Course Name: Power Electronics Applications in Power Systems

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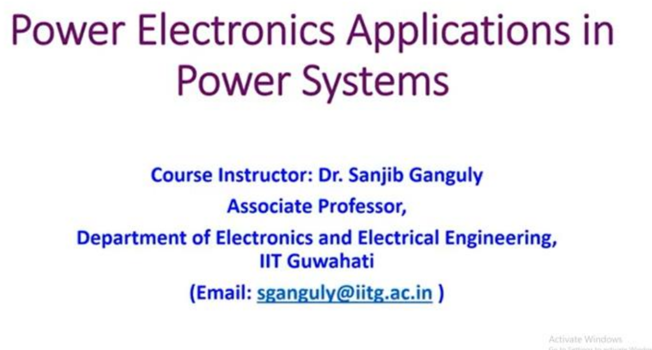


Lec 21: SVC in enhancement of steady-state power transmission capacity

So welcome again to my course Power Electronics Applications in power systems. In the last few lectures, I discussed different types of static power compensators. Now what is static power compensator? It is a kind of power electronic based reactive power compensator which can be used to absorb the reactive power from the system which also can be used to deliver the reactive power into the power system. Now this is a kind of reactive power compensation and this facilitates various aspects of power systems operation in an efficient manner. So in this particular lecture I will start the next module which is the application of static var compensator in power system. And basically I will discuss that in which way the application or usage of SVC can be helpful in power system operation in an efficient manner.

So, let us proceed. So, the topic of this lecture is SVC in or rather SVC applications in power systems. So, there are various applications of SVC in power system. I will discuss them in one by one. So, what is the first application? So, what SVC can do is, SVC can increase the steady state power transmission capacity. So, I will show you in comparison with an uncompensated line. An SVC compensated line can enhance the power transmission capacity of the transmission line. So, this is what the application of SVC in steady state behavior. So, SVC can also be used in dynamic aspect of power system in specially it can enhance or it can increase the transient stability.

SVC can increase the transient stability of power systems. So, this is the application of SVC in dynamics. Now, SVC can be used in damping power system oscillation which is a very important application of SVC. I will discuss this in very detail. This is again the application of SVC in dynamics. And lastly, but most importantly, SVC is used in voltage control of power systems. In fact, this last application, I will discuss in very detail in a different module in the latter part of this lecture. So, these are the possible applications of SVC. We will start with the first you know the application of SVC which is to increase steady state power transmission capacity of a power system. So, let us write that SVC in enhancing the steady-state power transmission capacity.

For long line model,

$$P = \frac{V_1 V_2}{Z_c sin\beta l} \sin\delta$$

Where, $Z_c = \sqrt{\frac{L}{C}}$

For short line, $sin\beta l \approx \beta l \approx \omega\sqrt{LC} \times l$

$$P = \frac{V_1 V_2}{\sqrt{\frac{L}{C}} \times \omega l \sqrt{LC}}$$

$$P = \frac{V_1 V_2}{\omega L l} sin\,\delta$$

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

The theoretical steady state power transfer capacity limit corresponds to $\delta = 90°$

Thus, $\Rightarrow P_{max} = \frac{V_1 V_2}{X}$

Compensated line

For a midpoint SVC compensation, the power transfer capacity will be $P_c = \frac{V_1 V_m}{\frac{X}{2}} sin\frac{\delta}{2}$

$$\Rightarrow P_c = \frac{2V_1 V_m}{X} sin\frac{\delta}{2}$$

The theoretical power transfer capacity limit for a mid-point compensated line,

$$(P_c)_{max} = \frac{2V_1 V_2}{X} = 2P_{max}$$

To have the enhancement of theoretical power transfer capacity, SVC needs to provide the following reactive power compensation.

$$Q_v = 2Q_m = 2 \times \left[\frac{V_m^2 cos\frac{\beta l}{2} - V_m V_s cos\frac{\delta}{2}}{Z_c \sin\frac{\beta l}{2}}\right]$$

For short line, $\frac{\beta l}{2} \approx 0 \Rightarrow cos\frac{\beta l}{2} \approx 1, Z_c \, sin\frac{\beta l}{2} \approx \frac{X}{2}$

$$Q_v = 2 \times \left[\frac{V_m^2 - V_m V_1 cos\frac{\delta}{2}}{\frac{X}{2}}\right]$$

$$V_m = V_1 \Rightarrow Q_v = \frac{4V_1^2}{X}\left[1 - cos\frac{\delta}{2}\right]$$

For symmetrical line, $V_1 = V_2 = V$

$$\Rightarrow (Q_v)_{max} = \frac{4V^2}{X} = 4P_{max}$$

Now to understand that we will take two different systems, one is an uncompensated transmission line, another is a compensated transmission line. Now suppose this is a representation of a short transmission line connected to an infinite bus. It is a kind of single-machine infinite bus system where this voltage is represented by V 1 at an angle delta. This voltage is represented at V 2 at an angle 0 that is the reference voltage. So, we assume that our assumption here is, our assumptions here is that this line is lossless which we used to take then second is it is a kind of short line.

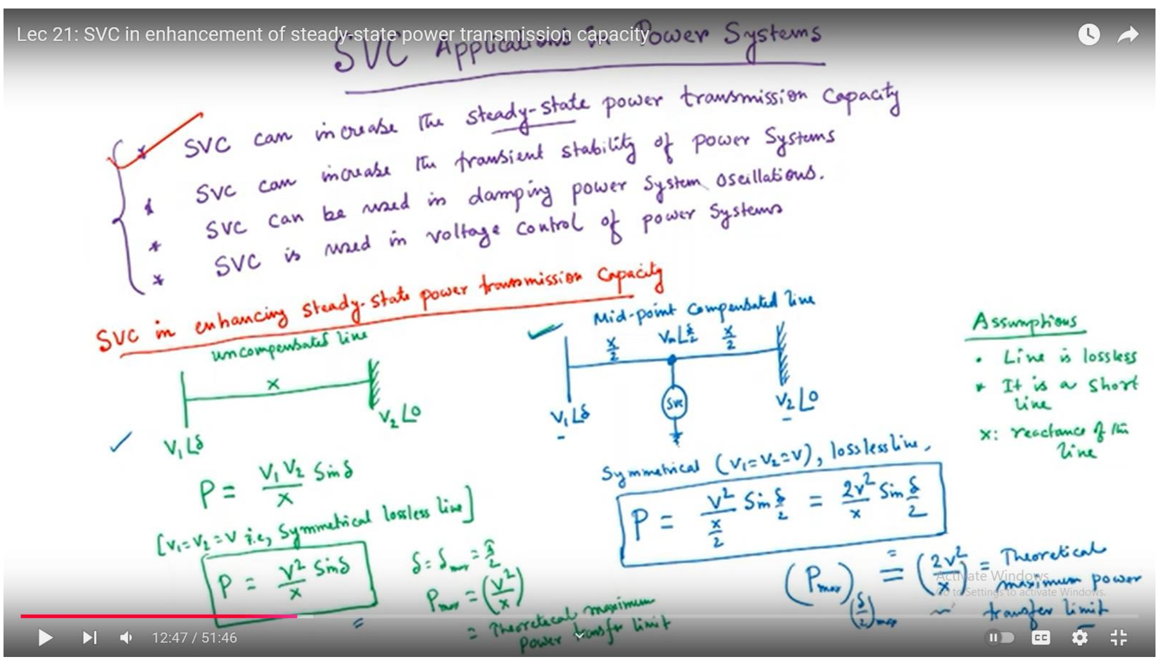
So, these are our two assumptions. So, here this is an uncompensated transmission line whose reactance is considered to be X. So, X is the reactance, X represents the reactance of the line. Now, we also take another case where we have a compensated, midpoint compensated transmission line. This is a midpoint compensated line.

So here, suppose this is the sending end voltage similar to this uncompensated line, it is represented by V1 at an angle of delta and this is the infinite bus bar to which this line is connected. This voltage is V2 at an angle of 0 and at the midpoint of this, we have a SVC connected. So, this divides this transmission line into two part and the reactance of these two half of the transmission line is represented by half of the total reactance of the uncompensated line. So, this is the midpoint where the voltage is Vm and the angle is as, we know it is some, there would be some angle if we consider that the line to be symmetrical that is V1 is equal to V2. Then Vm would be equal to delta by 2, Vm angle of Vm would be delta by 2.

But let us consider this is having an angle which is delta by 2 considering that it is a symmetrical lossless short transmission line model. Okay. Now, what would be the expression of power for this particular case, already we have derived for this particular case, since the line is lossless. So, the expression of power, active power would be equal to v1, v2 divided by x multiplied by sin delta. Now if we consider v1 is equal to v2 is equal to v that is symmetrical lossless line, then this expression would be equal to v square divided by x sin delta.

So this already we have derived. Now, similarly, we also consider for midpoint compensated line, this it is a symmetrical line. So, therefore, for a symmetrical lossless line, symmetrical that means v1 is equal to v2 is equal to v comma lossless line. The expression for active power would be equal to this v square divided by x by 2 multiplied by sin delta by 2. So, which means that it is equal to 2 v square by x sin delta by 2.

So, this is what the expression of active power of the midpoint compensated line. So, this is what the expression for active power for uncompensated line and this is what the expression for active power for symmetrical lossless midpoint compensated line. And we can see that there is a difference. In particular, corresponding to delta is equal to max that is delta is equal to delta max which is equal to pi by 2, this P max is equal to that is what the theoretical maximum power transfer limit is equal to this. So, this represents theoretical maximum power transfer limit. Whereas, for the same for the symmetrical midpoint compensated line, P max corresponds to the delta by 2 max which is equal to 180 degrees. So, it corresponds to 2 V square divided by X. So, this is what the theoretical vertical maximum power transfer. So, now look at the difference between this and this. So, one is v square by x, another is 2 v square x. That means the theoretical maximum power transfer limit of a midpoint compensated line becomes twice of the theoretical maximum power transfer limit of a uncompensated line with identical length.



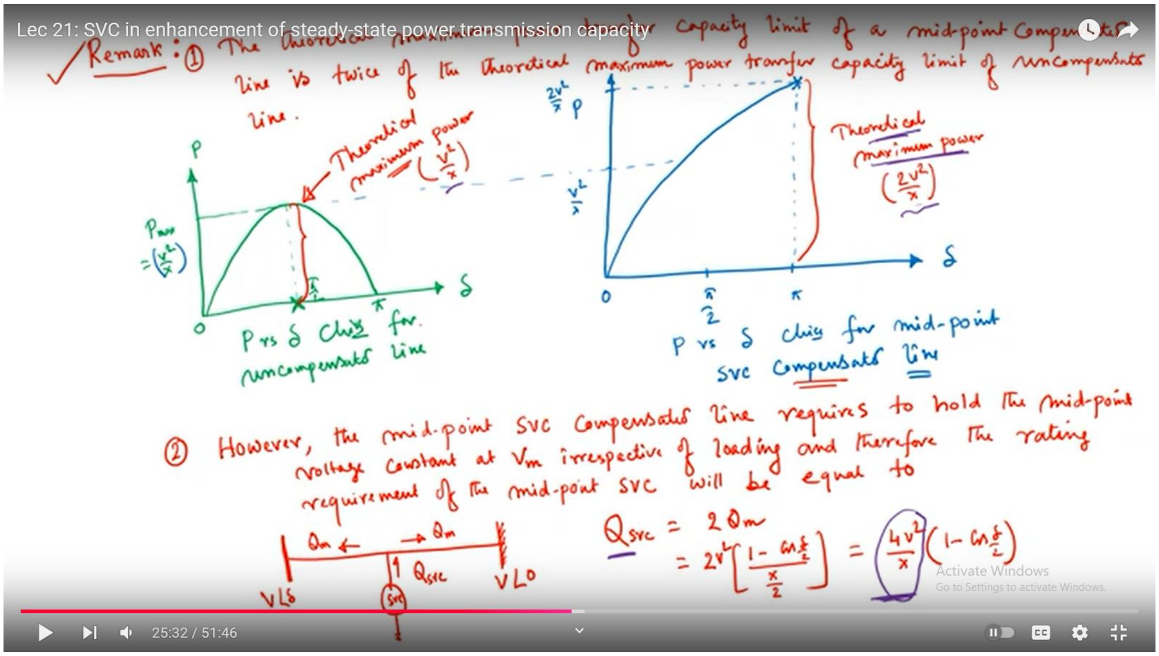
So, let me write this in a comment remark. So, our remark for this case study is that the theoretical maximum why I am calling it a theoretical maximum because you know the steady state power transfer capacity corresponds to the maximum possible angle of this delta that is load angle and that corresponds to delta is equal to pi by 2. So, that is what it is the theoretical maximum power transfer capacity limit of a midpoint compensated line, the midpoint compensated line is twice of the theoretical maximum power transfer capacity limit of the uncompensated line. This is our first remark. But remember, this is not in general the comparison of the power transfer capacity, power transfer flow or power flow of this compensated line and uncompensated line.

But we are comparing here the theoretical maximum power transfer capacity limit of a compensated midpoint compensated line, which is SVC compensated at the midpoint and an uncompensated line. So, this is what the important point that you can note down. Now, we can also plot this power plot of this uncompensated line and midpoint compensated line. So, the plot of these two would be something like that. So, suppose this is p, this is delta and this is the representation of power flow which is equal to this, this is basically equal to P max, P max which is equal to V square divided by x.

So, this is P versus delta characteristics, P versus delta characteristics for uncompensated Now, in comparison to that, how would be the plot of this P versus delta for compensated So here you know that this is the maximum power, theoretical maximum power and this corresponds to when delta is equal to pi by 2. So this is delta is equal to 0, this is delta is equal to pi. So theoretical maximum power corresponds to delta is equal to pi by 2. So, similarly, if suppose if we want to plot this power versus delta characteristics for this, now let us increase this. So, suppose this is, this corresponds to v square by x.

So, and this corresponds to 2 v square by x and suppose this corresponds to 0 pi by 2 and pi. Then you know that the theoretical maximum power transfer capacity for this SVC compensated line would correspond to the delta being equal to pi because you know here this delta by 2 should be equal to pi by 2 for maximum power for p is equal to p max. So delta should be equal to pi for p is equal to p max for this particular line which is having a midpoint SVC compensation. Now if we plot this, these characteristics will be something like this. So, this is what this P versus delta characteristic for SVC for the midpoint SVC compensated line.

So, this is what the difference of these P versus delta characteristics or power flow characteristics. It is often called as a power flow characteristics of a compensated line and an uncompensated line. This is what the difference. So, here this you can see that this is what the theoretical this is what the theoretical this is what the theoretical maximum power and here this is basically the theoretical maximum power which is twice of twice of the theoretical maximum power of the uncompensated line. If it is v square by x, then this is equal to 2 v square by x.



So, this gives the justification how a midpoint compensated line, or rather I should say for precise terminology that for a midpoint SVC compensated line, the theoretical maximum power transfer capacity is increased to twice of that of the uncompensated line. So, this is what the remarks we have shown are. However, this will occur, that is our second remark, suppose this is our first remark, the second remark will be, however, the theoretical. However, the midpoint SBC compensated line requires to hold the midpoint voltage midpoint voltage constant at V m at V m irrespective of loading irrespective of loading and therefore, the rating requirement of the midpoint SVC will be equal to this. So this is something like this, we have this sending end bus and this is what this receiving end bus which is considered to be this infinite bus. So we consider this to be V at an angle 0, this is V at an angle delta and here we have a SVC connected.

So SVC needs to provide this compensation let us say Q SVC and that would be equal to 2 i sub q m, 2 i sub q m which is equal to 2 Q m and we know that this 2 Q m is basically equal to 2 V square if I put this V square outside 1 minus cos delta by 2 divided by this line reactance up to midpoint. So, that means this is equal to 4 V square by X multiplied by 1 minus cos delta by 2. Now, you look at this particular term which represents the maximum q s v c and this is 4 times of the v square by x. So, we need that much of this reactive power compensator rating for this particular SVC in order to achieve this theoretical maximum power twice of this theoretical maximum power of the uncompensated line. So, that means this to have this twice maximum theoretical power transfer capacity of uncompensated line, we require a compensator at the midpoint whose rating should be as high as 4 v square divided by x.

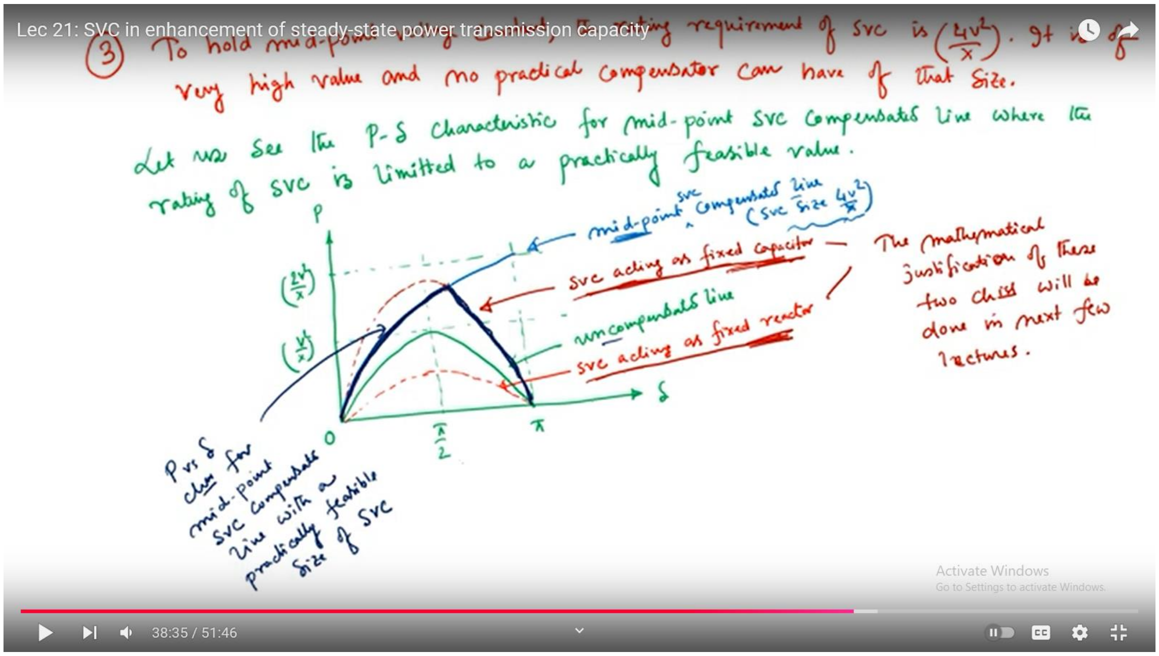
And this is pretty high, this is pretty high. And this size itself would be the main limitation to achieve this twice maximum power transfer capacity due to this midpoint compensation. So therefore, our third remark would be, remark 3 is to hold midpoint voltage constant, the rating requirement of SVC is 4 v square divided by x. So, it is of very high value and no practical compensator can have that much of that size can have of that size.

So, this is very important. So, already I have shown you in a numerical example when I discussed this midpoint compensation of a long symmetrical lossless transmission line that whatever this rating requirement of the midpoint compensator is to hold the midpoint voltage always constant irrespective of the different loading that is very high. Actually, if the rating is very high it would be very costly as well and no practical compensator with a reasonable cost will have such a high rated. So, therefore, we need to understand that although there is a possibility of that higher power transfer capacity enhancement, but midpoint compensation cannot ensure this twice of this, this is theoretical, theoretically it is possible but no practical compensator of a reasonable size and reasonable cost can achieve that, what I discussed so far. You have to understand that in that particular numerical example that I have discussed during that time when I discuss midpoint compensation that we need to limit the size of the compensator to a practical value. Then the question would be how would be then these P delta characteristics will get change.

So, this only I will discuss right now. And this will make sense that although there is an increase in power transfer capacity, but it is not possible to achieve the theoretical maximum power transfer capacity even with a midpoint compensator light, because it requires a very huge amount of or very high rated compensation, it requires a very huge amount of compensation or a very high rated compensator. So, therefore, so let us see. The P-delta characteristic for midpoint compensator for midpoint SVC compensated line, where the rating of the SVC is limited to a practically feasible value.

So, this is what we need to check. So, what I mean to say here is that although this is a representation of the P-delta characteristic for the uncompensated line and this is what the P-delta characteristic for the midpoint SVC compensated line. To achieve this theoretical maximum power twice of the theoretical maximum power of this uncompensated line, we need a compensator which is of very high size. Now, if it is not so, if the size is limited to a practical value, then how would be the p delta characteristics then? So, that is something we need to understand. So, then again we will plot this is suppose p delta characteristics, this is suppose v square by x and this is suppose 2 v square by x. This corresponds to delta 0 this corresponds to delta pi by 2 this corresponds to delta pi.

So, we know that this for uncompensated line the characteristics is like this ok. So, this is for this is this characteristics is for uncompensated line. Similarly, we also know that for midpoint compensated line with unlimited rating. So, this is the characteristic. So, this is the characteristics for midpoint compensated midpoint SVC compensated line, where SVC size is 4 v square by x.



Now since 4 v square by x is pretty high value, so we may not achieve these characteristics in a practically feasible SVC compensation. So therefore, these characteristics would get changed when we limit this midpoints compensation size. What will happen if we can remember that my last discussion on midpoint compensation that considers that a practically feasible midpoint compensator or practically feasible size of the SVC, then it will follow these characteristics, this midpoint SVC compensator line with unlimited size or high size, these characteristics as long as it reaches its maximum limit. And, then it will act as a fixed inductor or it acts as a fixed capacitor. Now, how would be the characteristics of this midpoint compensated line, when you have a midpoint fixed inductor or fixed reactor and midpoint fixed capacitor.

This is something you need to understand and this is we need to plot. Eventually, this expression will derive in the latter part of this lecture or the next lecture, but this we can predict right now. So, when this SVC will act as a fixed inductor, then characteristics midpoint cap, then p delta characteristics will be like this. So, this corresponds to SVC acting as fixed reactor. Similarly, when this SVC will act as a fixed capacitor, the characteristics will be something like this.

So, this is characteristics of this midpoint SVC compensated line, where SVC acting as fixed capacitor. Now, I will mathematically justify these two characteristics in the latter part of this lecture. So, the mathematical justification of these two characteristics will be done later, will be done in the next few lectures. You have to understand that these are the characteristics when SVC, both the characteristics correspond to the midpoint SVC compensated line, but these characteristics will be, will happen when SVC will be acting as a fixed capacitor, these characteristics will happen when SVC acts as a fixed reactor. So, if you can remember my discussion in this midpoint compensation with a numerical example, so what actually will happen is for midpoint you know compensated line with a finite or practically feasible size of the SVC, actual characteristics will follow these characteristics till this point when it hits this limit and then beyond that it will follow the characteristics of the fixed capacitor.

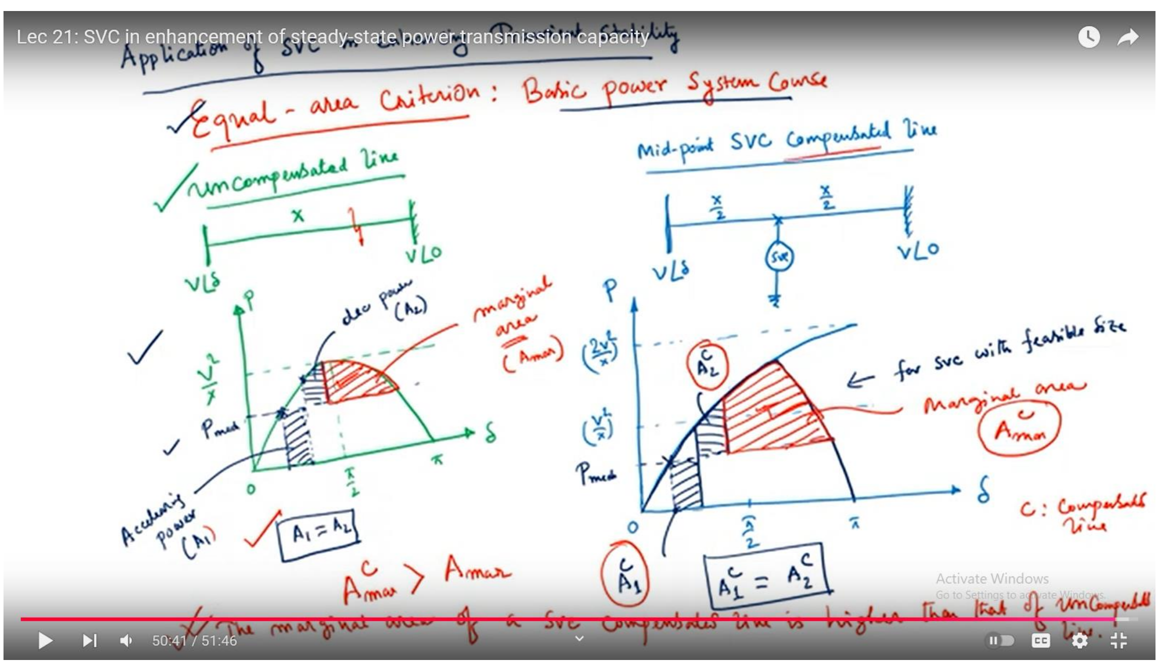
So, therefore, the actual plot of this P-delta characteristics will be like this, this, and this. So, I will increase the breadth of this line like this. So, this will be, this will be the P versus delta characteristics for midpoint SVC compensated line with a practically feasible size of SVC. So, the characteristics definitely is above the uncompensated line, but it will not follow this midpoint compensated line rather this will follow this. And, this illustrates that although for a practically feasible size of the SVC for an SVC compensated line, the characteristics would not be as it were for theoretical, theoretically maximum power limit of the midpoint compensated SVC line with SVC size is 4 v square by x.

So, it will not be following this blue characteristic ever, but it will be this black characteristic when the size is limited to a practically feasible value. This is something one needs to understand and this is very important to understand because this gives some sort of assessment when you or some sort of understanding when you talk about this transient stability enhancement using SVC. So, next what we will learn over here is that we will learn the application of SVC in enhancing transient stability. So, now what do you mean by transient stability? What do you mean by Stability? It means the ability of a power system to remain in synchronism even if it undergoes or even after any sort of disturbance like a fault in a power system or maybe that is a very high load change or something like that for a major disturbance. And whatever the disturbance might be we can show that SVC with the SVC compensated line the transient stability is somewhat improved.

Now, this we will do basically pictorially by considering the idea of the equal area criteria. To understand this one needs to have an idea of equal area criteria. So, this is taught in the basic power system course. This is usually taught in basic power system courses because I will not go into very detail of this equal area criteria, but I can show you that how an SVC compensated line can improve this transient stability and in order to understand this transient stability one needs to go for the understanding of equal area criteria. So, to do so what we will do is, let us consider an uncompensated line.

To do so, we need a single-line diagram. Here, suppose the voltage is v at an angle delta. Here, suppose this is connected to infinite bus. So, it is v at an angle 0. The line is represented by its reactance x. So, therefore, the p delta characteristics which are used in equal area criteria are something like that. Suppose this is representing v square by x which I already discussed and this is representing the p delta characteristic. This corresponds to theoretical maximum limit that is pi by 2, this is 0, this is pi. This is basically the p delta characteristics for uncompensated lines. Now, what actually happens if there is any fault on this particular line, suppose there is a fault in a particular line and the fault is of transient type. So, what actually happens, suppose this is the operating point.

This is the operating point. This corresponds to this mechanical power that is PMEC. So, you know that operating point for a lossless transmission line assuming that there is no inherent damping we are ignoring the losses. So, there would be no damping on the system that means we are ignoring the damping as well. So, this is what the operating point of this particular system. Now, when the fault happens, what actually happens? This electrical power becomes zero, but still this mechanical power will be intact. So, what will happen? There is an increase of delta or that means the machine will run in a higher speed. And suppose at this particular point, this fault is cleared. So, then at the corresponding to this value of delta, this is what the operating point, but still the delta angle will increase because it is in accelerating mode and it will keep on increasing till area, which is called acceleration area, which is the area for which this mechanical power was along operating in a synchronous generator. So, this is what called accelerating power is equal to this area, which is called decelerating power.



It is called accelerating power. So, suppose this area is represented by A1 and this area is represented by A2. So, A1 should be equal to A2 in order to fulfill this equal area criteria. That is what is called equal area criteria. And this is actually well known if you understand the basic power system. Now, this in this particular diagram, this area is the area which is having an importance. So, this area which is the area after this decelerating power is taken up. So, this area is called marginal area. And, if this marginal area is 0, then this equal area criteria will never be met. So, therefore, this particular system will never be stable.

So, that is what we know. Suppose, this marginal area is represented by A margin. Let us see what would be the case when we have an SVC or midpoint SVC compensated line. So, suppose this is what this midpoint SVC compensated line similar to this previous uncompensated line only difference is that where here we have a compensator which is SVC connected at the midpoint which makes the line divided into two part one is this part x y 2 another is this part and the voltage is as it is this is V by angle delta and this is V angle 0. Now, we will again plot this p delta characteristics for this line and to find out this equal area criteria similar to this uncompensated line. Suppose you know that here we have this is v square by x and suppose this is 2 v square by x.

So, suppose this is 0, delta is equal to 0. So, this is delta, this is p as we know. So, this is pi by 2, this is pi. So, for an unlimited compensator rating, the characteristic is something like this. But we eventually learn that for a practically feasible size of SVC, the characteristics will look like this. So, that means the actual characteristics of this would be something like this. It will follow this characteristic till it hits the maximum rating then it will follow the characteristics of what we call that fixed capacitor. So, these are the characteristics, P-delta characteristics for an SVC with a feasible size. So, for this is for SVC with feasible size. Now, suppose this is an operating characteristic similar to this.

So, this is what this P mechanical. So, this is what the operating point. Now, this is what the operating point corresponding to delta. Now, if there is a fault in the line, then again this similar to this case uncompensated line delta will keep on increasing till this fault is cleared. Suppose at this point fault is cleared. So, this will constitute this accelerating area for compensated line. So, this is what A1 for compensated line and then this would be for a 2 that is decelerating power for compensated line and we know this area under this accelerating power and decelerating area should be equal. But what is important to see is that here this becomes the marginal area or the margin for which we can if there is a fault then this fault can be mitigated. So, this area is the marginal area which is we can call it A mar C. Here C represents the compensated line. So, A1c is basically accelerating area for compensated line, A2c is the decelerating area for the compensated line and this marginal area is representing by ACMAR. Now, if you compare this area and this area, obviously which one is higher? This area is higher.

So, therefore, we can write this A marginal area for the compensated line is higher than a marginal area of uncompensated line. So, therefore, we can write the marginal area of an SVC compensated line is higher than that of an uncompensated line. So this is very important and that is how this SVC compensated line has more ability to improve the transient stability to accept the disturbance or to mitigate the disturbance during this faulty conditions or similar type of conditions. So this is something one needs to understand. So this we will revisit again in the next lecture and to try to understand this in more detail but I hope this is understood at this time being. So, we will meet again in the next lecture.