Power Electronics and Distributed Generation
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Lecture - 5
Circuit Breaker Coordination

Welcome to class five on topics in power electronics and distributed generation. So, we have been discussing models of components of the distribution system. We have looked at the transformer model, the line, then D G models and then we are looking at models of what going to protection, equipment, fuse, reclosers, and sectionalizers. We are starting to look at the circuit breaker, the inverse current characteristic.

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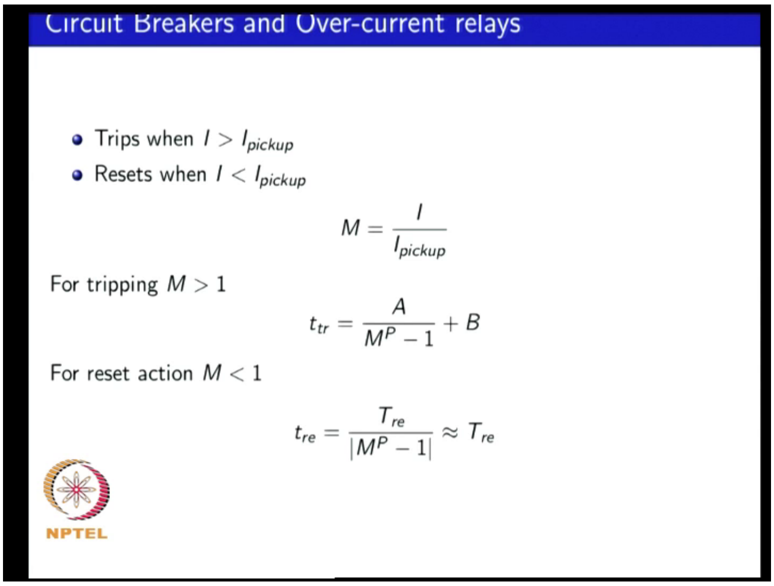

So, if you look at the circuit breaker, you have equations that actually model both its tripping characteristic or it is a reset action. So, it trips whenever its current flowing through the breaker or over current relay is greater than the pickup current. So when the ratio M; when the ration M becomes larger than one, it initiates a tripping action. And the time required to trip depends on the value of this ratio M. So, the larger the ratio M is, the shorter it requires to trip. The parameters A, B, P, t r e are constants. Depends on the based on the type of characteristics that it is following; the breaker or the relay is following. So for M larger, greater than one, it trips; and for M less than one, it resets.

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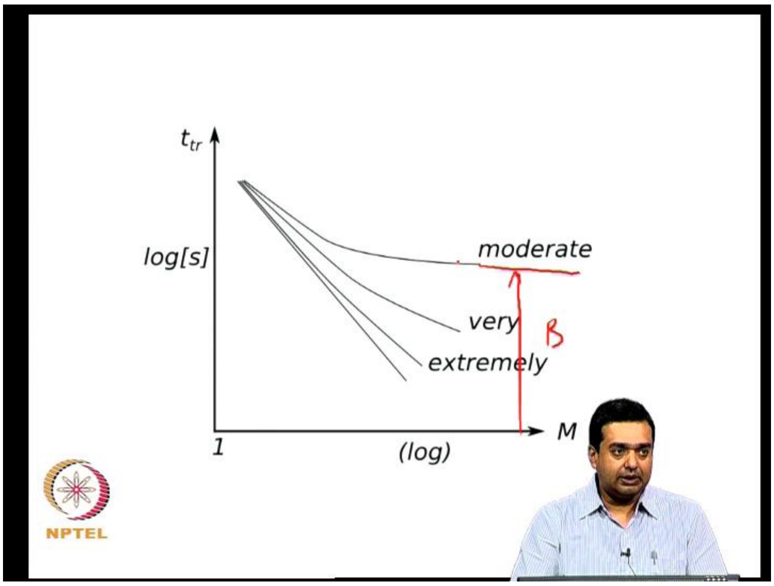

So, if you look at the parameters A, B, P etcetera you can actually classify your over current protection devices as moderately inverse, very inverse or extremely inverse; are inverse characteristics.

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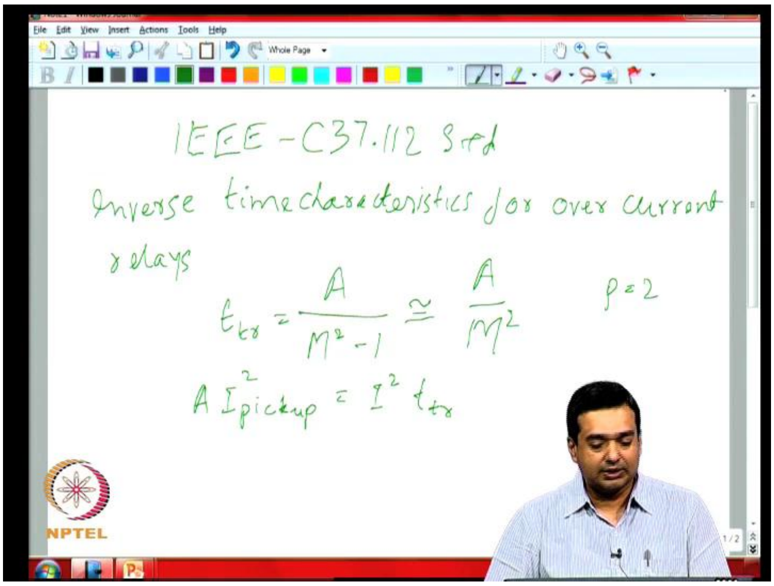

Good reference for this is IEEE. So, if you look at the characteristics of the relay, if you… For the extreme and the very inverse type of characteristics, the value of P in the equation is close to 2. So, if you look at a large value of M much greater than one and the value of B which is close to 0, we have a trip time. The trip time is given by A by M square minus one. And for M being much larger than one, this is roughly equal to A by M square. And we know that M is I by I pickup. So, you have A into I pickup square is equal to I square into t t r.

So, essentially what you get for P is equal to 2. It is a characteristic of I square t. It is a constant, which is a similar to that of a fuse characteristic. So essentially in a fuse, your I square r t represents the energy that is dissipated in the fuse. So, you end up requiring time depending on the amount of energy that is deposited in the fuse.

So, this sort of characteristic with P is equal to 2 for small values of B represents to that of a fuse; is similar to that of a fuse. If you look at the B and the previous equation, the B term over here, this represents the definite time aspect of the I D M T characteristic. So, if you look at having a positive value of B; so if you look at the B, it essentially shifts the characteristic to a finite value; which says that no matter how large your current is. It needs a certain delay before the actual protective device can act. So, essentially if you look at this sort of characteristics, it can allow a large amount of current to flow for a short term without tripping the breaker. But, if that is large amount of current continues for much longer, then the breaker would trip.

So, this type of characteristic is useful when you have, say, components such as motors, where your motor starting current might be large; which means that you will be operating at M which is large. But, then once the motor speeds up, then the current would come down. So, you can actually operate your device without causing your breaker to trip when you are starting the machine.

If you look at the reset time of the circuit breaker, the t is your reset time. The reset time also depends on the ratio of current. But, typically if you look at your nominal current that is flowing through your circuit, it might be much lesser than your pickup current. So, you can take M. In that particular case, on the normal condition to be operating to be much smaller than one; which means that t r e can be taken as roughly equal to capital T r e for M close to 0.

So also for simplicity, we can assume that the rates at which your reset or your trip action is occurring is at constant trip rates or reset rates. So depending on the time required for tripping, it is going from a point of normal condition to a trip condition. And if the fault current goes away for some reason, then it is going at a constant rate and back to the normal condition.

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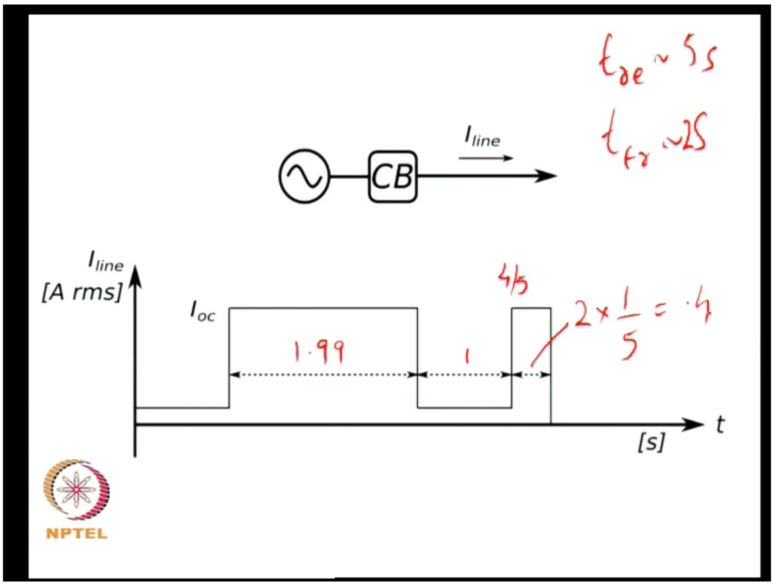

So, if you look at example of, say, a electromechanical type of relay or a circuit breaker, essentially tripping action in such a breaker occurs when your electromagnetic torque generated by the coil for tripping exceeds the restraining torque of your actual spring or the spring in the relay. So, whenever your generated torque is exceeding (Refer Time: 08:45), a protection disc moves forward and it reaches a point where it would actually cross the circuit breaker to act.

So, this sort of actions that I had just mentioned also emulates not just of a fuse, but also of an electromechanical type of a protective device. So, if you look at an example of a, say, a circuit breaker, where we will assume that it is a reset time. It is of the order of, say, 5 seconds and it is having an over current level I o c. And at that particular value of I o c with your parameters of the breaker, suppose you had a trip time of, say, 2 seconds.

So, if you had 2 seconds of trip time, then we can look at a couple of situations. Say, this could be a situation where you had a source, you had a circuit breaker and you have current flowing in the line. And that is what is shown in the plot below. Where at some particular point, your current went up and you have a over current which cause your M to have a value much greater than one. And at that particular value of over current, your trip time is 2 seconds. But for some reasons, say, if your over current lasted, say, for 1.99

seconds and the over current went away. It means that the breaker nearly tripped, but it did not actually trip. So, it is still staying close at this point. And over here, it is actually having a reset action.

And, suppose this duration is 1 second, and then during this particular 1 second, the circuit breaker was going through a reset action. So to fully reset, it would have required 5 seconds. So, in one second it would have reset by one-fifth of the reset value. So, it would be; at this particular point, it would have been at four-fifth of the value to actually trip the actual tripping device.

So the question is, now if your over current again came up it will not need to the same value of I o c, it is still not need another two seconds to trip. But, it will need a smaller amount of time to trip and the amount of the try time that it would need to trip is about; it would have typically required 2 seconds. But, you have only one-fifth of the distance for the tripping action to occur. So, it would need about 0.4 seconds for it to trip. So, you can see that assuming constant, say, tripping rates and reset rates, you can actually look at what happens when current goes up and low in some switched manner.

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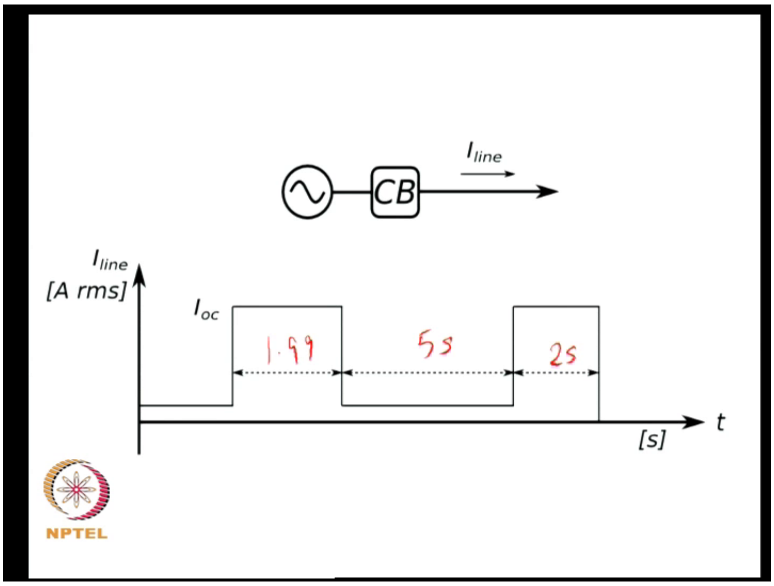

So, if you had another situation where, say, you had a similar level of over current and the over current lasted for, say, 1.99 seconds and then the current went away or came back to a level much lesser than 1 for say 5 seconds. It means that at this point, now your circuit breaker is fully reset. Now if your over current level went up to a higher level, it would need actually full 2 seconds to actually trip again.

So, depending on your calculated trip time and your reset time, you could actually evaluate for what duration your circuit breaker would need to actually operate with devices such as reclosers; where your current level can actually potentially go high and low. Again, this analysis of assuming, say, constant trip rates and reset rates, is a simplified analysis.

So, if you look at what we are doing, we are trying to look at what are the implications of adding a distributed generator to a distribution system, rather than actually doing a precised analysis on how to set protection levels. In fact, today there are lot of softwares, which is available which can be used to do actually precised coordination and calculations. But, this simplified analysis can give you a good feel of what are the implications of adding of coordinating protective devices and the implications of adding distributed generation source to your actual system.

So now, before we actually do a protection and coordination based on these models, what we have to do next is actually evaluate what the fault current levels are and to actually calculate your fault current level. It depends on where the fault is occurring; whether it is occurring at a zone that is closer to the substation or a zone midway through the feeder or at the distribution transformer at the consumption point. It depends on the type of fault, whether it is a three phase fault or a single phase fault. The fault impedance; whether it is a dead shot or it is a impedance fault. So, there are variety of such aspects that is to be considered when you are doing fault calculations.

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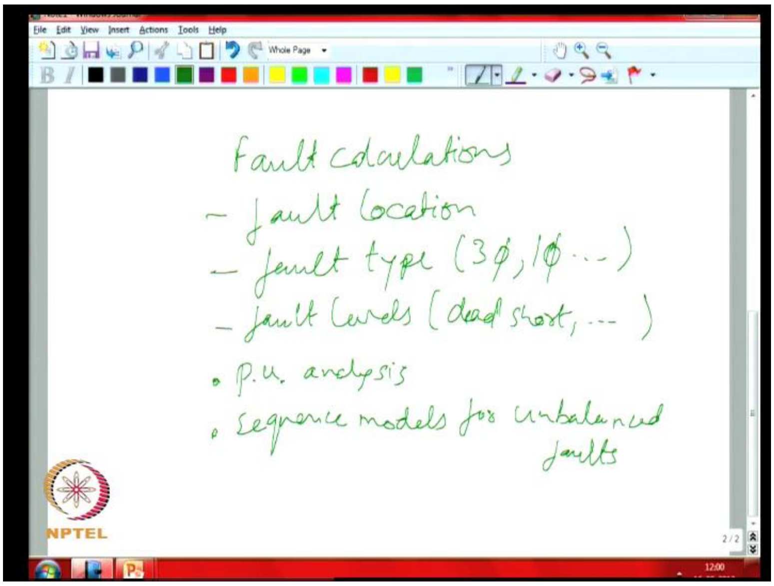

So, if you are looking at whether it is a three phase or a single phase, different types of a combinations line to line etcetera, then fault levels. So to do these calculations, what the analysis tool that is used is what you would have studied in a Power Systems Analysis course. One is a per unit analysis. So, you look at the different components or normalize bases and then evaluate what the fault currents are. And to look at the situations of unbalanced faults, you will do essentially a sequence models.

So, these both aspects are important. I mean, if you look at a three phase type of fault, it is easy from the calculation perspective. But as we discussed in previous class, the most common type of fault is single line to ground fault, so looking at different situations with a sequence models become important.

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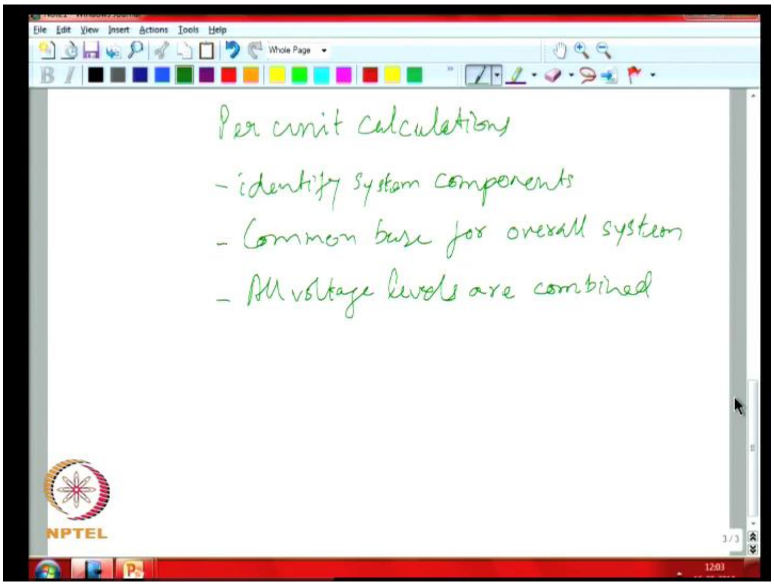

So, if you do a per unit type of calculation, first you need to identify all the components in your system. Then, even if the components are all provided to you on a per unit basis, they might be on different base. You might have items, which are closer to substation at higher power levels and at a higher voltage levels. The systems closer to the consumption point would be at lower power levels and lower voltage levels.

And to do the analysis, you need to bring them to a common base. And you identify the location of interest to you. It might be your consumption point, where you are doing a calculation or some distribution transformer, where you are doing a calculation depending on the region where you are trying to do your Engineering analysis; you bring it to the common base associated typically with that particular point. Then, you transform all the values to this particular common base corresponding to this common point. And essentially when you do that with transformers, essentially your transformers become transparent on a per unitize basis.

So, all your voltage levels, your transformers are transparent and you bring in all the impedances for the different locations at some different voltage levels to a consistent per unitize basis. I mean, you will get a better feel for it when we look at an actual example, where we can go through and do what calculations we would need to do.

If you look at; so once you do the analysis, you get your results on a per unitized values. So, what you really need is the physical values that you need for sizing a circuit breaker or setting your relay. So, if you make use of your base quantities to get back your actual values for your currents, voltages, etcetera. If you look at the use of per unit analysis, compared to the past, the use is reduced today; because of again the extensive availability of software to do these calculations.

So, all the normalization etcetera can be handled at a numerical level, rather than you having to handle per unitization etcetera. However, there are many applications where it gives you intuitive feel for; does it make sense if you do the calculations on a per unitization basis.

Also, when you look at the Power Electronic Design, even though you do not need everything on a per unitize basis, for your controller design per unitization is an important aspect; because often you are implementing your control on a fixed point processor. So, you need to actually normalize it to the fixed point. Floating point processors are more expensive than fixed point. And even if you are using powerful processors, you need to do some level of normalizations, especially when you are interfacing A to D converters which have fixed voltage ranges and finite number of quantization levels, etcetera, D to A or PWM ports; again, which have finite bit resolution. So, having normalization and doing such an analysis is actually useful in multiple ways.

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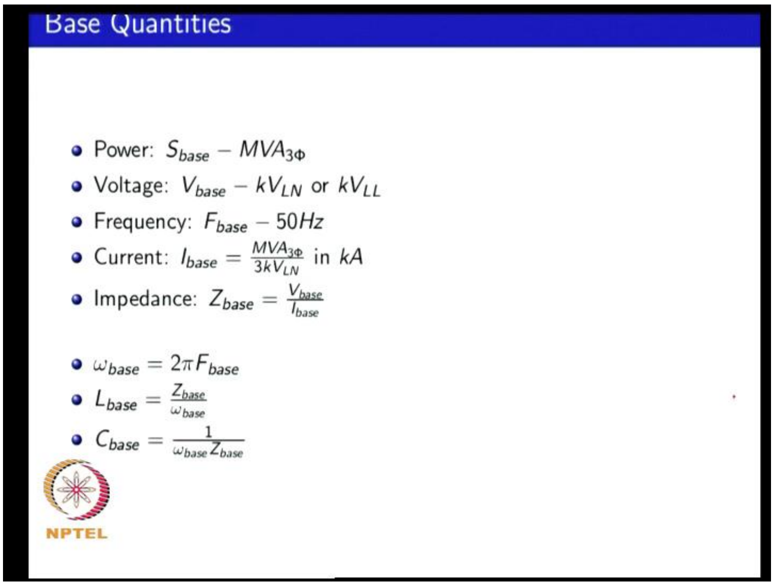

So, if you then look at what the base quantities need to be; the common base quantities are the power. It can be the parent power, the S base on a… If you are looking at the distribution system, we might be talking about M V A on a three phase basis. Your voltage can be; you have to get a base voltage. It can either be your kilovolts on line to a neutral basis or line to line basis.

In this course, we will look at the voltage on a line to neutral basis. But, often it can also be done on a line to line basis. In fact, when people state a voltage of a three phase system, when they talk about 415 or 690 or 11 K V, they are actually referring to line to line voltage. So, unless otherwise, specified people give the physical units of a three phase system, the voltage on a line to line basis; that is the normal convention. For the base quantity, we will use the line to neutral voltage as V base. The frequency there is the fundamental frequency. In India, it is 50 hertz; that is the nominal frequency. Your current base can be defined as your power base divided by 3, divided by your voltage base on a line to neutral basis. So, this gives your base current in kilo amps.

Your impedance is Z base; is your V base by I base and you could have derived quantities. These are useful, especially when you are designing power converters when you are looking at a filter design, etcetera. Your omega base is 2 pi F base, your L base can be obtained as your Z base divided by omega base. And your C base can be obtained as 1 by omega base Z base.

So, these are useful especially when you are looking at power converters, filters etcetera. So, if you have one per unit capacitance connected in parallel, it means, that it is filter drawing a lot of leading (Refer Time: 25:16). So, you can get a feel for how much (Refer Time: 25:21) are being drawn by looking at these components on a per unit basis. So, if your L base is 0.3, it means that there could be a substantial drop across that inductor, series connected inductor, when rated current is flowing. So, looking at the impedances in per unit basis is useful.

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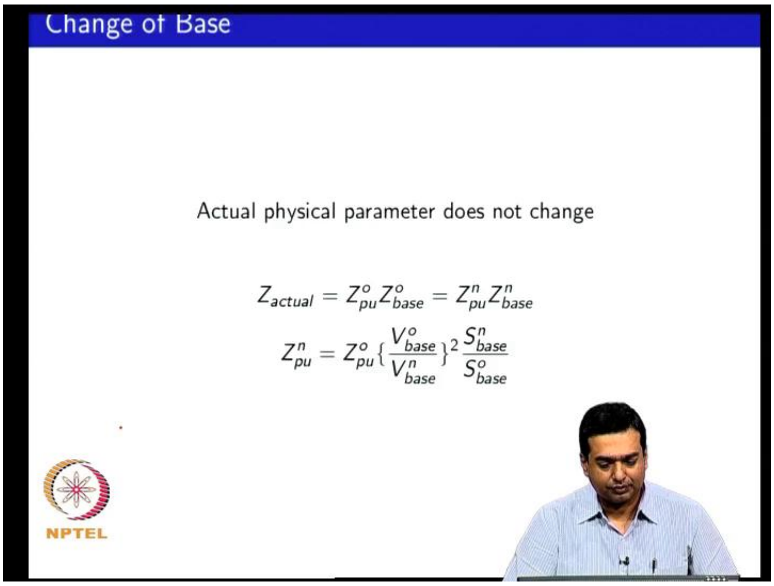

So, the next thing is to convert from your… one base to another, for actually your normalization calculations. One thing that I would like to just point out; when you make a statement that one per unit equals, say, 230 volts, you are committing multiple levels. One is per unit; means, it does not have dimension. 230 volts is in volts. So, you are talking about quantity, an equation where the dimensions do not match. And one is not 230. It would be okay to say 1 per unit corresponds to 230 volts or the base value is 230 volts. So, be careful when you say about quantities on a per unitized basis.

So if you look at change of base, your actual physical quantity; the idea of the change of base is that your physical quantity is not changing. If you change a base from one system to another system, the per unitized value might change, but your physical quantities stays the same. And you are saying that concept will get your per unitized normalized impedance on a new basis to be the old value multiplied by the ratio of old to new base quantity square and the ratio of new power to old power to the power of one. There are implications of having such an expression for change of bases.

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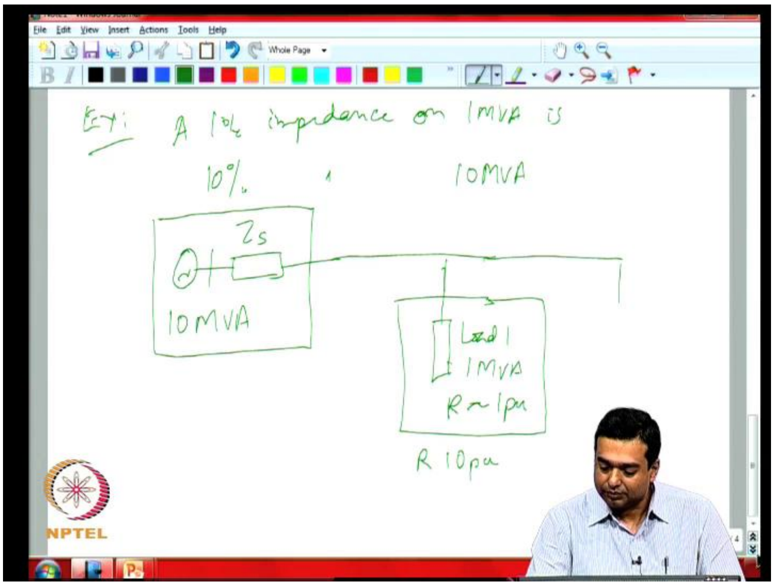

So, if you look at, say, a change of bases, one percent; so example 1 percent. So, if you go to a new bases because your ratio was your new equal to the old on a per unitized basis with the new value divided by old value. So, if you go up on to a new bases which is at a higher power level, your impedance quantity becomes larger and the implication of this is that, say for example, if you have a load which is a small. So, if you have a system where you have a source and you have some source impedance and you have, say, multiple loads.

So, if you look at your load of 1 M V A, which on its particular bases it might be a 1 per unit load. Essentially, now when you shifted to the 10 M V A level, this becomes; your load resistance is now 10 per unit rather than 1 per unit, once you bring it to a common bases. So, essentially what it means is the small individual loads becomes; seen as smaller and smaller entities. And is the reason why you might lump a lot of loads together and see it as a single load, power p q load, etcetera on at the consumption point and rather than looking at individual loads, when you are looking at larger and larger systems to which it is connected.

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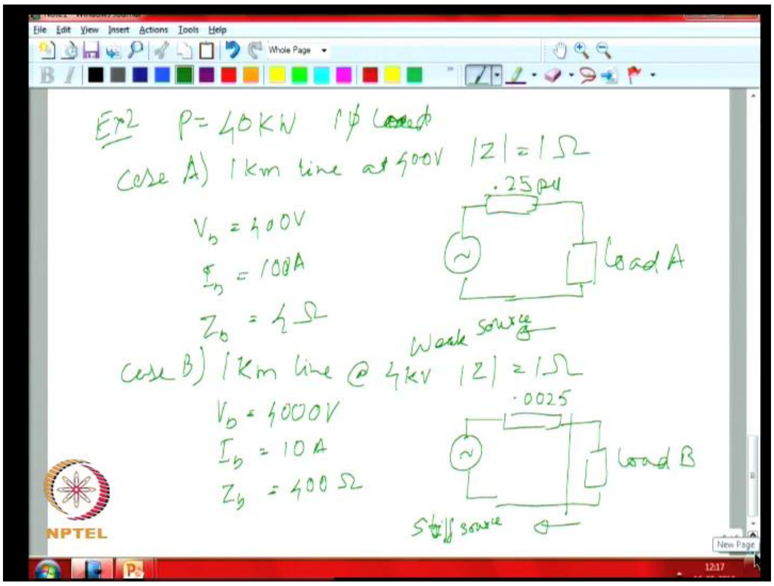

If you look at another example, where you look at the implication of, say, change in voltage level. So, if you have, say, a load, which is having a power level of 40 kilo watts and single phase. And you have say two situations. So in case A, you have 1 kilometer overhead line at 400 volts and the impedance of the line is, say, 1 ohm. So if you look at, we might define your V base as 400; I base as would be 100 amps because P is forty kilo watts. So, your Z base is 4 ohms. So, if you look at now the models of this source with your load, your impedance of your source is now 1 ohm by 4 ohms, which is your base. So, it has a value of 0.25 per unit.

So looking back, you are looking at a weak source; this source impedance is fairly large. Now if you take the same, the one kilometer line, and if you increase the voltage level because of better insulation, but you keep, say, the diameter of the line, its geometry etcetera similar.

And, say, you consider case B where you have one kilometer line at 4 K V and say the magnitude of its impedance is again 1 ohm. So, your V base in this case is at 4 K V, 4000 volts; I base is 10 amps; Z base is 400 ohms. So, if you look at the model of the system in this particular case, the load B, now this particular physical line is now showing source impedance of 0.0025; which means that if you look at it from the load perspective, this is now a stiff source.

And this is essentially when you look at it on a per unitized basis, you will see that it goes as the square of the voltage. So, you can see that now if you just take the same one kilometer line, it becomes important to look at it on a normalized bases to figure out whether you are actually encountering a situation, where you having weak grid or a stiff system.

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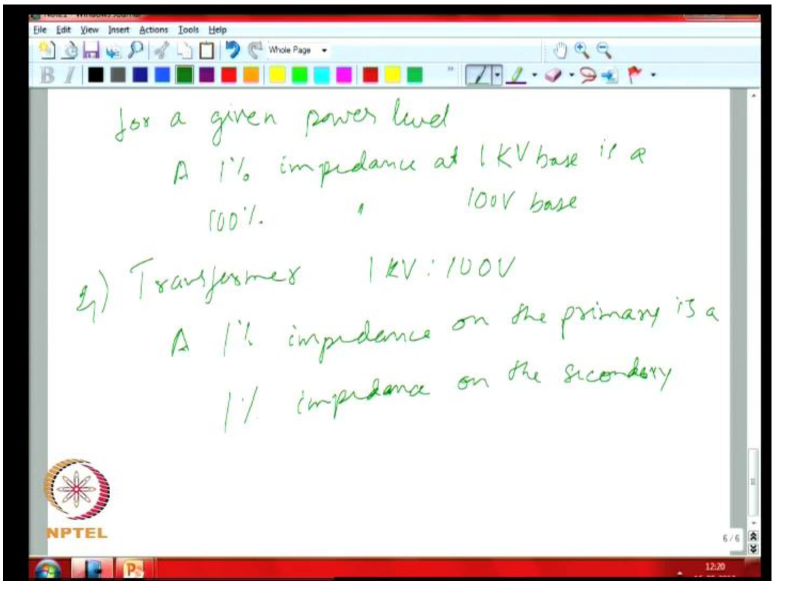

So for a given power level, 1 percent impedance at 1 K V base is 100 percent impedance at 100 volts base. So, as one goes up to higher voltage levels, similar impedance will appear actually much smaller. So, if you look at your transmission system, your voltage levels tend to be very high. So, looking at it from the load side, you can actually get closer to the assumption that your grid is getting more and more ideal when you are looking back into the system.

So, if you look at another example, suppose, you have now a transformer which is a 1 K V to 100 volt. So, you are having a transformer going from 1 K V to 100 volt. Then, essentially 1 percent impedance on the primary is 1 percent impedance on the secondary. So, this is because your base on either side of the transformer has to be consistent with your turn ratio of the transformer. So, essentially when you are handling transformers, it becomes transparent in your per unitize analysis for this particular reason.

So with this, we will actually look at an example of a system and look at how we could make use of what we have just covered to calculate what are the ratings of some components such as fuses and circuit breakers could be on a system. Ok.

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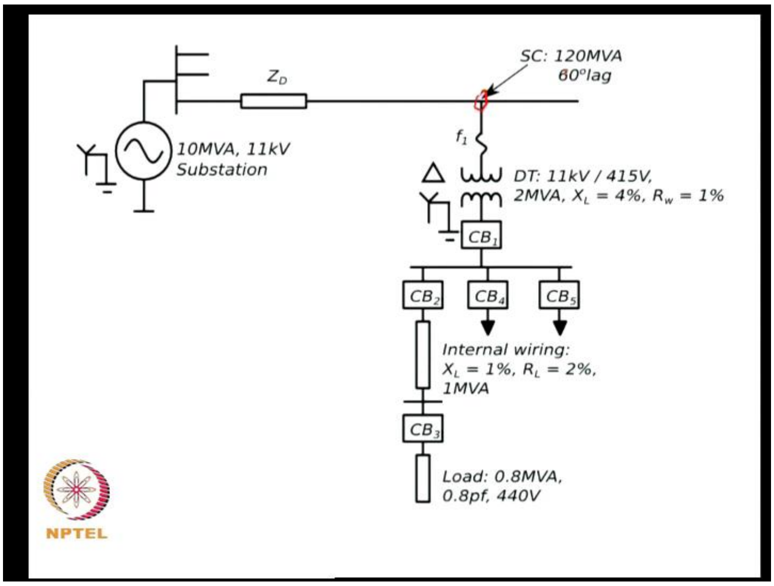

So, we are looking at, say, a system coming in from a substation. You have a substation grounded 10 M V A, 11 K V feeder coming. From the secondary side of the transformer of the substation, you have impedance of the line. And so this is the distribution line feeder impedance. And say, you are adding a new facility on this particular feeder, a fairly large facility with the interconnection transformer at 2 M V A. So, it is a fairly substantial facility. And at such power levels may be you might consider, say, this particular point over here as the point of the common coupling. Essentially, the term point of common coupling is used as the point at which you connect with the public system.

For example, if you look at a house, the point of common coupling for the house into your street or for your transportation coming in and going out is your gate. So, essentially in the distribution systems you can have different points of common coupling depending on where the responsibility of the utility ends and where your responsibilities starts. So if you take a home, it would be at a 230 volts or 415 volts after the meter because the meter is actually owned by the utility. You do not go and make any changes to the meter. Your responsibility is whatever is downstream of the meter. So depending on the size of the facility, you might; for large ones, you might put your meter all the way up at 11 K V. For smaller homes, it would be at the consumption level. And here you want to add a fairly large facility and it is rated at a 2 M V A.

And, you want to actually, say, size, the protection components on this particular system and for which you need to know the fault current levels. One common way of explaining what the fault current level could be is in terms of your short circuit capacity. So, when someone says it is 120 M V A. So, that represents the product of the fault current and the nominal voltage of the system and to evaluate what the short circuit capacity at that particular point is. And the utilities can actually provide it to you. Especially when you are connecting large systems, this would be an important aspect of the information that you would need for sizing the interconnection.

So you have a fuse, then you have a distribution transformer going from 11 K V to 415 volts. Its impedance is 4 percent, 4 percent reactance and winding resistance of 1 percent is at delta y. And you have a circuit breaker at the secondary of the transformer and you have the internal winding within the facility and you have a distribution bus before that. And you have different circuit breakers feeding each load from your distribution bus within the facility. And say, you have one particular large load, which is the wiring to it is rated for 1 M V A with a given inductance and resistance, impedance, reactance and a resistance. And then, you connect it to a load through another particular breaker to actually may be to protect that load.

So, the question is can we get a feel for what should be the values of the ratings for, say f one, C B 1, C B 2 and C B 3 in such a system. So, the first step is to evaluate the short circuit current at your P C C based on what is the equivalent impedance facing back. So, the impedance facing back from the P C C is this feeder distribution line impedance. You might have the substation transformer impedance; you might have the primary side of your substation transformer, which is at a higher voltage, which gets reflected back. So, you are looking at the overall impedance facing back. So, that can be calculated from this short circuit capacity at this particular point.

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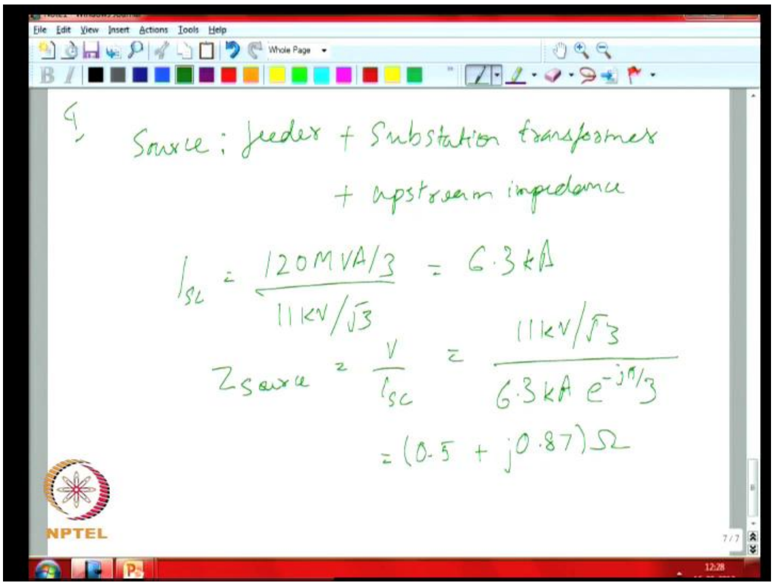

So, if you look at the short circuit, the source. So, the first thing is to look at the source side. This source side impedance would consist of the feeder and you told its short circuit capacity is a 120 M V A. So, your short circuit current is 120 M V A divided by 3 divided by 11 K V divided by root 3. So, this gives 6.3 kilo amps as your short circuit current level. So, if you look at your source, you would; it is V by I s c and it is 11 K V divided by root 3 and you have told that at this current is at 60 degree, short circuit M V A at 60 lag. So, e to the power of minus j pi by three. So, you can calculate the numbers. This is, this turns out to be 0.5 plus j 0.87 ohms. So, you got the physical value of this impedance that this impedance now represents this total impedance as seen from the point of common coupling. And if you want to say look at it what does this mean on a per unit basis.

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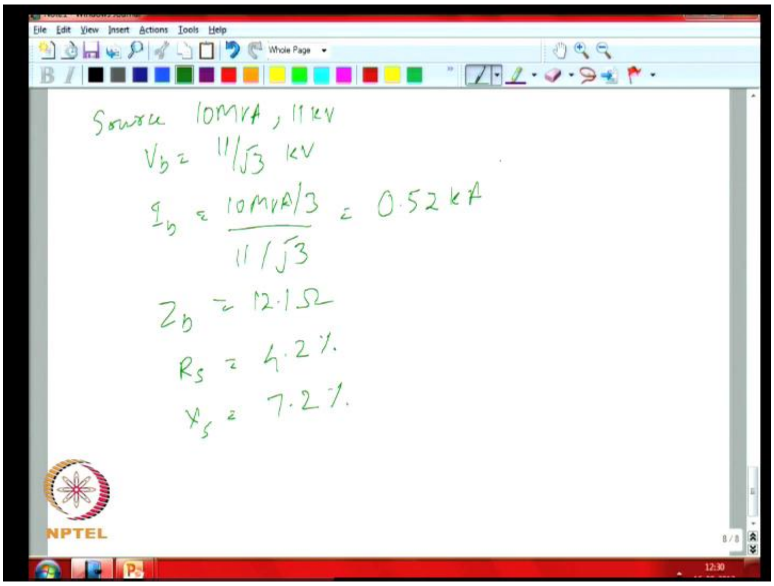

You know, your source is 10 M V A. The source by source; I mean at the substation, this is 10 M V A. So, your V b is 11 root 3 K V. I base, yes, that base is your V b by I b which is 12.1 ohms. So, if you look at your value of your R s, this would be 0.5 divided by 12.1 into 100 to give it in percent. So, this would be 4.2 percent and your X s is 0.87, which we calculated; divided by 12.1. In percentage, this would be 7.2 percent. So, now we could look at the fuse. The fuse in this particular system should be rated assuming that you could have a fault right here and the primary of the transformer. So, the only element that is limiting the fault current level is the source impedance. So, that would determine what is the fault current level that would flow through the fuse.

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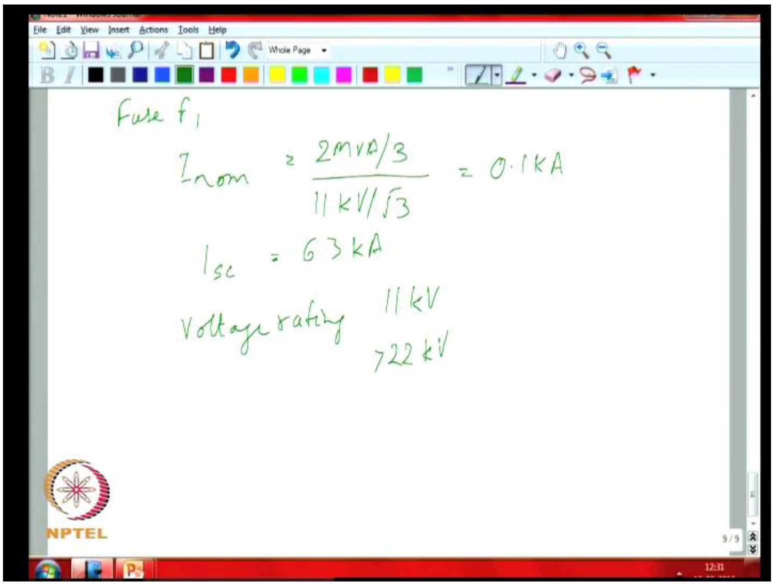

So, the load of the fuse is 2 M V A transformer. So you know, based on your 2 M V A rating that your nominal current for the fuse is the nominal current. See that the fuse would see is 100 amps and your short circuit current from your previous calculation is 6.3 kilo amps R M S or 9 kilo amp peak. So, that gives you two of the quantities that you would need for actually selecting the fuse; you know, that your voltage is rating.

Your nominal operation is 11 K V; your isolation voltage has to be much larger than that. If you take it as twice that, you are saying greater than 22 K V. So, this would help you in selecting the fuse. So, you look at the fuse. In terms of the nominal current, it would, it needs to carry and also your peak current that it would need to interrupt, if there is a fault on the distribution transformer on the primary side. So, the next element that we would look at is then the distribution transformer itself. So, once you look at the distribution transformer, you could actually then calculate what is the fault current that could occur in your breakers C B 1 through C B 5.

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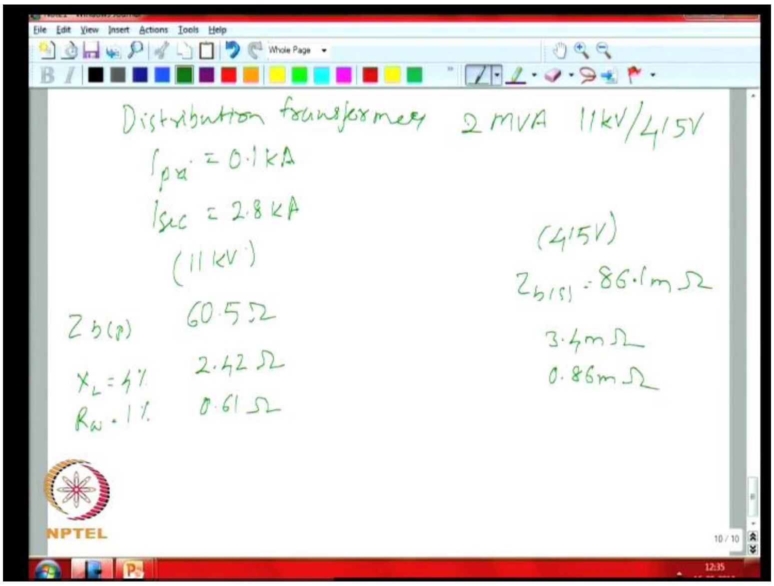

Its primary current is 1 Kilo Amp, 0.1 Kilo Amp; which we just calculated. And the secondary current can be calculated with its turns ratio. This is about 2.8 kilo amps. So, if you look at; then, your base quantities for this particular transformer, it depends on whether you are looking at it from your 11 K V side or whether you are looking at it from your 415 volt side. So, if you calculate your Z base from your primary side, this turns out to be 60.5 ohms. And from your 415 volt side, this turns out to be 86.1milli ohms.

So, when you say your X L is 4 percent and your R w is winding resistances, say 1 percent. Essentially if you are looking at it from the high voltage side, this would correspond to 2.42 ohms. On the low voltage side, this would be 3.4 milli ohms. And your R w would be 0.61 ohms and on the low voltage side you would have 0.86 milliohms. So, to calculate now your fault current within the facility, you need to combine both the per unit quantities of your distribution transformer and whatever you have from the source side, which is the upstream feeder, etcetera.

And, what we will do in the next class is combine it to the voltage level of the transformer; because may be you are more interested in designing the particular facility and look at the components that going to the facility. So, we will make use of that in the next class to actually continue with this particular example of how to do the calculations and make use of the per unitize calculations for sizing your components, protection components.

Thank you.