Course Name: Power Electronics Applications in Power Systems

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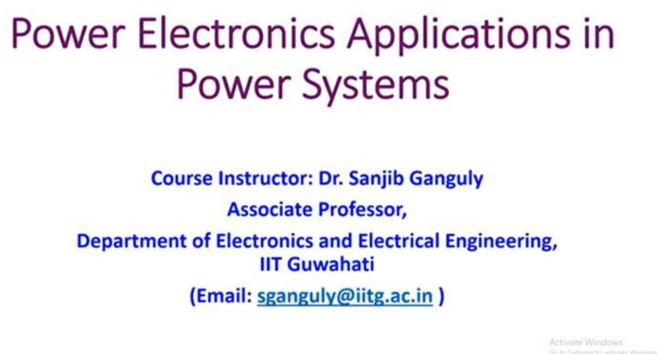


Lec 12: Numerical example of mid-point compensation: Part B

So welcome again to my course Power Electronics Application in power Systems. In the last class I discussed midpoint compensation of long symmetrical lossless transmission line right. And, I started solving a numerical problem and this numerical problem also I will continue in this particular lecture. So, let us have a quick recapitulation what we did in the last lecture. So, we discussed what midpoint compensation is. And, we also come out with the expression of this amount of compensation required at the midpoint to hold a given value of this midpoint voltage constant.

This is the amount of compensation required in order to maintain the midpoint voltage at this VMC line to line. So, this is what I discussed in the last class. And then I started this numerical problem If you look at this numerical problem, then you will see it is a problem of a symmetrical lossless long transmission line with these following parameters. These parameters are of this line inductance, line capacitance, line length, this nominal voltage level, frequency, etc. And, we have been asked to design a compensator to hold the midpoint voltage V to 1.05 per unit. So, here whatever I was talking about this Vmc line to line, so this one is basically this 1.05 per unit, considering that the line to line base voltage is 735 kV. Then what we did, we first determine this surge impedance, then surge impedance loading which is coming out to be 1954 megawatt.

And, we also determine the midpoint voltage Vm when there is at no load which is cos beta l by 2 that is 1 upon cos 29 degree around 1 upon cos 29 degree which is coming out to be 1.14 per unit. Now, this gives the information that there is around 14 percent overvoltage at the midpoint of the line at no-load condition. And, this is not acceptable actually. So, this 14 percent overvoltage at the midpoint of a transmission line is a huge amount in terms of this kilovolt.

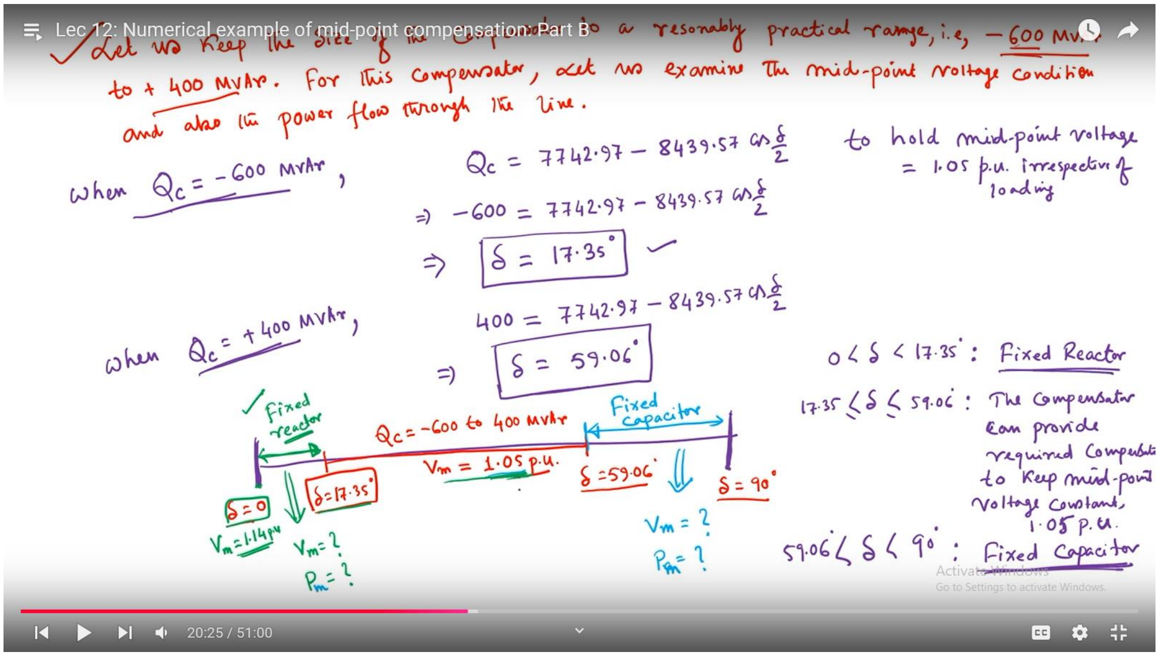
So, this is not acceptable. So, what is to be done is to mitigate this overvoltage. And in order to mitigate this over voltage and in order to this make the midpoint voltage constant irrespective of the loading and that midpoint voltage we are keeping constant at 1.05 per unit that is 1.05 times of 735 kV. So, what we did? We did design a compensator. And, this is what the compensator range or rating that we developed. And, if you look at this rating, this compensator rating is of course function of this delta. It means that it will vary according to this value of the delta. And as you know, this angle delta is the angle between the voltages of sending end to receiving end.

And this is what the angular difference of the voltage phasors of the sending end to receiving end. When we have so, this delta will vary according to the loading or according to the load connected at the receiving end side. So, when this load changes, the amount of compensators required to keep the midpoint voltage constant to 1.05 per unit is also varying. And what we come up with this that the range, the two extreme ranges of the compensator, one corresponds to the delta is equal to 0, another corresponds to the delta is equal to 90 degrees.

These ranges are very wide. One is minus 696 MVR, another is 7742.97 MVR. So, this is a quite wide range and no practical compensators with reasonable cost can provide such a wide range of compensation. So, it needs excessively high rated compensators and which will incur with excessive high cost of investment.

Now, in this lecture what we will do is that we will try to restrict this range in a reasonably practical limit. And then we will try to understand that under that conditions what would be the midpoint voltage under varying loading condition. So, the goal is, goal of this today's lecture is let us fix the size of the compensator to a reasonably practical range. That is minus 600 MVAR to plus 400 MVAR. So, our intention is to keep the size of the compensator to a reasonable range, so that the compensator would not be excessive costlier.

And then we will see what would be the midpoint voltage condition. So, for this compensator, let us examine the condition or midpoint voltage condition and also the power flow through the line. So, this is what we will learn today. So, if we keep the rating of the midpoint compensator to a reasonably practical range, which is considered to be minus 600 MVr to 400 MVr, then what would be its impact on this midpoint voltage conditions and also the power flow of the line. Now, we already determined the expression of this midpoint voltage.

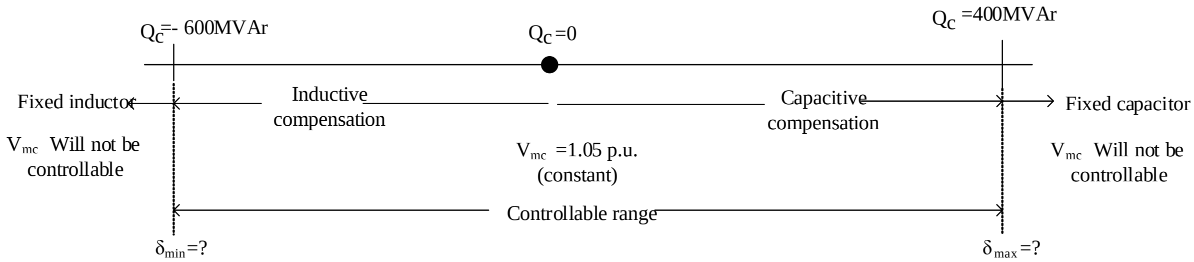


We also determined the expression for midpoint compensator rating, which is this. And from this expression, if we put this to extreme MVR limit, then we will come up with some value of delta. So that means, suppose when this compensator Q c, compensator rating is minus 600 MVAr, then what we can write is for this equation let me copy in this slide that is Q c is equal to 7742.97 minus 8439.57 cos delta by 2. That is what the rating requirement of the compensator that we derive to hold. Midpoint voltage equals to 1.05 per unit irrespective of loading. Now, when Qc is equal to minus 600, so we can write this is minus 600 is equal to 7742.97 minus 8439.57 cos delta by 2. If you solve this equation, you will get a value of delta. So, this delta we obtained as 17.35 degree. So, that means when the compensator rating is minus 600 MVR, the corresponding loading of this, according to this compensator compensation equation will come up with a value of delta is equal to 17.35 degree. Qc is equal to plus 400 MVAr. Then we will also put this 400 in this particular equation. So, we can write 400 is equal to 7742.97 minus 8439. 57 cos delta by 2. So, if you solve this, then we will come up with a value of delta is equal to 59.06 degree. This is according to my calculation. I hope this calculation is correct. Now we will get a value of delta corresponding to Q is equal to minus 600.

We also get a value of delta corresponding to Q is equal to plus 400. So, within these two values of the delta, it is assumed that the compensator can provide any any compensation required. Now, as I said, this delta is the load angle. Delta is the angular difference of the voltage between the sending end voltage and the receiving end voltage. And it is because of the angular difference, the power flows.

Range of practical compensator

Let us design a VAr compensator which can provide a reasonable range of compensation i.e. -600MVAr to 400MVr. So, the compensator will hold mid-point voltagw 1.05 p.u. and act as fixed capacitor or fixed reactor beyond its range. The range of compensation provided practical compensator is shown.



$Q_c = 7742.97 - 8439.57cos\frac{\delta}{2}$

For Q_v= $-$ 600MVAr

$\delta = 17.35^o$

Below this load angle, compensator will act as fixed inductor.

For Q_v= 400MVAr

$\delta = 59.06^o$

Above this load angle compensator will act as capacitor.

When loading corresponding to 17.35^o to 59.06^o the compensator can hold the mid-point voltage fixed at 1.05 p.u.

So power flow is basically controlled or changed by this variation of the delta. So this delta, that is why we call this delta as a load angle. So according to the loading at the receiving end or according to the change of the load, this value of delta will get changed. Now, the theoretical limit of this delta is 90 degree. So, let us consider that this is the variation of the delta according to the load and this is delta is equal to 0 and this is delta is equal to 90 degrees or pi by 2 which is the theoretical stability limit.

Now, with this compensator design what we get is that from this delta is equal to 17.35 degrees till the delta is equal to 59.06 degrees with this range of this compensator that is

Q c is equal to minus 600 to 400 MVR; 400 MVR will be capable enough to hold the midpoint voltage Vm constant at 1.05 per unit. So, whatever compensation is required for this variation of the delta starting from the delta is equal to 17.35 to the delta is equal to 59.06. That means during this amount of loading, which corresponds to delta 17.35 degree to delta 59 degree, the compensator can comfortably provide whatever compensation required to hold the midpoint voltage constant at 1.05 per unit. Now, what will happen when this delta will vary from this 0 to 17.35 and delta will vary from 59 degree to 90 degree? So, what will happen is, during this period of time, this compensator will not give the guarantee that it will be able to hold the midpoint voltage to 1.05 per unit, but it will act as a fixed reactor and thereby it will mitigate this over voltage to some extent, because you know that when delta is equal to 0 corresponding to this value of delta, this midpoint voltage is 1.14 per unit, which is around 14 percent higher than the nominal voltage. And since these values of this delta, starting from the delta is equal to 0 to the delta is equal to 17.35, this compensator will act as a fixed reactor. It will mitigate definitely some amount of overvoltage, but it cannot ensure that midpoint voltage would be remain constant to a desired value. In this problem, this value we consider to be 1.05 per unit. Now, during this period of time, when delta varies from 59.06 degree to 90 degree, this compensator will act as a fixed capacitor.

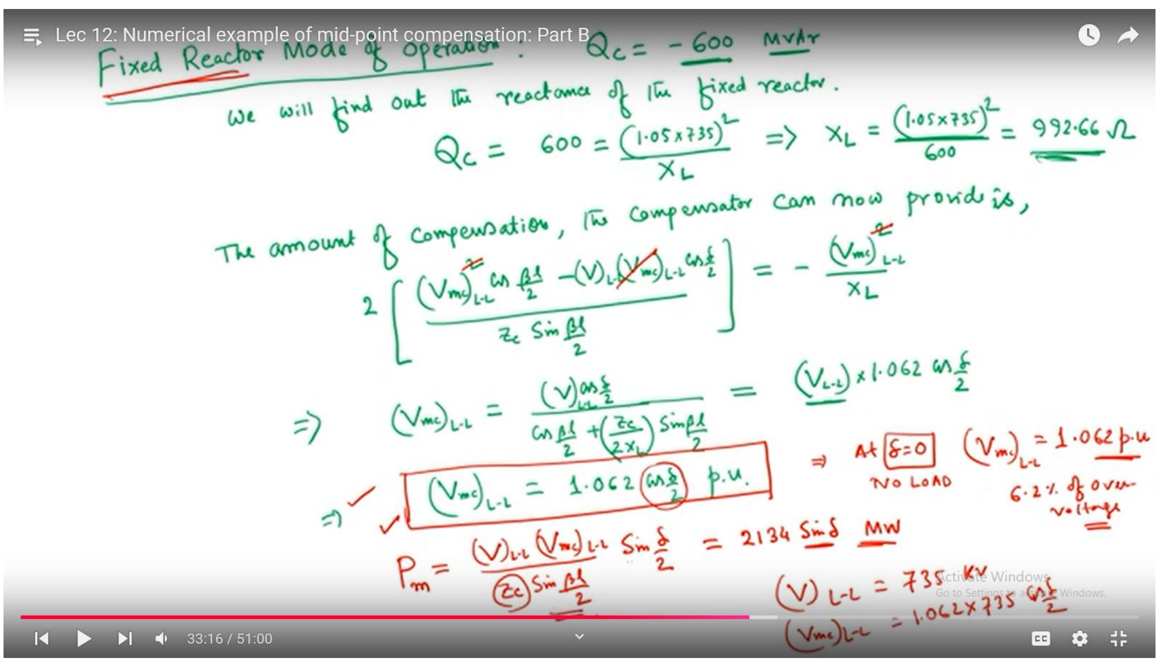
Thereby, it will, when we have a fixed capacitor at the midpoint, it will definitely mitigate some sort of under voltage. But it cannot guarantee that the midpoint voltage will always be remain constant to the desired value. In this problem, we consider that desired value is 1.05 per unit. Now, the question is, if it is so, then we will be curious to know that what would be the midpoint voltage condition during this period of time, when your compensator will act as a fixed capacitor, as well as when the compensator will act as a fixed reactor.

So, we will be curious to know what will be the midpoint voltage condition as well as what will be the compensated power during this fixed reactor range that also we will be interested to know. So, this is what we will be determining in this, this will be the midpoint power or the active power flow through the line because as you know that it is a, we assume that the line is lossless. So, whatever amount of power is flowing through the midpoint, the same amount will flow through the other part of the line also. So, now if we summarize what we have learned so far, what we can write is when the delta is equal to, the delta will be in between 0 to 17.35 degree, this compensator will act as a fixed reactor or fixed inductor mode.

When delta or I should not use a hard deadline, when delta will vary in between 17.35 to 59.06 the compensator will provide required compensation to hold to keep the midpoint voltage constant that is 1.05 per unit. And when delta will vary in between this 90 degrees to this 59.06 degrees, then it will act as a fixed capacitor mode. So, on this mode of operation, fixed capacitor and fixed reactor, the compensator cannot guarantee to hold the midpoint voltage to 1.05 per unit. So, I repeat this statement once again. So, when the compensator is operating at fixed reactor and the fixed capacitor mode, the compensator cannot guarantee that to hold the midpoint voltage constant.

Because, they will have some limited amount of compensation and they cannot provide the required amount of compensator to maintain the midpoint voltage constant. So, if we understand then, we will also determine what would be the expressions for midpoint voltage under these two modes of operation. So, now let us find out that what would be the voltage conditions when the compensator is operating at a fixed reactor mode. Fixed reactor mode of operation So, as we have seen that at this particular condition that this compensator will provide a fixed compensation of Q c is equal to minus 600 MVR irrespective of the loading. So, at this condition this Q c will be equal to minus 600 MVR irrespective of the loading.

So, at this particular condition, we can find out the reactance of the fixed reactor. So, what we consider here is that to find out, so we will find out the reactance the fixed reactor at this particular condition. So, in order to find out that, so let us find out what would be the expression of this, this minus 600 would be equal to the voltage square divided by the reactance. So, that is basically, if we just ignore the sign for this time being because we understand that inductive type of compensation is opposite to capacitive type of compensation.



So, it is negative. We will consider it later on. But in order to find out the value of the reactance, let us ignore this sign. And then what we can write it that this is equal to 1.05 times of this 735 kV voltage line to line divided by this xl. as we know this line-to-line voltage square divided by this reactance value is equal to the amount of compensation the fixed compensator can provide. So, from this, we can find out the value of x L is equal to 1.05 multiplied by 735 square divided by 600 which is coming out to be as per my calculation 992.66 ohm. So, that is what the reactance of the fixed reactor we obtain from this given value of the Qc. Now what we will do is, we know that since this compensation is fixed, now if the load is varying, it will not be able to maintain a fixed voltage.

Rather the voltage would be varying in nature. Now, what would be that voltage? This we will identify. Now, when this is the fixed compensation, so what we can write is that the amount of compensation the compensator can now provide provide is this is equal to 2 multiplied by Vmc line to line of course square cos beta l by 2 minus this is V line to line Vmc line to line cos delta divided by Zc sin beta l by 2. This is the expression that we obtain to determine the compensator rating and this is the same expression we have also used to determine the compensator rating that is this equation I am talking about. Then I will equate this equation with the voltage condition that is minus V m c line to line square divided by this x l that is So, I can find it out.

So, this 1.05 we consider that this Qc is providing minus 600 MVr and beyond that it will not be able to maintain this 1.05 per unit voltage at the midpoint. So, the voltage will get change and this Vmc itself will get change and we are interested to find out the expression of Vmc here. Now, if you look at this expression, so here you can see this from this particular equation, if you equate right hand side and left hand side. So, once Vmc, this Vmc and this one Vmc will be cancelled out, okay.

And then we will come up with a Vmc expression, now is Vmc line to line is equal to V cosine delta by 2. So, this is simply I just multiply this Zc sine beta L by 2 here and bring it to the left-hand side denominator, the numerator. So, then what we can write is that V cos delta by 2 multiplied by if you multiply this Zc sin beta L there in the both sides, then what we will get is cos beta L by 2 plus Zc 2XL sin beta L by 2. So, this is the expression that we get.

So, here V is line to line voltage. So, this is what the expression we get. Now, you know that here this cos beta l by 2 is known to us, z c is also known to us, x L already we determine the value of the x L and sin beta l by 2 is known to us. So, what we can find it out here from this particular expression, this if we consider, this is V line-to-line, then this is multiplied by 1.062 cosine delta by 2. So, therefore, we can write that the Vmc line to line for this case is 1.062 cos delta per unit because we consider that this V line to line is our base voltage. So, that is what the voltage condition now at the midpoint when the compensator works as a fixed reactor mode. Now, of course, if you look at this particular compensated voltage now, then you can see at delta is equal to 2, at delta is equal to 0. That means delta equal to 0 corresponds to the condition that the system is working at no-load condition.

Then the midpoint voltage Vmc line to line is equal to 1.062 per unit. It means that there is some amount of overvoltage, but which is much lower than this 14 percent of overvoltage, if we do not provide any compensator, which we obtained here in this particular time, that there will be 14 percent overvoltage at the midpoint at the no-load, when there is no compensator. At this condition, we assume that there is no midpoint compensator is there. Now, if you look at when we designed this midpoint compensator rating to maintain the midpoint voltage at always this 1.05 per unit during that required amount of compensation required was minus 696 MVR.

Q. What will be the mid-point voltage of the transmission line when compensator acts as fixed inductor?

- $\delta < 17.35^o$ ⇒At this condition overvoltage voltage will be observed and the compensator will act as a fixed inductor.
- The value of inductive reactance(X_L) at this mode is given by

$$X_l = \frac{\left(\frac{V_{mc}}{\sqrt{3}}\right)^2}{\frac{Q_C}{3}}$$

$$X_l = 992.663\Omega$$

The amount of compensation, the compensator can now provide is,

$$2\left[\frac{(V_{mc})_{L-L}^2 cos\frac{\beta l}{2} - V_{L-L}(V_{mc})_{L-L} cos\frac{\delta}{2}}{z_C sin\frac{\beta l}{2}}\right] = -\frac{(V_{mc})_{L-L}^2}{X_L}$$

$$(V_{mc})_{L-L} = \frac{(V)_{L-L} cos\frac{\delta}{2}}{cos\frac{\beta l}{2} + \left(\frac{Z_C}{2X_L}\right)\sin\frac{\beta l}{2}} = (V_{L-L}) \times 1.062 \cos\frac{\delta}{2}$$

$$(V_{mc})_{L-L} = 1.062 \cos\frac{\delta}{2}\ p.u.$$

At $\delta = 0$, $(V_{mc})_{L-L} = 1.062\ p.u.$

6.2% of over voltage

$$P_{comp} = \frac{(V)_{L-L}(V_{mc})_{L-L} sin\frac{\delta}{2}}{z_C sin\frac{\beta l}{2}} = \frac{735 \times \left(735 \times 1.062 \cos\frac{\delta}{2}\right) sin\frac{\delta}{2}}{276.4 \times sin\ 29.135°} = 2131.66\ sin\delta \text{ MW}$$

Now, if we keep the operating this midpoint, at this, at a fixed reactor mode, then we have come out with the expression of midpoint voltage is 1.062 per unit. That means, there is 2 percent overvoltage, percent of overvoltage is there, but that is less, that is significantly less as compared to 14 percent of overvoltage. So, almost 50 percent reduction in overvoltage is possible even if you operate the compensator in a fixed compensation mode or fixed reactor mode.

So, that is what we obtain from here. Now, from this also, we can find out this expression for active power which is flowing through the line. If you put these values, this Vmc in this value, then we know that this expression is V line-to-line, then V m c line-to-line divided by Z c sin beta l by 2 multiplied by sin delta by 2. Now, if you put this V m c value over here, V L L is 1 per unit. So, if you multiply these base values as well, then you convert it to megawatts. Then whatever the value we will get that is coming out to be 2134 sin delta that much of megawatt.

Because you know there is a cos delta over here and that cos delta and sin delta are multiplied and we consider the 2 sin delta by 2 cos delta by 2 is equal to sin delta and then you put all these values V L to L is here considered as 735 kV. And Vmc is of course line to line is 1.062 multiplied by 735 kV multiplied by cos delta by 2 and Zc sin beta L by 2 already we know these values already we obtain at the very beginning of previous lecture. So, if you put all these values you will come up with this expression of power.

So, we obtain this now. We obtain this now, both of these, one is Vm is 1.062 per unit and Pm is obtained as 2134 sin delta. So, this is obtained for the reactor operation at fixed mode or for the compensator operation at fixed reactor mode. Let us find out when the compensator is operated at fixed capacitor mode. What will be the Vm midpoint voltage compensated at this particular condition? So, in order to find that we will also use the same approach that let us first find out the fixed capacitor reactance which is represented by Xc.

So, we will obtain similar to what is similar to the approach we used before in the case of fixed reactor operation. So, in order to find out we know that in this particular mode Qc is providing a fixed compensation of 400 MVAR. So, we know Qc is equal to 400 MVAR is equal to 1.05 multiplied by 735 kV, kV square is basically nullifying this MVAr. You have to understand that 400 MVAr means there is 10 to the power 6 to be multiplied with 400.

Similarly, 735 kV means there is 10 to the power 3 to be multiplied with this. Now, 10 to the power 3 square would be 10 to the power 6, that will be eventually cancelled with this MVAr, that is 10 to the power 6 in the left-hand side. So, this is divided by Xc. Now, if you do that, then Xc is found out to be 1489 ohm. So, you just put this x e to left hand side and bring 400 to the denominator of the right hand side and solve it and you will get x is equal to that. Now when we get X is equal to that, again we will put this value of Xc in order to find out what would be the Vmc, that is midpoint compensated voltage at this particular condition. Now to do that, so we know that Qc is equal to twice Vmc line-to-line square cos beta l by 2 minus V line-to-line multiplied by V m c line to line cos delta by 2 divided by Z c sin beta l by 2 that is what our expression of the compensator is equal to this V m c line to line square divided by this X c. So, similar to this, what we did in the previous part, this similar to, instead of X L, I just put it to X C and the rest are the same. Now, in that way, we can find out that V m c line to line is equal to V line to line cosine delta by 2 divided by cos beta l by 2 minus z c divided by 2 x c sin beta l by 2.

So, this is what the expression we obtain. Now, as we know that we know the values of beta L by 2, we know the values of Zc by 2 Xc also. Zc is known to us, Xc is already determined to 1489 ohm. We also know the sine beta L by 2 values also. So, if you put all these values, then whatever you will get as the voltage is equal to 1489 that is equal to V line to line multiplied by 1.2068 cos delta by 2, that much of kilo volt. Now again, when we convert it to per unit, then what we will get it as Vmc line to line is equal to 1.2068 cos delta by 2 per unit, because we consider V line to line is 735 is our reference voltage or base voltage. So, considering this as a base voltage, if you divide it this Vmc, then whatever the voltage we will get that will come out to be a per unit voltage. So, this is what the voltage we determined. Now, similarly, we can also determine this power as well, this active power flow during this fixed capacitor mode of operation of the compensator.

We can find out the power flow expression for the fixed capacitor mode of operation of the compensator is, in order to find this out, we can write Pm is equal to this again Vmc line-to-line multiplied by V line to line divided by Zc sin beta l by 2 multiplied by sin delta by 2. Now you know that Vmc line to line is this. V line to line you multiply twice because if you want to convert it to, per unit to megawatt and then Zc sin beta L by 2 known to us. So, if you do all sort of thing then what you will be coming out to be an expression of 2425 sin delta that much of megawatt.

- $\delta > 59.06^o$ ⇒At this condition undervoltage will be observed and the compensator will act as a fixed capacitor.
- The value of capacitive reactance(X_c) at this mode is given by

$$X_c = \frac{V_{mc}^2}{Q_v} = 1489\,\Omega$$

$$Q_c = 2Q_m = 2\left[\frac{(V_{mc})_{L-L}^2 cos\frac{\beta l}{2} - V_{L-L}(V_{mc})_{L-L} cos\frac{\delta}{2}}{z_c sin\frac{\beta l}{2}}\right] = \frac{(V_{mc})_{L-L}^2}{X_c}$$

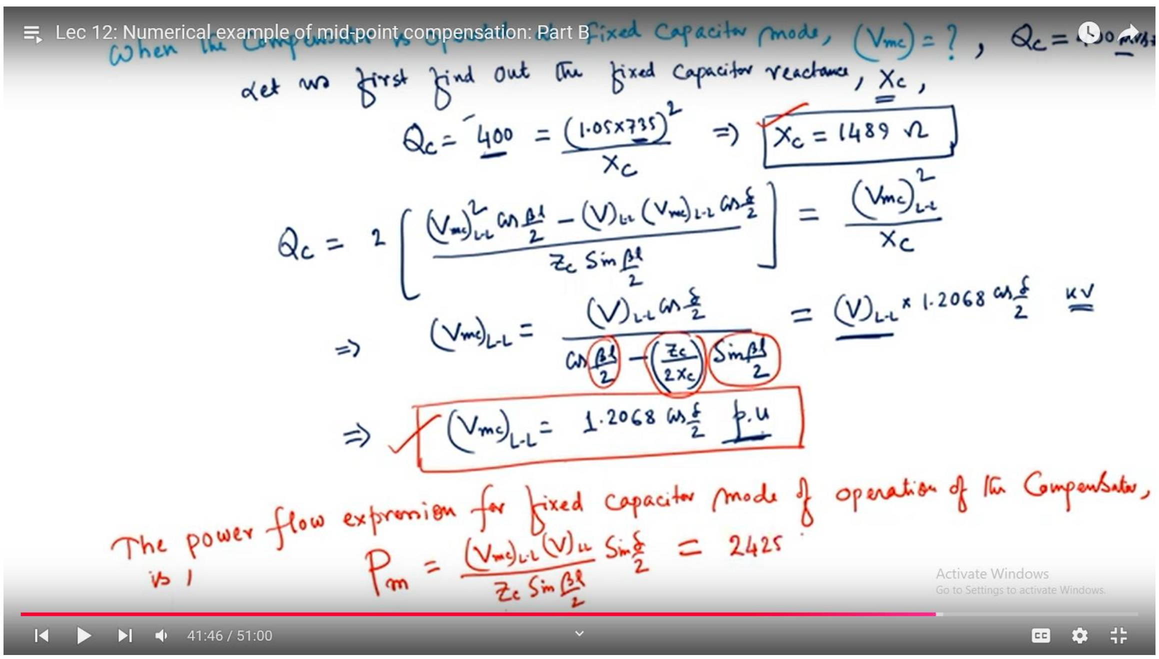
$$(V_{mc})_{L-L} = \frac{V cos\frac{\delta}{2}}{cos\frac{\beta l}{2} - \frac{Z_c}{2X_c} sin\frac{\beta l}{2}}$$

$$(V_{mc})_{L-L} = V_{L-L} \times 1.2068\cos\frac{\delta}{2}\ kV$$

$$(V_{mc})_{L-L} = 1.2068\cos\frac{\delta}{2}\ p.u.$$

The power flow expression for fixed capacitor mode of operation of the compensator,

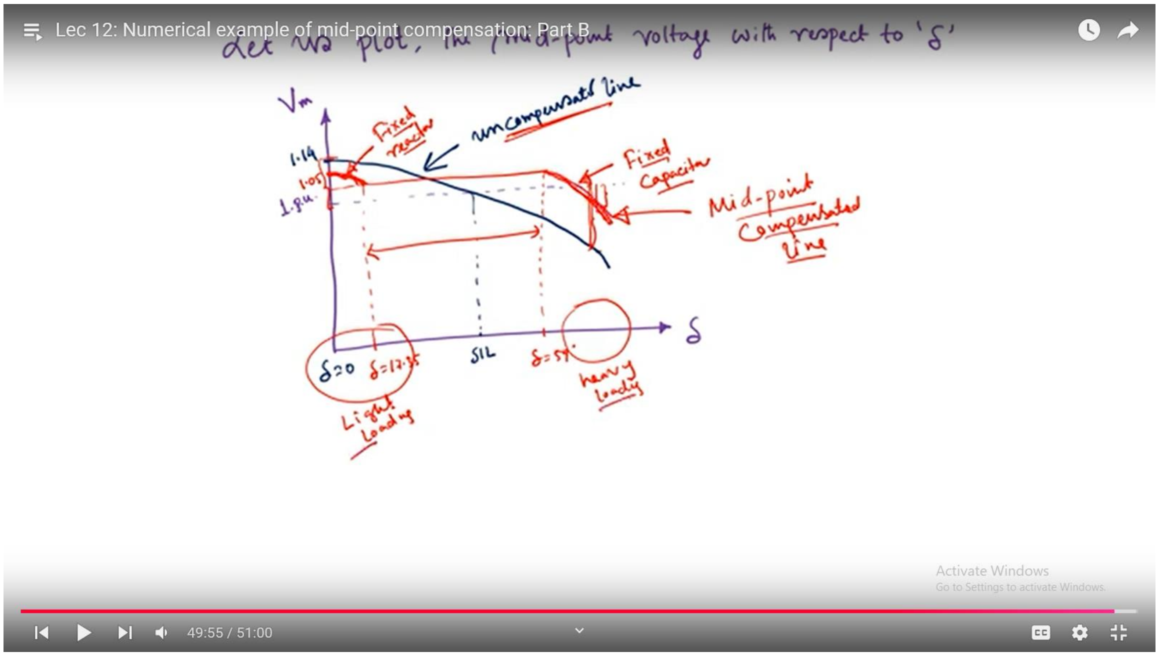
$$P_{comp} = \frac{VV_{mc}sin\frac{\delta}{2}}{z_c sin\frac{\beta l}{2}} = \frac{735\times\left(735\times 1.2068\cos\frac{\delta}{2}\right)sin\frac{\delta}{2}}{z_c sin\frac{\beta l}{2}} = 2425\ sin\delta\ \text{MW}$$



In fact, this was also that much of megawatt. Now, we will copy back this again here. So, now what we get this V m here is now this V m c rather this V m c is equal to 1.2068 cosine delta by 2 per unit and P m is find out to be 2425 sin delta. Now, this value of V m c is basically corresponding to delta is equal to 0, but actually, under this fixed reactor mode of operation, the expression of V m c as we obtained as in this next slide. Here it is basically this expression I am talking about this is equal to 1.062 cosine delta by 2. So this is what the expression of VMC now, this is what the expression of VMC, this is what the expression of VMC when it is operating as fixed capacitor mode and this is what the expression of line flow. So you can see line flows are also getting changed here, so as the voltages. Now what we can do is that we can plot this midpoint voltage. So let us plot the midpoint voltage with respect to the angle delta.

So, this is suppose this midpoint voltage and this is suppose angle delta. So, this is midpoint voltage and this is angle delta. So, this is we are intending to plot. So, if we intend to plot this, then what we will get as we have seen that suppose this corresponds to the, this corresponds to this Vm midpoint voltage corresponds to this 1 per unit So, without compensation, there was a 14 percent more over voltage and there was also under voltage. So, corresponding to delta is equal to 0, this Vm was 1.14 and then it was declining and it is decreasing like this. When this happens, this corresponds to this SIL loading. This corresponds to SIL loading, surge impedance loading, when this midpoint voltage will be 1. And this is what the expressions, this is what the plot of this midpoint voltage for uncompensated lines. Now, if we also try to plot this midpoint voltage for the compensated line, we can eventually plot by considering the voltage equations that we get between delta is equal to 0 to delta is equal to 17 degrees, this is the equation that we will be using to plot the voltage.

And during this period of time that is in between this 17.35 to 59.06 degree, it will remain constant. And during this 59.06 to delta is equal to 90 degree, it will follow this equation. So, accordingly, anybody can plot by using any software that you can use including the MATLAB. And if you plot that, then what we will get is Suppose this angle corresponds to delta is equal to 17.35 degree and this angle corresponds to delta is equal to 59 degree. So, between this period of time starting from this angle to that angle, the midpoint voltage will remain constant. From here to here it will act as a fixed capacitor and fixed reactor mode. So now, so this period of time it is acting as a fixed capacitor mode and in this period of time it is acting as a fixed reactor mode. And during this period of time, it is providing the required compensation to hold the midpoint voltage to 1.05 per unit. So this, if you compare these characteristics with this uncompensated line, this red one characteristic is the correct voltage condition for a compensated or midpoint compensated line. And if you compare this red curve with this black curve, you can understand that when the system was operating at light load condition during this period of time, there is overvoltage still because it is operating at fixed reactor mode. But the amount of overvoltage is significantly less than the uncompensated line. Similarly, when this is operating at this relative to higher loading condition, even if you have fixed capacitor mode of compensation, there is some kind of under voltage.



But the degree of under voltage as compared to the uncompensated line is significantly less. And that is what the benefit of having a compensator. And there are various types of this compensator exist which can perform this particular task. And we will discuss them one by one. So, if we summarize the whole numerical analysis, what we learn today is for uncompensated lines, there exists a significant amount of over voltage and under voltage during low load conditions or light load conditions, during light loading or heavy loading. So, during light loading you can see that there is a serious amount of over voltage during heavy loading you can see there is a serious amount of under voltage.

But if you use a compensated midpoint compensated line that means we have a practical compensator at the midpoint So, what it does is, it mitigates a significant amount of overvoltage during this light loading condition and a significant amount of undervoltage as well during this heavy loading condition. So, that is what the main concept that we understand in this particular lecture. And, we will continue this in next lectures, when we will discuss of several types of practical compensators and their types, their modeling aspect and various other things. So, for today, this is up to this and thank you very much for joining. Thank you all.