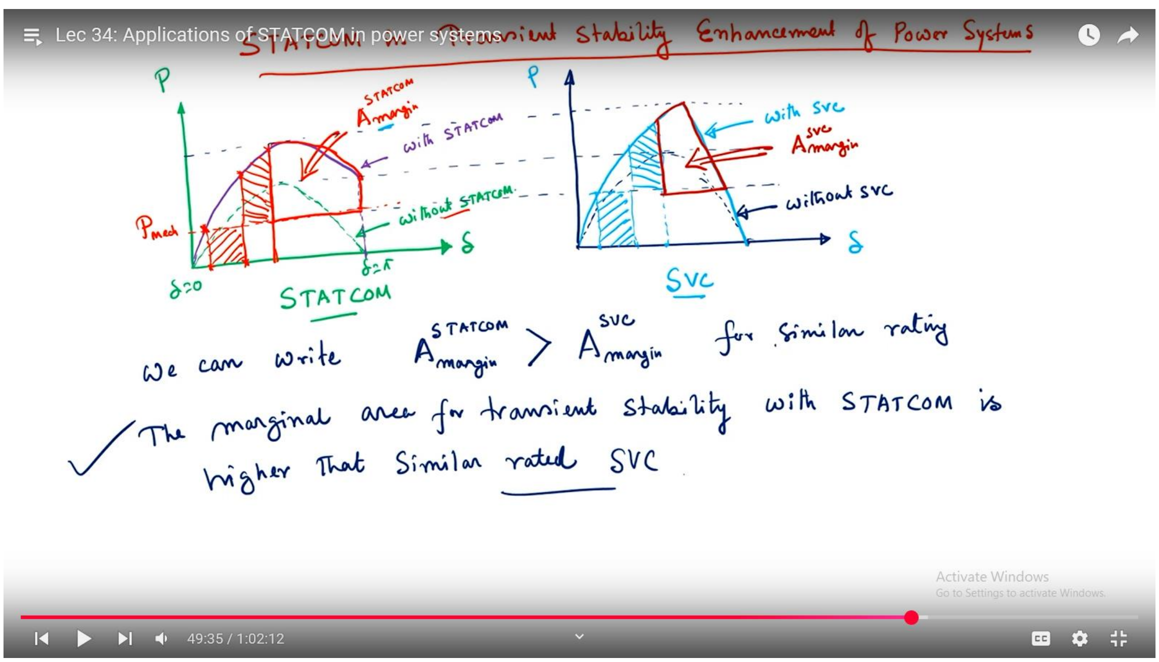
Now with STATCOM as I said this power flow through this transmission line would be non-zero or would be some positive value when delta is equal to pi. So if we plot then this P delta characteristics it would be something like this. Suppose this is what the expression for power flow when delta is equal to pi. So, then this power flow expression if you plot this, this will be the power flow expression with STATCOM. So, this simply shows that there is an enhancement of power flow or power transfer capacity.



So, this characteristic shows, so this characteristic shows that there is enhancement of power transfer capacity with STATCOM. If you consider that this corresponds to these characteristics for a particular IC max or I c 1 max that means this corresponds to the p delta characteristic corresponding to a particular capacity of the STATCOM. If we increase the capacity of the STATCOM this characteristic will be higher like this. So, this corresponds with STATCOM corresponds to a another capacity of this STATCOM which is higher than I c 1 max where i c 1 is as you know this already I discussed this STATCOM control characteristics it was something like this if we consider certain slope. So, this was supposed to correspond to i c 2 max then this was corresponds to I C 1 max.

So, this is what I statcom characteristics. So, when you increase this you know rating of the STATCOM then this P delta characteristics will be uplifted. So, that is what the thing you need to understand. So, STATCOM in general enhances the steady state power transfer capacity, and also depending upon the size of the STATCOM the P delta characteristics would be uplifted as I have shown here in the figure. So we have completed up to this the steady-state power transfer capacity. Now next what we will discuss is the STATCOM in transient stability enhancement.

So STATCOM in transient stability enhancement of power systems. STATCOM in transient stability enhancement of power system: Now, here I will discuss the comparison of STATCOM's ability to enhance the power transfer capacity enhancement and the transient stability enhancement with that of the SVC or static power compensator. So, let us plot this STATCOM p delta characteristics and explain its ability to enhance the transient stability enhancement and then I will compare it to the SVC. So, to do so, what we will do is, let us plot these P delta characteristics once again. P delta characteristics once again: So, this is suppose the characteristic without this STATCOM. So, this is without STATCOM. So, this is you know delta is equal to 0, this is delta is equal to pi. Now, with STATCOM as I have told you or as we have found these characteristics will be uplifted and it will be something like this. It will be something like this. So, these are the characteristics with STATCOM. So, these are the characteristics with STATCOM. Now, suppose this is the mechanical power Pmech. So, this was the operating point with the STATCOM. Now, suppose at this operating point there is a fault and this fault is cleared here. At this particular point, this corresponds to this particular delta. Now, as you know, so this gives you the accelerating area, where electrical power is 0, but mechanical power is constant.



Now, if fault is cleared over here. So again at this instant, this electrical power is higher than the mechanical power. So the machine will start deceleration and then it will again go for increment here and at and we know that this till this accelerating power is equal to deceleration power until our equal area criteria is getting satisfied, so the machine will oscillate. This is the area, already I discussed, this is the area, this is the area which is called the area margin, a margin or marginal area with STATCOM. So, as compared to this without STATCOM case, this marginal area is much higher. So, now if we have similar kind of p delta characteristics with SVC, with SVC and this is what our mechanical power, this is the P delta characteristics without SVC. So, this is without SVC. Now, with SVC as we know for similar dating with STATCOM, the P delta characteristics will be something like this. The P delta characteristics would be something like this. It will operate up to this its capacity and then it will act as a fixed capacitor. So, this is the P delta characteristics with SVC.

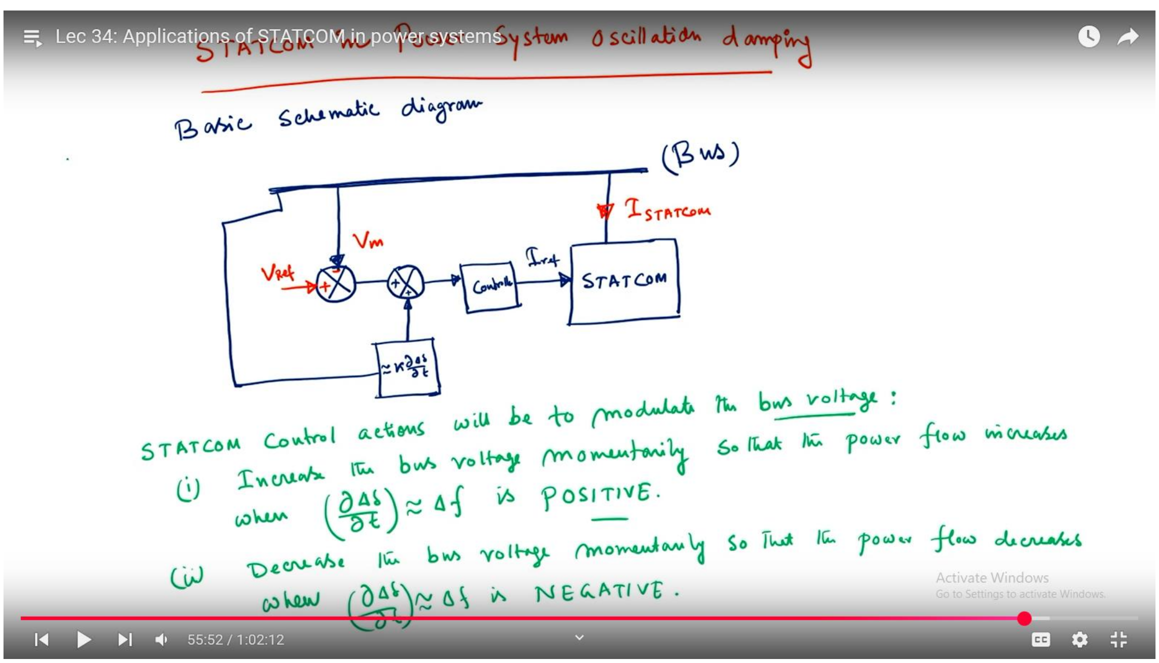
So, this is P delta characteristics with SVC. Now, if we have this is the operating point and this is higher this fault occurs and this is at the same point almost same area this fault is cleared. So, this is what the acceleration area similar to this TATCOM and this would be the deceleration area, so that the deceleration area would be equal to the acceleration area. This I discussed many times and the machine will oscillate up to this. So, here the marginal area would be somewhere like this. This is a marginal area due to this, this SVC would be something like this. So, this is now this A margin with SVC. Now, as we already discussed, this is considering the placement of STATCOM and this is considering the placement of SVC. Now, if you compare them, then you can see, look at this area, this A marginal area and this area. So, which area would be bigger? Of course, this is A marginal STATCOM. So, therefore, we can write A margin due to the STATCOM placement is higher than A margin due to the SVC placement for a similar rating.

We can write as a statement the marginal area of transient stability area for transient stability with STATCOM is higher than similar-rated or same-rated SVC. That is what the main conclusion point I want to draw over here. So, if we have a similar rated or same rated SVC and the STATCOM both will obviously enhance the marginal area for transient stability. However, the STATCOM will provide much area or it will provide much higher area for this marginal or available area to keep the system stable.

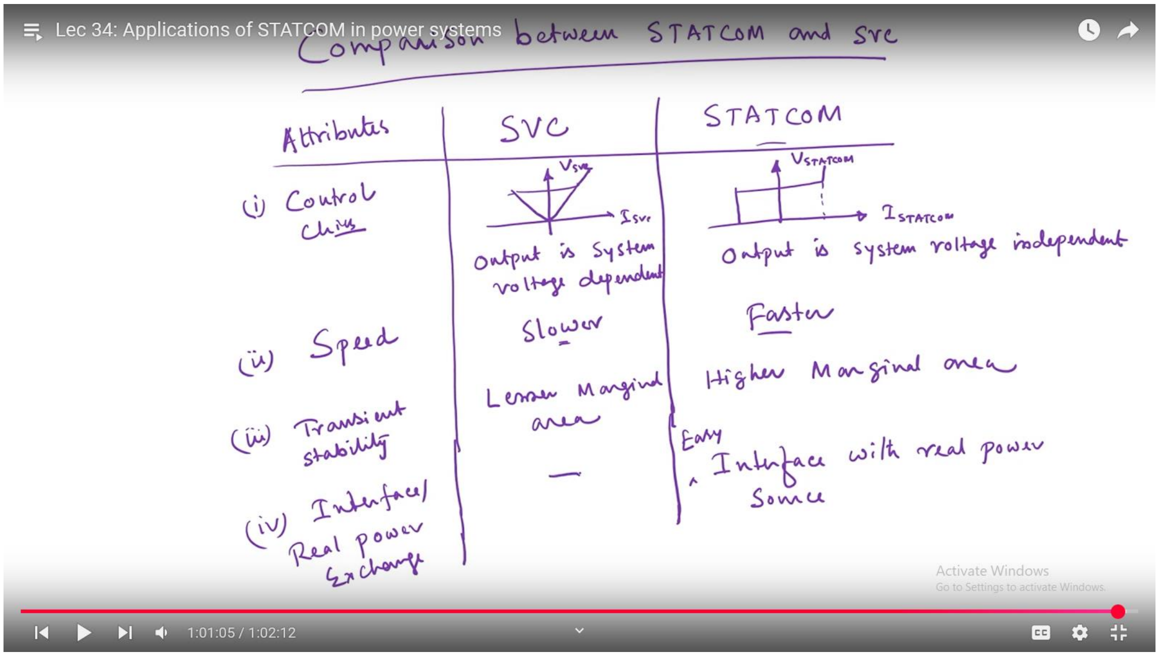
So, it will offer more available area to keep system stable from the transients. So, that is what the main point I am trying to draw it. So, this is what you can see pictorially from this particular figure. So, we complete up to these applications of the STATCOM up to these applications. So, only thing is left is this power system oscillation damping. Or how the STATCOM can be used in power system oscillation damping. So, let us do this right now. So, we will be doing this last you know applications for STATCOM over here. STATCOM in power system oscillation damping: So, let us draw this schematic diagram once again. So, basic schematic diagram or basic control block diagram also. So let us consider that this is the bus where we will place this STATCOM and this is what our STATCOM is.

This is what our comparator is, here we have this measured value of this voltage to be fed that is Vm, it will act as a negative feedback. Then we will be having a reference V reference as we know already, then the error voltage will be fed to another comparator, where it will feed also some auxiliary control input which is similar to K del delta del t and it is to be measured and feed from the particular bus where the STATCOM is placed. This is what the bus where the STATCOM is placed. Then the next signal will be fed to the controller and then it will be it will generate a I reference it will fit to the STATCOM. So, the STATCOM can generate the appropriate signal to draw the given value of reference given value of current from the system.

Now, what would be the control action here the STATCOM actions STATCOM control action actions will be to modulate the bus voltage so that it can increase the bus voltage momentarily. The power flow increases when this del del delta del t which is similar to the variation of the frequency which is similar to the variation of the frequency is positive. That means when this you know the power system frequency is going to be increased del f is positive. So, what is to be done is to increase the flow of the power. So, this change can be arrested. And that is possible by using STATCOM by modulating the bus voltage wherever it is to be placed. That is an important role. In fact, this plays an important role in power system stability. Similarly, it will decrease momentarily decrease the bus voltage momentarily so that the power flow decreases just when del delta del t which is similar to del f is negative or frequency tied to negative.



So, that is how this STATCOM can be used in damping the oscillations of power systems. This is very important role of the STATCOM in particular the stability due to the small signal or stability due to, you know, very small frequency oscillations of power systems. Now, I will end this particular lecture with a comparison of the SVC and STATCOM. So, first, let us draw a table, here we will have SVC, here we will have STATCOM, and here different attributes. So, the number one attribute is in terms of the control characteristics, control characteristics. In terms of the control characteristics, if you look back this control characteristics of stat SVC, it was something like this.



Suppose this is V SVC, this is I SVC, so it was like this. The control characteristics were like this. So, from this however the STATCOM the control characteristics if you compare that is VSTATCOM and ISTATCOM it is something like this. Now, if you compare these two, so what we will can see that its output is system voltage dependent, whereas here output is system voltage independent. This is first come you know active view twice then based upon speed it is faster. It is slower, primarily because the transportation lag in the case of SVC is at least 10 to 20 times higher than the STATCOM.

So, that is why the STATCOM is a much faster device and a faster device would be more useful in dynamic performance as well. Then this, their capability in transient stability. So here this STATCOM is higher marginal area which I already discussed. So here is lower or lesser marginal area. And there is another issue that this due to this converter based topology of the STATCOM it can interface with the interface or I would say seamless interface or easy interface with real power sources.

So, interface or real power exchange. So, this is what easy to interface with the real power sources as compared to SVC. So, these are the different performance indicators or different attributes the difference between the SVC and STATCOM or the difference between the behavioral you know aspects of SVC and STATCOM. So, with this, I will conclude my discussion on STATCOM and this will conclude the 11th module of this course. Thank you very much for your attention and I will look forward to see you in the next lecture. Thank you very much. Thank you.

Steady-state power transfer capability enhancement using STATCOM:

The steady-state power transfer capability enhancement can be understood by developing the expression for power flow in a transmission line with STATCOM.

Consider a 3-phase, lossless, short transmission line with a lossless STATCOM connected at its midpoint. Since, the STATCOM voltage is in phase with the system voltage, there is no exchange of real power. The system can be represented by a single-line diagram shown in Figure 1.

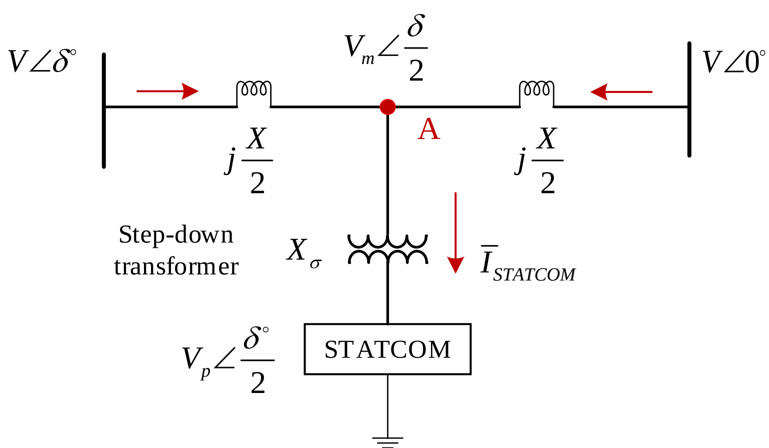


Figure 1: Single-line diagram of midpoint compensation using STATCOM.

Here,

$V\angle\delta$ = Sending end voltage

$V\angle 0$ = Receiving end voltage

$V_m\angle\frac{\delta}{2}$ = Mid-point voltage

$V_p\angle\frac{\delta}{2}$ = STATCOM output voltage

Applying KCL at the midpoint A, we have:

$$\frac{V\angle\delta - V_m\angle\frac{\delta}{2}}{j\frac{X}{2}} + \frac{V\angle 0 - V_m\angle\frac{\delta}{2}}{j\frac{X}{2}} = \frac{V_m\angle\frac{\delta}{2} - V_p\angle\frac{\delta}{2}}{jX_\sigma}$$

$$\Rightarrow \frac{V\angle\delta + V\angle 0}{\frac{X}{2}} = \frac{2V_m\angle\frac{\delta}{2}}{\frac{X}{2}} + \frac{V_m\angle\frac{\delta}{2}}{X_\sigma} - \frac{V_p\angle\frac{\delta}{2}}{X_\sigma}$$

$$\Rightarrow \frac{V\angle\delta + V\angle 0}{\frac{X}{2}} + \frac{V_p\angle\frac{\delta}{2}}{X_\sigma} = V_m\angle\frac{\delta}{2}\left(\frac{4}{X} + \frac{1}{X_\sigma}\right)$$

Let, $\frac{4}{X} + \frac{1}{X_\sigma} = K$

$$\Rightarrow \frac{V\angle\delta + V\angle 0}{\frac{X}{2}} + \frac{V_p\angle\frac{\delta}{2}}{X_\sigma} = KV_m\angle\frac{\delta}{2}$$

$$\Rightarrow V_m\angle\frac{\delta}{2} = \frac{V\angle\delta + V_m\angle 0}{K\frac{X}{2}} + \frac{V_p\angle\frac{\delta}{2}}{KX_\sigma}$$

Equating imaginary parts of both the sides we have,

$$V_m sin\left(\frac{\delta}{2}\right) = \frac{Vsin\delta}{K\frac{X}{2}} + \frac{V_p sin\left(\frac{\delta}{2}\right)}{KX_\sigma}$$

The power flow through the line with STATCOM placed at the mid-point is given by,

$$P_{comp} = \frac{VV_m}{\frac{X}{2}} sin\left(\frac{\delta}{2}\right)$$

Using equation (above) we get,

$$P_{comp} = \frac{V}{\frac{X}{2}}\left[\frac{Vsin\delta}{K\frac{X}{2}} + \frac{V_p sin\left(\frac{\delta}{2}\right)}{KX_\sigma}\right]$$

$$\Rightarrow P_{comp} = \frac{V^2 sin\delta}{\frac{KX^2}{4}} + \frac{VV_p sin\left(\frac{\delta}{2}\right)}{\frac{KXX_\sigma}{2}}$$

Now,

$$\frac{KX^2}{4} = \left(\frac{4}{X} + \frac{1}{X_\sigma}\right)\frac{X^2}{4} = X + \frac{X^2}{4X_\sigma}$$

$$\frac{KXX_\sigma}{2} = \left(\frac{4}{X} + \frac{1}{X_\sigma}\right)\frac{XX_\sigma}{2} = 2X_\sigma + \frac{X}{2}$$

Therefore,

$$P_{comp} = \frac{V^2 sin\delta}{\left(X + \frac{X^2}{4X_\sigma}\right)} + \frac{VV_p sin\left(\frac{\delta}{2}\right)}{\left(2X_\sigma + \frac{X}{2}\right)}$$

At $\delta = 0,\ P_{comp} = 0$

At $\delta = \pi,\ P_{comp} = \frac{VV_p}{\left(2X_\sigma + \frac{X}{2}\right)} \neq 0$

This is unlike the case when there is no STATCOM. At $\delta = \pi$, the power flow is zero when there is no STATCOM present in the system.

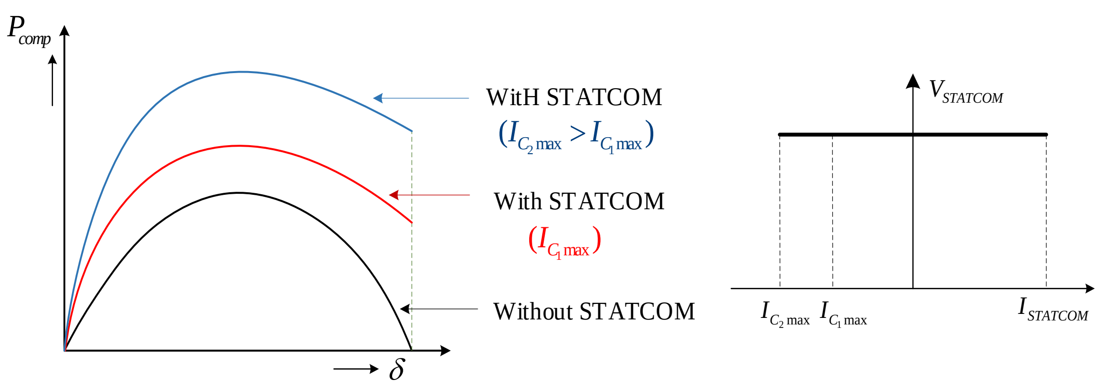


Figure 2: Power-angle characteristics with STATCOM.