Power Electronics and Distributed Generation

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Lecture No - 14
Distribution system problems and examples continued

Welcome to class 14 on power electronics and distributed generation. We have been discussing some example problems in the last class; we will continue with these problems. And people who are watching the video, my request is to try and workout the problems by yourself before watching the solutions.

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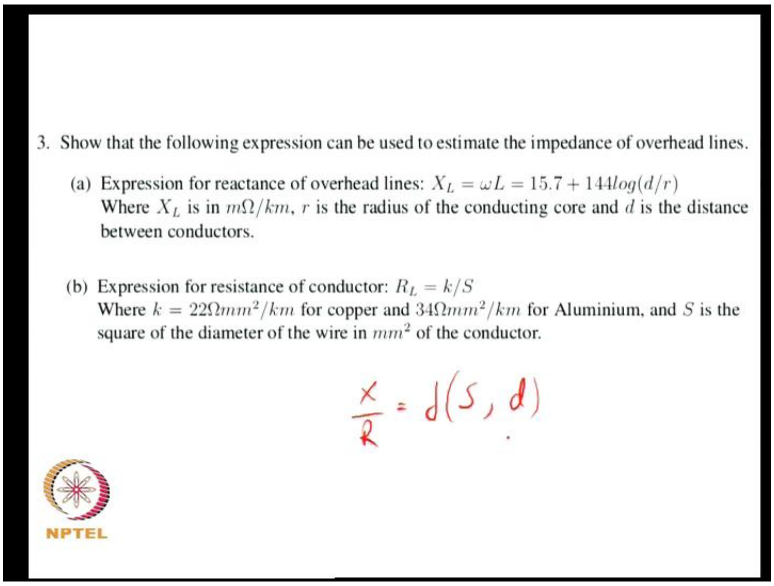

So, in the last class we were working out an expression for the reactance and resistance of the line, and we got an expression for the reactance- the expression that is shown over here; and the expression for the resistance of the line which is determined by the properties of the conductor and cross-sectional area. So, once you have the X and R values of the line you could then plot the X by R ratio of the line. So, you can get an expression for your X by R ratio as some function of the occupied area, and say the distance between the conductors, and check what its typical value would be.

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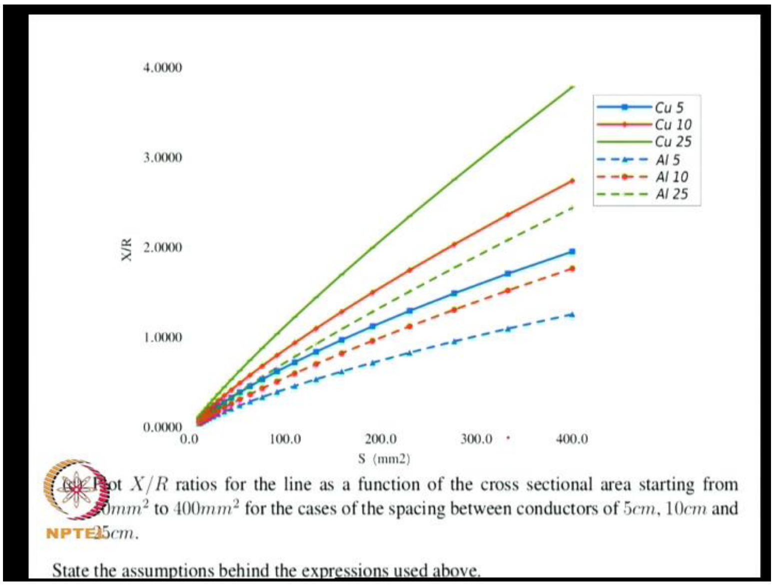

And this is what is asked in the next problem where you are looking at cross-sectional area starting from 10 mm square, the occupied area rather than the cross-sectional area, from 10 mm square to 400 mm square. And, for spacing between conductors from 5 centimeters, 10 centimeters, and 25 centimeters; so depending on what the distance between the conductors are, and for the case of copper and aluminum.

So, you can see that when the cross-sectional area of the conductor is small you have low values of X by R which means that the wire is almost a resistor. So, at the consumption point within your house, within a small establishment you can actually model the wire as a resistor, as that could be good approximation; whereas, if you now go to the large cross-sectional areas, you are having a larger X by R ratios, so, for your feeder your probably even at the secondary distribution.

Depending on the cross-sectional of the wire you can, you have to actually consider the inductive effects. But for many distribution systems the cross-sectional area may not be as large as what is there for the transmission systems which means that compared to transmission systems the distribution systems may have X by R ratios which are closer to 1. Whereas, at higher power transmission, sub-transmission you might have a higher levels of X by R ratios that are seen for your conductor.

Also, you can see that the copper wire has higher X by R ratio. So, the blue curves have higher X by R ratios which essentially is because copper is a better conductor. So, its resistance is small. So, the X by R ratio would be there. You could also see that when your spacing between the conductor is large, so for example, for 25 mm, for 25 centimeter spacing, you have higher value of X by R compared to 5 centimeter spacing which means that if you have a loop of wire, if you increase the distance between the conductors you would have more inductance; so, this is to be naturally expected.

So, if you want to have very low inductance you want to bring the conductors closer by have a put in a small twist so that you can actually ensure that the wires stay close by. So, you depending on the enclosed area for the flux you can actually, so, you can explain why the, these curves look in this particular manner.

Then, some of the assumptions behind the nature of these curves, you can see that we have assumed that the relative permeability of the material is 1. So, you are assuming that there is no magnetic material in the wire; some of the over head lines would, might have steel reinforcement to carry the weight of the wire. So, you are ignoring things like that. You are, also derive the expression for a single phase system, so, 2 conductors.

We are also assuming that the current flows uniformly in the cross-section of the conductor. So, even at 50 hertz if your cross-section is quite on the larger side, your skin effect can be quite a factor and has to be considered. So, we have ignored things like skin effect and you are assuming uniform current distribution.

We are also ignoring things neighboring materials you might have shields, you might have race wheels through which you are passing your conductor. So, packaging effects, you are ignoring stranding effects. So, that the conductors might itself be stranded, but it gives you a field for what range to expect for your X by R ratio. Also the resistance we have considered the resistivity at 20 degree centigrades at higher temperatures the resistance would be higher.

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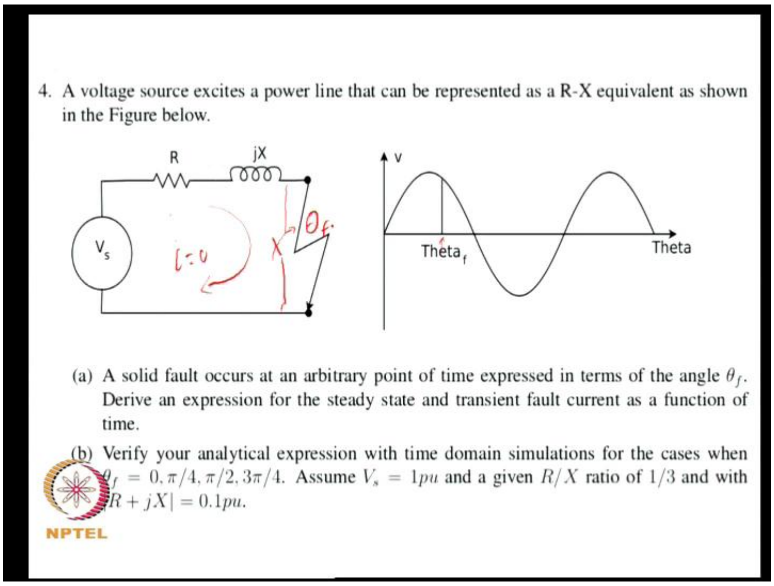

So, in the next problem we are looking at the transient effects during fault. So, by that what I mean is if you have a fault occurring at some instant then you want to see not just what the steady state fault current is going to be. You are also going to repair what can be the fault current on shorter time frame basis. And, once you have inductive component in addition to the resistive component you will have dynamic effects in any system. And, so, you want to see what could be the worst case fault current or peak fault current to analyze what is happening in the system.

So, the simplified model that we have is of a wire which is modeled as R, and a reactance term and the voltage are sinusoidal voltage terms and you are having a fault, but it is occurring at some arbitrary point of time. So, the fault occurs at some point theta f. So, before the fault occur the current in this particular loop was 0, and you can think of this fault as a switch where the switch closed at the instant theta f.

So, your analysis is of a circuit where the switch was opened around circuit were the switch was opened initially and closed at theta f, and the source driving the, this fault current is a sinusoidal source. So, first question is to derive an expression for the steady state and the transient fault current as a function of time.

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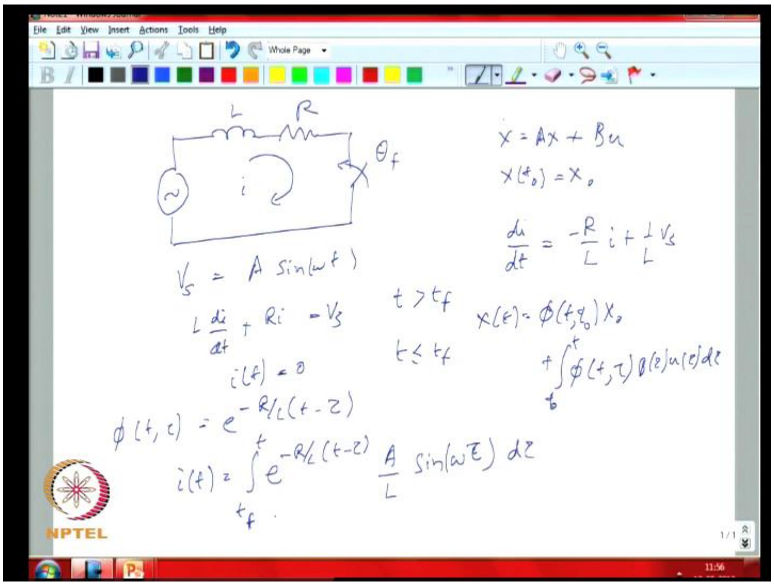

So, for this model we assume our source voltage V s is A sin omega t; so, a sin sort of voltage. And, the circuit equation is simple where d i by d t plus, R i, is V s, for t greater than t f; and, we know that i of t equal to 0 for t less than or equal to t f, the time at which the fault occurred. So, you can write this in dynamic equation form. So, X dot is equal to A x plus B u, and X at t naught is some X naught. So, our equation in this case is d i by d t equal to minus R by L i plus, 1 by L V s.

So, we know what the general solution for such a equation is, X of t is, using the straight transition t matrix times X naught plus, integral t naught to t, phi (t, tau), B (tau), u (tau), d tau. And, we know that the straight transition matrix for this simple first order system is, e to the power minus R by L (t minus tau). So, you can write an expression for your, i (t); it would have the form; and for our case, our i at t naught is 0. So, this term goes away. So, you have an expression for i (t) is t f to t; so, this is, you need to integrate a exponential with a sinusoidal.

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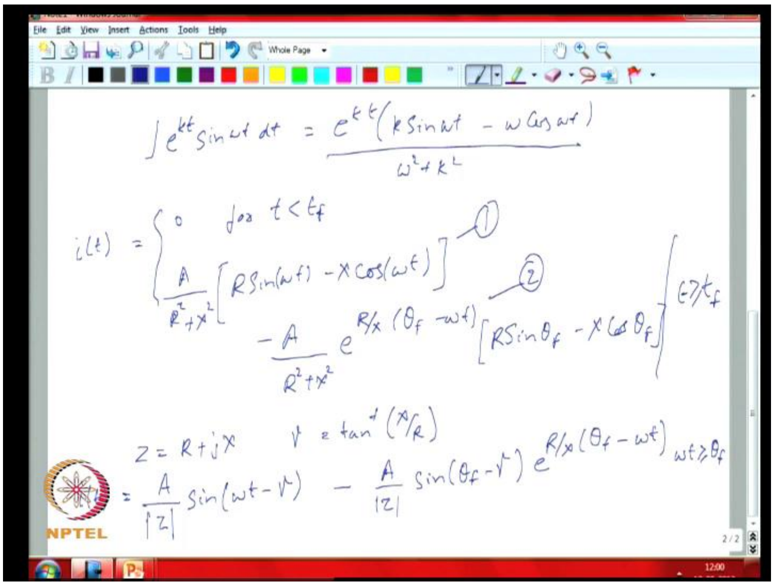

So, we can use an expression for integral of that form, e to the power of k t sin omega t d t, is equal to, e to the power of k t, k sin omega t minus, omega cos omega t by, omega square plus, k square. So, we will use this expression and substitute what we had in our previous equation. So, you get your i(t) is equal to 0 for t less than t f; and for t greater than t f, greater than or equal to t f you have, A by R square plus X square.

So, if you look at this particular term say, the first term, this is a term, the sinusoidal term what you would expect normally when you expect a R, X to the sinusoidal side; the second term over here is exponentially decaying term. So, that is the transient term; and this expression over here, this second expression is for t greater than or equal to t f. So, our term 1 is the A c term and term 2 is the, is a exponentially decaying term.

And, you could take z is equal R plus j x, and gamma is equal to tan inverse X by R. So, gamma is the fault angle, the impendence angle. So, you could then rewrite this particular expression for i(t) as a, A by magnitude of z, sin omega t minus gamma, and A by magnitude of z sin(theta f minus gamma) e to the power of R by X, theta f minus omega t, for omega t greater than or equal to theta f, or t greater than t f.

So, you can see that essentially the first term is the A c term that is what you get from your phased analysis. So, when you do 3 phase of fault analysis or a sequence model analysis what you are actually getting is the first term. The second term is essentially a transient component. And, typically when you look at dynamical system you assume that the transient component is being cost by initial conditions.

So, the initial conditions caused transience, and the transience die away. In this case the transient is not being caused by initial condition; it is being caused by the sudden application of the sinusoid. When we talk about a sinusoid it is occurring from minus infinity to infinity for all time, as here you have a sinusoid which is getting applied at t to t f that introduces a transient term.

So, you can, if you look at this particular expression you can see that, if you look at the second term, this is again the second term, you have a component, sin of theta f minus gamma. So, you can see that depending on how theta f is related to gamma you can have different types of exponents.

So, if, theta f equal to gamma, if your fault is occurring exactly at the impedance angle of your R L network, you will not have any transient term. If, theta f is less than gamma, then you would have a additional transient term which is adding to your steady state component; and if, theta f is greater than gamma, then essentially you would have a subtracting term.

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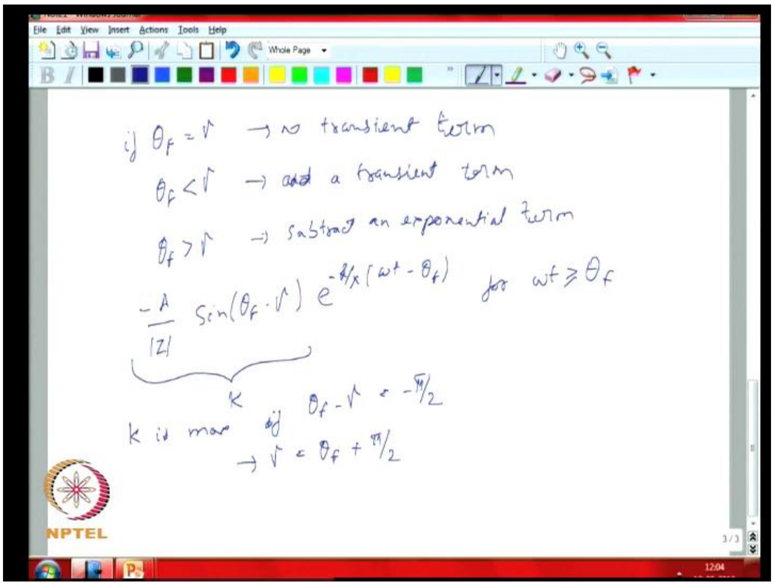

So, for a given X by X ratio if, theta f is less than gamma, a transient exponential term is being added. So, again if you look at that particular term you had, what we had was, minus A by magnitude of z sin theta f minus gamma e to the power of minus r by x, omega t minus theta f, for omega t greater than or equal to theta f. So, if you take this particular term as K we can see that the K would have a maximum value when theta f minus gamma is equal to minus phi by 2 because you have a minus term over there, or gamma is, theta f plus phi by 2.

So, if your impendence angle is, theta f plus phi by 2, then essentially you would have the maximum of this term. And, we know that in physical systems the maximum value of the impedance angle in a R, L, circle is 90 degrees, right. So, the next point is to look at what theta f should be to actually result in the maximum peak for fault current.

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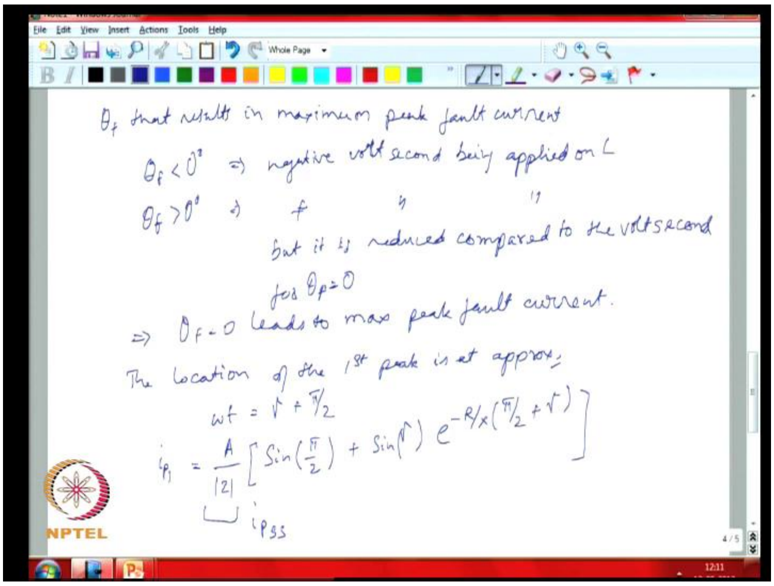

So, you can, if you look at the circuit that you have, you have a R L circuit which is being excited by a sinusoid. So, you can see that if theta f happens before 0 then essentially you are applying a negative volt second to the inductor, and if theta f is greater than 0 you are having a positive volt second being applied on the use; you have actually a positive volt second being applied, but it is reduced compared to the volt second for theta f equal to 0.

So, if you look at the R L circuit, the maximum value of volt second that you would apply on the inductor because the integral of the voltage, volt second is proportional to the current to the inductor. So, the maximum volt second that you would apply on the inductor would be for theta f equal to 0. So, to maximum; So, then we could actually look at the question that we had in the, our question we were given R by X of 1 by 3, and magnitude of impendence to be 0.1, magnitude of z to be 0.1.

So, if you look at what is being asked over here, for magnitude of the impendence being 0.1, and for these values of theta f prior and given R by X of 1 by 3, look at the expressions for your fault current.

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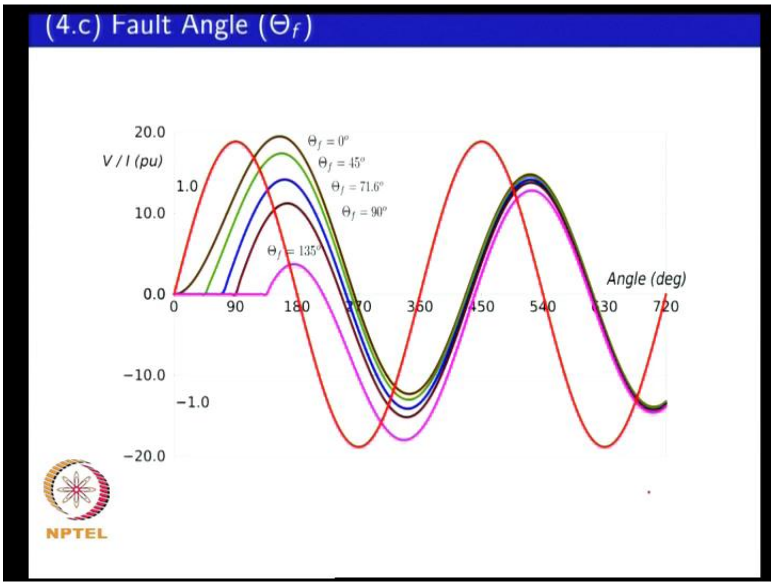

So, what is plotted over here is essentially, what is over here is the voltage v, and what is shown over here is the value of the current, for different values of a fault angle. So, this is for theta f is equal to 0, this one is for theta f is equal to 45 degrees, and this is for theta f equal to 90 degrees. And, this particular case is for theta f equal to, the blue line is for theta f equal to 71.6 which is the same as the impedance angle.

And, we can see that the peak fault current has reached steady state. But, from the beginning there is no transient term. So, only when theta f is different from your fault angle of that R L circuit we would, you get the transient term. For theta f is equal to 135 degrees you have this pink line over here. So, you can see that theta f equal to 0 as expected gives you the peak fault current.

So, when, the next question is to locate the first peak of the fault current. Again, you can actually write an, derive an expression for the first peak by looking at the fault current taking the derivative and setting it to 0; what we will assume is that this roughly occurs at the fault angle plus pi by 2.

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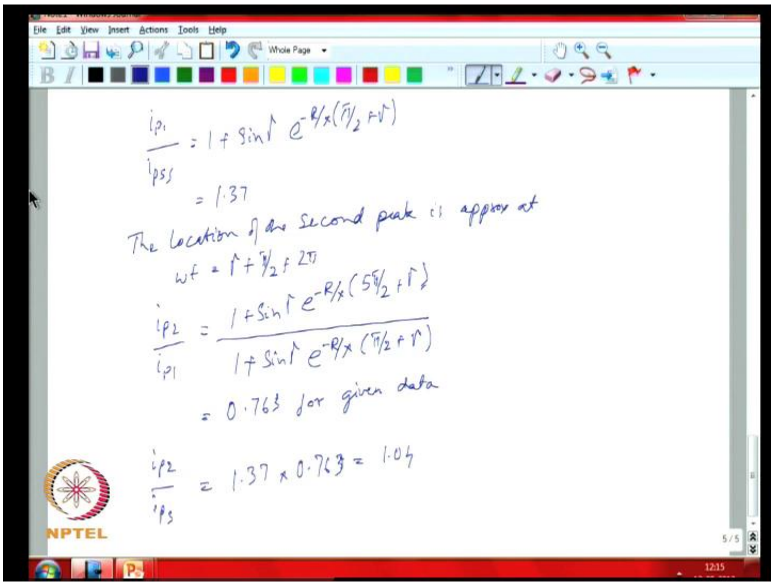

So, then you have an expression for i p 1 is equal to A by magnitude of Z, sin (pi by 2) plus; so, this is again assuming that your theta f is visible which is source in the maximum fault currents. So, you can see this term over here; this is your, A by magnitude of Z, is your, i p, steady state. So, you can write an expression for the ratio of your first peak in the fault current to your steady state current.

So, for the numbers in the given problem, this value is about 1.37, as your peak to steady state fault current value. So, if you then look at what could be the second peak, you can get an expression or the approximate location of the second peak, where 2 pi radiance later or 360 degrees later. So, you can write an expression for, i p 2 by i p 1 as; so, for the numbers that we had in the problem this turns out to be 0.763. And then, if you look at i p 2 by i p steady state that will be the product of this particular ratio times this particular ratio. So, this would be 1.37 into 0.763 is 1.04.

So, you can see that the second cycle even with X by R ratio of 3, your transient has died out. So, the transient depending for typical lines, especially in the distribution system, may not last for too long. But you have circuit breakers that can open at any point because it can open in response to a relay not just after measuring current and subsequent to that. So, you have to give relevance for the peak current that can potentially flow because if breaker is opening and a high level of current is flowing, the amount of charged ions in the gap when the breaker is separated would be proportional to the current. It has to be, we show the capability to interrupt whatever peak can potentially flow.

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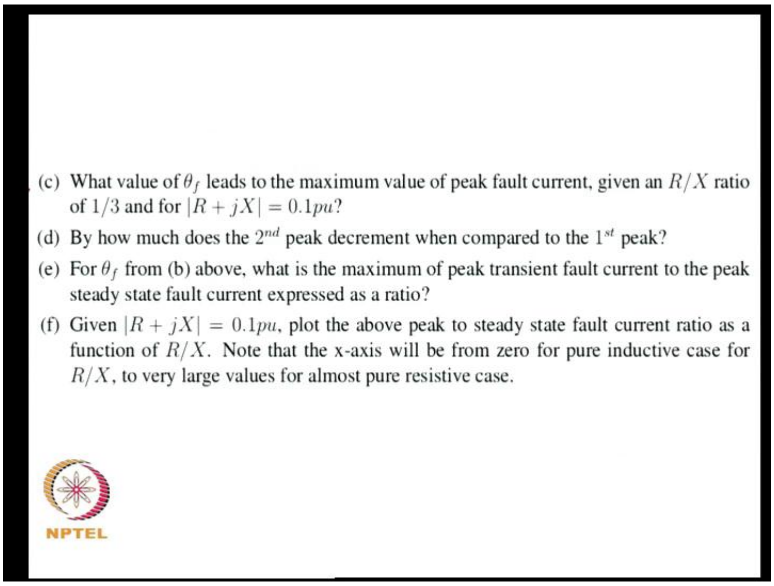

So, in next problem you are asked to plot the i p, the first peak by the steady state fault current as a function of your X by R ratio, R by X term; and so, R by X term being small would correspond to a circuit which is almost inductive; R by X being large would correspond to a circuit which is almost strictly resisted. So, you would like to see what the peak to steady state of our current level is as a function of your X by R ratio.

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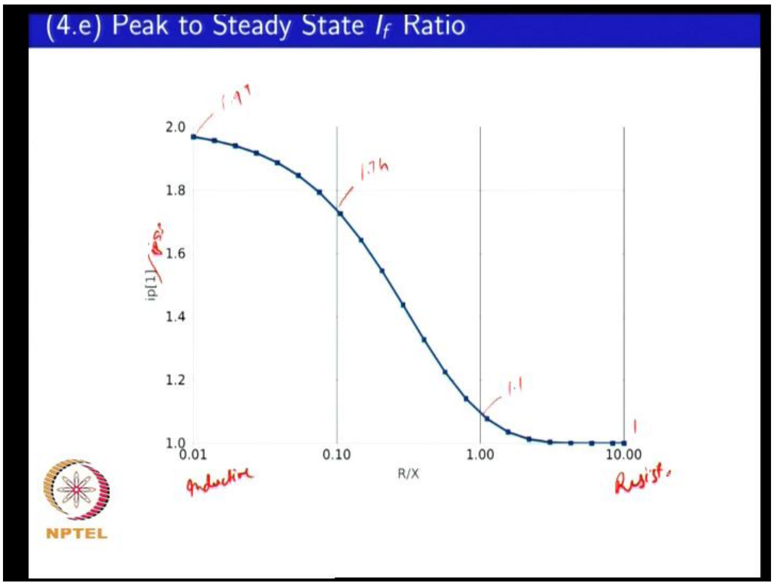

And, you can see that what is plotted over here is, i p 1 by i p steady state, at R by X ratio of 0.01 which this end would be inductive; you have almost twice the peak to steady state current which is what you would expect in, if you are just an exciting inductor with a sin wave, your peak current can have a bit d c out set which would take your peak to twice your value.

And, you can see, say for R by X of 0.1, you have a number which is 1.74; here it is about 1.97; here you are talking of 1.1. So, if you are having a R by X ratio of 10, it is almost this resistive, you do not see much of a transient term at all. And, obviously, your transient would be higher in the inductive case compared to the resistive case.

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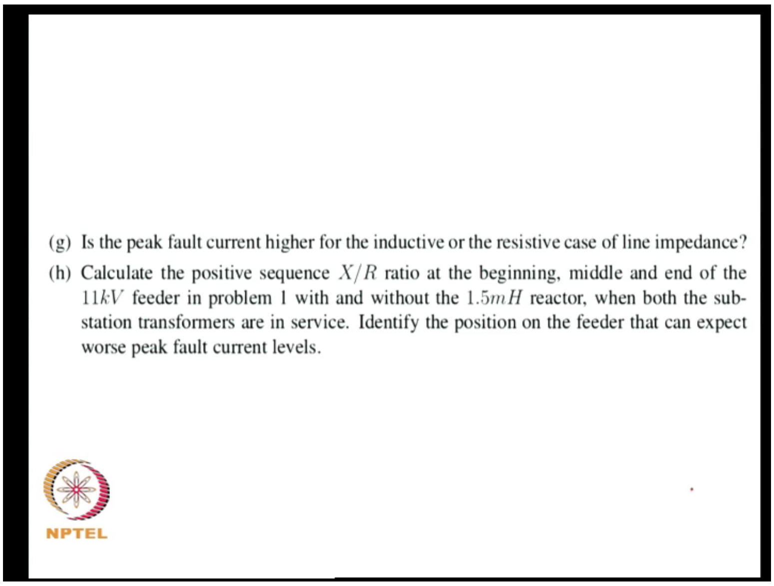

So, in the next case we are, we looked in problem 1 of a feeder with a, which was 4 kilometer long you had a transformer at the substation, and so you could then look what the X by R ratio is of that particular example is, depending on whether you have a fault close to the substation, would be at the feeder further down towards the end of the feeder. You also have the keys where what happens when you add a reactor to limit your peak fault current. You also have single phase fault case, the 3 phase fault case, and you can look at the X by R ratios for all these different situations.

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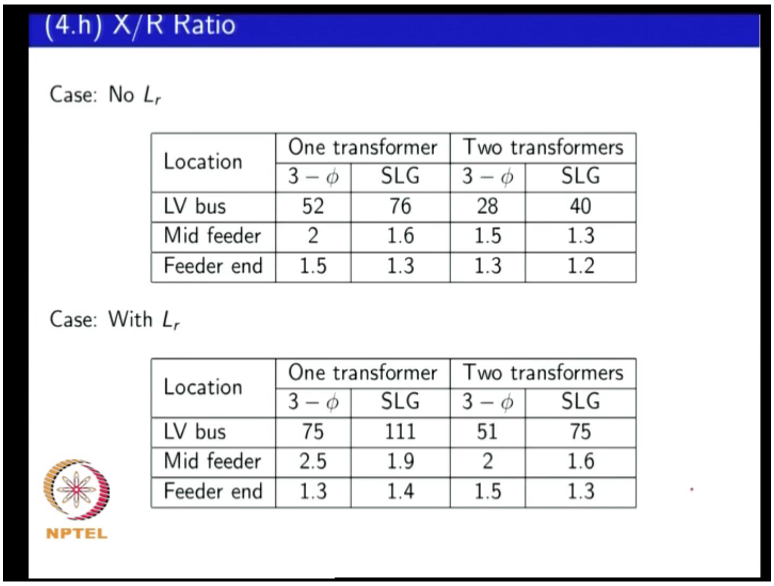

So, you can see that the general trend is that the X by R ratio can be quite large, especially, if you are close to the equipments such as transformers, etcetera. But further down on the feeder your X by R ratios are more typical of what you could expect on your distribution system, where it is more resistor. And, as we mentioned the distribution systems tends to be having lower X by R ratios compared to transmission systems.

So, if you are, in the case when you add, L r, you can see that your X by R ratio is going further up. But, when you go further down into the feeder you do not see much of a difference on the X by R ratios because your resistance term of the feeder is now dominating that ratio.

So, again this discussion is to impress on you some of the thought's that go behind how to select the protection components for your system. And also, we discussed in the class how this protection levels can get altered once a, d g unit, is added in; this gives you a flavor for some of the issues that can potentially happen.

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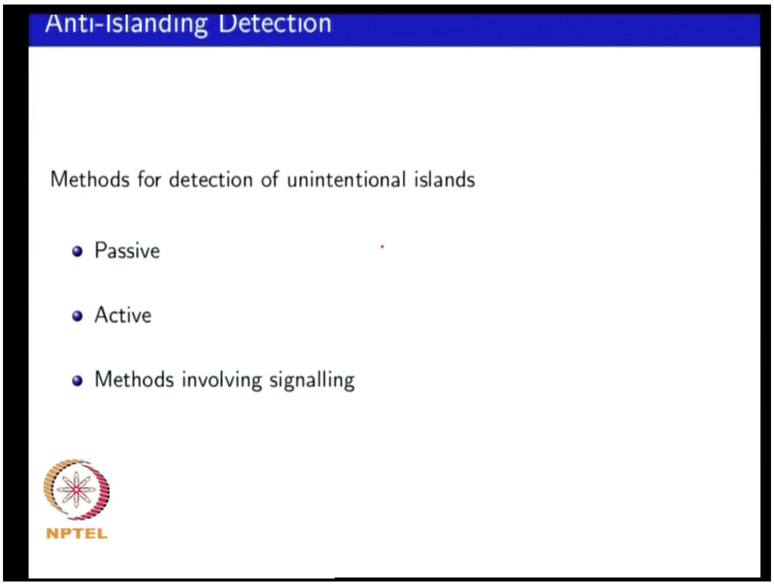

So, now we will continue with the discussion where we had left off, on islanding of a distribution system. And, we had talked about the different ways in which system can island. You can have an unintentional island or a intentional island. So, you might have a intentional island for power quality reasons, and unintentional islands for a variety of reasons; there upstream breaker might open.

Also, you, we saw that intension islands are, can result in situations where which you want to avoid when you could potentially damage equipment, etcetera; and so, there is a need for detecting a situation of an unintentional island. And, anti-islanding algorithms are ways of detecting a situation of an unintentional island. And, the types of anti-islanding algorithms can be passive, active, or it can involve signaling.

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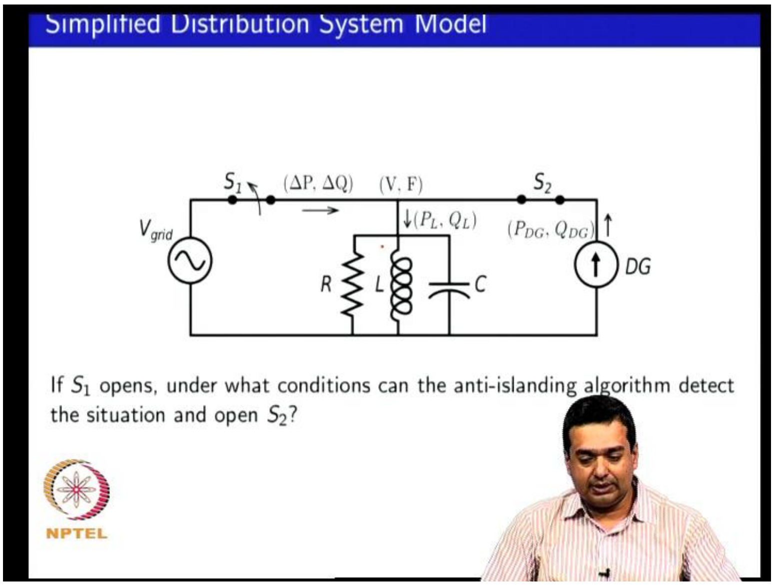

So, we started with then looking at model of a feeder as a R L C circuit. And, when we started looking at the situation where you want to detect by passive methods the situation of a unintentional island, the problem can be simplified as following. Where, if a circuit breaker upstream on the feeder is opened and the feeder has nodes are modeled as, R L and C, a parallel R and C network; and the DG is modeled as a source injecting a real and reactive power into the network. So, by monitoring voltage at the DG, so you monitor the voltage and make a decision on whether to open the breaker located at the DG.

And so, then to analyze the situation we defined what the problem should be, under a nominal conditions if you have a situation where your power that is injected by the DG exactly matches the resistance, the power consumed by the feeder; and, if the injector reactive power of the DG is 0 so essentially the DG is operating at unity power factor. And, if whatever reactive power is drawn by the loads on the feeder is exactly compensated that would correspond to a situation of a R L circuit which is at resistance at 50 hertz.

Another assumption that we had was that the quality factor of this resistance is greater than 1 which means that the effect of the l c oscillations is dominating over the effect of any damping provided by the load, or mismatching between the load power consumed and the power injected by the DG.

So, if you have a situation where exactly the loads are matched, and the load power is matched with the DG power and the Q load is that is being drawn by the load is 0 then delta P and delta Q would be 0 should correspond to a condition where the current through this particular switch S 1 is 0. And, if a current through a switch is 0, it becomes difficult to say whether the switch is actually carrying 0 current or whether the switch is actually opened circuit because the current is invisible. And, the voltage over here would continue to oscillate because you have a resonance circuit which can continue to oscillate for a long time.

So, now we will consider the situation where, consider a situation where you have some mismatch in the power consumed by the load and the power being injected by the DG. And, we will first look at the situation where you are trying to detect a situation of unintentional island by looking at the voltage magnitude.

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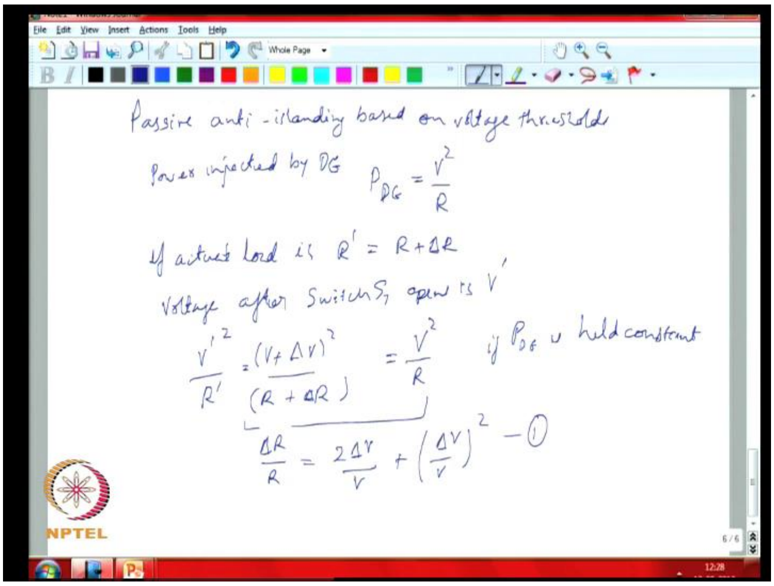

So, the power injected by the DG; and, nominally and if the actual load on the feeder is slightly different. So, if actual load on prime is R plus delta R; then you have now a delta p flowing into that network, so if you open the switch instead of having the original voltage V you will have a different voltage V prime. So, if we assume that the power injected by the DG is continuing to be the same, as what it was previously. The original power was V square by R.

So, if it continues to inject the same power, the power could be from power current could be from some other controls it could be from say for a P V system it could be the max m p p t tracking which determines how much power is being injected. So, we will have now the prime square by R which is R prime is, V plus delta V, whole square. So, you could simplify this. You could, you can then write delta R by R; simplifying this expression you can write delta R by R is 2 delta V by V. So, you can get a relationship between your delta R, and your change in voltage to be expected.

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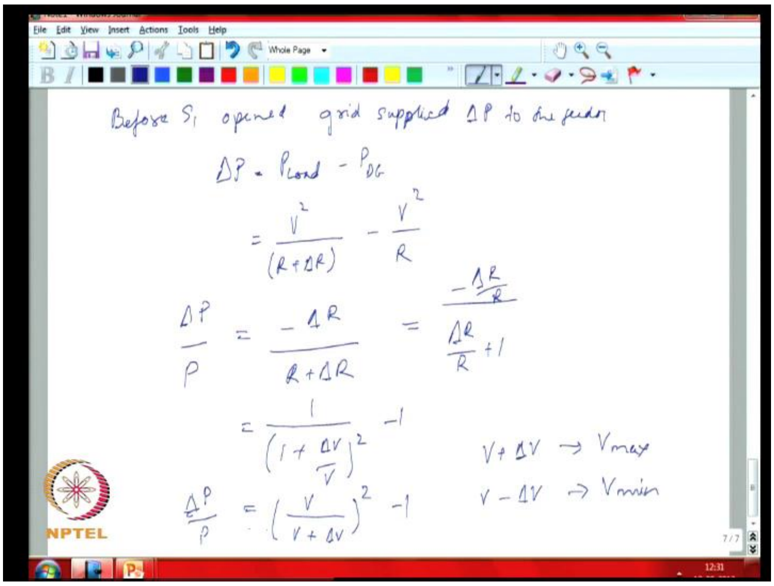

So, if you, before the switch S1 is opened. So, the power that was originally being consumed in the load as, V square by R plus delta R; the power put out by DG was V square by R. So, you can now write an expression for delta P by P; power P is V square by R, so you can; so, dividing this particular expression by V square by R you can get a expression for delta P by P in terms of delta R.

So, after simplifying this expression you can get this particular relationship between your delta P and delta R. So, you could take the expression for delta R by R from the previous page, and substitute it in this particular expression over here. And, for further simplification you can then express your delta P to be equal to; so, essentially we can relate the delta P and the voltages on your circuit, and we could consider V plus delta V to be corresponding to the situations of upper thresholds and lower thresholds. So, we can take V plus delta V to correspond to some V max, and V minus delta V to correspond to some V min; and then you can actually write an expression relating delta P by P to V max and V min by substituting in this particular expression.

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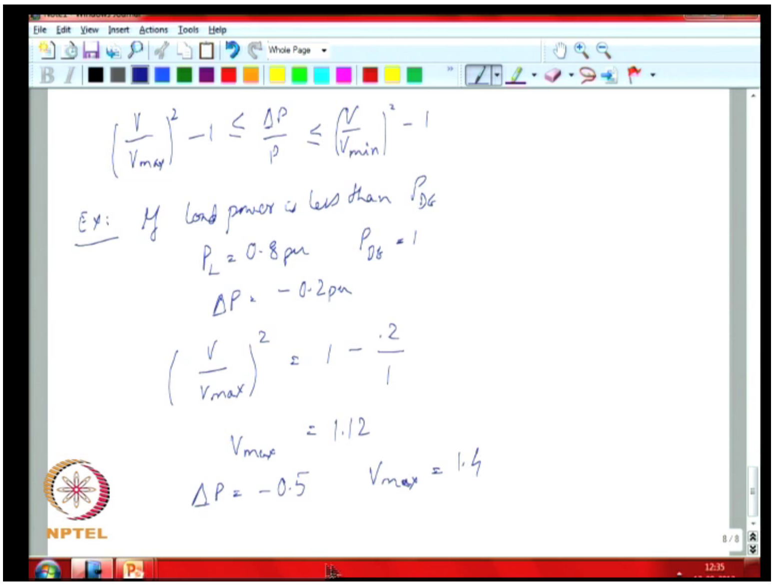

So, you can write V by V max. So, this gives a way of relating how much difference in power would lead to what change in voltage once a upstream breaker opens. So, we will look at a few example numbers. So, for example, if you have a feeder, say, if the load on the feeder is less than the DG power. Then, essentially what you would expect is you are injecting power back into the grid; and if a upstream breaker opens we would expect a higher voltage on the feeder.

So, if P L is 0.8 per unit, and P DG is 1 per unit, then your delta P is minus 0.2. So, you can write an expression for V by V max, 1 plus delta P by P. So, this is equal to; so, essentially if you look at what V max is. So, you can see that in this situation where the load power was 80 percent of what was being consumed, being injected by a DG unit. Then, if you open an upstream vehicle you could expect that 12 percent of your voltage.

So, if you had over voltage relay at the DG which was detecting say 10 percent of a voltage, at 12 percent of a voltage, it would immediately say open your DG breaker and disconnect the DG. So, you would able to detect a situation of unintentional island.

So, if you do a similar exercise, if delta P is minus 0.5 which means that if the load was only 50 percent of the power that was getting pumped in through your DG unit, you get V max of 1.4. So, we get a much higher voltage if your power being pumped in by the DG is higher. Of course, at a voltage of 1.4 you can damage the DG, damage equipment you do not want the voltage to go that high.

So, here, we have a quite a few assumptions we are assuming the feeder to be R L C components, and you are assuming that power injection is still happening at a constant rate. So, beyond some critical limits you might this assumptions may not be valid, but definitely you will see an over voltage. So, you could also look at the other situation where say, the other situation where your DG power is much less than the load power; that might be more common where DG might be a few solar panels, and your feeder might be having a much larger total loading.

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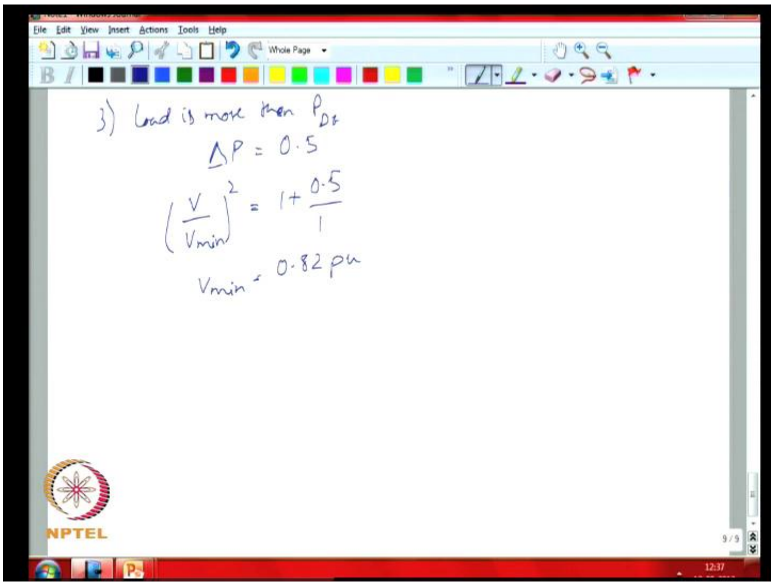

So, if you look at a case where; so, we will assume that your power that is being pumped in by the DG is just a half of your feeder load power, then delta P is plus 0.5. So, you have V by V min. So, in this case, where your feeder power, your DG power is 50 percent of your feeder power then as soon as your upstream breaker opens then the model indicates that your voltage would settle down at 82 percent, again assuming that the DG is still injecting the same level of power.

So, in this case say, suppose you had say, a relay which was looking at under voltage and you set the under voltage relayed to 85 percent then it would disconnect the DG because the DG would be say, under voltage in this case. So, here you are looking at just the voltage, and based on the voltage you are determining windows; and depending on the mismatch between your DG power and your load power then you could see whether there is a greater chance of forming an unintentional island or is there a remote chance of forming a unintentional island.

So, in case where you have just a few solar panels and your feeder power is in mega watts then the chance of an unintentional island is small, but as the penetration of DG units become more then you have greater possibility of forming a unintentional island.

So, next we will look at how you could make use of again the RLC model of the feeder, and then make decisions on whether there is a unintentional island or not, based on frequency. So, depending on what your L and C values are, you can have frequencies which shift from your nominal frequency. So, based on the feeder model we can write down expressions for what the change in frequency would be, and use that to determine whether a unintentional island has been formed.

Thank you.