Power Electronics and Distributed Generation

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Lecture - 18
Feeder Voltage Regulation

Welcome to class 18 on topics in power electronics and distributed generation. In the last class, we were talking about relays for connecting DG, for the DG operation, for the interconnection and for protection. We linked it to these requirements to standard ANSI relay protection usage. What you could do is then work out the logic required to say operate the interconnection protection or the generator protection. So, each of those relay functionalities can be linked to under what conditions should some particular breaker. For example, 523 when should it open and when should it close.

So, that logic can be done as a fairly simple combinate for a logic exercise from the outputs of the relays. I leave that exercise to you, so another aspect that need to be considered when you do such an interconnection is that, what should be the actual settings of the protection relay value. For example, in this 59 and under voltage relay the question might be what would be the neutral voltage setting that has to be included. For example, in the 51 g what is the ground current level, what is the over current level at under, what o frequency under frequency would the decision be made to disconnect the device.

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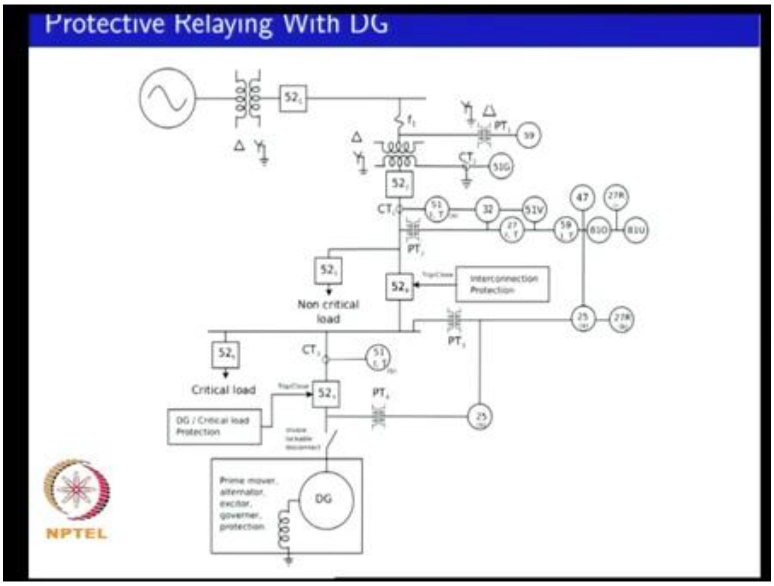

So, these are actually the engineering evaluations that you as a system engineer would have to decide on whether what setting is required. Those settings would be typically be based on the analysis based on the ratings of this units the sizing of the components, the fault calculation etcetera, which you have got a feel for this point of how to do this calculations. So, another think to keep in mind is that in these relays that have are implemented all of them are quite our standard relays. I mean you do not have something, which is not already there available as a standard. The only thing, which could be considered as being something that is not already there, is a the issue of how to detect unintentional is landing especially, when you have a wide range of situations.

For example you could use this 32 as a reverse power relay to actually detect whether the power is going out of your P C C to detect whether it is a unintentional islanding, but then that would restrict you to have a D G, where the power is not allow to go out. If you have say large solar form or a large wind form, your actual intension of operating the device is to send power out.

So, you do not have standard a anti-islanding protection relay other than that everything else is actually standard protective protection equipment, which you could actually program. The other thing to keep in mind is that scaling. This functionality to at a power level tens of kilo Watts or hundreds of kilo Watts might be, because you need to add say the protective devices for interconnection the senses etcetera.

In terms of the cost at hundreds of kilo Watt power level. It may not be a significant cost addition to the D G cost in terms of the protection additional equipment required for interconnection and D G protection. However, if you looking at small one kilo Watt solar panel, that you want to interconnect to the grid. If you want all this functionality then the cost becomes significant factor compared to your photovoltaic system cost. So, scaling it to lower power level is still a challenge to some extent. This issue of scaling to lower power level can be overcome. Because, now the digital controllers that are available today can do a lot of complex functionality within one single controller.

So, potentially you could have then a lot of functionality now embedded within the controller of your low power D G that you are trying to interconnect, but if you want to have separate relay packages to implement this, then to scaling to lower power level is a is a challenge. The other thing to keep in mind that what we are shown over is just an example your protection requirements would change depending on whether its. For example, whether transformer is delta y y y y delta or the whether the grounding is different whether its low impedance high impedance grounding etcetera. So, you would have to actually modify your protection schemes to according to actually address those circuit and component issues, that you are having in your actual examples in actual system.

This is just an example to give you a feel for the issues that you need to address, when you are doing interconnection of a distributed generation generator to the grid. So, today will look at another issue, which is a of importance is a is that of the voltage along the feeder. The voltage at the feeder especially at the point of common coupling is a important parameter. So, suppose if in this case if this was a high power facility, this was a point of common coupling. You want to ensure that that particular voltage stays closed to the nominal value. So, you may not able to have voltage exactly at the nominal value their might be at some acceptable range plus 5 percent minus 10 percent.

You want to keep it within that range and you want to do that not just for one particular location, but you want actually to do it for all along the feeder. So, respective of whether you are closed to the substation or whether you are sitting at the end of the feeder. You want actually stay within the tight range. Physically it might mean that respective of whether you are sitting at distance zero or a distance of multiple kilometers away. You want to actually make sure that your voltage is in a tight tolerance range how it is done.

Then the we will also look at issue of how adding a D G can actually affect, how the voltage regulation can be accomplished. So, we will start with a simplified lamp model of the system.

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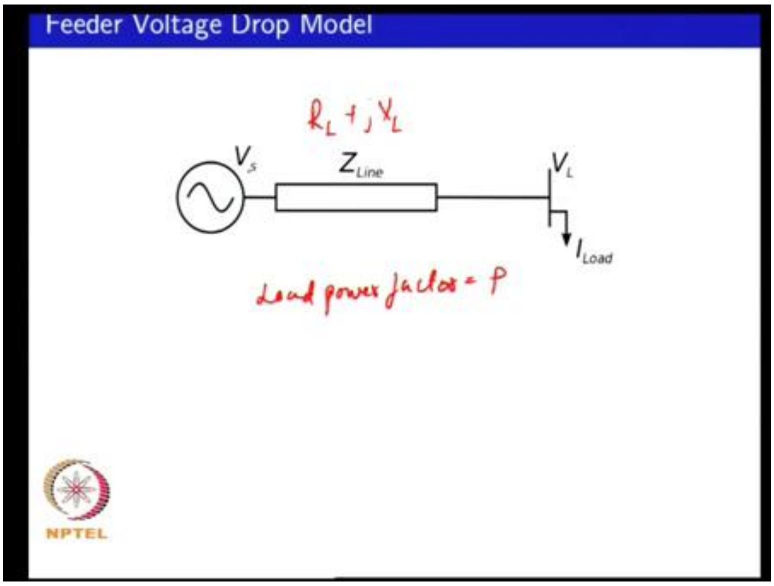

We will take the substation voltage the source voltage as V s and will lamp the impedance of the line to a Z line, which could consist of some resistance and reactance to get the overall impedance. Again, will lamp the load together at one point and call it the load voltage. You have some load current drawn and we will assume that the load power factor is some is load current at the some power factor P.

So, we would be able to estimate what the resistance of the line is and what resistance of line is. We saw in the exercise were we looked at calculating the X by R ratios of your line, how to actually estimate this parameter. Once, you know the resistance and reactance you could then get the what could be the voltage load. If you have source at given voltage amplitude, you can then calculate what is regulation is.

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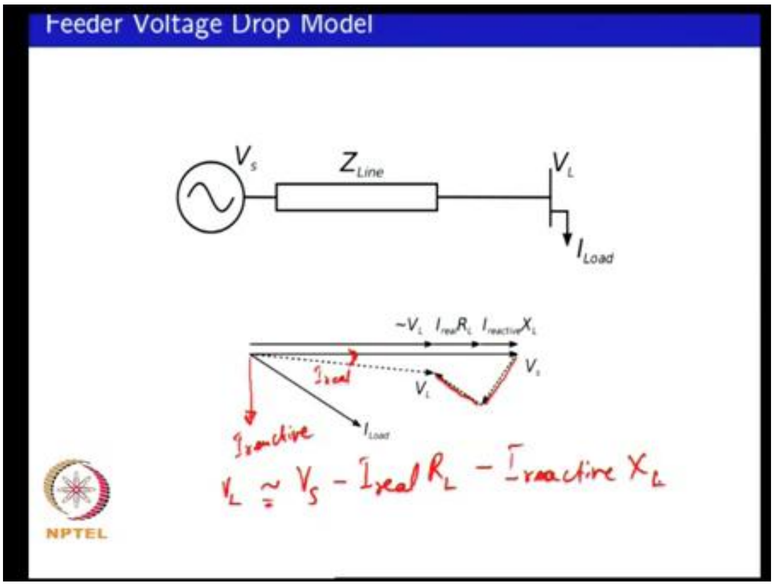

So, you could then do it what you do is a then solve a facer analysis. So, you have your source voltage V s we have your current I load lagging as angle theta with respect your voltage. Then you can have a drop term corresponding to your resistance. You can have a drop term corresponding to reactance. Then find out what is amplitude of good voltages is the we can actually simplify further. Because, we assume that drop is quite small. So, we could take your load current to be consisting of the in face comp real term I real reactive term. Then you can calculate we can approximate real voltage as. So, we know that your I real is I load times p, which is your power factor you can get your reactive component of the current.

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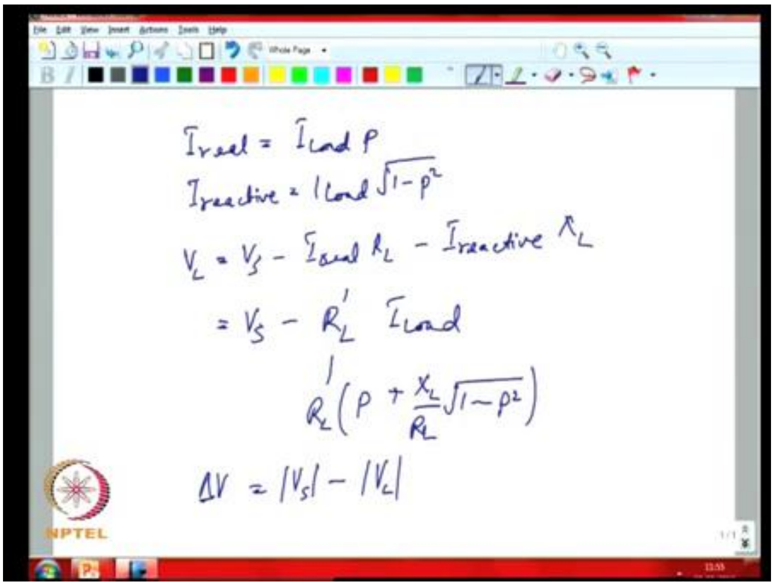

Then you could then write down the expression that we had, which was a V L and substituting for I real and I reactive. You could get this to be equal to v s minus some R L prime I load where R L prime is equal to R L in to P from the real voltage drop term plus X l by R l square root of 1 minus P square and X L by R L is now your X by r ration of your feeder. So, you can see that what we have done is we have taken solution, which would have been on facer domain. Then we have simplified it in as a allergic equation instead of have faced a complex number. So, it carries two real numbers values in it.

So, if you are now we have reduced it to one real equation. So, with that we can then calculate what is your voltage regulation at the load. Your voltage drop that you would see is essentially your amplitude of your source voltage minus the amplitude of the voltage seen at the load. The you could see what is the effect of now connecting loads all along the feeder. So, we will make an assumption that you have a feeder, where you have source sitting at some point X equal to 0 and you have a line of length d.

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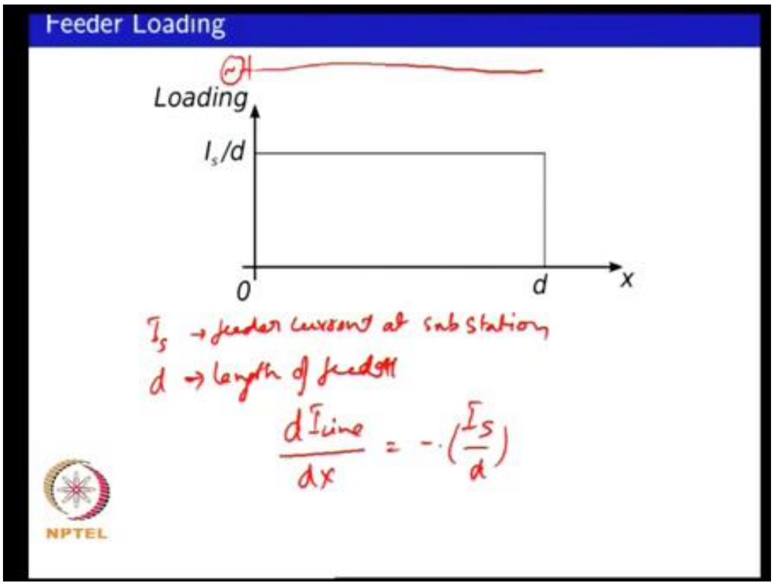

You are assuming that loading is uniform all along the feeder. So, the load so the load per unit distance would be I s what would the source seen at the substation end divided by d. So, could think of I s station current, so the load is I s by d. You can then calculate your current would be all along the feeder. Your current would reduce be the maximum at substation and be reduce to 0 at the very end of the feeder. So, you can you have d I line by d X equal to I s by d. Because, it reducing as you go forward, so you have a negative slope.

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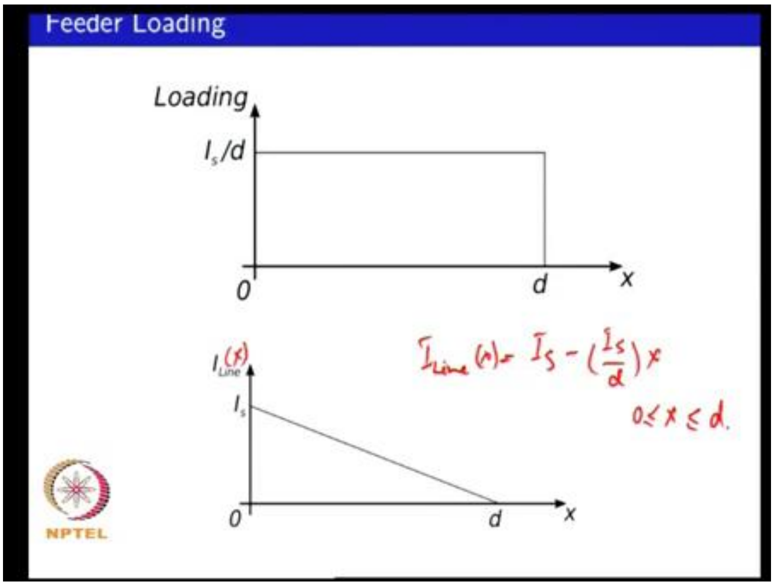

So, if you plot your I line as a function of a distance versus the point along the feeder, you will get the current profile along the feeder, which is having a triangular shape. So, you can write an expression as I line of X. So, now the you know what the current is along the feeder you could now calculate, what your feeder voltage is going to be at a different points along the feeder. So, to do that you have if you consider a point along the feeder at some point x.

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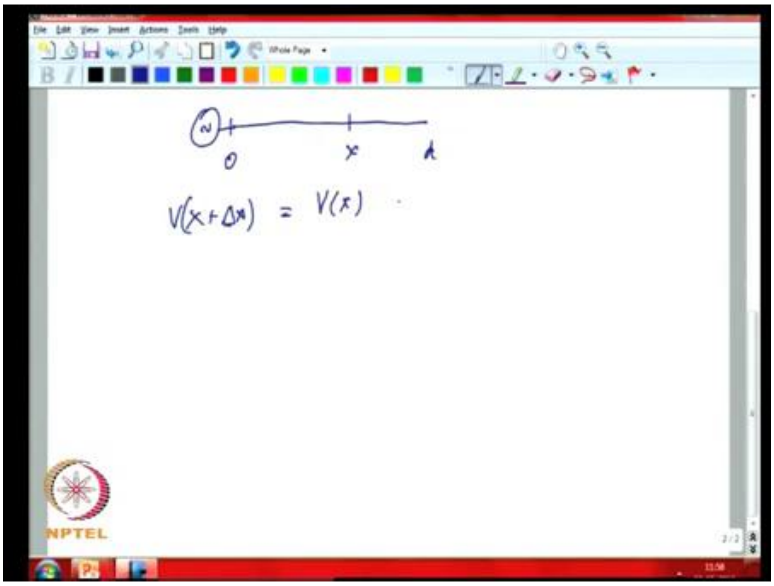

Say, this d and this 0 we can calculate V at of X plus some delta X ahead would be equal to V of X minus. So, V at X plus delta X is V at X minus essentially the resistant per unit length times, the small distance delta X times the current carried at particular point along the line.

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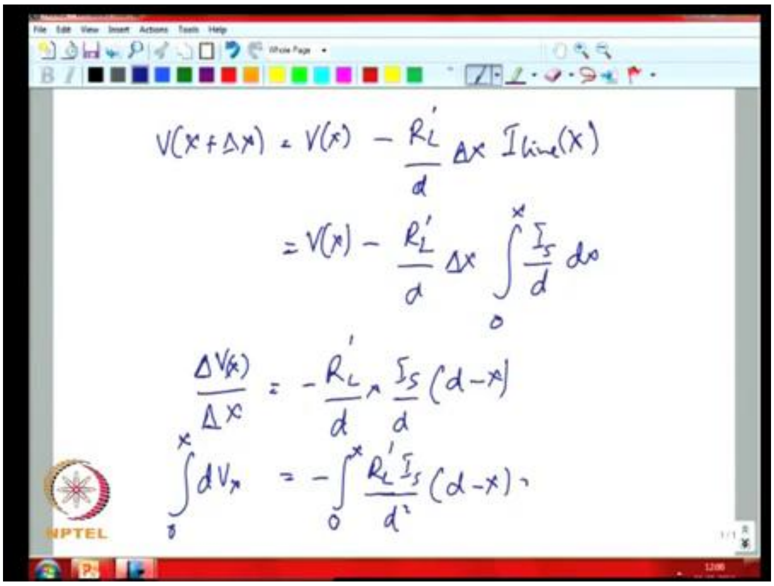

So, you can now substitute for I of X from the expression that we had previously. So, could write this is as V of X minus. So, you could then simplify it and then get delta V X by delta X to be equal to minus R L prime. So, we could then integrate this to get your voltage along the feeder. So, V at 0 is a V s, so you can write V s minus V of X. So, essentially what you get is.

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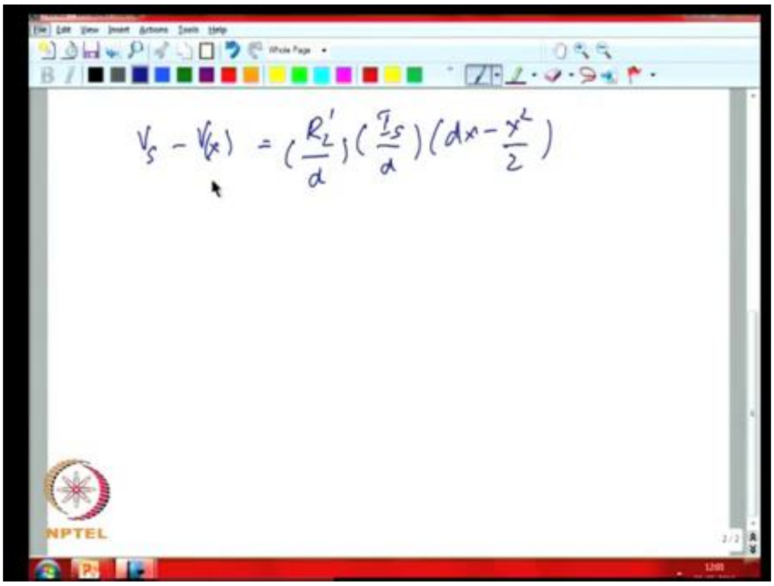

You can write an expression for V of X you will get that to be equal to V X minus some term as you proceed along the feeders you get the expression for your voltage. That is actually parabolic, so you get V of X.

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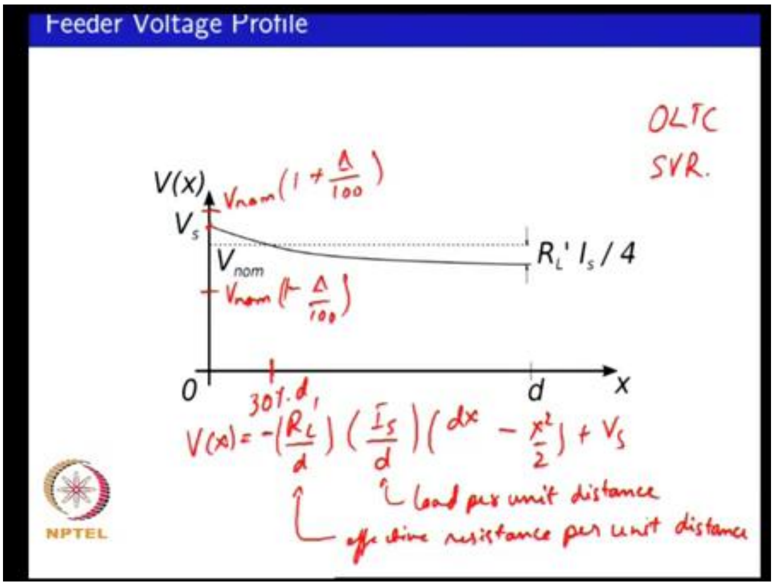

So, essentially you get a parabolic expression and if you look at a I s by d this is essentially the loading per unit distance of the line. R l prime by d is essentially is the effective resistance per unit length including the terms considering the power factor term and a essentially the objective then is the term. If you have a profile along the length of the feeder, which is parabolic you want to fit this particular profile to be a equal a nominal value. So, your nominal value is some V nom you want this profile to be sitting write across straddling the nominal in a symmetric manner, such that one end does not see over voltage. The other end see under voltage if keep it such that you are straddling the nominal feeder would give you a fairly a close value to the nominal.

So, you might say that your maximum voltage might be some V nom with some delta percentage. So, say delta by hundred and your minimum might be V nom into 1 minus some delta by 100. So, depending on what your delta is you want to keep entire feeder voltage to be within this window. Then the other thing that can be noticed is you are not trying to the voltage at the substation end to excitedly equal to normal, you want the voltage, which is some distance away to be the nominal. So, that your over all feeder requirement is satisfied.

So, typically you look a trying to fit parabola along the nominal you would find that roughly around 30 percent of the distance. If you keep that particular voltage to be the nominal. You would fit this requirement of a being able to keep your overall voltage within the value of plus or minus V nom delta plus or minus delta percent range. Then you could ask what could we done in a typical distribution system to adjust a voltage a along the feeder.

So, one thing you could have is a tab changer at the substation you could have online tab changer O L T C, which could adjust the tab to actually get such a profile such as this. So, tap changer would do it for all the feeder at the substation you could also have you could also have a series voltage regulator. You could have a series voltage regulator for each line, these voltage regulators can be located either at the substation of if you have a really long feeder it could be further down the feeder to get your required voltage to be within a acceptable range. To get at the substation or you could have a series voltage regulator to get your profile in a decide range.

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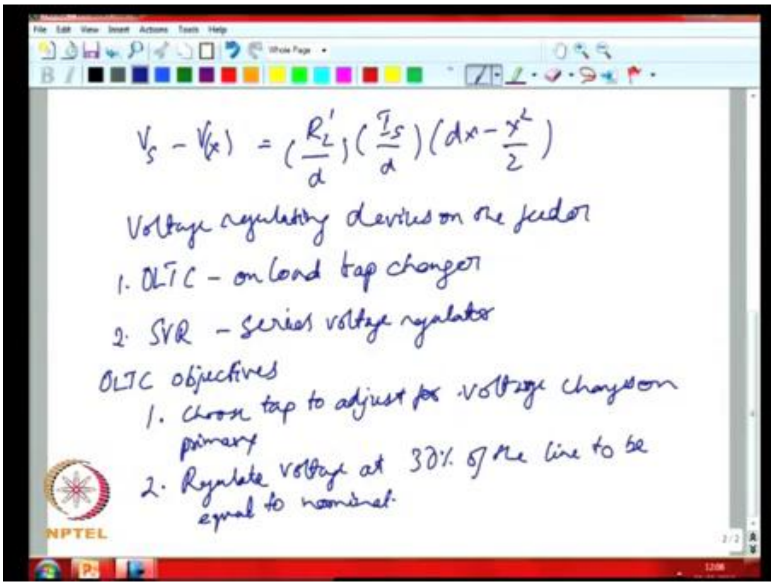

Then you could ask what would be the objective of the say that tap changing transformer. So, one objective to be to ensure that if the primary voltage coming in at the substation is high or low. You need to ensure that the distribution voltage is independent of changes that may happen on the primary side. Because, your transmission size of the voltage might go up and down, depending on what is happening on over all larger system, but you want to keep your distribution voltage constant. The other thing is to regulate your voltage along the feeder.

So, the second objective might be to regulate voltage at say 30 percent point. So, you could adjust the tab on the high voltage side to meet this requirement. One next to keep in mind is that your not actually commanding your low voltage side your 11 k V voltage side to be excitedly equal to nominal.

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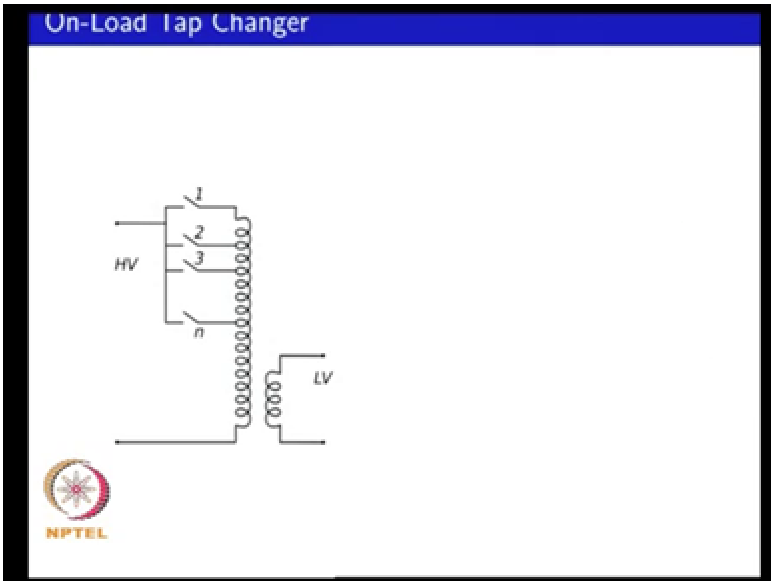

You are actually commanding, your voltage on the secondary side to be some nominal value plus some boost voltage correspond to the impedance up to the 30 percent distance times your current being drawn by at the substation. Because, you physically cannot take a sensing wire put it few kilometers out to sense the voltage of the particular point. What you physically have at the substation is the voltage at the substation.

So, you are making use of the line current that you know that is coming to the feeder to actually predict what is happen, what is the voltage, that would be there at 30 percent distance down along the feeder. So, essentially you are adding a boost term voltage, so that the boost term would correspond to essentially this particular value above the nominal, which you trying to boost.

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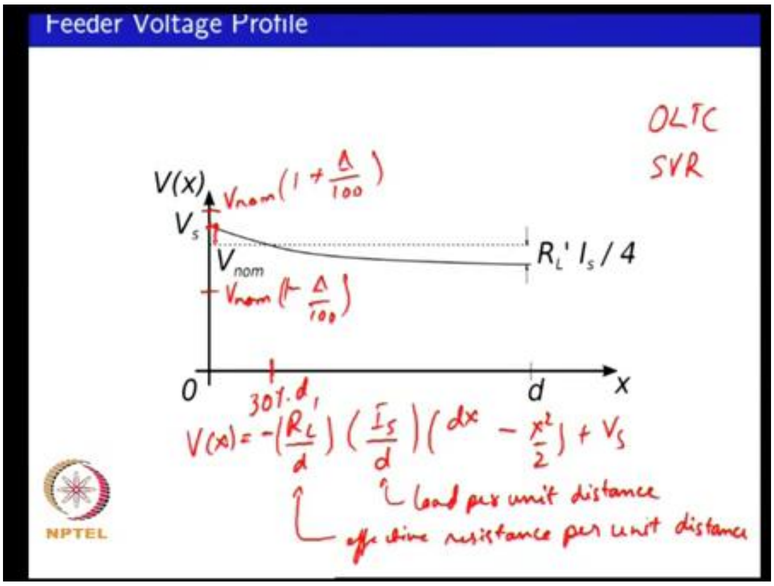

So, in a transformer such as this you are say operating at tap one. Then your voltage step down ratio is higher. If you are operating you say operating the tap n over here you will have high voltage moving on the secondary side, by adjusting your tap one you could get the decide voltage at the secondary point. Then you could say for example, in a situation is this you have a tap changes, where you might de energize the transformer while changing taps, but you do not want to de energize the entire feeder the output of the substation, that you will switch from one tap to other. So, you would have a on load tap changes say for example, you can have a mechanism such as shown over here.

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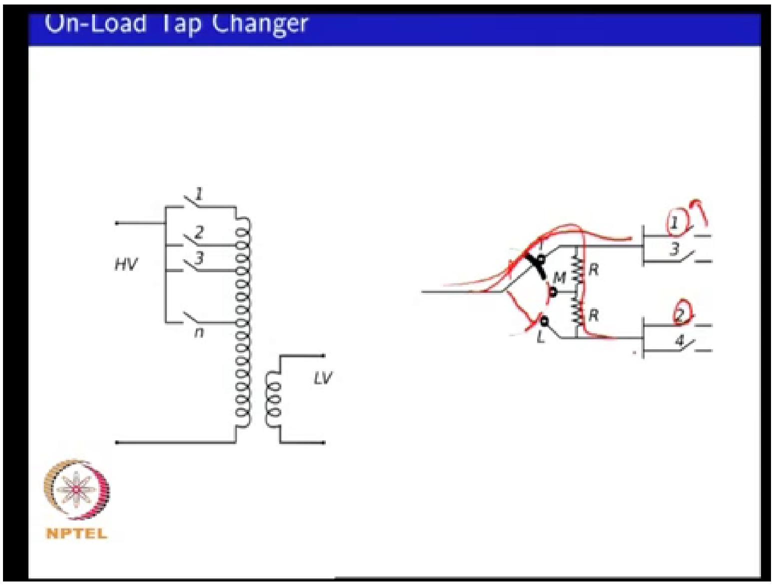

To actually ensure that when your changing from one tap to another tap you do not have a over current. Say, for example if you directly close switch one and two you would end up with short circuit in that particular loop. Whereas, say for example, if you want to go from switch one. So, you might you might do is when your position of your pole is at the top point you might say close switch two. Then essentially this resistors would limit your current that is flowing in this particular loop.

So, that transformer then as you shift your pole from the top to the middle to the loop point of your contact. Then essentially always ensure that you have energy flowing through at least one particular circuit. It might be through this particular circuit or through this particular circuit, but you will not have a short. Because, you always has resistance in the path, eventually you will come to point such as here. Then at this particular point one and two close. Then you open one and then you continue with position two.

So, you could have tap changing when you still energized, your loads are energized that why it is called a on load tap changing. So, when you are trying to do such an action such an action, you could also have for such an example a series voltage regulator, also functions in a similar manner.

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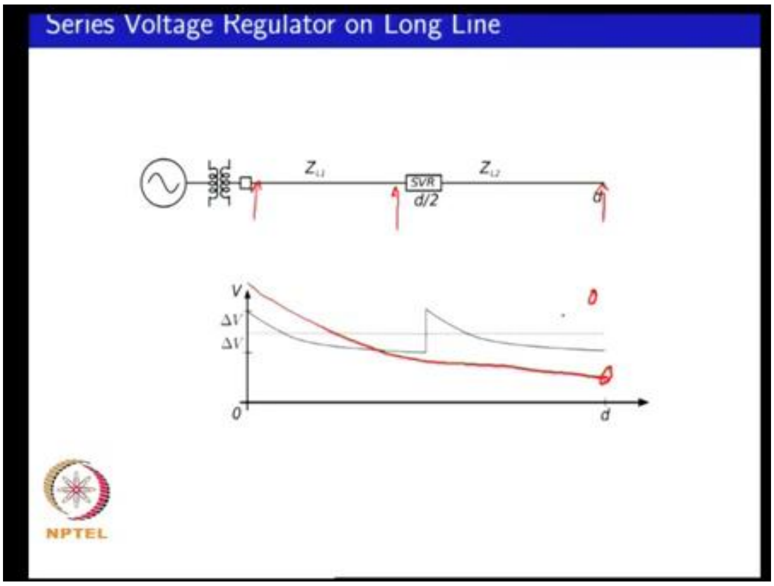

You could have series voltage regulators and the substation end or further down the line. So, if you have for an example really long feeder might be here for the order of 10 kilometers long feeder. Then if you just allow one particular substations to regulate, you might end up with a large drop in voltage all along from one end to another end. So, prevent that you could then add say a series of voltage regulators say in between the line to obtain the necessary boost.

Then the question is what when you connect a D G to a system such as a this once that you connect D G to a system. Such as this we will see that you could have a D G that is connected at different point at the it could be at the feeder. It could be in the end it could be just above the series voltage regulator or just downstream ah.

So, we look at the different possible cases and we will see that now if we have d g s that are of a reasonable size. So, the power rating of the similar magnitudes of the feeder of the power. Then you could have situations where you might end up with the maybe under voltage at the end of the feeder or you might have voltages at differed locations, on the feeder based on your D G connection. So, we will look at the different cases, so the first case we look at when there is no D G.

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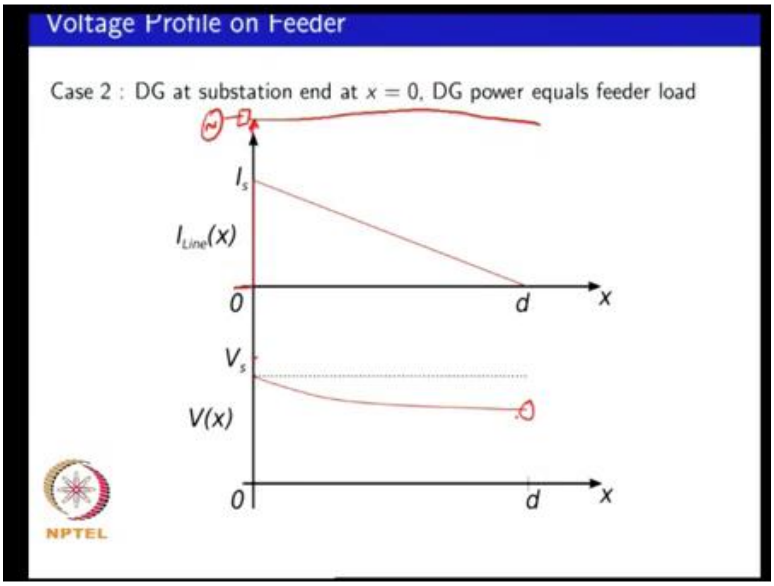

This is what we discussed you have a triangular current distribution along the feeder starting from the substation up to the end of the feeder, end up with a parabolic voltage profile along the feeder. We will then consider the case when adding the D G.

So, the first case that we will consider is a adding a D G at the substation in. So, you have the substation and say you connect the D G right at this point X equal to 0. We will assume that the D G power equals to the overall feeder load. So, essentially you have the same current profile along the feeder as what you had accept that now. Because, your D G power equal to substation power essentially. It means that what is now come in from the substation end is actually zero, because you are your D G is actually providing the entire power.

So, you can in this particular case the voltage profile be parabolic, but now you do not have say a boost term at the substation. Because, the current that the operational senses see at substation would be 0, because the entire power being provided by the D G, which means that you now have a situation, where you are your voltage is. So, that the feeder end would see ad reduced voltage compared to the case, when there was no D G. So, this is because the O L T C in this case is not adding a boost term. You could then look at another situation, where you have a D G connected at the end of the feeder.

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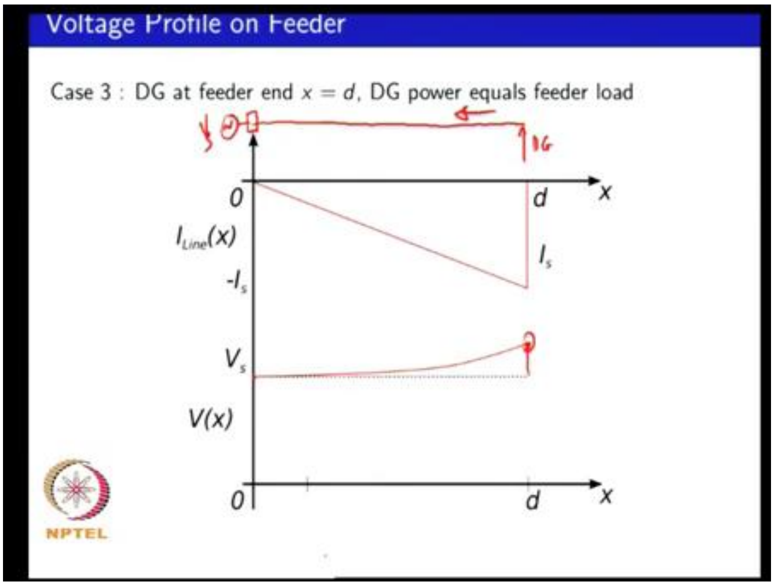

So, you are looking at the situation where the D G is connected at the end and if you look at the shape of the current profile. It is a some triangular current profile, but a shown at is been negative. Because, instead current now flowing from the substation towards the end of the feeder the current is now flowing in the other direction, which means that essentially you would have maximum current at the end of the feeder, because of the D G power is equal to the entire feeder power. We are also assuming that the D G power is being injected at power factor, that is required by the feeder in this particular situation.

So, essentially at X equal to 0 you would have 0 would be your feeder your actually current that is being drawn in drawn from v sine. This case you again do not have a boost term, but now instead of having a voltage drop you have a voltage boost, which is now coming toward to the end of the feeder. If you look at the voltage you will end up essentially with higher voltage at the end of the feeder. Then what we had at nominal feeder, then what you had at nominal situation had. So, here you see increased voltage at the end of the feeder compared to the case, when you did not have a D G unit connected. So, we will look at another situation where a you have a D G connected at the end of the feeder, but now the D G power is equal to essentially half the feeder power.

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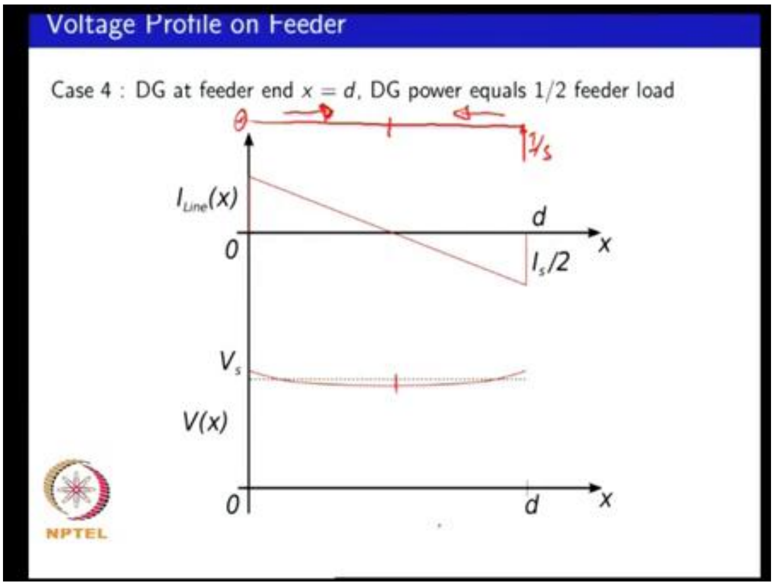

So, essentially your are injecting I s by two at the end. So, if you look at it then again assuming the uniform loading. The conditions for the analysis now the second half of the feeder would be the power would be provided to the D G unit. The first half of the feeder the power would be now we sourced from your substation. So, if you now look at your overall voltage profile on the feeder you would have essentially. Now, a parabola not just a part of what we saw you would have two parts. One corresponding to the portion from the substation the other considering portion from D G end.

So, you could see that there is a reduction in the in the amplitude of the voltage that you are seeing across the voltage drop, that you are seeing across the feeder. So, we will then look at another possibility, where instead of the D G being connected at the end of the feeder. We will look at the situation, where may be the D G is connected further in between along the feeder.

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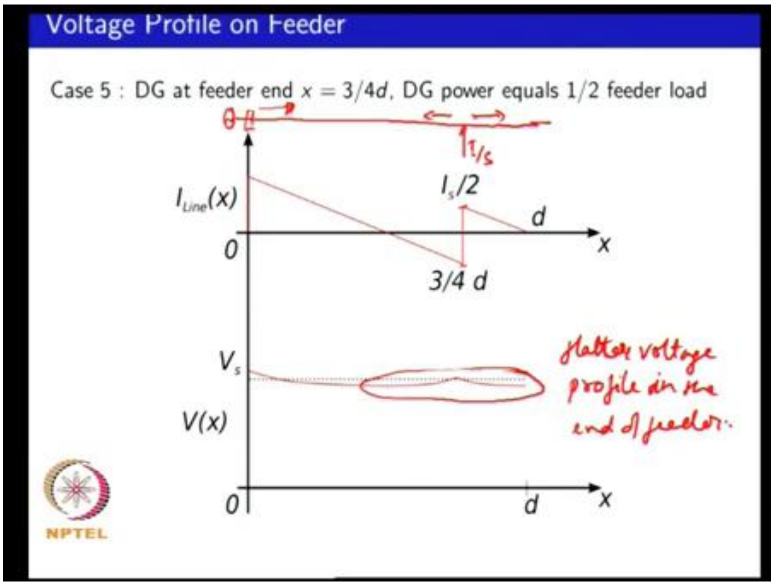

So, you are injecting I s by two half the feeder power, but located at three fourth the distance along the feeder. So, you look at the current profile it will again be triangular in shape you have a jump of I s by 2 at three fourth distance. So, in this particular distance equation the power flowing in either direction from the three fourth point. For the first half you have the power flowing from your the source V s. So, if you look at the overall voltage profile you will see that there is a further improvement in voltage regulation in the second half of the feeder. So, then you could ask if you had a singled g unit, where your power could be appropriately, it could be sized to a appropriate level, where could where would be the ideal location for locating such a D G. What would be the power level at which you could operate. Then you would see that. If you have a D G unit, which is two thirds of the rating of the feeder power.

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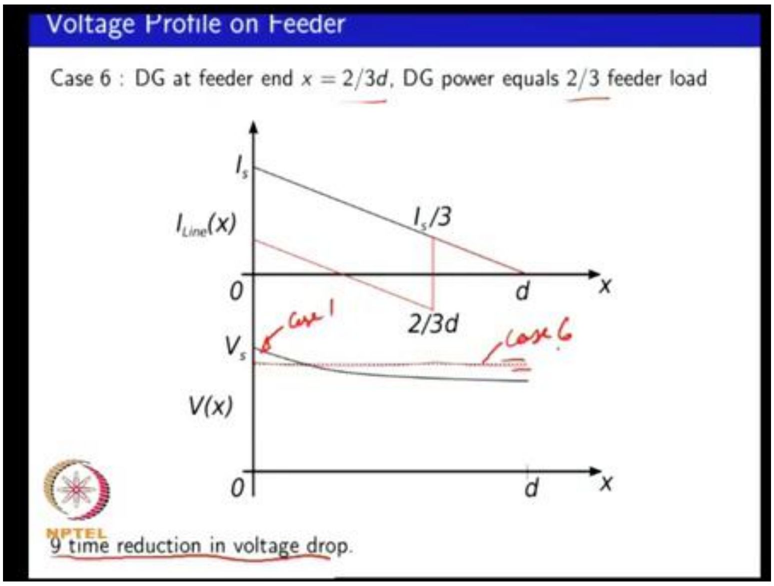

So, at that two thirds power level located two thirds distance away from the feeder. Then essentially you will see that you will end up with the voltage profile quiet flat. You would see is compared to the case of your case, where you had no D G. You will see that the voltage regulation along the feeder compared to your this is your case one. This compares to case six compare to case one you have a factor of nine reduction in voltage along the feeder.

So, you can see that it becomes almost flat to the nominal condition by adding a single D G of a appropriate size along the feeder, but again keep in mind that this is a static analysis, which will load on the feeder will be changing depending in the day. Sighting at a D G at a particular point will not be visible in all the situation.

You also know that the loading we have made a assumption on the loading etcetera, but you can get a feel for what is the possibility in terms of improvements, where are the what are the situation where we have the concerns. That is the possibility of low voltage or under voltage in different locations. You also have by appropriately sighting or appropriately having your D G unit, it is also possible to get a flatter profile all along the feeder.

So, if you look at the ideal situation, where if you had situation rater then the one D G you could have multiple d g. Then the ideal situation would be the where every facility on your feeder has a D G, where a whatever power consumed by the D G by the load by the particular location is being sourced from the D G, which mean that essentially your voltage all along the feeder would be totally flat not drawing any power, which means that losses around the feeder would be eliminated. We will also look at what the loss and the comparison would be for the case one and case six what would be the distribution losses. So, if you look at the power dissipation on the feeder, we saw that our line current is I s and if R is your total resistance as a line.

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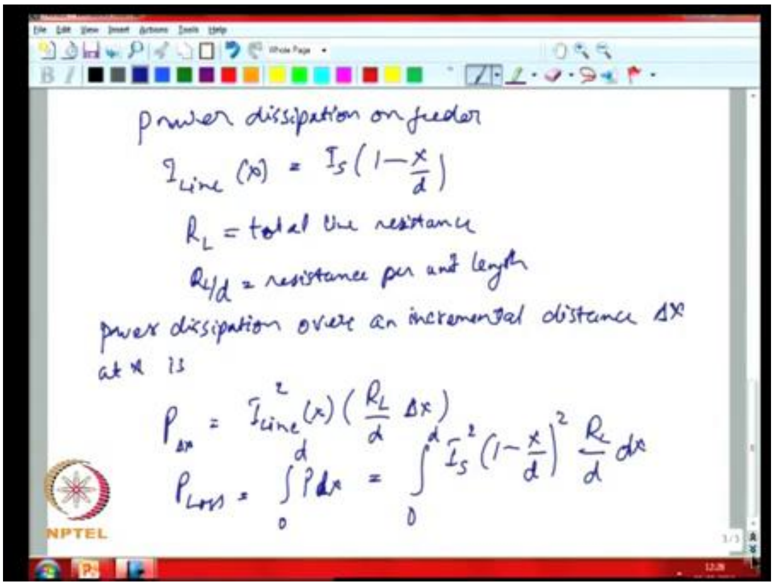

So, R l by d is resistance per unit length you can calculate the power dissipation at some over a section at delta X at X p over the incremental length over the xi line square of X times R l by d times delta X, which is essentially the resistance of that particular section. We can substitute for, we could then calculate the total loss by integrating over the entire the length of the feeder 0 to d P delta X P d X. So, it could be 0 to again this is we have the assumption of uniform loading etcetera. You could evaluate the integral as, so this is a loss per phase of the feeder.

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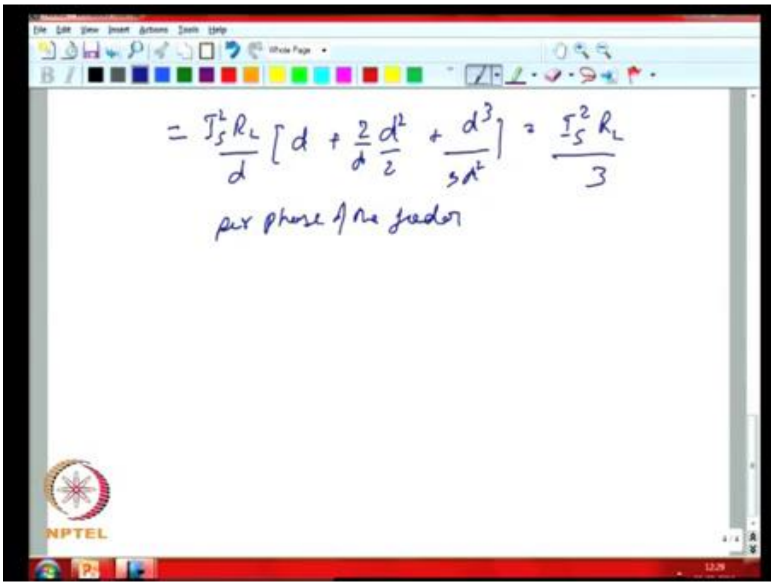

So, you should multiply by 3 to calculate the three phase loss. So, if you now compare with case six, where you had the D G of two thirds rating located, two thirds down the feeder. You could then consider a each of this case as one small feeder for this particular size and three such sections one over here section over here and that section over here.

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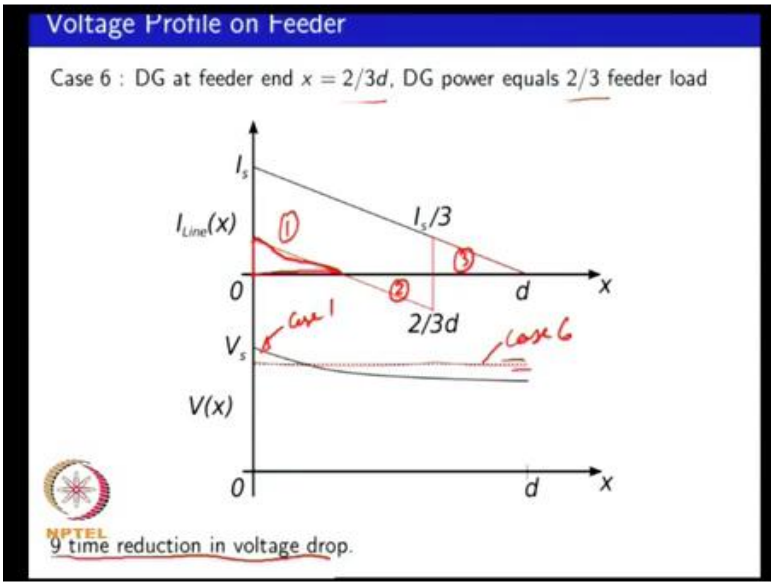

If you look at the profile of the current in each section similar to what you have in all three section you could calculate the losses in one section and take three times the particular amount. So, you can see that again you have a factor of 9.

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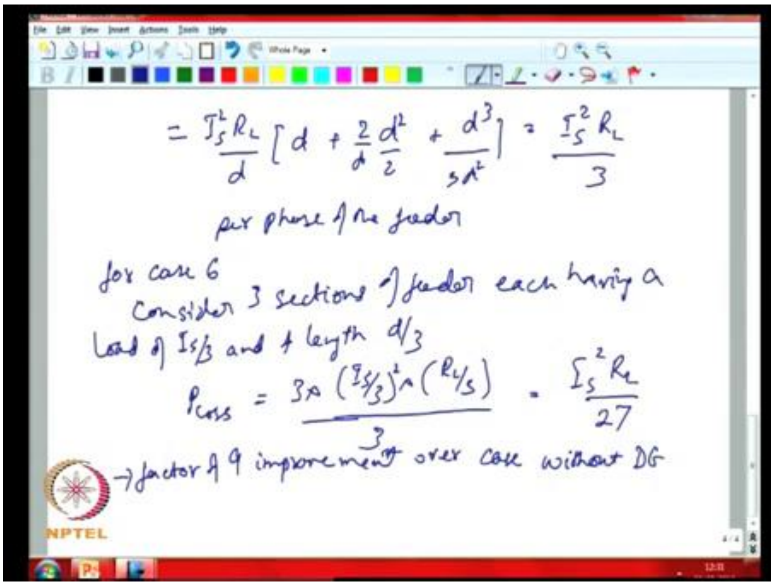

So, reduction in losses is by almost an order of magnitude if you have a well sized D G well sighted then even a single D G can actually bring down the losses by quite a bit. So, you can see that there can be substantial improvement in terms of reduction in losses. Possible improvement in voltage profile by appropriate D G, which you would also heard from people, who talked at that can be possibility in reduction in a transmission distribution losses by D G introduction of D G into the system. We will also look at in the next class at the case, where what could happen in the case where you have other types of distributions.

For example, one can look at the case where what we have studied, so far is the case of a radial distribution system. You could look at what would be the impact, when you look at say a ring type of distribution system. You also have challenges when you D G in network type of distribution system. So, we will look at some of those issues in the next class and look at some of the power quality related issues. The concerns that again come up when you have a distributed generation connected to the grid.

Thank you.