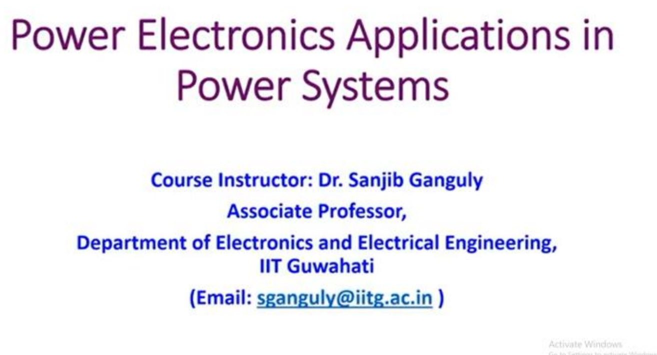
Course Name: Power Electronics Applications in Power Systems

Course Instructor: Dr. Sanjib Ganguly

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

Week: 08

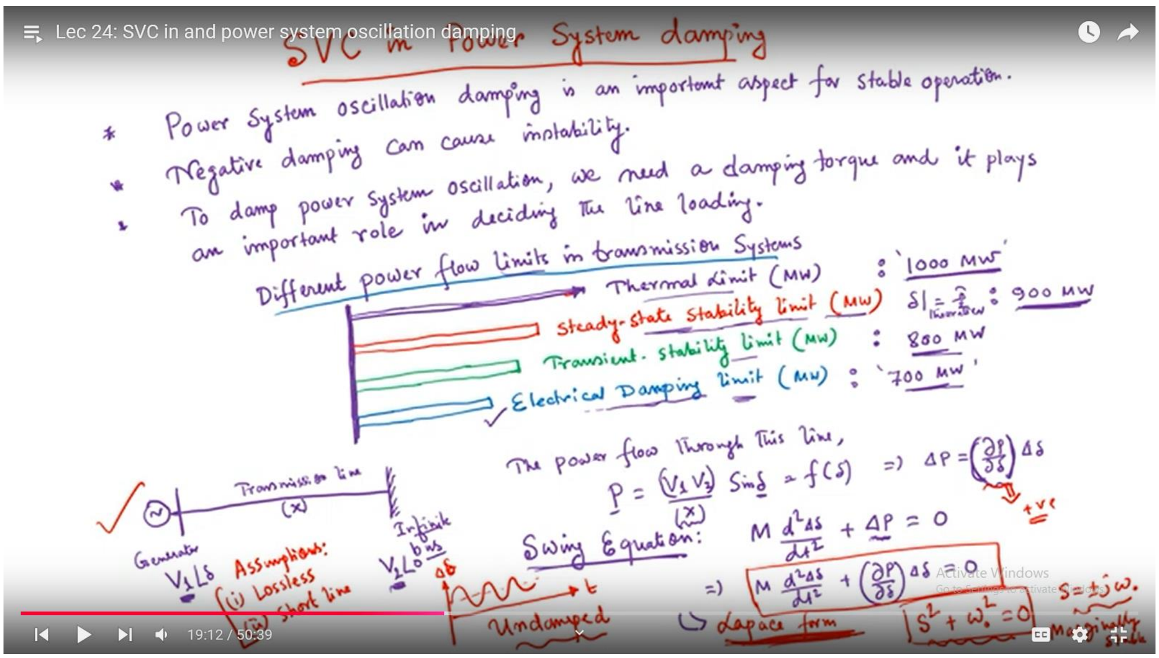
Lecture: 01



Lec 24: SVC in and power system oscillation damping

Welcome again in my course power electronics application in power systems. In the last three lectures, I am discussing the applications of static var compensator in enhancing various capacity or on enhancing the performances of power systems, right. And, in the last couple of lectures, I basically discussed how SVC can be used in enhancing the transient stability of power system. Then, the next application is the SVC can also be used in damping of power system oscillations. Now, in order to understand what is damping of power system oscillation, you have to also understand what you mean by power system oscillation. And why do we require, why do you need the damping in a power system, that is very important.

So, in this particular lecture, I will discuss how an SPC be used in damping power system oscillation. Also, I will discuss the significance of the power system damping and or rather power system oscillation damping and how can we do so by using a SVC control. So, let us proceed. So, today's lecture the theme or the goal is to understand the role of SVC in power system damping. So, we will understand the power system damping. Now, before I discuss, let us write some important point about this power system oscillations or rather power system damping. So, first of all, this power system damping power system oscillation damping rather to be more precise is an important aspect for stable operation. Then the second important point is that this negative damping can cause instability. This is also another important point. And third point is, to damp power system, we need a damping torque, a damping torque and it plays an important role important role in deciding the line loading. These are the three important points which provides you the significance of power system oscillation damping. Now, we have not talked about so far how it is done, but I am trying to give you an idea that why it is so significant in power system. In fact, I will draw a diagram which will further illustrate you how it is crucial to decide the loading of the transmission line. Suppose I have different, let us draw different power flow limits in transmission systems.



So, if I just represent in a kind of bar chart, then it would be something like this. So there are various limits in which decides the power flow in transmission lines or transmission systems. One of them is thermal limit. Suppose this is the thermal limit, this arrow is representing or this barge gum is representing the thermal limit of a typical transmission line. Then, the next limit is the steady state stability limit. Steady state stability limit is usually lower than the thermal limit. So, this is steady state stability limit. it is also represented in terms of megawatt. Then the next limit is transient stability limit, which already I discussed in the last few lectures, which represents the angle till which we can load the power system transmission line. So, suppose this is the transient stability limit that is also in megawatt. So, then the next limit exist is the damping limit, electrical damping limit. okay, that is also in megawatt. Now, if you, this bar gump or bar chart characterize the different power flow limit in a typical transmission line. Suppose, if I give a tentative numerical value, the thermal limit of a transmission line let us say is 1000 megawatt.

What do you mean by thermal limit? Thermal limit is decided by the conductor size of the transmission line. So, it is based upon the maximum current carrying capacity of the transmission lines and it used to be much higher than the other limits or in fact we can say that a typical transmission line is designed to withstand a given amount of power flow and that is what the thermal limit and this limit is primarily decided by the conductor size, conductor type, conductor configuration and a conductor material using which the transmission line is constructed. Even if a thermal limit of a typical transmission line is 1000 megawatt, it is not possible to allow the power flow through this transmission line up to 1000 megawatt. Because there are several other limits which further decide that how much should be the safe or acceptable power flow without losing the stability of the system. So, next limit is steady state stability limit, already I discussed about this, this corresponds to delta theoretical value which is equal to pi by 2 and a typical value for this particular transmission line which is having thermal limit of 1000 megawatt would be much lower, maybe it is suppose I consider it is 900 megawatt.

I am giving a tentative indicative value that does not mean that it has to be like that only, but this gives a idea that stability limit is much lower than the thermal limit of a transmission line. Which implies to the fact that even if we can load or you can allow the power flow of a typical transmission line based upon the conductor configuration to 1000 megawatt, we cannot allow the power flow up to 1000 megawatt because steady state stability limit is lower than that, ok. Then we have transient stability limit. It decides that how much should be the acceptable flow of power, keeping it, keeping it, keeping the consideration that it would be able to withstand a major disturbance like transient fault. These things already I discussed.

So, suppose if your steady state stability limit of the same line is 900 megawatt, then transient stability limit can be lower than that. Let us consider it is 800 megawatt and again this numerical values does not have any idea does not have any sense, apart from that it gives a relative values of the different limits. Then the next limit is basically electrical damping limit, which will be further lower than this transient limit, let us consider it 700 megawatt. So, this gives you an idea that even if a transmission line which is constructed and designed to accept this power flow of 1000 megawatt, effectively this electrical damping limit decides that how much should be the allowable amount of flow of power that is eventually much lower than the your thermal limit. So, that is what the main essence of this fact.

So, electrical damping limit is the most crucial limiting factor in deciding that how much power should be allowed to flow in a typical transmission line. Now to show you how this damping is decided or how the damping is important for a particular transmission line, I will show you how an SVC placement can improve the power system oscillation damping. So, let us start with a simple transmission line. Or a single-machine infinite bus system, where this is connected to an electrical generator and this is connected to an infinite bus. This is generator, this is infinite bus. In power system terminology, we call it single machine infinite bus system and this is what the transmission line. This is what the transmission line. Let us consider voltage at this bus is V1 at an angle delta. And this infinite bus voltage is V2 at an angle 0. This is representation of a short line.

So, it is modeled with its reactance, which is x. So, therefore, the power flow through this line, the power flow through this line is p is equal to v 1, v 2 divided by x sin delta. Now, if we assume these voltages are regulated at the both end, you know the infinite bus the voltage will not change that is what the you know definition of infinite bus. So, we assume that numerator remain constant and x is the design parameter it will also remain constant. So, P is proportional to So, line loading basically depends upon the angular difference between the two buses, one is sending end bus, this another is receiving end bus.

If we go back and write the swing equation for the system, so what would be the swing equation? So, again I said that swing equation is something which is taught in basic power system course and we take this idea also when we discuss this equal area criteria and this is I assume that you know. So, therefore, the swing equation is as we know M d 2 del delta d t 2, this is already I have already discussed plus del p is equal to 0. Now, we represent this del p means a small change of this power and p is the function of only delta, p is the function of delta. So, therefore, del p is basically representation of del p del delta multiplied by del delta. So, if we write it over here, then as you know what is del P del delta, we discuss a lot regarding this in the last couple of lectures.

As we know, without SVC

$$P = \frac{V_1 V_2}{X} \sin\delta$$

We also know from swing equation

$$M \frac{\partial^2 \Delta\delta}{\partial t^2} + \Delta P = 0 \qquad ($$

Now, if we assume the voltages at both ends are regulated

$$\Delta P = \frac{\partial P}{\partial \delta} . \Delta\delta$$

$$M \frac{\partial^2 \Delta\delta}{\partial t^2} + \frac{\partial P}{\partial \delta} . \Delta\delta = 0 \quad \Leftarrow$$ This equation shows an undamped system

Now, let us consider that there is an SVC at the mid-point

Single machine infinite bus system with SVC placed at the mid-point of the line. The single line diagram of SVC compensated line is shown in Fig. 2.

$$P_{comp} = \frac{V_2 V_m}{\frac{X}{2}} \sin \delta_m$$

Two options:

i. Let keep V_m = constant, $P_{comp} = f\left(\delta_m\right) \Rightarrow$ Undamped

ii. Let keep V_m = Variable according to line loading, $P_{comp} = f\left(V_m, \delta_m\right)$

$$\Delta P_{comp} = \left[\frac{\partial P_{comp}}{\partial V_m} \Delta V_m\right] + \left(\frac{\partial P_{comp}}{\partial \delta_m}\right) \Delta \delta_m$$

$$\Delta P_{comp} = \left[\frac{\partial P_{comp}}{\partial V_m} .K \frac{\partial \Delta \delta_m}{\partial t}\right] + \left(\frac{\partial P_{comp}}{\partial \delta_m}\right) \Delta \delta_m$$

[we are varying the mid-point voltage such that $\Delta V_m = K \frac{\partial \Delta \delta_m}{\partial t}$]

Swing equation of SVC compensated line,

$$M \frac{\partial^2 \Delta \delta_m}{\partial t^2} + \left(\frac{\partial P_{comp}}{\partial V_m} .K\right) \frac{\partial \Delta \delta_m}{\partial t} + \left(\frac{\partial P_{comp}}{\partial \delta_m}\right) \Delta \delta_m = 0$$

Laplace transformation

$$s^2 + 2\xi \omega_n s + \omega_n^2 = 0$$

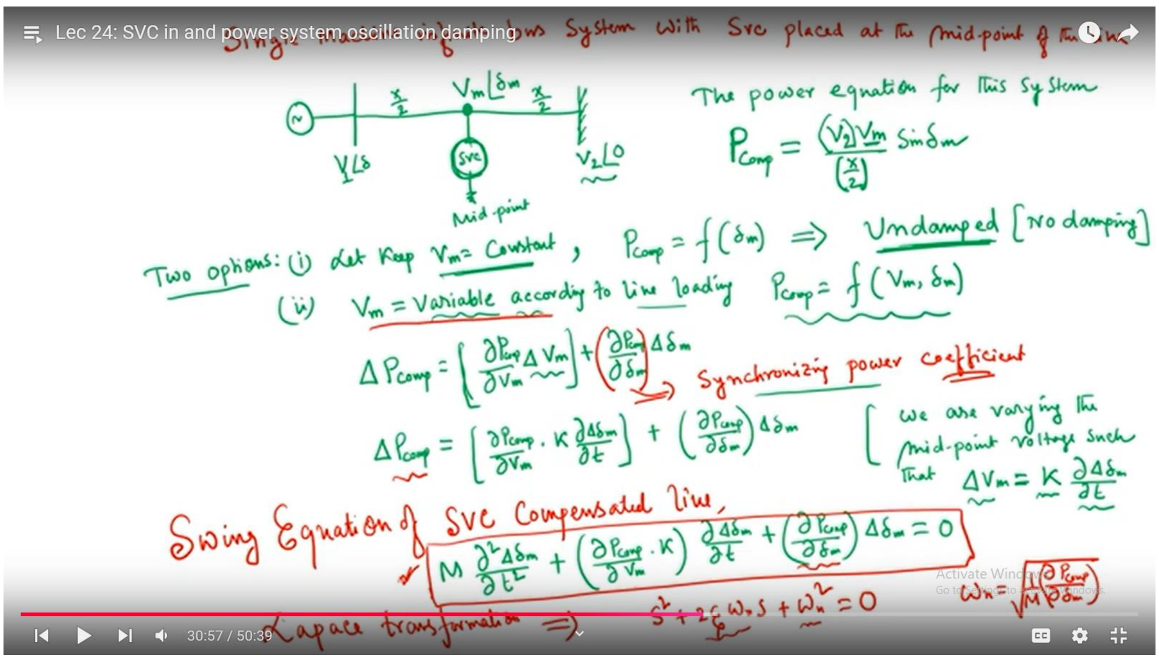
$$2\xi \omega_n = \frac{\partial P_{comp}}{\partial V_m} K$$

Damping ratio

$$\xi = \frac{1}{2\omega_n} \left(K \frac{\partial P_{comp}}{\partial V_m}\right)$$

$$\xi = \frac{1}{2\sqrt{\frac{1}{M}\left(\frac{\partial P_{comp}}{\partial \delta_m}\right)}} \left(K \frac{\partial P_{comp}}{\partial V_m}\right)$$

This is basically the rate of change of power flow with respect to the angle delta and that is called synchronizing coefficient of the line. So, this can be written as m d 2 del delta d t 2 plus the synchronizing coefficient del p del delta multiplied by del delta is equal to 0. Now, if you just convert it to Laplace domain, if we convert it to Laplace form, I will again assume that you know what is Laplace transform. Then this is a second order differential equation and if we convert it to labless domain, it will represent the characteristic equation which is similar to S square plus omega naught square is equal to 0. Now, here where S will lie because we know that dp d delta will has to be positive for a stable operation.



So, S is basically representation of plus minus j omega naught. So, it means that here this pole of this characteristic equation, this is what the characteristic equation that we will get from this swing equation by converting it to the Laplace domain, and the root of the characteristic equation will lie to the imaginary axis. It means that the system will be marginally stable. So, this means the system will be marginally stable. And if we plot this variation of del delta over here, then what we will see that del delta will be oscillating without converging to a particular value or without being 0. So, it will be oscillating like this. this will be del delta plot with respect to t. So, it will not come out to be a given value or it will not come out to be 0. So, that is what will happen if we consider a single-machine infinite bus. Here our assumptions are, we have lossless system, we have short line model.

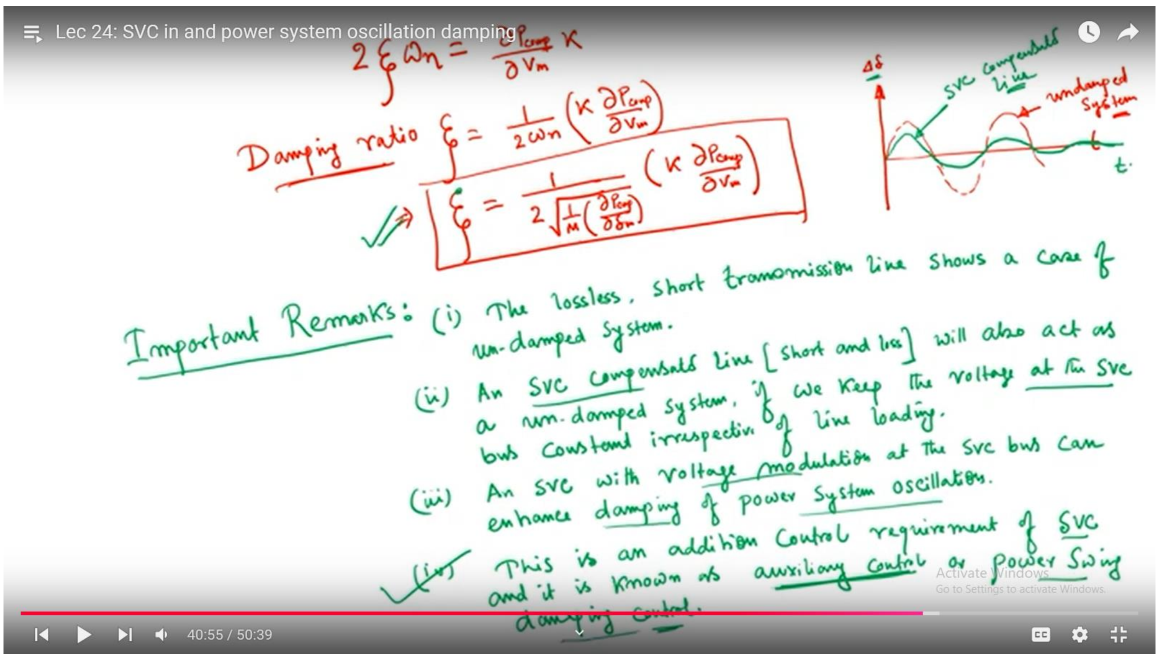
So, if we have a lossless system, effectively there is no damping. So, it is a case of undamped operation. Those who have learned this basic control system course, they know what is the damping of a second-order system. So, roots of the characteristic equation lie only on the imaginary axis, then it is a case of marginally stable and also it is a case of undamped system. So, there is no damping of the system and this del delta will keep on oscillating. So, that is what the thing is. we will see that how this SVC placement may enhance the damping. So, we will see the single-machine infinite bus system with SVC placement. Single machine infinite bus system with SVC placed, let us say at the midpoint of the line. Now, let us redraw this single machine infinite bus system, here we assume this is generator bus, this is what our transmission This is infinite bus system and this is where we have this SVC connected. So, this voltage is again we consider V at an angle delta, V1 at an angle delta.

This voltage, let us consider V2 at an angle 0. This voltage you consider Vm at an angle del m. Now, when we have this system, then we know the power flow equation will be this, for this system will be, here you also assume that this is midpoint, this is midpoint. So, the reactance of midpoint to this sending end site is x by 2 and reactance from the midpoint to the receiving end site also x by 2. So, the power flow equation will be P compensated.

Why we write P compensated? Because it is a SPC compensated line. So, therefore, this equation of this power flow will get revised. So, it will be P compensated which is equal to V1. Or rather I should write V 2 V 2 V m divided by x y 2 then sin del m. Now, you see that let us consider that V2 is regulated and it is infinite bus system, we will assume that V2 is constant, x by 2 is the line reactance, it is also a constant quantity. So, therefore, but this Vm we can vary. So, we have two options in controlling the SVC, number one is that we can keep Vm constant irrespective of the loading. Number 2 or option 2 would be we can vary the V m according to the line loading or according to the variation of delta. So, we have 2 options or 2 cases or 2 options rather I say number 1 let keep V m is equal then if you have so, then this P comp will be function of only del m. So, in that case, your situation would be same as that of we have seen in the last page here.

So, this corresponds to the same equation and same property of this and this will corresponds to a clear case of undamped system. So, therefore, if we do so, if we keep this V m constant irrespective of the line loading, so then overall system will be undamped system. That means, what do you mean by undamped system? That means, there will be no damping in the system as discussed before. Now, the second option is that we will vary this V m. So, V m is variable according to line loading if it is so then P comp will be function of this V m as well as del m.

So, now let us see what type of case this would be. So, in that particular case the small perturbation of this P comp will be equal to del f del V m multiplied by del V m plus del f del del m multiplied by del del m. Now, or rather I should not use this f, I can write this also del p comp, del vm and del del m. Now, you can see this basically represents this del p com del del m, it represents the synchronizing coefficient, synchronizing power coefficient and we have determined this value of del P comp del del in the last lecture this. So this basically represents del P del delta that is for the synchronizing power coefficient for SVC compensated line and which is different than the uncompensated line.



That is what I want to say over here. Now if we can however this is known to us the synchronizing power coefficient is known to us. Now, if we keep this del V m 0, that means V m constant, then it will be a case of undamped system, this term would be completely 0 then, but we are not interested to doing so, we are interested to vary this V m according to the line loading in this option 2. So, therefore, what we will do is that, we will keep that this del P comp del V m as it is and we will vary this del V m such that it will be equal to k some constant k then del del m del t. Then rest of the equation would be same that is del p com del del m multiplied by del del m. So here we are varying, we are varying the midpoint voltage, midpoint voltage such that del V m is equal to some constant.

Basically, what it is doing, we are varying this del V m proportionally with the rate of change of del del m, ok. We are varying this del V m proportionally to del del m del t and this proportionality constant is k. Now, we will use this del P comp equation in the swing equation of the SVC compensated line. So, let us write the swing equation again of SVC compensated line. So, what we will get? We will be replacing this part in particular del p part with this whatever expression we have got right now.

So, what we will get is m del 2 del del m d t 2 plus this part we will write del p comp del V m multiplied by K multiplied by del del m del t plus this part del P comp del del m del del m is equal to 0. Now, this is what our swing equation. Now, if you convert it to the Laplace domain, if you convert it to Laplace domain by Laplace then what you get, this is also a second order differential equation, but the characteristic equation of this particular swing equation for SVC compensated line for having this V m variable according to the line loading would be something like this, S square plus 2 zeta omega n S plus omega n square is equal to 0. Now when you have this, this is a you know that characteristic equation for a standard second order system with damping. Without damping this part was 0, this zeta was basically 0 and zeta is called the damping ratio which is well known, those who have done the basic control system course.

Now, omega n is your natural frequency of oscillation. Now, here if you just compare this equation with that equation, then omega n would be equal to root over this del P comp, del P comp that is synchronizing coefficient for SVC compensated line divided by 1 upon m. So, that is what this omega n is. So, this is natural frequency of oscillation. This basically depends upon the, m is constant we know and it is basically depends upon the synchronizing power coefficient of the line.

Now then, what will be this 2 zeta omega n? 2 zeta omega will be equal to this, because it is the coefficient of this term, which brings this S term over characteristic equation. So, we can write 2 zeta omega n, 2 zeta omega n is equal to del p comp del V m multiplied by this k, where k is the proportionality constant we consider. Because, we are here interested to vary this V m, what is V m? V m is the midpoint voltage of the SVC compensated line, that is the voltage at this point. So therefore, we are interested to vary this according to the rate of change of del delta, rate of change of del delta. So, therefore, this is basically equal to 2 zeta omega n, where zeta is equal to, zeta is damping ratio, zeta is equal to 1 upon 2 omega n, then this K multiplied by del P comp del V m.

So, this can be, you know, we already know what is this omega n, natural frequency of oscillation, this is, so we can replace it by this. So, 1 upon 2, 1 upon m, then the synchronizing power coefficient that is del P comp del del m multiplied by this k del P comp del Vm. So, this is what the damping ratio and by doing so, we can provide the appropriate damping to the system. So, this zeta will bring the appropriate damping to the system. Now, as compared to the del delta plot, suppose this is the del delta plot, del delta plot with respect to t.

Suppose this is what the del delta plot for undamped system, this is for undamped system. Undamped system, which already I explained that if we consider lossless line, so it is eventually similar to an undamped system. But of course, in practical power system or practical transmission line, there is certain amount of losses fortunately, which causes certain amount of damping, as well. But, if we consider this is very less, then by using this SVC control, we can provide or we can control the damping. And therefore, the plot of this SVC compensated line, the plot of this del delta with respect to T for SVC compensated line would be somewhat like this, it is a damped plot, damped oscillation it will go to 0 up to a certain point.

So, this is what the plot of SVC compensated line. That is the main essence of the fact that I want to establish here. Now let us write the important remark what we get from this whole analysis important remarks. Number 1, so SVC with appropriate or I should write first, the first is the lossless short transmission line shows a case undamped system. Number 2, an SVC compensated line. Line is of course, short and lossless. This will also act as a undamped system if we keep voltage at the SVC bus, here we assume that SVC is placed at the midpoint of the line. So, here it implies to the midpoint voltage. So, we keep the voltage at the SVC bus remained constant or we keep the voltage at the SVC bus constant irrespective of line loading. This is an important remark. So, in fact, in my in our previous study, we have considered that the SVC is responsible to hold the midpoint voltage constant.

Now we are deviating from that. In fact, we have to deviate when there is a dynamic condition, when there is a dynamic situation like this. And during that time, this SVC should modulate the midpoint voltage according to the requirement, thereby it can provide the appropriate damping. So, the third remark is that an SVC with voltage modulation. Instead of keeping this voltage constant, this voltage modulation at the SVC bus can enhance damping of power system oscillation.

This is what we have shown in this particular analysis. They can bring this damping ratio and this should be suitably done and this should be suitably designed to control, so that SVC can effectively modulate this SVC bus voltage, so that it can effectively damp the power system oscillations. Now the fourth question is, this is an additional control requirement of SVC and it is known as auxiliary control or power swing damping control. So this is very important point to be understood that this feature of SVC provides you additional control requirement that is called auxiliary control or power swing damping control. Whereas, the main purpose of SVC is to control or regulate the voltage at which it is placed. Here in the whole study in everywhere we consider SVC is placed at the midpoint of the line.

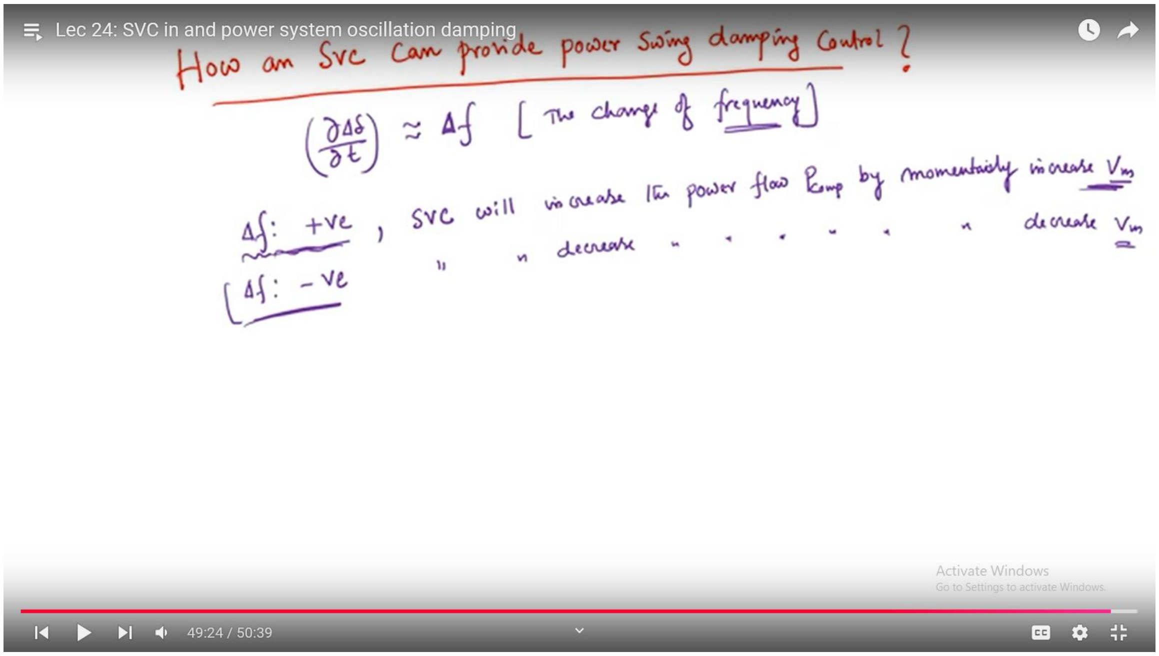
Now, it may not be placed at the midpoint of the line, but wherever it is placed, its primary role is to regulate the voltage at that particular bus. However, this is what the main control functionality and I will discuss how it is to be done in the next few lectures. However, apart from that, SVC also needs to provide some auxiliary control action one of them is to damp this power system oscillation or power swing damping control. This is an additional task of SVC and that usually it provides like an auxiliary control action. Now, you have to also understand how this SVC can provide this auxiliary control or power swing damping control.

An SVC can provide auxiliary or power swing damping control. So I will finish this lecture by answering this question that how an SVC can provide power swing damping control. You understand at this point I believe that SVC can provide power swing damping control by modulating the voltage at the bus at which it is placed. So here we consider that SVC is placed at the midpoint of the transmission line. So it has to modulate the midpoint voltage and by doing so it can provide the appropriate damping. Now the question is modulation of voltage means you have to sometimes momentarily increase the voltage at the midpoint or sometime you have to momentarily decrease the voltage of the midpoint.

Now the question is when we should increase the voltage, when should we decrease the voltage? In order to understand that you should have a idea of the basic power system that usually this rate of change of del delta. What it is basically representing? This is basically representing the rate of change of frequency of this particular voltage of the system. So, it is basically the change of frequency. Now the question is what do you mean by that? Ideally we believe that the frequency of the power system will always remain constant and India it will always remain constant at 50 Hertz. But if you go and see and monitor the frequency of this voltage that the grid is providing to you, then you can see it is eventually never be constant to 50 hertz throughout the day, rather it will always vary. Now why it will vary? It will vary primarily because of the load and generation imbalance. Sometimes power generation is not adequate enough to supply all the load demand. This happens when we have a scorching summer. So, during that time we use many of the air conditioning load and all the other different types of load to cool ourselves.

So, therefore, the load demand eventually in India during summer is very high. During April, May, June, July, it is very high. So, during that time this situation happens when the generation is not adequate to the load. So, therefore, what would be the consequence? Then the frequency will fall. When it is happening the frequency will fall. But eventually during midnight if we have a sufficient generation and our load demand is not as high as our generation is, during that time frequency will rise. So, frequency is a certain quantity which is always changing throughout the day. Now, the question is, when sometimes there will be positive, so del f, the deviation is the, it is basically the change of the frequency, sometimes it will be positive and del f sometimes will be negative. Now, when this del f is positive, what does it mean actually? This means that there is a over speeding of the generator. So, the frequency is increasing that means obviously we have a surplus generation than the load.

So, therefore the generator is over speeding. So, during that moment of the time what essentially that this role of the SPC would be it will increase the flow of the power. So, when it is positive, so SVC will increase the power flow, power flow that is P comp. How it is possible? This is a very momentary operation by momentarily increase Vm. You can see from this particular expression if V m is momentarily increased then P m will also increase. Now if P m this P comp increases that means power flow through the transmission line will also increase that means the torque in fact you have I hope that you know that there are two torque acting in a typical synchronous generator one is load torque another is this mechanical torque.



So, here load torque will increase So, mechanical torque was high and that is why this del f was positive and if we can increase the load torque, we can balance eventually that and we can mitigate this del f, we can arrest this del f and that is eventually possible by momentarily increase the V m. Now, how can SVC momentarily increase the voltage at the midpoint? So, you know, SVC has two, you know, mode of operation, one is inductive mode of operation, one is capacitive mode of operation. So, when SVC operate its full inductive mode, it momentarily reduce the voltage level and when it acts as a full conduction mode in the capacitor region or capacitive zone, it can momentarily increase the voltage level.

So, by doing so, it can arrest this del f. Similarly, positive del f. Similarly, when we have a negative del f, so what will be the role of the SVC? So, SVC will decrease the power flow P comp by momentarily decrease this V m and simply by doing so SVC can arrest this negative f that is the negative change of the frequency. And this is how this SVC can also be used in regulating the frequency of the system and it can eventually also provide this damping to the system. So this is how it eventually this, this arrest the rate of change of frequency or the change of the frequency, ok. So, this is all about this. Now, with this I have completed this, this, this important application of SVC that is how it is dammed this power system oscillation.

One thing is only left to us that is how SVC is used voltage control of power system which is the main function. Main function of this SVC and this I will discuss in very detail in the next 2-3 lectures. So, till then, thank you very much for attending this course once again. Thank you very much. Thank you.