Power Electronics and Distributed Generation

Prof. Vinod John
Department of Electrical Engineering
Indian Institute of Science, Bangalore

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~~Module No. #01~~
Lecture - ~~No. #0~~4
Distribution System Protection

Welcome to the ~~4~~ forth class on power electronics and distributed generation, so in the last class we started looking at the Distribution Systems more closely, we are looking at a models of the components on the distribution system. We looked at a transformer model, the line model, and we are discussing the fault model, so we looked at the value of the fault impedances, that could be used in the system.

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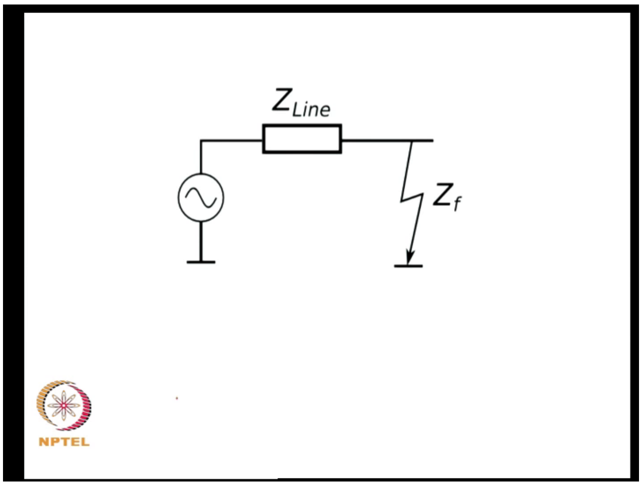

So, if you have a over current of at least twice, their value for the rated for the given section, then potentially protective devices can start operating. So, we are talking about fault impedances starting from a dead short, corresponding to Z f equal to 0 to larger values of Z f, but it has to be a small value of Z f compared to 1 to have the appropriate level of current, so that you could actually initiate protective devices.

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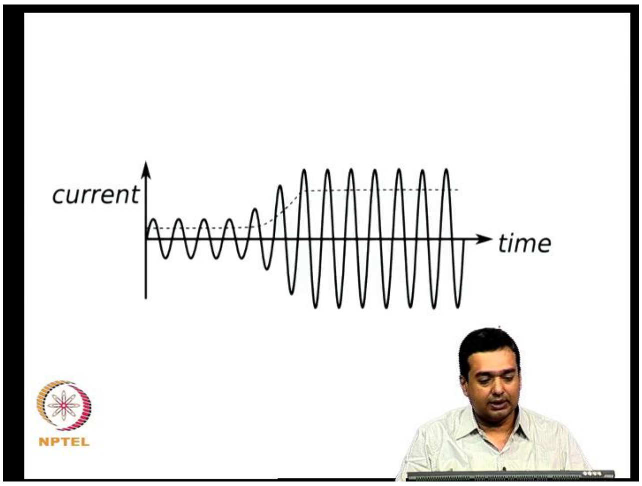

One thing to consider when you are looking at the fault current models in power systems and distribution system, traditional protection application, when you are talking about current levels, voltage levels you are talking about things in a RMS time frame. So, if you look at the instantaneous currents it might be going in a sinusoidal manner, that is what your ideal voltages, sinusoidal voltage ideally your current is sinusoidal current, and its value is going from a peak to a negative peak going to 0. But, if you look at in a envelop bases or RMS bases, say if you have a fault, then on RMS bases you could think about the current level increasing.

So, when people talk about instantaneous protection in a power system bases, you are talking about 2 to 5 cycles time frame and so you are talking about 10' s of mille seconds. So, you are talking about 10 mille second, 20 mille seconds going up to may be 100 mille seconds and it is not the instantaneous time that the students in power electronics are typically looking at where for a power semiconductor device, you are talking about switches that can operate and micro second or in 10' s of nano seconds. So, the instantaneous from the power electronics perspective and instantaneous from the power system perspective, one has to keep the appropriate time frame in mind, when you are looking at a how the systems respond.

When you are talking about instantaneous trip of a circuit breaker, you are talking about 1 to 3 cycles rather than micro second level and on a instantaneous bases from the power electronics perspective, you are your actual wave form might be a sinusoid. Whereas, if you looking at the on a RMS bases, you can think of as a slowly varying quantity which can vary on a cycle to cycle bases; and depending on the r m s values you would decide on whether to open a breaker or a keep the breaker closed. So, you have to keep the time frame in mind when you are actually discuses in the protection level in the systems.

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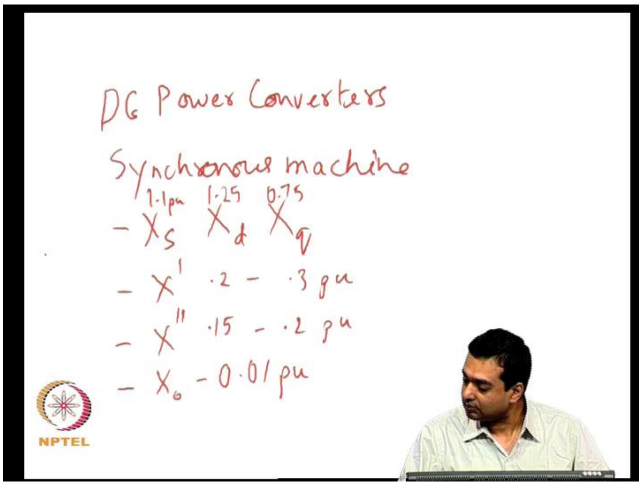

So, another model that we would then look at is, what would be the appropriate model for power converters in DG applications. So, the simplest power conversion device that you could have for distributed generation is actually a electric machine, and quite commonly synchronous machine is used and given the on the large number of there. The synchronous machine is a important component consider for what could be a power conditioning system or a interconnection power conversion device, that is being used in DG application.

So, if you look at a synchronous machine, you can think for of it has a voltage behind the impedance model that would be considered again, what the impedance is depends on the time frame of analysis that you would consider. And you would be familiar with terms such as a your stator, inductance or your d axis and your q axis in impedance of the machine on for salient pole machines, that you would consider for your steady state analysis. If you are looking at shorter time frame, you have your transient inductances, you can have for much shorter time frames sub-transient inductance, so your transient inductance might be of the time frame of a may be a second also, your sub-transient inductance could be the order of cycle or a couple of cycles.

So, depending on the time frame you are looking at, you could look at a different impedances for the machine. So, if you are looking at typical parameters for these inductances, you are talking about 1.1 per unit for axis, you are talking about slightly larger impedance for your direct axis impedance of a synchronous machine, because your pole is facing that particular axis. Your coordinate chair axis, in case of a machine would have a smaller value of impedance, but you can see that the numbers are quite large, if you are looking at steady state bases.

Whereas, if you look at for shorter time frames what you might be looking at for faults, you might be looking at smaller value of impedances in the range of say 0.2 per unit to 0.3 per unit for your transient impedance. And you might be talking about 0.15 to 0.2 per unit for your sub-transient impedance. So, essentially whether it is a sub-transient or a transient, it depends on how deeply into the synchronous machine poles your fluxes is penetrating. So, for a sudden change in operation may be your flux is penetrating just at the pour show level, and you would have your dynamic quantity is die out in a shorter time frame.

Whereas if you are looking at your damper windings etcetera, it might take longer for your transients to die down, so you are talking about transient durations depending on the the level of penetration of flux into the machine on a steady state bases, you are looking at the d and q axis impedances of the machine. Another aspect that is important especially when you are looking at distributed generation applications, where you are looking at just 3 wire, but 4 wires situation is 0 sequence impedance of a machine.

The single sequence impedance of a synchronous machine can be quite small of the order of 1 percent or 0.1 per unit or it can be one smaller. Essentially, if you look at a standard three phase windings on, because three windings are specially displaced, if you are applying equal currents in all the three phases, which is volt your zero sequence component would do, then essentially the fluxes are trying to cancel each other. So, if you get very little flux with the application of current, it means that your impedance is small.

So, you end up with the small impedances, so you will end up with some unusual situations for example, in a synchronous machine where you are single line to ground faults or single phase faults might end up taking more current than a three phase fault. So, you end up with situations which or slightly unusual when you have situations such as this.

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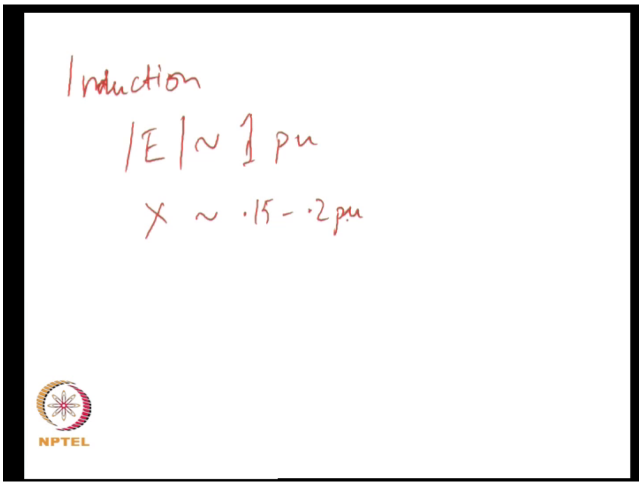

If you look at say a induction machine, which could be another component which is used as a interconnection device between your distributed generation source and the electric grid. And if you look at your impedance, you are talking about a impedance of about 0.15 to 0.2 per unit. And if you look at the inductance value that is used it is essentially the leakage inductance of the machine, some of the stator and the rotor leakage inductance. If you look at how much current would enter a induction machine when you do a direct online start, common number that people would consider is you will take the 5 times the rated current as you are starting current of the machine.

And the reason is quite simple you have 1 per unit of voltage and your leakage in inductance is what limits the currents, so that is having a value of 0.2 per unit, you will end up with 5 times, 5 per unit of starting current in a induction machine. So, again for fault, when you have a fault on a short term bases the induction machine would contribute about 5 per unit volt, but again the flux in the machine would decay down. So, it will not last for a long duration of time, but your initial currents could be of this particular order of magnitude.

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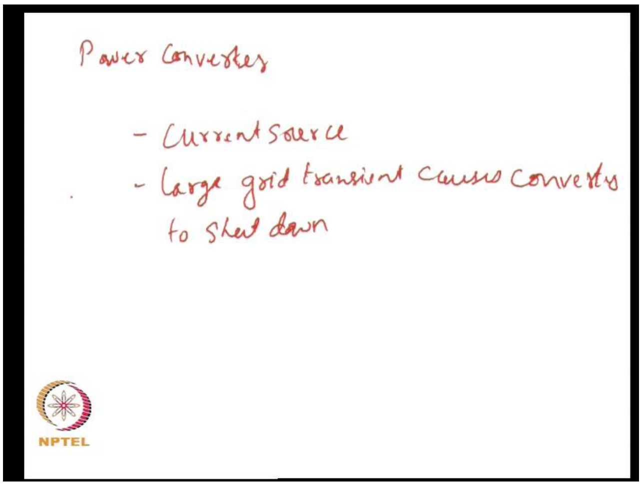

If you look at a electronic converter based power conditioning interconnection, typical power converter that is used to connect with the grid is a current regulated power converter. So, you would be doing current control to ensure the quality of current is sinusoid, you may want to ensure that the current that you are injecting is in face in the voltage, so that you get unity per factor. So, often you will have a current regulation, so you might be able to model your converters current injection as that of a current source; if you look at the converters that are available today, if you have a large transient in the grid.

For example, the grid voltage suddenly collapses down or if there is a big surge in the grid voltage, where the value of the voltage goes up many power converters would just trip and shut down. So, large transients unless you specifically design your converter to actually handle this large transients in the grid, your converter would shut down, but being able to handle the large grid transient is actually emerging requirement. And is already a requirement for many applications such as wind energy, where if you have low voltage in the grid, you have to have a power converter which is able to right through the low voltage.

So, you have things like a low voltage right through fault, 0 voltage right through, fault, right through, characteristics etcetera, which become more and more important for power converters. And again when you are talking about fault, you are talking about time durations of the order of a 10' s to 100' s of a mille seconds. So, your power converter will have to be able to operate for the 100 of mille seconds, when fault has occurred in the power system, you have extreme imbalances or under voltage levels and the power converter should operate through that situation without actually shutting down. So, that can come back into operation when once the grid gets back to normal.

So, another thing that will consider next, after considering the power conditioning devices which can be machines or power converters is what sort of protection equipment would be a there on a typical distribution system. So, if you are looking at protection equipment you are looking at over voltage protection or over current protection.

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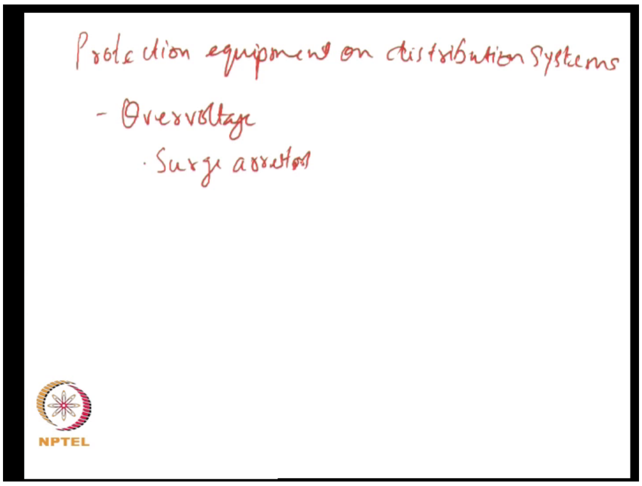

So, if you are looking at over voltage protection you are looking at a things such as a surge arrestor, so the type of surge arrestors that you would use in your equipment depends on your distribution system. So, for example, whether your transformers are solidly grounded or impedance grounded, so for example if you have solidly grounded ah transformers, it means that you are neutral shift when you have a fault would be small. So, you could have lower margins for your surge arrestors, whereas if you have impedance grounding, your neutral could potentially shift by larger amount, which means that your surge arrestor would need to have higher voltage margins.

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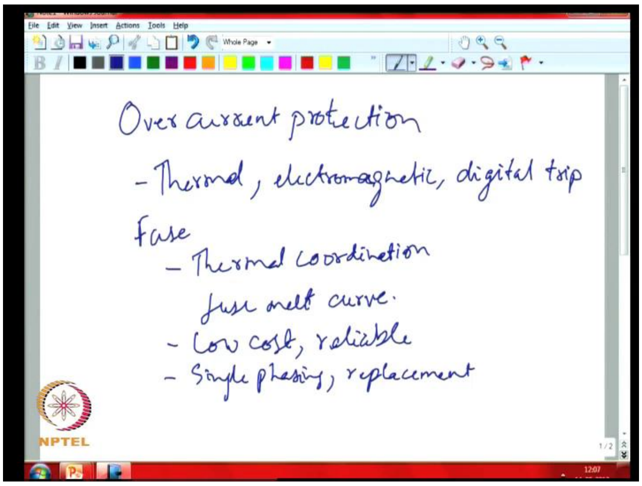

If you are looking at over current protection, you are looking at devices such as fuses, circuit breakers or relays and if you look at the way the protection is being would be done in such devices, you could have thermal which is essentially thermal over current protection in a fuse. It can be a electromagnetic, in a circuit breaker you could have digital trip units, in a relay package especially in your relay packages come with quite sophisticated digital trip units. And each of these things for example, your digital trip unit has to be backward compatible with what is already there in the systems.

So, you cannot make your digital trip unit respond as fast as your processor can calculate, but you are digital trip unit should be able to emulate the type of characteristic, that is there in a thermal over current protection or the electro mechanical relay. So, as to have the backward compatibility, so your newer protection device should be able to operate with your older protective devices. So, that is a important aspect of a power system, you cannot say every fuse has to be replaced by a newer device, so what where newer equipment that you have bringing in has to be compatible with your equipment that is already there in the system.

Again as I mentioned your instantaneous strips have to be on, is actually on a RMS bases, rather than on a real time instantaneous bases that you would consider a on a wave form, so you are talking about number of cycles to trip even when you are talking about instantaneous. So, if you look at a fuse, for a fuse you are talking about a essentially thermal coordination and you are selecting your fuse based on it is the point at which your fuse would start melting, so you are depending on the fuse melt curve. So, if you are thinking about fuse operating at some nominal current levels, the participation in the fuse would be such that, it would not heat up to the point where it would melt.

But, once it goes above some critical value your fuse will melt depending on the amount of current that is causing dissipation in the fuse. So, you are looking at your melt curve to determine at what point it would melt, depending on what current level is actually going through the fuse. The fuses are actually quite reliable it is low cost and reliable, because there is nothing complicated where you would have, you do not do any sensing and evaluation of algorithm if the current is more melts.

So, it is quite simple which lengths itself to our reliable operation, but you have other concerns that if you have a three phase system, the over current might actually cause the fuse in one phase to melt and not all three phases; so you could have a single phasing of lines, you will not be able to ensure that all fuses simultaneously operate. So, you might end up with situations where some loads could potentially face problems in your actually having fuses the only protective devices. Single phasing is a concern and every time fuse blows it has to be replaced, so replacement is a concern where as in circuit breaker, you have a trip you could reset it and get back to operation.

Because, it is low cost and quite reliable, often it is used in the end of the system where a cost is very critical closer to the end of your distribution radial structure, or it can be used as backup protection. Say if you are taking a circuit breaker and you want to have backup over current protection for your breaker or your relay, then you could use a fuse to provide backup protection in case your breaker is not operating. So, your fuse would not typically melt, because the breaker would typically operate, in case it fails you now have a backup protection.

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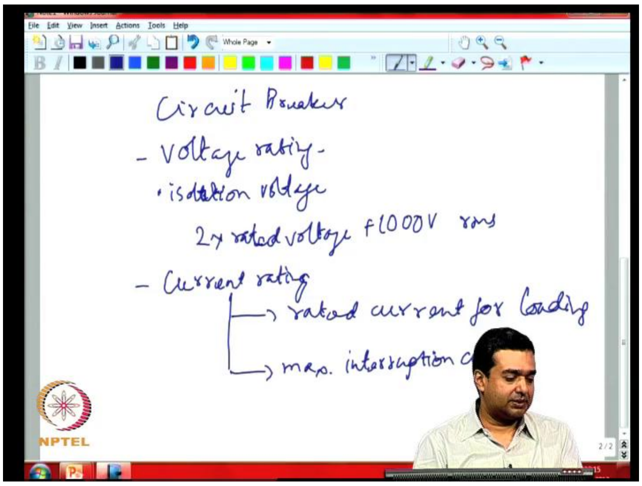

If you look at the next device which is commonly used for over current protection it just a circuit breaker, and if you look at the circuit breakers that are available there are bimetallic circuit breakers, which operate on a thermal bases. You have electromagnetic circuit breakers you or many large larger size of breakers available today have electronic trip units, which actually operate decide on whether the breaker should open or stay closed. So, you could have different control packages to actually operate the breaker, so the actual breaker is a device which would make or break the current; whether it should open or close is decided by your trip unit.

So, if you look at the ratings of the breaker you will have both your voltage ratings and your current ratings, so your voltage rating is to be based on the voltage level at which you would operate. So, whether it is a 230 volts, 415 volts, 690 volts depending on application you would have voltage rating, the voltage at which you are expecting your breakers to operate. The other item that is important is also your isolation voltage, voltage level where essentially if you have a voltage spike coming across the circuit breaker or on a from 1 point to your frame which might be connected your cabinet etcetera.

You also have your isolation voltage level where having opened what voltage it which can before things are cover, so your isolation voltage is also a important parameter of your breaker, so often for many low voltages circuits, you would need isolation voltages level of at least twice your rated voltage plus some margin on a RMS bases. So, that even if you are talking about voltage level at which it would operate, your ability to isolate has to be much higher than the ability at which you are actually operate.

If you look at your current rating, the current rating of your circuit breaker, there are couple of important current ratings that need to be considered; one is if you select any device what is the current at which it would typically operate. So, if you are using a circuit breaker which is getting connected to a 10 AMP circuit or a 15 AMP circuit, you need to have at least the capability of 10 or 15 AMS' s, so that the breaker does not over heat under an number loading conditions. The second aspect of this current rating which is important is, so you use a 10 AMP' s or 20 AMP circuit breaker, but when there is a fault downstream of the circuit breaker, your fault current is much higher it could go up to 100' s of AMP's 1000' s of AMP' s.

So, how much current can it actually interrupt, so the interrupt rating of your circuit breaker is also a important parameter. So, if you look at the aspect also there are multiple issues that you would need to look at before you select a circuit breaker, how it is used and what would be the fault conditions under which it has to protect your actual load. If you think about a circuit breaker it is a form of a switch, so it is a switch that is on or off. But, if you look at what are the different verities of switches that are there, breakers imply you have the ability to interrupt fault, whereas a normal switch may not have the ability to interrupt a fault.

So, if you are using a contactor in a power electronic application, it can carry rated current. it might be able to switch off your nominal current level, but it will not be able to interrupt a fault current level. So, if you try to interrupt fault current level using just a regular contactor, your contactor contacts would could can potentially melt. So, you need the structures of circuit breaker to actually provide appropriate arc impedance in your circuit breaker, and ability to estimate the arc and dissipate the energy in the arc.

So, you need more extensive structures in a circuit breaker compared to a regular switch, if you are looking at just a isolation switch, you are looking at the ability to maintain isolation voltage, you are not even looking at the ability to interrupt load current. So, depending on the type of switch that is being used you would have different levels of complexity. So, because the ability of the circuit breaker is for application, which is intended to handle much higher fault conditions your circuit breaker would be more expensive than just a contractor.

So, if something is designed to handle much more challenging situations, you would have associated cost with it. So, depending on what you are intending that particular switch to be applied and you have to make use of the appropriate variety of switch.

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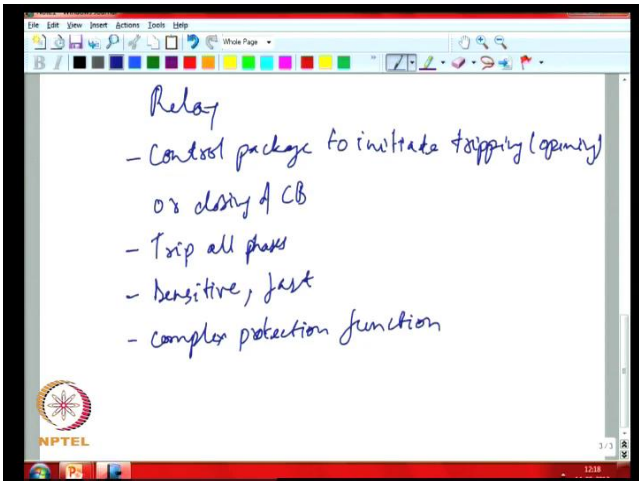

If you look at a relay, you can think about a relay as essentially the control package which governs for the switch needs to open or close; and for over current protection you are looking at a over current relay. So, essentially the relay is a device which initiates, whether to trip the breaker or a some breakers have abilities to reclose or close, so the relays can actually give such comments to a circuit breaker. And tripping or opening relays tend to be more expensive, so it is a newer relays are that are available today are mostly electronic relays.

So, with a relay now you can actually trip all three phases, so you can actually ensure that all the phases get disconnected simultaneously, it can be made more sensitive. And depending on your algorithm can be made to respond in a rap fast manner, and it is possible to implement many sophisticated fashions, like directional, impedance evaluations etcetera. So, in fact the newer relays that are available are multifunctional relays, if they are often called intelligent electronic devices, IED and can be used in a variety of situations. So, if you look at another protective device which could be used in a distribution system one can think about say a recloser.

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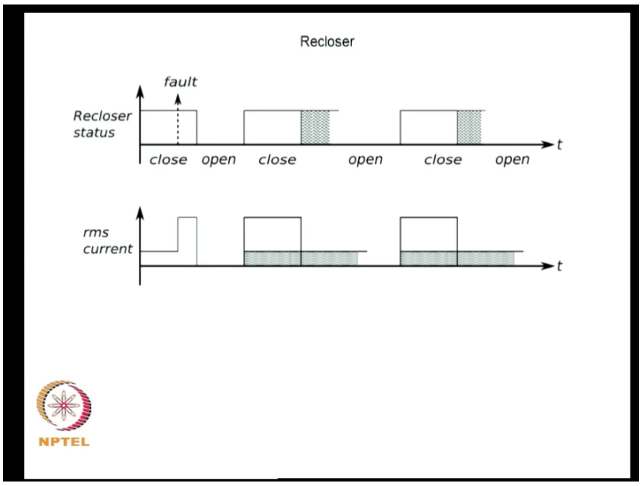

So, essentially the idea behind recloser is that many faults are large number of faults are temporary. So, if you are able to open the reenergizes your line for a short duration and the fault clears, then when you reenergize it, you can go back to normal operation without physically someone going there and having some manually intervention. So, if you are able to open your circuit breaker for some time and once the fault is cleared you close it again you can potentially continue normal operation. But, if you have say for example, situation where you have something where there is permanent damage, then when you reclose again you end up with a over current.

And so you might try a few times to actually reclose and that some point you decide that yes, this is actually a permanent fault, then you stay logged out. So, essentially you would have recloser or essentially you can think of it as a circuit breaker with a relay package, which can actually close a reclose a number of times, you can have a programmable number reclose cycles say 1 to 4 reclose cycles are could be commonly used. And again for thinking about what the sequence of operation is it would be good to think in terms of the RMS current levels, when you have a fault.

So, in this example over here, what is shown is the recloser status, either it is a closed when the logic is indicated high and it is open when the logic is indicated low. So, initially it was closed and things were on the normal conditions and say you have a fault at some instant say T naught. So, at this particular instant say you had a fault, which caused your current to actually come up to a last extent a to a higher level, then in a short duration may be on a instantaneous bases depending on you would actually open your recloser.

So, after opening the recloser you wait for some duration and then, where your recloser is in the off condition and the line is de-energize and you reclose. And you have two possible scenarios over here, one is the fault has cleared in which case you go into a current level in this hashed area and you continue operation in the hashed zone. Second situation is may be the fault being get cleared by this initial pulse of current, when you re-energize you go back to the fault condition, so your current level continues at the high fault current level itself. And again now you wait for a certain closed duration and then, you again opens your recloser.

So, you could think about say durations you might call it can give names for these durations, and so once you have opened again when there is a fault seen during this first recloser cycle, you again wait for some time and you open the breaker, and so under this open condition there is no current flowing. And here now you try to close for a second time, so the anticipation is now you have reclose for a second time, you potentially have cleared the fault. So, you might go back to normal operation or in case you have something really solid on the feeder, then causing a fault, then you go back to your high current level you wait for some more time duration and then you will lock out.

So, at this point if the fault is still continuing, your recloser will lock out and stop further reclose a terms, so this is a recloser with two reclose cycles. So, you have one opening, a second opening and then, it would lock out, if the fault is permanent and if the fault is temporary now it has two chances to get back to normal after the first reclose cycle or the second reclose cycle. So, you can see that if you have a temporary fault on this particular feeder it would get cleared with minimal disturbance and you would you could reenergize go back to normal operation.

So, if you think about a recloser it can be thought of as a circuit breaker and the circuit breaker might have it is own time over current characteristics, and the circuit breaker might also have a program to actually execute this reclose action. And if you are having already relays in the substation you can actually now incorporate this reclose logic along with the feeder circuit breaker sitting at the substation. So, you could look at improving the power quality or the time of up time of feeder when there are potentially faults on the feeders; and this logic can be easily incorporated into your substation protection logic.

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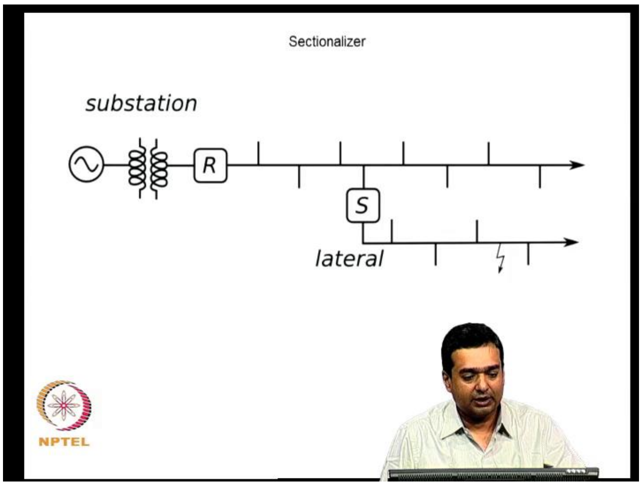

So, if you look at another item that we had mention we had also mentioned sectionalizer, so a sectionalizer is a device which is intended to operate along with a recloser. So, suppose you have a feeder coming from a substation, so you have a feeder and you have branches or laterals on this feeders and say you locate your sectionalizer on this particular lateral. And you want to actually see isolate this particular lateral when there is fault lateral, rather than reenergize the entire feeder, so we will see how it can potentially be done.

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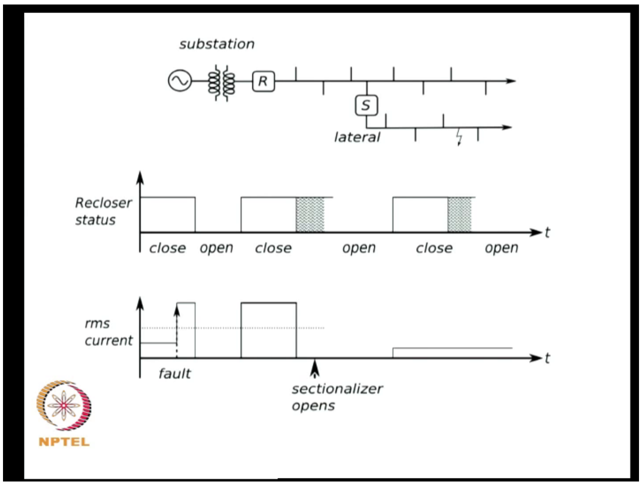

So, suppose you have fault on this particular lateral downstream of the sectionalizer, what the sectionalizer does is it would count the number of current fault pulses, and it can shut down or lock opened after counting a given number of current pulses flowing through it. So, in this case will again assume that your upstream recloser has two reclocycles and you have a fault at this particular location downstream on this particular lateral.

So, you have multiple situations, if this particular fault was a temporary fault, then this recloser which was initially closed after it is first opening, you potentially if this fault cleared you can go back to normal operation nothing would change on your recloser of the sectionalizer. Suppose, you have this recloser with two reclocycles and say this sectionalizer is counting for two current pulses. So, in this particular case you have say a permanent fault occurring at this particular location and at the initiation of fault at a time T naught.

You end up with one current pulse flowing through the sectionalizer at the end of your during a first reclocycles, you end up with now a second pulse now going through this particular sectionalizer; and then a through this particular sectionalizer and then, the recloser opens. So, when the recloser opens essentially this sectionalizer would count now two cycles and lock open. So, when the recloser now recloses for a third time the sectionalizer is opened, which means that this feeder can go back to normal operation and this lateral has actually opened and got disconnected where you have the permanent fault.

So, you can see that there are two things that are happening over here, the logic for at is not complex, because you are just comparing current pulses rather than doing more complex time over current characteristic. The second thing is sectionalizer is opening when the recloser is open which means that you just need a simple contactor type of switch, rather than a circuit breaker, so it is interrupting at low current levels, ideally as 0 current levels, so you could have lower cost device as sectionalizer.

So, in this particular case you had a two cycle recloser and you had a sectionalizer, which counted two pulses and locked opened. So, you isolated this particular lateral and you go back to normal operation sectionalizes, you do not just be on laterals it can also be on really long feeders, you may want to sectionalize the tail under the feeder and the front end of the feeder, so you could have different configurations. You could also have chain of sectionalizes, you could have sectionalizer one, sectionalizer two depending on how you are connecting your laterals.

There are other simple protective devices that are used in the distribution system, you can have fuse to disconnect, jumpers etcetera, essentially they are isolation devices which are opened before a line man comes in and works on the particular feeder, or before the person does any repair work on the distribution system. So, if you now look at more closely at what is the characteristic that one would need, when you are looking at a protection, in terms of fuse or a circuit breaker, you are looking at the time over current characteristic of your protective device.

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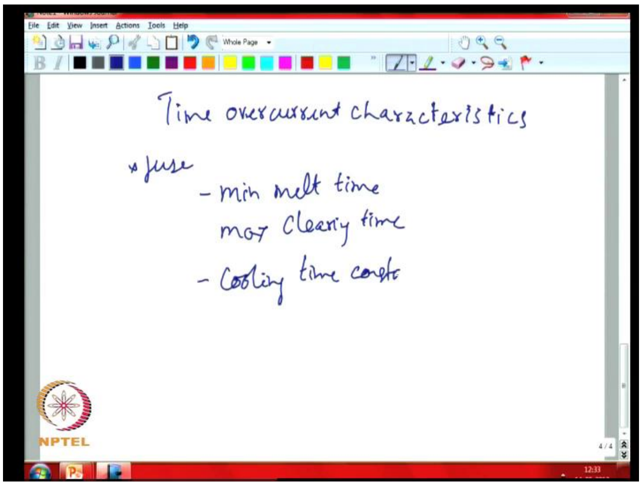

And you looking at fuses, circuit breakers, relays etcetera and so with a fuse you are looking at the fuse of the appropriate voltage rating, at which it would interrupt the current. And you are also looking at your current rating of the fuse, the nominal current at which the fuse would be expected to operate depending on the downstream loads connected to it and also the interrupt capacity of the fuse. So, you have fuses of different interrupt capacities, you have some fuses which might need to interrupt high currents, like HRC fuses, High Rupture Capacity fuses etcetera.

So, depending on the type of requirement, you would need to use appropriate type of fuse and aspects of a that are important is what is your minimum melt time. So, the time required for the fuse to melt depends on couple of things, one is what is the temperature at which it was nominally operating, so if it was initially operating at a elevated temperature, it can actually melt more quickly. Another aspect which is important is how much current level is there, because it is the I square R loses in the fuse which dissipates energy into the fuse and causes the fuse to melt.

If you think of it as a adiabatic causes, which means that energy is going in which is not dissipating outside, then essentially you would have, you would be looking at what is the minimum melt time. Similarly, you would have characteristic of what is the maximum clearing time, how much would be the maximum time before which the fuse can actually be considered open. Another aspect of the fuse which is important is suppose you have a fuse and you have some over current flowing through that particular fuse, and the over current is for a short duration and before it melts the over current went away then how does the fuse return back to the normal condition.

So, you also have the cooling time constant, where the fuse heated up to some extent, then it could cools down depending on your thermal time constant of the particular fuse. So, essentially you can think about the cooling time constant as some sort of a set mechanism of the fuse, where it got exposed to a over current and when the current went away it cools down and resets back to normal operation.

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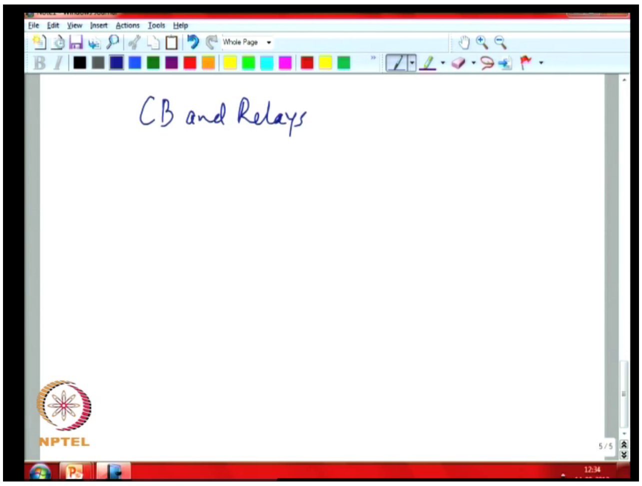

If you look at a circuit breakers, you are looking at now something people referred to as the IDMT characteristics, Inverse Definite Mean Time characteristic, essentially it means that larger the current you will take short duration for your circuit breaker to operate. If your current level is small, then it would take a longer duration to operate, but even at very high current levels, there is some fixed delay before which your circuit breaker will not operate.

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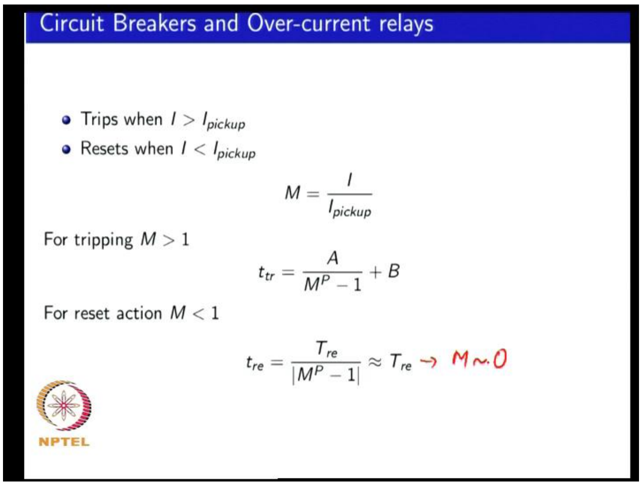

So, if you look at from your tripping characteristics of your circuit breaker, you can think of a critical level as a pickup current level, if your current is greater than the pickup current level, then you would be initiating tripping action in the breaker. If your current is below your pick up current level you will be having reset action going on in the breaker. And you can define a ratio between your actual current and your pickup current and depending on this ratio M, your circuit breaker would operate with a given speed.

So, you for tripping the value your value of M has to be greater than 1 and your time trip can be expressed as a expression, say A divided by M to the power of P minus 1 plus B, so this would could emulate the IDMT type of characteristics. Similarly, for when M is less than 1, you would have a reset time can be again expressed as some const T r e divided by M to the power of P minus 1 at the absolute value of it. And if your operating closed to your nominal current level, and if your nominal current level is much smaller than your pickup current level, then M can be considered as closed to 0.

So, you could take your reset time to be approximately given by your capital T r e, so you could take consider your reset time to be roughly constant, just from to simplify your analysis, for M closed to 0 your T r e is roughly constant. And in these expressions your A, P, B etcetera are constants, your T r e these are constants depending on the type of characteristic you are trying to emulate in your circuit breaker.

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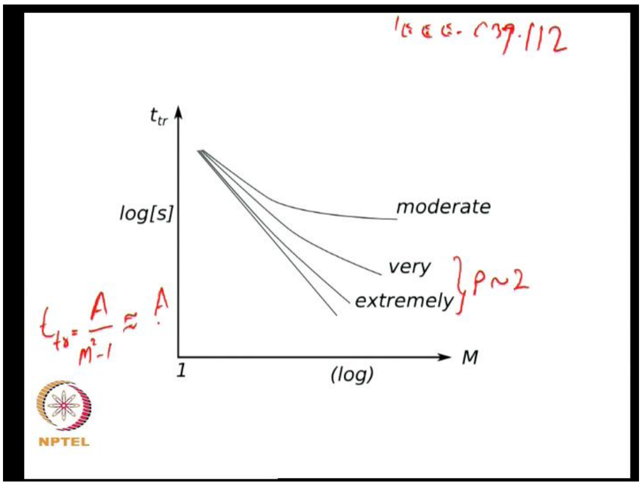

So, depending on the value of you are A B P etcetera, you can have different definitions of what would be your inverse current characteristics, so IEC defines circuit breakers, which are moderately inverse, vary inverse, extremely inverse etcetera, for the time current characteristic. So, good reference for this would be is I triple E, standard C 37 dash 112, which is the inverse time current characteristics for over current relays. So, the type of curves are essentially if you have very large value for the multiplier, essentially the time required to trip is quite small.

So, if your value of the multiplier which is M, which is the ratio of your actual current by your pickup current is a smaller number closer to 1, it would take a longer time to trip, so if you now plot it on a log log scale, it would have look curves which are shown here. So, for your extreme and very inverse type of characteristics, essentially you could consider a P approximately 2 and the expression for your trip time can be written as the assuming your b a small, essentially the definite time is small.

And again for M which is much larger than 1, you could take this as approximately A by ((Refer Time: 54:35)), so that M is your ratio of your actual current by your pickup current, so if you substitute that. So, at this point what will do is will wrap-up this particular session.