Course Name: Power Electronics Applications in Power Systems

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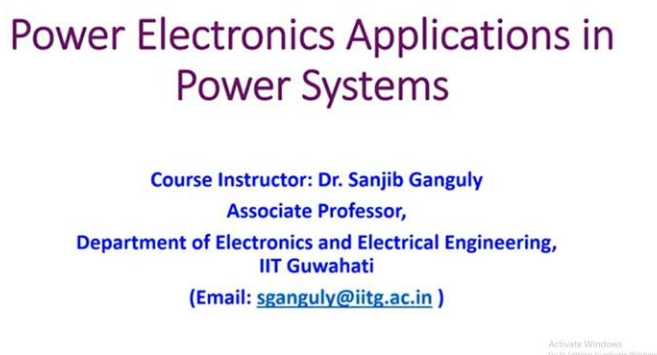


Lec 25: SVC in voltage control of power systems: Modelling

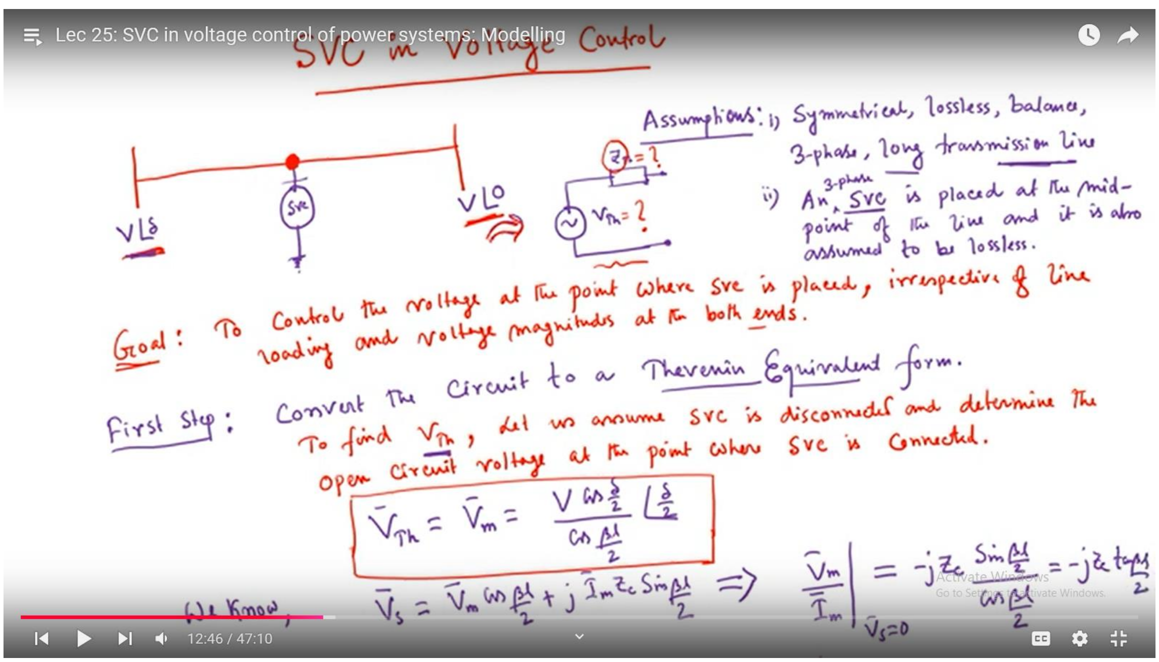
Welcome again to my course Power Electronic Applications of Power Systems. So, in last few lectures, I am discussing the application of SVC in various capacities to improve or enhance the power system performance. This includes the steady state power transfer capacity which also includes this transient stability which also includes the damping of the power system etc. However, the main purpose of SVC is to control the voltage wherever it would be placed. So, that is what the main application of SVC and in next few lectures I will be discussing that. So, how an SVC could be able to maintain the voltage of a location, where it is placed, what are the factors involved in it and those things I am going to discuss in this few lectures.

So, let us start. So, today, I will discuss the applications of SVC in voltage control. So, let us consider we have a symmetrical long transmission line. Here our assumptions are we consider a symmetrical lossless balance 3-phase long transmission line. So, as usual we consider this line is symmetrical, lossless, balanced. It is of course three-phase even though I do not mention many times and it is a long transmission line. And let us consider voltage at this end is V at an angle delta, voltage at the receiving end side is T at an angle 0. So, what we will do is that we will put an SVC or we will place an SVC at the midpoint like this. So, this is the midpoint where we will put the SVC.

So, this is the first assumption. Second assumption is that an SVC is placed at the midpoint of the line and it is also assumed to be lossless. Of course, it is a three-phase SVC, you have to understand, it is a three-phase SVC, even though I do not mention many times, but you understand all these discussions, these devices, compensators, these transmission lines, they are of three-phase. Now, these are our assumptions. Now, what is to be done is that, what is our goal then? Our goal is to control the voltage at the point where SVC is placed.

So, here this point is eventually the midpoint. So, basically this SVC, the purpose of this, main purpose of this SVC is to control the voltage at the point where it is placed. Now, we should also write irrespective of, irrespective of line loading and voltage magnitudes at the both ends. So, this is the goal of modeling the SVC is to control voltage at which this SVC is placed here it is incidentally the midpoint and this voltage control action should consider and it will hold to be true or it will maintain the control at irrespective of this line loading and the voltage conditions at the both end. So this is what our goal.

Now what is to be done? The first step to do so is to convert the circuit to a Thevenin equivalent form. So, Thevenin equivalent is very important idea which works for this linear circuit. It is usually taught in basic electrical engineering course and I hope all of you are familiar with this. Now, in order to model this SVC, we will first convert the whole circuit into a Thevenin equivalent form. Now, what is Thevenin equivalent form? Usually we convert very large complex circuit when Thevenin equivalent form and that form consists of the Thevenin equivalent voltage and the Thevenin equivalent impedance there.



So basically you have to understand that this we are going to convert it to a Thevenin equivalent form where this will represent V Thevenin and there would be an impedance which will represent Z7. So that is what we are going to do here. Now the question is, here we have to find out the magnitudes of V Thevenin and the magnitudes of Z Thevenin, so that we can say that these represent Thevenin equivalent form of this actual circuit. And once you do so, then this circuit will work for any change in the line loading as well as any change in the voltage of the both ends. Now, to find V Thevenin, what is to be done? So, let us disconnect, let us assume SVC is disconnected.

- **Thevenin equivalent circuit:**

To find V_{th}, let us assume SVC is disconnected and determine the open circuit voltage at the point where SVC is connected.

$$\overline{V}_{th} = \overline{V}_m = \frac{V\cos\frac{\delta}{2}}{\cos\frac{\beta l}{2}}\angle\frac{\delta}{2}$$

$$\overline{V}_S = \overline{V}_m \cos\frac{\beta l}{2} + j\overline{I}_m Z_C \sin\frac{\beta l}{2}$$

$$\left.\frac{\overline{V}_m}{\overline{I}_m}\right|_{V_S=0} = -j\frac{Z_C \sin\frac{\beta l}{2}}{\cos\frac{\beta l}{2}}$$

$$|X_{th}| = Z_C \tan\frac{\beta l}{2}$$

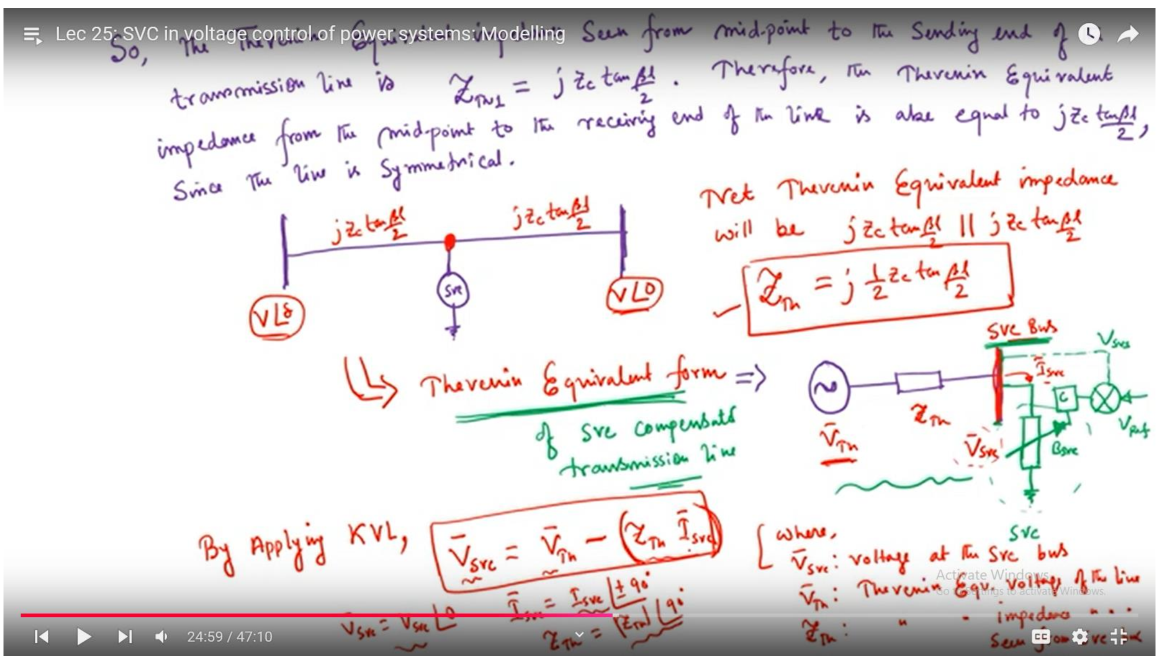
Net Thevenin equivalent impedance will be

$$X_{th} = jZ_c \tan\frac{\beta l}{2}\ ||\ jZ_c \tan\frac{\beta l}{2}\ = j\frac{1}{2}Z_c \tan\frac{\beta l}{2}$$

Then, measure or and determine, I should write determine the open circuit voltage at the point where SVC is connected. And that open circuit voltage will represent V Thevenin. That is what the usual practice or that is what the usual convention that we follow. So, what we will do? Simply assume that SVC is disconnected from here and then measure the open circuit voltage. Now what would be the open circuit voltage if we disconnect the SVC? So this open circuit voltage Vth will be nothing but equal to Vm, that is midpoint voltage. And the expression of the midpoint voltage already we have determined long time before, when I discussed the midpoint voltage current condition. So we know that this voltage is cos delta by 2 divided by cos beta L by 2 at an angle delta by 2. So, this is known to us. So, the determination of V Thevenin is somewhat easier. So, this represents the V Thevenin or Thevenin equivalent voltage which we are trying to get.

Now, the second question is how do we find out Z Thevenin? So, in order to find Z Thevenin, what is, what usually we do, we have two voltage sources, one is at the receiving end site, another is at the sending end site. What we do is that, let us short circuit both the source and find out what is the net impedance seen from this point. So, in order to find that, what we can do is that we know the relationship of these voltages and current among this midpoint voltage, midpoint current and the mid, sending end voltage, sending end current, also receiving end voltage, receiving end current. This we know. So we know how this sending end voltage is related to the midpoint voltage.

We know, this is already we derived. This sending end voltage Vs is equal to V m that is midpoint voltage cos beta L by 2 plus J i m Z c sin beta L by 2. So, from this we can find out the ratio of V m to i m. Vm to Im which is midpoint voltage to midpoint current when Vs is short circuited. Now if we do so then what we will get is this is basically representing minus Zc sin beta L by 2 minus Jzc of course sin beta L by 2 divided by cos beta L by 2. So, this represents minus Jzc tan beta L by 2. So, that is what the Thevenin equivalent impedance seen from the midpoint to the sending end site. So, the Thevenin equivalent impedance seen from midpoint to the sending end of the transmission line is Z Thevenin in let us say 1. It represents this is by z Thevenin 1. So, this is the magnitude wise it is equal to j z c tan beta l by 2, if we ignore the negative sign over here.



So, therefore, since the line is symmetrical, so therefore, therefore, the Thevenin equivalent impedance from the midpoint to the receiving end of the line is also equal to j jthc tan beta l by 2, since the line is symmetrical. So, therefore, we can redraw this line like this. This is sending end bus, this is receiving end bus and this is the midpoint where we have kept this SVC. So, what we have seen that if we look at this from this midpoint to the sending end site, here voltage we know V at an angle delta, here voltage we know V at an angle 0. So, Thevenin equivalent resistance from this midpoint to the sending end site is Jzc tan beta L by 2 and here also it is Jzc tan beta L by 2. And, both the lines are in parallel. If you look at from the midpoint, if we assume that this voltage and that voltage are short circuited, we consider this to find out the Thevenin equivalent impedance. So, therefore, so net Thevenin equivalent impedance will be j z c tan beta L by 2 in parallel j z c tan beta L by 2. So, which is equal to half of j z c tan beta L by 2. So, that is what the Thevenin equivalent impedance. That is what the Thevenin equivalent impedance. Now look at, we already determined the Thevenin equivalent voltage. We also now determined the Thevenin equivalent impedance. So therefore, we can convert this circuit to a Thevenin equivalent form. So we can convert, so this circuit in Thevenin equivalent form will be something like this.

Again, we consider this is a balanced three-phase circuit. We are, this is of course the single line diagram of this three-phase transmission line. So, I am also drawing the single line diagram of this Thevenin equivalent form. So, this is Thevenin equivalent voltage. This is Thevenin equivalent impedance. And this is what this SVC bus, where the SVC is placed. Now, we know that this is equal to V Thevenin, this is Z Thevenin and this is the SVC bus. Now, here we have the SVC connected. So, here we have the SVC connected. So, this is what let us see SVC or we generally can represent this SVC in terms of a variable susceptance the way we do.

So, this is a variable susceptance B SVC. And that is the representation of SVC. And usually what is done is that by using, by varying this susceptance of this SVC, so this is basically represent the SVC by varying the susceptance of SVC, we will be maintaining the voltage at the SVC bus to a desired value that can be a constant value or that can be within a allowable range, this we will see. And what we will do is here, this is basically representing this V SVC, it measures the V SVC bus voltage. And here we have some comparator where we will feed this V reference voltage and then we will have the appropriate controller. It is this controller and which will be used to adjust this SVC susceptance that is what the main task is. So, this is what the Thevenin equivalent form of the symmetrical long transmission line where this SVC is placed. So, once we determine this Thevenin equivalent form, this is Thevenin equivalent form of SVC compensated transmission line. We will be using this Thevenin equivalent form to describe the control functionalities of the SVC.

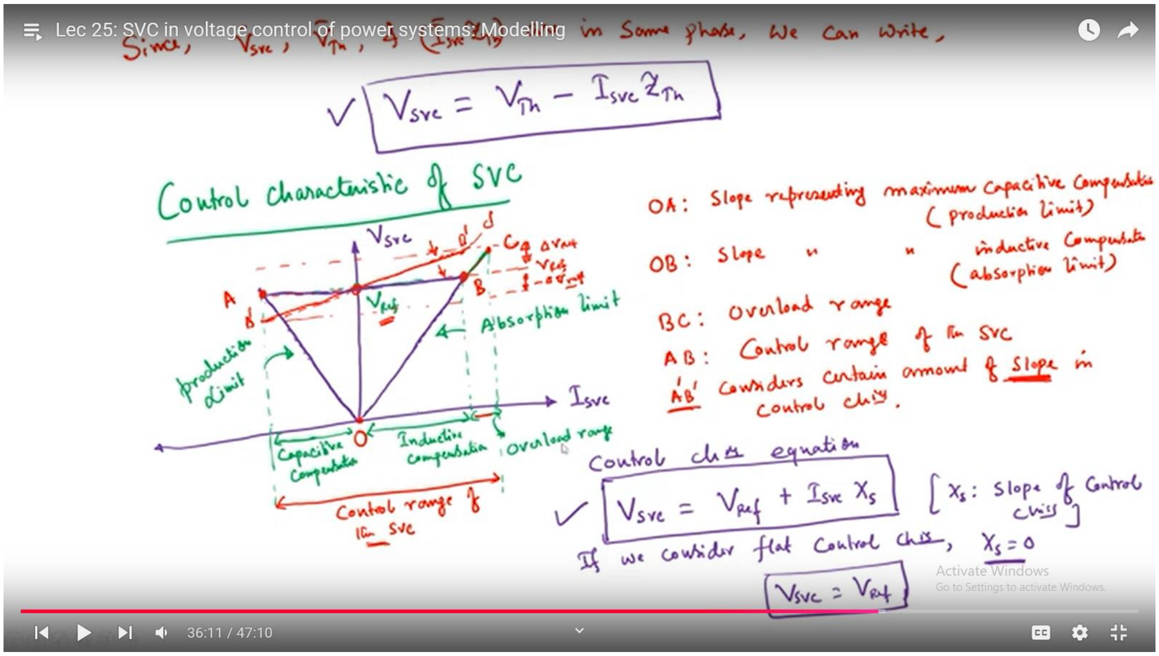
So that is what it is actually. So that is what it is actually. Now one thing also I tell that what would be the relationship of this Thevenin equivalent voltage with this SVC voltage. Suppose, the voltage at this bus is V S V C, V S V C and the current drawn by this is basically I S V C current drawn by this is basically I SVC. We have separate loads, the load current and SVC current are basically different. We have separate load, but here we, whatever the current drawn by this SVC that I am writing over here.

Now, if we apply Kirchhoff's voltage law, KVL rather, by applying KVL, what we will get? We will get the equation V SVC, V SVC that means the voltage across this SVC bus. So, this is equal to V th minus Z th I SVC. So, where this V SVC is the voltage at the SVC bus or the point where SVC is located V Th represents the Thevenin equivalent voltage of the line, equivalent voltage of the line and Z Th is basically Thevenin equivalent impedance of the line seen from SVC bus. So, that is what the thing is.

Now, this is what the KVL equation. If you look at this Thevenin equivalent circuit, if we apply KVL, so this is the voltage or Thevenin equivalent voltage source. So, this subtracted by the drop happens at the Thevenin equivalent impedance will represent at the SVC. So Vth minus this Isvc multiplied by Zth will represent the Vsvc. Now the question is what would be the phase difference of Vsvc and Vth? So since we already assume that this SVC is lossless, we already assume that SVC is lossless, so therefore what would be the, this phasor difference between VSVC and ISVC? So, if VSVC represents VSVC at an angle 0, then ISVC will represent ISVC at an angle plus minus 90 degree or pi by 2, plus minus 90 degree or pi by 2. This is already as we know, it is having some J operator.

So, it is having some magnitude, Z TH magnitude along with this 90 degree phase shift is there. So, that means, there will be J operator at the JTH, there will be J operator at the ISVC as well. Now, when we have multiplication of 2 J operator, it will give you j square that is minus 1. So, that means, this will be, this particular quantity will be having same phase with the VSVC. So, therefore, we can see that this VSVC, VTH and ZTH as ISVC will be in same phase. So, therefore, there is no need of the phasor representation. We can remove this phasor representation because they are in same phase. So, therefore, we can write, since Vs, Vc, Vth and Is, Vc multiplied by Zth are in same we can write the following equation, which is this Vs Vc is equal to Vth minus Isvc Zth. So, this we can write directly. So, why we can write this without having this phasor relationship, because they are in same phase, already I have explained in the last page.

So, once it is done, then next thing is to understand the control characteristics of SVC. So, let us discuss the control characteristic of SVC. Now, what is control characteristics of SVC? Again, we go back and plot this V SVC ISVC characteristics, which is already taught in the SVC module in very detail. And this plot looks like this. We have a absorption limit, we have a production limit like this, this is absorption limit, this is production limit, this axis is representing this ISVC, this axis is representing VSVC. And as we know this is the absorption limit, this is the production limit. So, this is the zone where it will operate as an inductive compensation. This is the point where it will act as a, this is the zone where it will act as a capacitive compensation. And this inductive compensation can be a little bit of extended. Suppose this is what our reference voltage is, this is our reference voltage is, this point is representing V reference. So, above this V reference, this inductive compensation or this absorption limit can be little bit of extended and this range is called overload range.



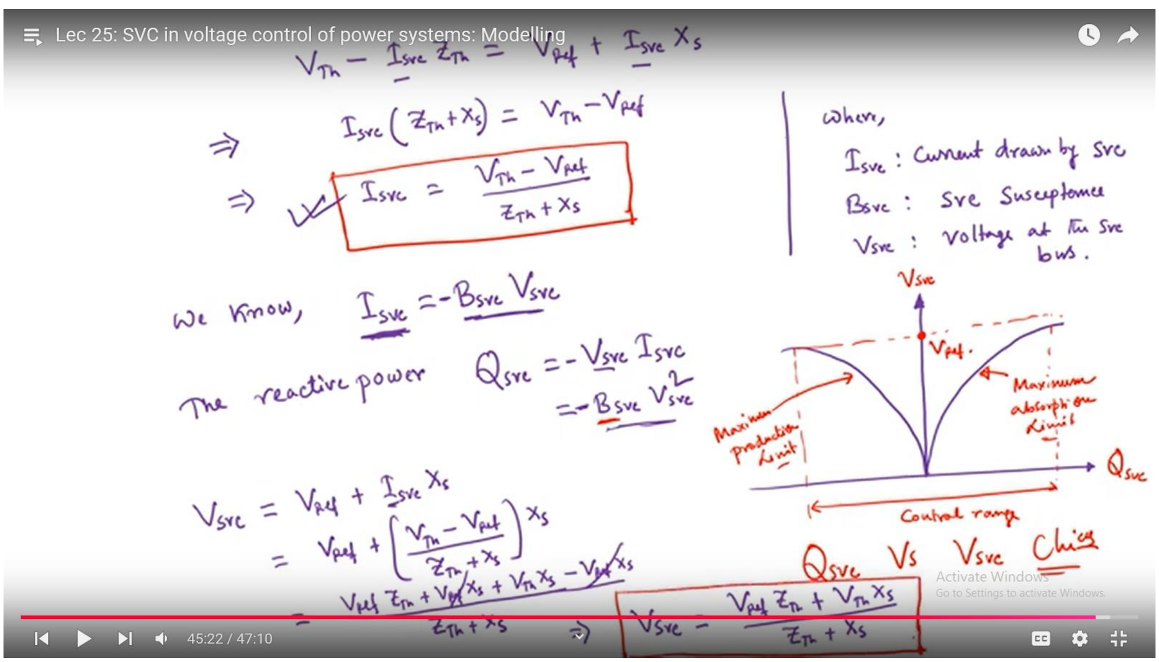
From here to here this range is called the control range of the SVC. This range is called control range of the SVC. This range is called control range of the SVC. Now, what is, what do you mean by the control range? The significance of the control range is that within this particular range, if this SVC is operated, it can effectively maintain the midpoint voltage constant at the reference voltage, according to these characteristics, these flat characteristics. So, if your system characteristics fall within this control range of the SVC, then it will be able to maintain the constant voltage at the SVC bus or at the midpoint of the line, wherever the SVC is placed.

That is what the purpose of the control range. So, suppose this point we consider point O. this point we consider point B, this point we consider A, point A, this point we consider point C, then what we can write is OA is representing slope representing maximum capacitive compensation. So, that is basically production range, production limit. OB basically represents slope or OB represents this slope representing maximum inductive compensation so that is the absorption limit and BC is basically representing the overload range. In maximum inductive compensation, considering that this inductor or reactor can withstand a certain amount of overloading, then we can extend the control range up to this, up to BC.

So this is basically representing overload range. And this A to C is basically representing or A to B it is basically representing the control range. So, this is what the control characteristics of the SPC. These characteristics already we have seen in the case of TSC-TCR, in the case of FC-TCR, in the case of MSC-TCR, as well. And when we have you know TSC or fixed capacitor or even MSC that is mechanically switched capacitor, then only we will have a finite amount of production limit in addition to this TCR absorption limit. Now, from these characteristics, what usually is done, this control range is not considered as a flat, rather it is considering having a certain amount of slope. That means, instead of this AB flat characteristics, the characteristics are considered to be this A dash, B dash and then we have this usual, this range.

So, usually, the control characteristics of SVCs represent that. Now, what is the difference between these characteristics to these characteristics? Here you can see that this A dash, B dash, A dash, B dash consider a certain amount of slope in control characteristics. So, this slope is having some important functionality and why it is so I will explain in the next lecture. So, keeping this slope is having some important functionality instead of keeping this SVC voltage constant at this V reference we are accepting a certain amount of slope. When you are accepting a certain amount of slope that means we are accepting a certain amount of voltage deviation plus minus a certain amount of voltage deviation with respect to, suppose this is V reference.

So, this is some amount of voltage deviation del V reference and this is some amount of voltage reference minus del V reference. So, we are accepting a certain amount of over voltage and under voltage at this SVC bus, instead of keeping it constant always within the control range. And that is why this we are accepting a certain amount of slope. And what is the advantage of this, I will explain in the next lecture. So, once you do so, then we can write the control characteristics equation as V SVC is equal to V reference plus I SVC multiplied by XS, where XS is representing the slope of control characteristics.



Now, if we consider flat control characteristic. x s is equal to 0. So, therefore, V s, V c is always equal to V reference. V s, V c is fixed to a constant value that is V reference. If we consider there is no slope that is a flat characteristic which I have drawn earlier like this, the flat characteristic. But if we accept a certain amount of slope, this is what the control characteristic equation. There are many advantages of having this slope, which I will discuss in the next class or in the next lecture. Now, we have two equations, one is this, another is that, both are representing this V SVC. So, from these two equations, we can write V th minus I SVC Z t h, which basically represents this equation. This equation, if we equate with this equation, then we should write this is V reference plus I s v c X s. Now since ISVC and ISVC are common on both sides, we can bring them together.

So what we can write is ISVC multiplied by Zth plus Xs is equal to Vth minus V reference. Or ISVC is equal to Vth minus V reference divided by Zth plus Xs. This is a new equation I got. So this is another new equation we got. We will be using this to establish a certain relationship and we will also discuss the advantage of this SVC placement and that we will discuss in the next class. Now another thing that we should know from here is that we determine this VSVC, so this basically control characteristics of SVC is basically VSVC versus ISVC characteristics. Now, we also have Q SVC versus V SVC characteristics. Q represents the reactive power. How would be that characteristics? So, to find that, what we have to do is, we know V SVC is related with I SVC and V SVC.

So, I should write rather I SVC is equal to V SVC, V SVC. So, where I SVC is the current drawn by the I SVC, this SVC, V SVC is the SVC susceptance, V SVC is the voltage of the SVC. So, let us write, where I SVC is the current drawn by SVC, B SVC is the SVC susceptance, and V SVC is the voltage at the bus. Now, the reactive power drawn or delivery of the SVC will basically be equal to Q SVC which is equal to the multiplication of V SVC and I SVC. Now you can see this I SVC can be positive, can be negative. We consider this negative sign in this particular equation to bring this capacitive current or capacitive compensation current in the left-hand side of the control characteristics and the inductive compensation current to the right-hand side of the control characteristics.

$\bar{V}_{SVC} = \bar{V}_{th} - \bar{I}_{SVC}X_{th}$

Where, $\bar{V}_{SVC} =$ Voltage at the SVC bus

$\bar{V}_{th} =$ Thevenin equivalent voltage of the line

$X_{th} =$ Thevenin equivalent impedance of the line.

Since, $\bar{V}_{SVC}$, $\bar{V}_{th}$ and $\bar{I}_{SVC}X_{th}$ are in same phase, we can write,

$V_{SVC} = V_{Th} - I_{SVC}X_{th}$

$V_{SVC} = V_{ref} + I_{SVC}X_S$

$V_{ref} = V_{SVC}\ when\ I_{SVC} = 0$

$X_S = slope\ of\ the\ control\ characterstic$

$V_{ref} + I_{SVC}X_S = V_{th} - I_{SVC}X_{th}$

$I_{SVC} = \frac{V_{th} - V_{ref}}{X_S + X_{th}}$

We know, $I_{SVC} = -B_{SVC}V_{SVC}$

The reactive power, $Q_{SVC} = -I_{SVC}V_{SVC}$

$= -B_{SVC}V_{SVC}^2$

$V_{SVC} = V_{ref} + I_{SVC}X_S$

$V_{SVC} = V_{ref} + X_S\left\{\frac{V_{th} - V_{ref}}{X_S + X_{th}}\right\} = \frac{V_{ref}X_S + V_{ref}X_{th} + X_SV_{th} - X_SV_{ref}}{X_S + X_{th}}$

$V_{SVC} = \left(\frac{V_{ref}X_{th} + V_{th}X_S}{X_S + X_{th}}\right)$

Where, $V_{ref} =$ Reference set point for SVC.

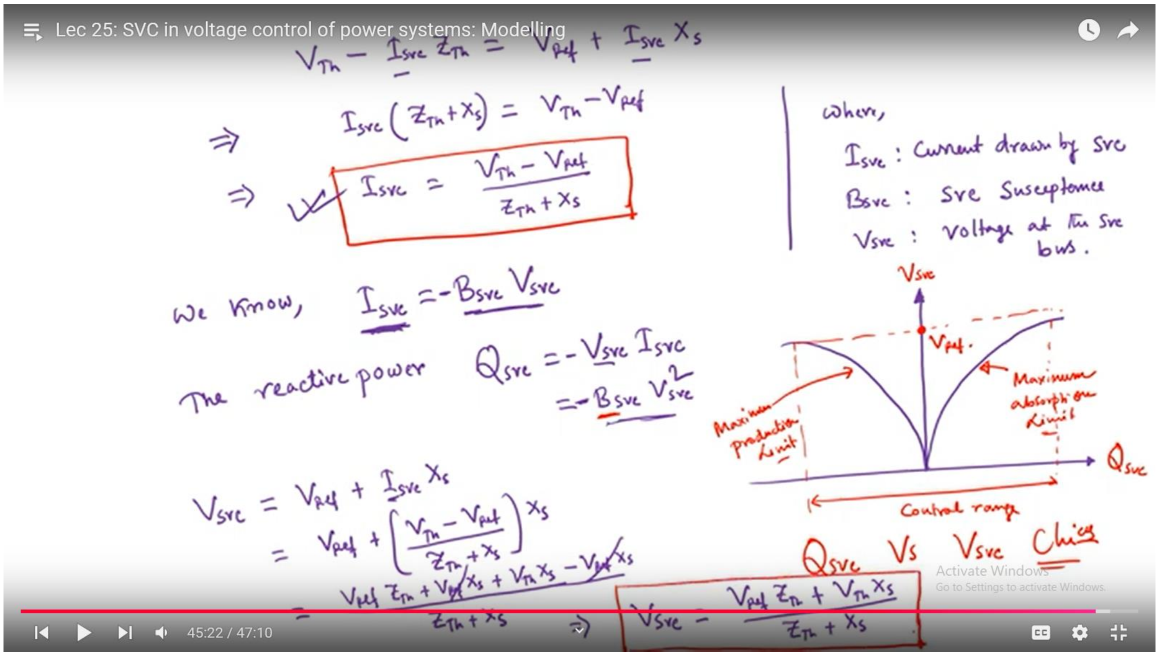
$V_{th} =$ Thevenin equivalent voltage of the line.

$X_{th} =$ Thevenin equivalent impedance of the line.

$X_S =$ Slope of the control characteristics.

We are ignoring this over here just to get a mathematical relationship of this QSVC. Now, here you can see that if we multiply this VSVC with ISVC, so this QSVC characteristics will be VSVC square. So, when you have so, then how would be the plot of this would be, in fact you may consider this is negative, so then this would be also negative, this would be also negative, but you know that when BSVC is positive, BSVC is positive when it is a capacitive compensation, BSVC is negative when there is an inductive compensation. So, therefore, the same equations will hold. Now, we know this is a straight line relationship passing through origin.

This is already we explained in these characteristics as well. And we also have explained in previous lecture. So, in reference to that, these characteristics will be varying proportionally to the square of the voltage. So, therefore, the characteristics will be something like this. So, this is suppose the control range, this is suppose the control range, this is you this is equal to Q SVC, this is equal to V SVC and this is suppose the V reference, this is suppose V reference. So, this is what the change of this control is, so this basically represents Q SVC versus V SVC characteristics which can be understood from this equation.



Now, as we know this VSVC is positive in the capacitive range, so therefore QSVC is negative. So, this is what the maximum production limit. Now, similarly this is what the maximum absorption limit. So, this is one thing that we will learn. Another thing I will discuss before I finish this lecture, that is from this ISVC characteristic plot, we know that V SVC, in terms of the control characteristics is basically V reference plus ISVC multiplied by this Xs, where Xs is the slope of the control characteristics which I explained over here. So, Xs is basically the slope of the control characteristics, the slope of the control characteristics.

So, therefore, if I put this ISVC expression from this particular expression, so what would be the modification of this control characteristic equation? So, that is V reference plus V Thevenin minus V reference divided by Z Thevenin plus Xs multiplied by Xs. From this, what we can write, so denominator we have z Thevenin plus Xs, the numerator would be V reference multiplied by z Thevenin plus V reference multiplied by X s plus V Thevenin multiplied by X s minus V reference multiplied by X s. So, V reference multiplied by X s and would be canceled out. So, this would be equal to, so we can write V SVC will be equal to V reference multiplied by Z Thevenin plus V Thevenin multiplied by X s divided by Z Thevenin plus X s, Z Thevenin plus X s. This equation would be useful in deriving then some of the equations which would be useful to explain this SVC characteristics in more detail manner by doing so.

So, this is what an important equation that we will be using in the next lecture. So, in the next lecture, what we will see, we will discuss the reason behind having a finite slope or finite value of xs or non-zero value of xs in a control characteristic. This is one thing that we will discuss. This is having an important idea behind it. There is an important practical consideration behind this, there is an economic consideration also behind this, those things I will discuss.

Also, I will discuss the significance of these equations and this equation, as well. In particular, the determination of this power flow which are going to be changed due to the SVC placement. So that is these things also I will discuss in very detail in the next lecture. Till then let me thank you for your attention in today's lecture. Thank you very much for joining once again. Thank you.