Power Electronics and Distributed Generation
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Lecture - 17
Relaying for Distributed Generation

Welcome to class seventeen on topics in power electronics and distributed generation. In the last class, we were discussing about the need for faster switching when you connect a DG to the grid.

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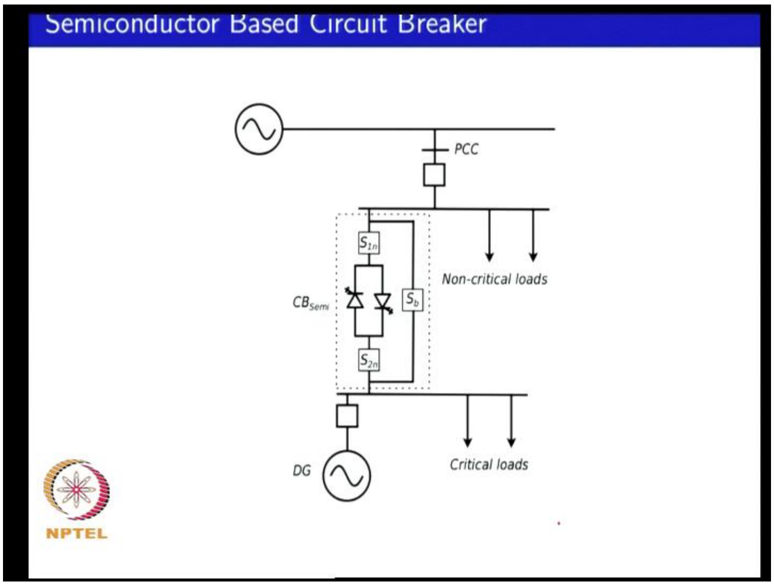

And then we discussed methods for having semiconductor-based switches. We talked about SER-based transfer schemes. And then this is an example of a static circuit breaker. And what we saw is that with semiconductor-based switch, you can have faster switching, and the number of cycles can be more compared to an electromechanical switch; however the power loss will be more and the electrical isolation capability of a semiconductor-based switch is not as high as a physical opened air gap or an opened gapped contact. So, electrically, it is considered less rugged and it is more expensive. So, today, what we will do is we will look at…

So, we looked at the physical switch. So, today, we will look at the smarts that go behind the operation of a switch, which would essentially be a relay or something that commands the switch to open or close. And for DG application, this would typically be a relay, which commands the switch to either connect or to disconnect. So, the operation of the switch would be controlled by an external device. If you look at relays; relays have been traditionally used as protective devices for protection of a variety of power system equipment. You are protecting for a variety of faults, different conditions. In a traditional power system, you have been using relays for generator protection, transmission protection at the substation level, for distribution systems. In a distribution system, you would have protection for substation at the substation level.

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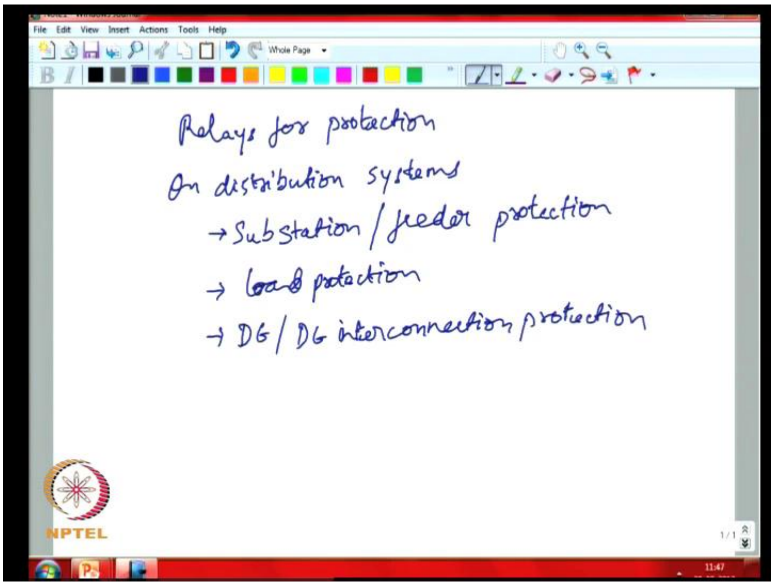

At the substation level, you could have large loads, where the cost of the load might be quite significant. So, you might have special relays for load protection like large machines, transformers, large equipment; and certainly a valuable device. If you connect a large distributed generator source, you would then think of protecting it with a relay. So, you would have the distributed generation or the DG interconnection protection.

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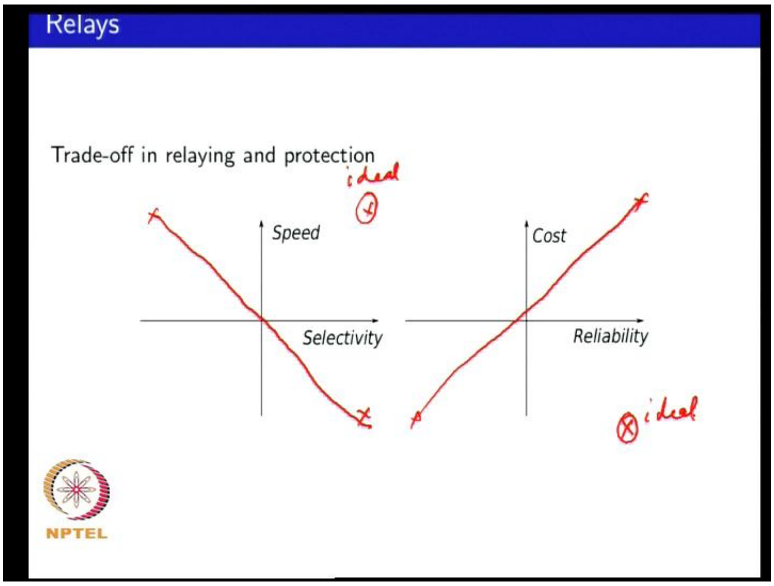

So, if you look at the attributes of a protective device; you are looking at a protective device that operates at high speed. So, it is capable of making decisions rapidly. You would also like to have selectivity; in the sense that, if you have a relay, which is making a decision of whether to trip or whether not to trip, it should trip where it is necessary. For example, if you have a fault in the zone of protection, it has to trip; whereas, if the fault is out of the zone, it should not trip. So, you should also not trip for under voltage when you are having an over current. So, it should be tripping for the right reason. So, it has to be selective in making the decision of whether to trip or not.

And typically, when you want decisions at high speed, you might be more prone to noise; you might be more prone to making the wrong decision. So, trade-off curve might be that, if the speed is very fast, you might be having poor selectivity. Or, if you are having more time to make the right decision, then the speed is naturally less. So, a trade-off might be along a direction such as this; and the ideal relay is – it should be capable of operating at high speed and high selectivity. So, ideal relay would be something which is high speed and highly selective; but, the trade-off in the algorithms would be between the speed and selectivity.

Another trade-off would be in terms of the reliability; you would like the relay to be extremely reliable; it should be fully protected against damage; it should be fully protected against malfunction, poor operation. And to add protective systems, to add redundant circuits, etcetera, you would incur more cost. So, many times, when you want to have very high reliability, the cost would be high. So, if you want to have very high reliability, the cost would be high. And if you try to eliminate the cost a lot, you might end up with poor reliability. So, you might have something very low cost and not reliable at all. So, the trade-off curve might be along a line like this. And in this situation, the ideal relay should be low cost, but highly reliable. So, the ideal situation would be somewhere over here. So, having an actual relay is a trade-off between multiple requirements; you may not be able to have everything being met at once; you might end up being having a more expensive relay, but it is meeting your requirement; you try to make it cheaper, you may have to trade it off with certain other aspects.

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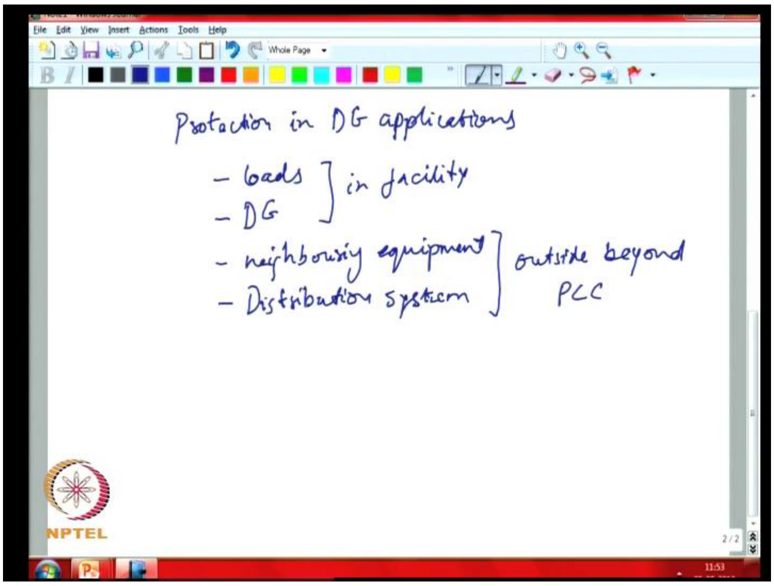

If you look at what you need to protect in a DG application, where you are bringing in a DG to the system; so in DG applications, one thing you would definitely want is to whatever loads are there in a facility should be protected. The second equipment that you would die to like to be protected is a DG itself – the distributed generator source. So, these are things within the facility. But, you also show that, you could have equipment, which say you could operate the DG and potentially damage maybe the neighbour's equipment, because of things like out of phase reclosing. And you want to protect the distribution in net system itself, because in a situation of unintentional islanding, we saw that, the operation of the DG can potentially damage the actual distribution feeder itself.

So, the protection is not just behind the point of common coupling; it is also upstream of the point of common coupling.

And, when you are incorporating the source, you need to actually ensure that, the protection is being adequately accomplished. And we saw when we are discussing protection, we need to identify zones of protection; you would have overlapping protection between zones; and potentially backup protection in case something feels is there adequate backup. And once you have protective relays, you need to think about what are its settings, how do you… what sort of faults are you trying to protect against. So, those aspects need to be decided.

If you look at that evolution of relays; what has been around in the system for a while; the earliest relay would be the electromechanical type of relay, where you have say currents, applying torques on disc, and then you would have springs and damping of the disc to determine whether the relay would trip. So, you would have individual electromechanical devices with moving parts; and each such device would accomplish some functionality.

So, you might have over current relays being one mechanical package; you might have imbalanced relays being another package; reverse power flow relay being another package. So, you would have electromechanical packages; one for each type of relay functionality. And if you look at what happened next, people then realize that, the electromechanical relays follow some particular dynamical function. So, it is trying to accomplish some differential equation. And if you have some equation that can be modeled, you could also implement it with analog domain with things like operational amplifier circuits.

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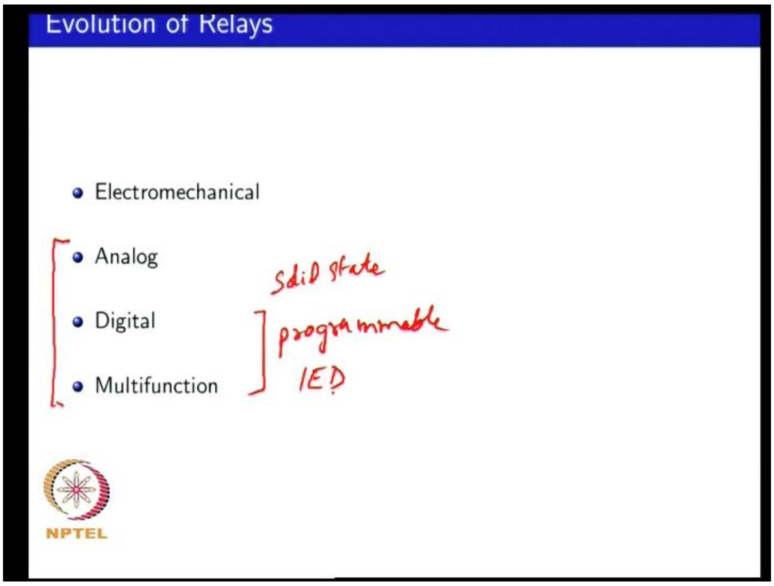

So, the next after the electromechanical relay, there came analog relays followed by digital and multifunctional. So, if you look at these three; these are actually solid state compared to the electromechanical relay, which is having moving parts within the relay package. Then after people started looking at analog circuits for relays, then by the 80s – the late 80s, you had microprocessors and people started having microprocessor-based relays. So, whatever was being written as an equation in an op-amp could now be implemented in a processor.

So, you had digital processors doing the calculation. And that was a start of a relay, where you could actually program the settings; you could have programmable relays. And by of late, the processors have become more and more powerful. So, you do not need multiple processors each for each one relay functionality; you could have many functions being accomplished within a single processor. And so you now, have multifunctional relays. And these are the programmable relays; they are also called IED's – intelligent electronic devices; where, you could actually do a lot of sophisticated programming and implement lot of sophisticated functions.

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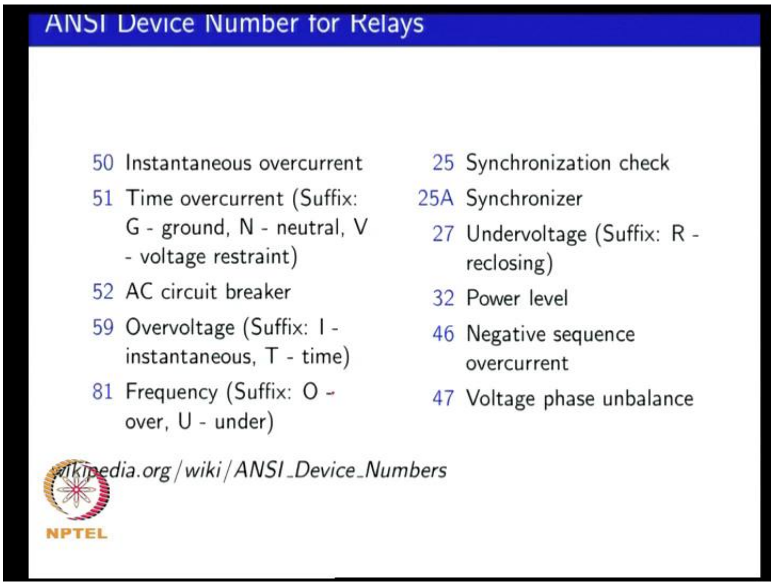

If you look at the relay types; ANSI has provided a list of relay numbers. For example, 52 would be of an ANSI number for AC circuit breaker. So, this 52 is an AC circuit breaker. You would have instantaneous over current relays that would correspond to ANSI number of 50; 51 would corresponds to time over current. You could have suffix for these numbers. For example, 51 G would mean a ground time overcurrent or a 51 N would mean a neutral time overcurrent; V – 51V would mean a voltage restraint time overcurrent. So, you could have different combinations such as that.

Then you can have overvoltage. You can have instantaneous or time overvoltage; you can have frequency relays – over frequency, under frequency. You can have relays, which are not just for opening; you could have relays, which guide closing of breakers. For example, if you have two sources and if you are able to have its amplitude to be aligned, its phase to be aligned, its frequency to be the same; then you could close a breaker without causing significant transients. And that is what a synchronization check relay would do.

And, you could have synchronizers, which explicitly give the comment to change the frequency setting or the voltage amplitude setting. Say suppose it is to a machine, it might give commands to a governor or an exciter to change the operating point. So, you could have synchronizers; you could have say for example, under voltage relays – again instantaneous or time. You could also have say suffix like R; which means that, say if you have under voltage, where the voltage is so low that you consider the voltage to be 0; which means that, you have a dead bus and you need to black start a dead bus; you might close a switch to energize a dead bus. So, you would have relays for functions such as that.

We also saw that, you could have relays, which operate as a function of power level. So, you calculate the power level. If it goes to high, you might be at a overpower condition. Also, you could see that, if the power goes negative; for example, we saw an example of anti-islanding function, where you look at the sign of the power – whether it is becoming too low. If it is going negative, then you could potentially detect an unintentional island. So, that would be a reverse power relay. You could have power quality-based relay functions like 47 is phase voltage imbalance. You could then… The result of a phase voltage imbalance would be a negative – say negative sequence over current. So, for example, in a machine load, it might be sensitive to overheating of negatives due to negative sequence current coming in. So, you would have relays for a variety of functions. This is just a sample; there is a large list; you can get the full list in say Wikipedia, they have a list of ANSI device numbers available.

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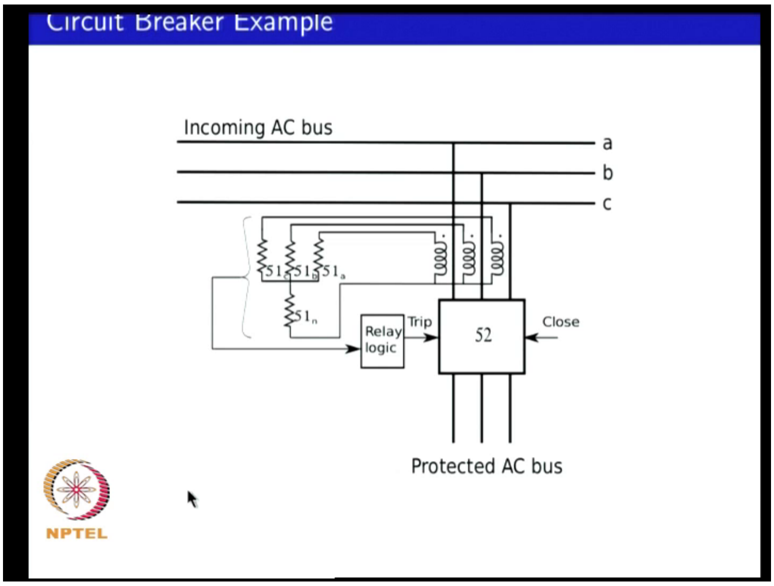

So, the question is now, with this, how to make use of it for operating protective device? And we look at an example, where you have a simple example of a three-phase circuit breaker. So, in here you have say a three-phase AC circuit breaker – 52 – you have an incoming AC bus – three-phase A C bus. And you want to protect some line, cable or load downstream. So, you have a protective bus downstream of the circuit breaker. And say you want to implement a three-phase breaker with over current protection; and also, have neutral over current protection. So, you might have a neutral wire for which you want to prevent over current in the neutral wire. So, this is an example of this. So, for relays, you would then need to make a decision; which means that, you need to sense what is happening.

So, here you have three CT's sensing the current that is coming through the line. And then you are applying it to over current relays. So, this is 51 is an over current functionality. So, you have 51 over current for phase a, for phase b and for phase c. And sum of the currents in phase a plus b plus c would be the neutral current. And then you can then look at whether there is an over current on the neutral. And based on this information, you have a logic, which would then decide on whether to initiate a trip of the circuit breaker. So, you would have a circuit breaker, where you can initiate a trip action.

Similarly, you could also initiate an action to close the breaker; which could say in many cases, for smaller breakers, you would just manually operate the breaker to close it. You could also have say circuit breakers the motorized; which means that you could then give a signal to actually close the breaker rather than manually go and close the breaker. So, the logic can be often it is expressed as ladder logic or it could just be the plain combinational logic to look at what should be the condition under which you operate the switch.

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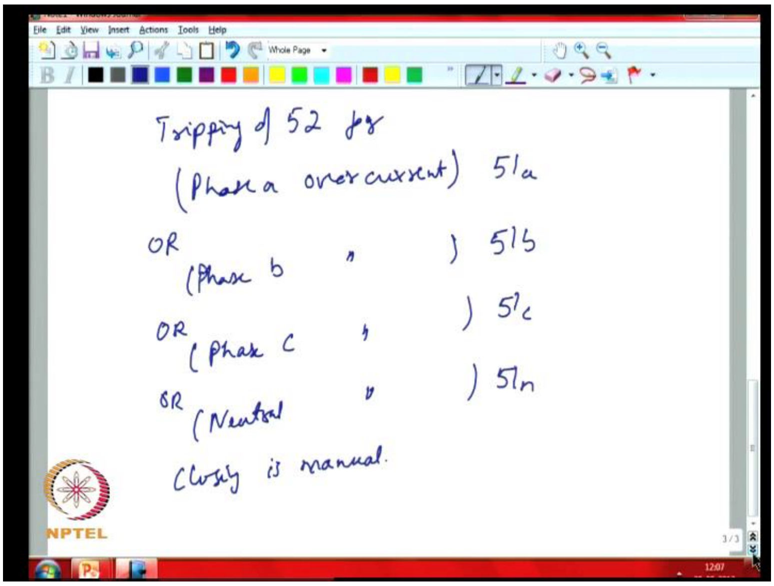

So, in this example, you might say a tripping of the breaker. For phase a over current, which is accomplished by the 51 a functionality or phase b over current or... So, closing in a simple case, the closing might be manual operation. And then you might say at what current level are you going to trip. So, you might have group setting for the phase over current levels; you might have a different setting for the neutral over current level. So, with a… Once you have a digital programmable platform, you can have a lot of flexibility on how even something as simple as a circuit breaker can actually implement the characteristic. And we saw in the… When we are discussing about circuit breaker protection, you could have now multiple say inverse time characteristics. So, to have short, long instantaneous. So, essentially, you are now grouping together multiple such functionalities to implement such functions.

If you look at the actual computation of whether there is over current that is happening or some action that needs to be taken; in typical power protection applications, you are looking at sampling rates of 8 to 16 times the normal 50 hertz rate. So, it is not as fast as what you would in a power electronic application, where the switching frequency may be 10 kilo hertz, 5 kilo hertz, 20 kilo hertz, etcetera. In relay, you are actually sampling at an intermediate rate to make a decision on whether to actually operate the relay or not. And often… And as we discussed, many times the decisions are based on at RMS time frame rather than the time frame of micro seconds, what you would typically associate with a semiconductor devices in a power electronic application.

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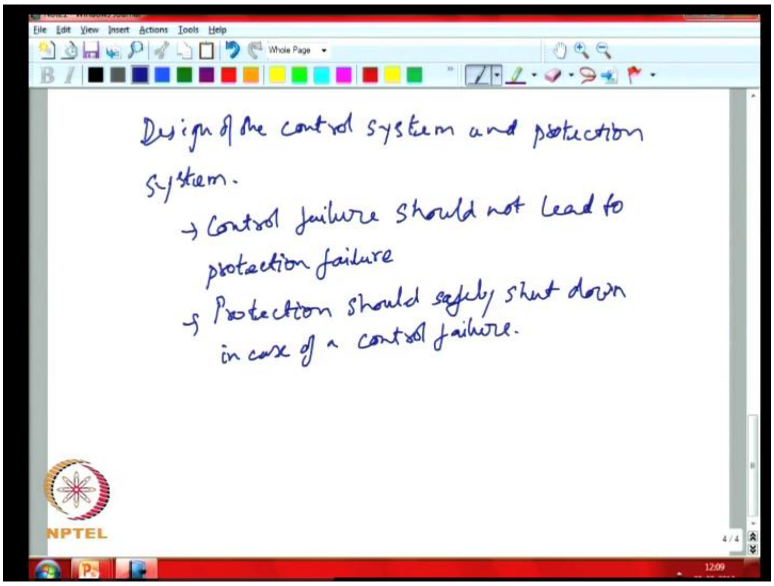

So, in a typical system, what you would also have is you might have a DG system, where you might have a control system and a protection system. And what you need to ensure in many applications is that, these control systems and protection systems need to be independent in what you mean is that, if you have a control failure, the protection should not fail. So, when things are going bad, you should be able to safely shut down; you should not depend on the control being right to protect yourself. And the protection system should be able to safely shut down the overall system in case of a control failure. And if you look at a typical high power DG interconnection, you would have separate protection systems for the DG; you would have separate for the interconnection; you would have separate protection; you would have separate control for the DG equipment.

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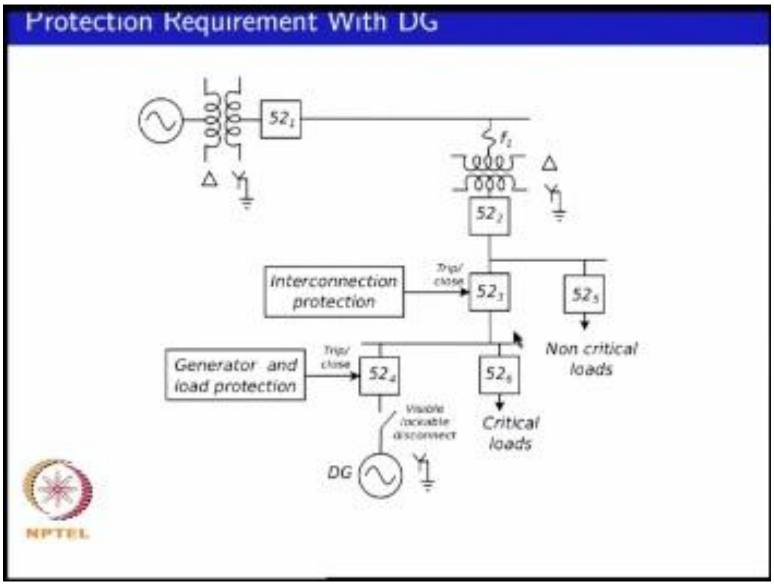

So, for example, this is an example, where you are connecting DG to a facility; and you are coming through the mains, the point of coupling might be just immediately downstream of the transformer. And you have the main breaker coming into the facility, you might say split it off into non-critical loads, which you might be able to shut off in case of failure of or poor power quality on the grid. Then you have an interconnection between now the DG and the mains. And then you would also say for example, open the breaker 52 3 to be able to provide poverty of critical loads in case the grid is… say for example, gone down. You would also like to have protection for the DG generator itself. And in case when 52 3 is open, the interconnection is opened. You want this breaker to also protect the critical bus. So, this would be the critical bus.

You might have one critical load or multiple critical loads connected to the bus – critical bus; and you need to ensure that, you have DG and load protection been implemented again in an appropriate manner. And that again should be independent of DG control. In the DG control, you are trying to ensure the right power level, the right voltage, the right frequency, etcetera. For the control of the DG, you might have say governors. If it is a power electronic converter, you might have PWM control; you might have current loops, DC bus voltage controls. So, those issues would be independent – ideally should be independent of the interconnection and the generator and the load bus protection. So, then you could ask what are the objectives of these protective systems. So, first, if you look at say this generator and the critical load bus protection, what would its objective be?

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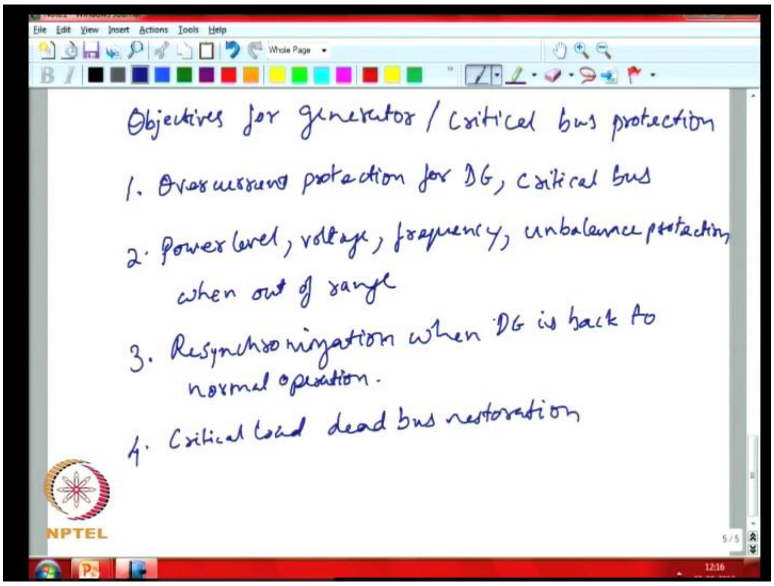

So, you would like to have the standard over current protection for the DG and the critical bus. You may want to ensure power level, unbalance protection when those corresponding parameters are out of range. Then you might also have say resynchronization; say for example, you might have a situation; where, the DG for some reason, it might be in service, it might be disconnected, and the power is being fed through the grid to the loads. So, once you want to reconnect this back, you might be able to operate the circuit breaker to resynchronize this machine back to this bus. So, when the frequency voltage amplitude phase is right, you connect back and resume an operation back with the DG. So, that could be one of the requirements.

So, after a shut down, resynchronization might be important. Another important aspect might be if for some reason say the system has gone down due to a black out and if your breaker say 52 3 is open; then if you are able to start the DG, after starting the DG, you might be able to close 52 4 to give a black start for the critical loads. So, you might have critical load dead bus restoration. So, many such functionalities would be governed by that particular interconnecting device. Then you could also ask what would be the objectives of operating this interconnection breaker.

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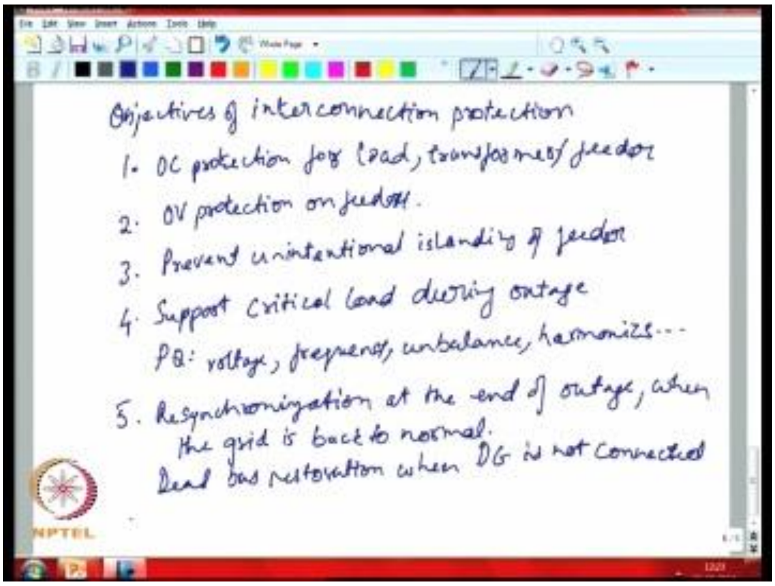

So, if you look at the objectives of that; so first is again the standard over current to protect against over current for loads, transformer and even upstream towards the feeder. So, you want that particular breaker to ensure that, now, you have two sources. So, you could have the grid causing over current damage downstream into the facility or potentially the DG causing over current damage upstream out of the facility. You might also want to prevent over voltage on the feeder. So, we saw that, in situation such as unbalanced faults, you can have the DG providing, causing over voltage on phases of the feeder. So, you would want the interconnection protection to actually prevent that. So, another important aspect is to prevent unintentional islands.

So, another requirement would be for this interconnection breaker to open rapidly when you sense a poor power quality on the grid. So, if the DG is working and you have sensed that, the grid power quality has become poor; then if you rapidly open the interconnection, then the critical loads will not see the poor power quality that is coming from the grid. The outage is one possibility you can have; other power quality requirements such as voltage, amplitude say just sag or swells, frequency, unbalance, potentially harmonics, etcetera. And you want to protect the critical loads from facing poor power quality from the source. You can also use the interconnection breaker for resynchronization.

So, if you have for example, a situation, where there is an outage on the grid and the 52 3 has opened; and the DG is now providing power to the critical load. Now, the grid has come back and you want to see when the grid voltage and the critical bus voltage matches in terms of amplitude, frequency and phase; then you can actually close this particular breaker and resynchronize to the grid. So, resynchronization would also be required at the interconnection protection. Also, you might have requirements for say reenergizing a dead bus. So, for example, you might have a situation, where the whole system is dead and maybe the DG is also disconnected.

And, if for some reason, this particular breaker is open, you need to ensure that, you are monitoring the voltages and ensuring that, it is a dead bus. If everything is dead, you can reenergize the critical loads as long as you are ensuring that, you are not reenergizing a connected DG, you are not reenergizing a dead DG. So, you do not want to start up a large machine or an inverter when it is still connected and when it is not supposed to function, you want to prevent that; but, you want to actually reenergize a dead bus.

So, dead bus restarting with the appropriate logic would also be required. Also, you might have some additional functionalities depending on the type of sensing that can be done; you might be able to monitor the amount of power that is now flowing out; you might be able to look at the real and reactive power that is going out into the PCC. So, you might have some additional functionalities, which could provide additional services to the facility by looking at not just the variables at the interconnection, but additional variables at different locations on the system.

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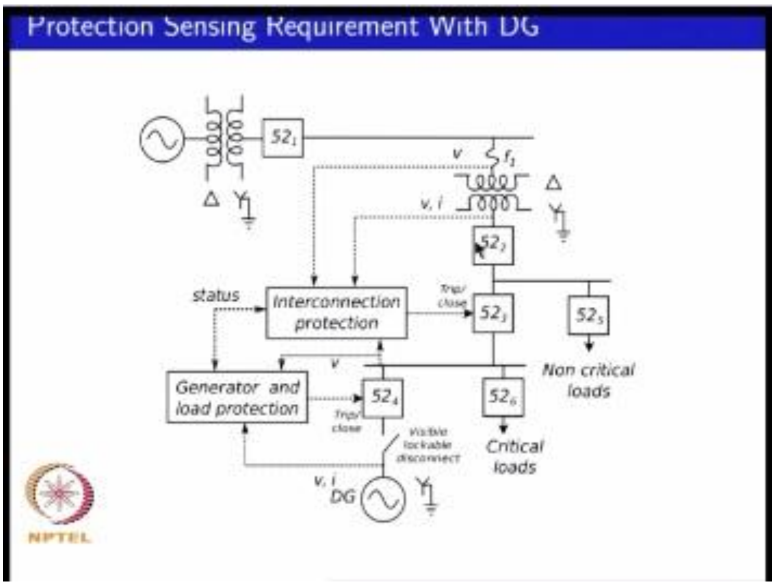

So, the next thing that you can ask is now, if you want to do all these functionalities, what all information would you need to measure in terms of what all sensing elements would be required for such protective operation. And typically, in a power system application for sensing voltages, you use a potential transformers PT's; and for sensing currents, you would use CT's. And you are… You would then be able to measure the voltage on a normalized basis. In acceptable range, you might have 110 volts secondary's PT; or, you might have 5 Amp CT; where, now, the actual information that is coming into the relay would be on a normalized scale rather than on a wider actual physical range.

And so you need to have the adequate number of PT's and CT's at different locations. So, for example, over here you might have voltage measurements at the high voltage side; which means that, you would need something that measures this at the distribution voltage level; whereas, over here if you are measuring the voltage, it would be at the consumption voltage level. So, depending on where you are applying, you would need different types of PT's and CT's.

And, often in a power system application, you would also differentiate between whether a CT is protection grid or relay grid or whether it is metering grid. So, a relay grid CT would be capable of measuring large over currents. Its accuracy may not be as high, but you are capable of measuring large fault current levels; whereas, a metering CT would be having a much higher accuracy, because billing is tight to it, but it is not capable of having large over currents. So, it will not be used for measuring say fault current levels. So, the details of PT's, CT's are acceptable can be obtained from manufacturer websites of these sensing devices.

So, in this particular case, you would have say for example, you might be making use of voltage sensing. So, you might be sensing the voltage on the high voltage side to see whether you are having say neutral shifts or neutral shifts because of say unbalanced faults, etcetera. When you have something like a delta y transformer, it does not pass zero sequence across. So, you might have to sense the voltage appropriately to see whether something has happened on the high voltage side. You might have secondary side voltage measurement; you might also have secondary side current measurement. So, with the voltage measurement, you will be able to look at power quality whether the voltage is in range, frequency is in range; whether there is distortions, etcetera. Once you have voltage and power, you can then measure power. Whether there is power is flowing in or back out into the system with the current, you can now make use of that sense current for over current protection.

Then, if you are having voltage that is now measured on the incoming voltage plus also on the critical bus; then you can make use of these two voltage measurements to do synchronization of the interconnection. Similarly, if you have voltage being measured at the critical bus and voltage being measured on the DG output; that can be used to synchronize and see whether you can actually close the DG or the load protection breaker. So, you could also then say for example, measure the power level. If you have voltage and current, you could then see whether DG is giving an over current situation to for say protection of faults on the load bus. You could also see whether DG is actually supposed to output power is due to a fault is power coming back into the DG. So, you could ask a variety of such questions. So, sensing is an important aspect for the overall protection of the system.

So, here also you might have interconnection between the generator protection and the interconnection protection. So, for example, when you want to reenergize a dead bus, you may want to know whether this status of this breaker is open and you do not want to energize a DG – a dead DG when it is a still connected. So, you might have some status information going back and forth between the protective elements. But, you would typically implement the protection such that, even if for example, some part of the system is non-functional, you would always end up in a safe mode rather than in a mode, where you can potentially have damaged. Then…

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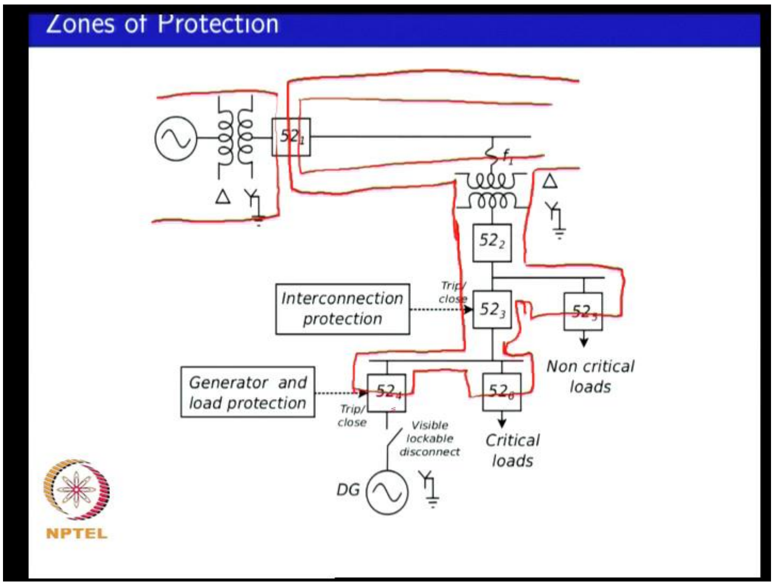

So, the next thing that you could say is in such a system, what could be the potential zones of protection. So, when we talked about the distribution system, we are talking about… Say you could have substation protection, where you might have relays, which protect the substation transformers and the equipment at the substation. You could have a feeder protection, where you are trying to protect the components whatever is there on the feeder. So, if you have now DG that is connected in a manner such as this, then you would say what is the interconnection protection doing, what is its zone. So, an interconnection protection might say protect downstream of the breaker to prevent over current from the grid flowing into the load. So, you might have the zone of the interconnection protection.

But, the interconnection protection is also trying to protect the distribution system and also the neighboring equipment. So, the interconnection protection has to protect a fairly large zone. So, when the DG is present and when the grid is present; if say for example, the 52 1 opens, you need to ensure that, the DG is still able to detect such a situation and open the interconnection in response to such a situation. And if the DG is absent and the grid is present, you want to make use of the interconnection protection to protect up till the next protective device, which would be in this case, 52 4 or 52 6.

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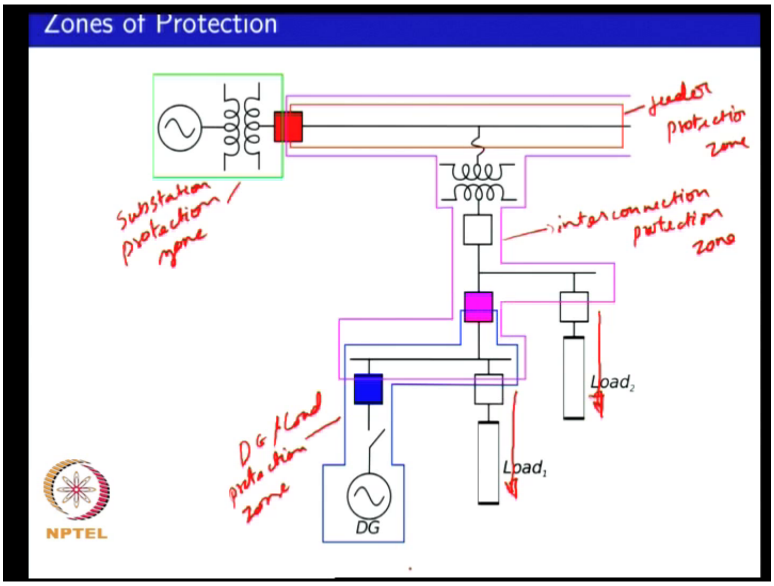

So, you could actually determine what would be the interconnection protection. So, this would be for example, the substation protection zone. So, what is shown over here is the feeder protection; what is shown in pink is the interconnection protection. And you want to ensure that, these devices are able to accomplish the required level of protection. So, if you look at the other CB's over here, here we had this particular CB would protect say the zone downstream over here; this circuit breaker might protect the zone downstream over here.

So, when you have the overall system, you want to ensure that, every part of the system is protected; you do not have the zones that are left out and protected. You also want to have now in a situation such as this that, you might have a situation, where you now have maybe just the DG or maybe just the grid or combination when both DG and grid are operating. And in all those combined situations, you do not have any possibility of some zone being left on protected in all these cases.

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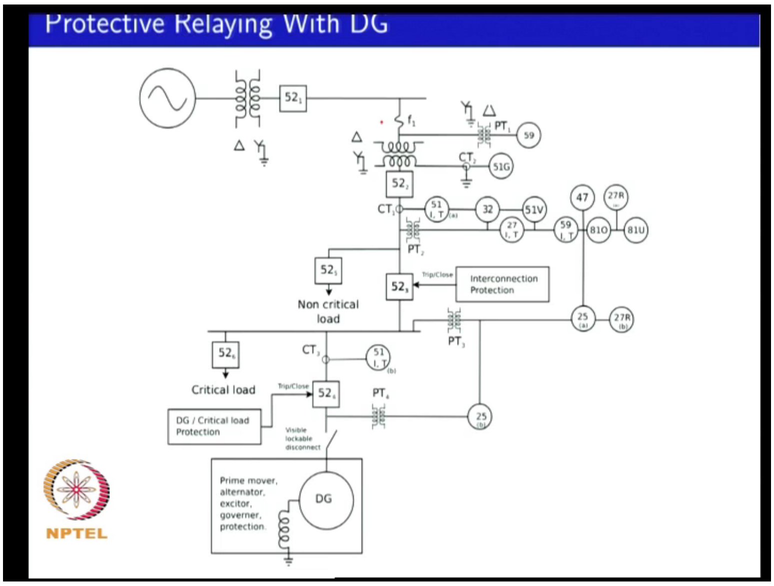

So, the next thing is we will see… Now, that you have identified what could be the zones of protection and what could be considered interconnection and say critical load protection; then you could consider what could potentially be some of the relaying functionality that could be used to accomplish some of the protection. And here what we are looking at is say an example of a DG that is interconnected through a delta y transformer; and you might have a facility, where you have non-critical loads, which can be turned off and critical loads, which needs support in terms of power quality; plus you might be ensuring that, you are trying to compensate and prevent say peak loading over here; you might be trying to pump powers, so that the demand on the facility does not exceed some particular power level, because many times the utility will charge if the demand is higher. So, you might have a variety of such requirements; and then you would ask what sort of relaying would be required to accomplish such objective.

So, we will discuss this in the next class. We will… So, we have seen that, it is not just the switching functionality, but also the protection that goes behind, the smarts that go behind such functionality; that is important. So, if you look at the overall protection diagram, it might look complicated. But, if you look at it as one function by one by one, it is actually a relatively simple and straightforward to actually see what type of protection would be required; what would be required to trip and what would be required to close a circuit breaker. And even though it looks like you are having a large number of such functions, in a modern multifunctional protective relay, all these functionalities will be implemented in a single package. So, in terms of hardware, it does not increase the amount of hardware that you would need to have to actually implement all these functionalities; of course, you need the sensors. Without the sensed information, you cannot make a decision. But, once the sensed information is available, then it is just the smarts or the algorithms that you implement to actually see whether the objectives, which we discussed can be accomplished.

Thank you.