Power System Protection
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Lecture No. 47
Protection Challenges of Transmission Systems with Renewables

Welcome to NPTEL course on Power System Protection, we are in the modules on Network Protection with Renewable Sources.

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In today's lecture, we will go into the concepts related to presence of renewable plants and the issues with transmission network protection, where we will see three issues, fault type classification, directional relaying, distance protections of course there are other related issues in this domain also.

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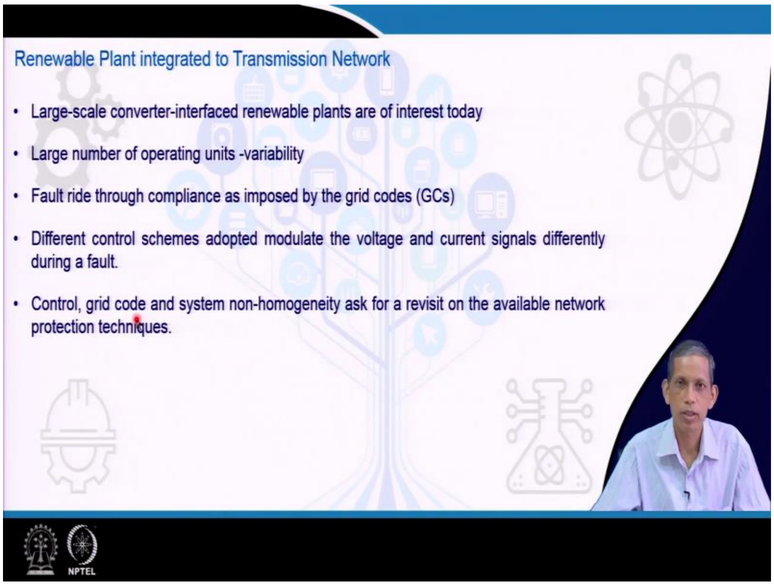

Now, in this module, we have already address on the role of renewables and associated protections. In the last lecture, we talk about how the renewable sources affect relay performance in distribution system, and other allied protection issues. Now, to the transmission system, we say these days the renewables are being integrated at the transmission level also, starting from 100s of MW to of the order GW also. So, this large scale integration to the transmission system, does it affect the transmission line protection? That is the question of this lecture. We like to address on that perspective.

What happens in this case, these large scale converter based renewable plants that consists of several such units and the area coverage becomes pretty large. So, that introduces variability, how many units operating at a time, if it is solar what is the amount of solar irradiance available at a time, variation among the units at a time, wind velocity across different units in the same plant? So, that introduces variability in the overall output of the plant.

Fault ride through compliance through different grid codes that we have already discussed in earlier lectures also. So, that during fault, voltage dips at high voltage system, these units are not allowed to be withdrawn, otherwise further degradation in system, stability will be challenging because of their large capacity. Different control schemes adopted in the inverter management system modulate the corresponding voltage and current during fault significantly, that we have learned in fault characterization of inverters also.

Control, grid code, another point is system non-homogeneity, that we have already talked in distance relaying perspective, the impedance angle is a challenging perspective that is why network protection is under scrutiny.

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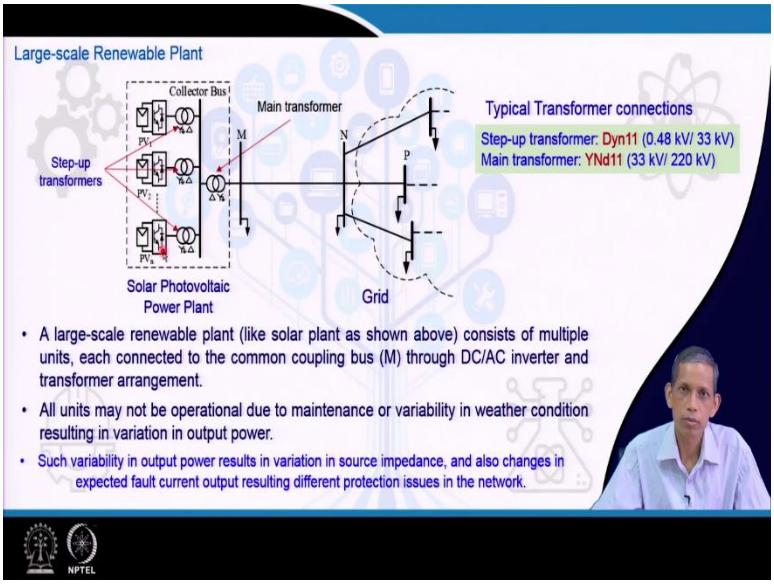

Let us come to a large scale renewable plant, where we have several such units depending upon the each capacity of the corresponding PV plant and its associated inverter. And then aggregate some of that leads to a step-up transformer. And such multiple units are connected to a common collector bus. Then again, that large scale integration is being connected to a high voltage bus through a, another main transformer, a step-up transformer, a typical example will be having 0.48 kV to 33 kV at first level and from 33 kV to 220 kV or 400 kV at the next level.

So, this large scale renewable plant in the order of GW or so can be connected to high voltage transmission system and then to the grid. Now such a plant arrangement leads to the corresponding transformer connection is of importance on the operational and protection perspective. The control and the grid code associated on the inverter is also of importance in the perspective of protection. So, we have already, adjust variability of output powers, we will see also the corresponding source impedance, variation. All these perspectives makes the protection more challenging.

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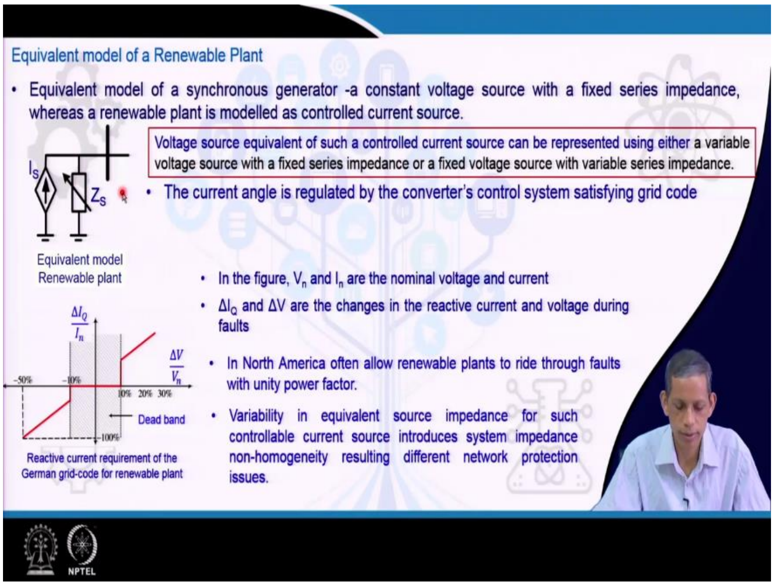

Now, let us go into further details. Equivalent model of the renewable plant. We already know PV plant is being modelled as a current source. Now, in this case, the corresponding synchronous generator is a constant voltage source, they have fixed internal impedance and so. Whereas, a renewable plant is modelled as a controlled current source as shown here. Now, if you like to consider it as a controlled voltage source for that perspective depending either a variable voltage source with a fixed impedance or a fixed voltage source with variable series impedance. So, these are the 2 possibilities, which you can consider the corresponding current source converter to a voltage source operating at a particular instant, because every instant, the corresponding current source changes, and that is what we can call it as controlled current source. The current angle is regulated by the converter's control and that control action has to be satisfied with numerous grid codes associated. Now, let us come to this German grid code perspective here, where the current versus the voltage perspective.

So, we see, V_n , I_n are the corresponding normal voltage and current. ΔI_Q and the ΔV are the changes in the reactive current and voltage during faults. So, this is a dead band zone a thing like as their wish, but once the corresponding voltage changes becomes more and more because of the fault or so, then the reactive power continuation by the inverter becomes more and more for maintaining the system voltage. So, that is what we say the operational perspective of the inverter interfaced source as compared to the synchronous machine-based source. Further, another North American grid code says, renewable plants to ride through faults with unity power factor. So, these are the variations on the operational perspective of the corresponding converter during fault, how the current injection happens to be there, is it unity power factor or is it reactive power support? And so that makes the corresponding fault current with respect to the voltage at that bus to be different one as compared to the synchronous machine perspective. Variability in equivalent source impedance for such controllable current source introduces system impedance non-homogeneity.The angle of synchronous machine impedance and the angle of the transmission system impedance in our earlier distance relaying perspective was considered to be of similar value, but here that does not hold good because of these control operations and the corresponding equivalent impedance of the source, that varies significantly with time even during fault and also the corresponding associated angle. And that angle may not be similar value, matching with the corresponding transmission system impedance.

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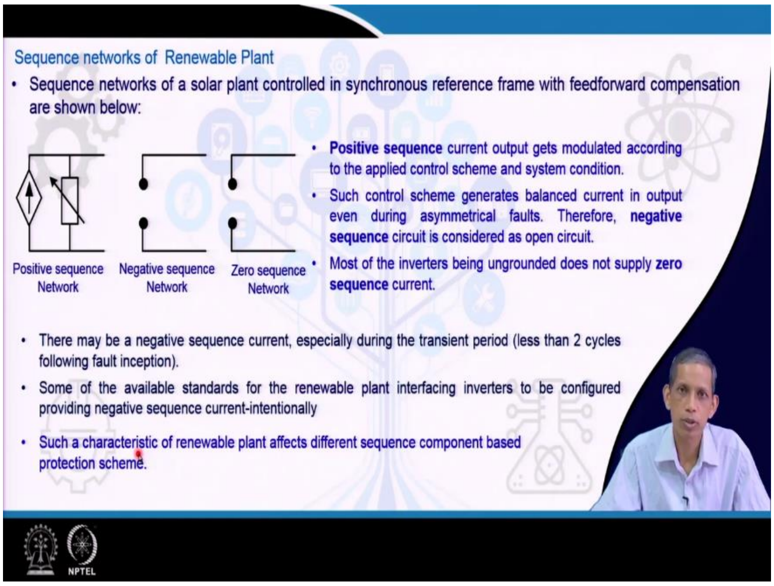

Now, on the sequence networks of renewable plant. So, the corresponding positive sequence network is this that is what the balance current from the PV plant. And note that we have already learned that such sources, even during unbalance fault provide balance current. That implies no negative sequence current, no zero-sequence current. Therefore, the negative sequence circuit is considered to be open. Note that no negative sequence current from the source also no zero-sequence current. Therefore, these negative sequence and zero-sequence network happens to be open circuit. And most of the inverters as already mentioned are ungrounded that is why the corresponding zero-sequence current becomes not available, even the fault involved with ground or so. The positive sequence current output gets modulated according to the applied control scheme and that changes the corresponding network impedance accordingly.

But we have already mentioned earlier that less than 2 cycles following the fault inception, the current can have a normal flow. And during that period, only some negative sequence current may be available. But that does not ensure that afterwards the negative sequence current will available, so negative sequence components based approaches on protection for network, which is being pretty common as you have learned earlier maybe under scrutiny, Some of the available standards in renewable plant interface inverters configured to provide negative sequence current intentionally, so that available protections schemes and control schemes in the grid will still be functioning properly. Such a characteristic of renewable plant affects different sequence component based protection schemes, and that is the question how will be the performance of the network protection schemes.

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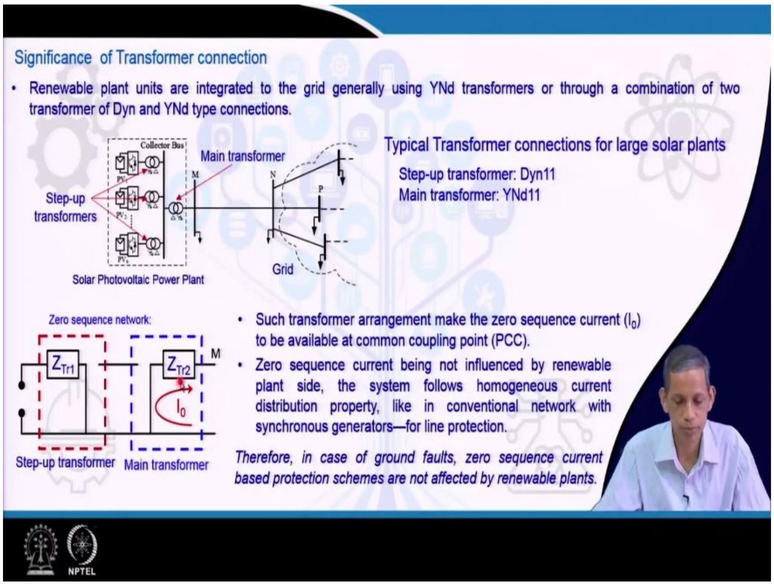

One important factor is on the transformer connections. So, we see 2 stages of stepping up the voltage, at the first stage and the second stage. So, we see that a corresponding transformer connections this is Dy11 and this is Yd11. It means that the corresponding the angle at this stage and between this stage, the corresponding network, the angle, get cancels out with these two transformers, and that is being maintained in terms of that. Such transformer arrangement make the zero-sequence current to be available at common coupling point.

See here, what happens to the zero-sequence network in this case? So earlier, we have seen the sequence component on networks for positive, negative and zero for the converter, up to the converter. Now in the transformer part, the first stage for this Dy11 part, so that becomes this, because we say this from the grey, from the converter side, this side remains open and this transformer is a Y Δ. Therefore, for this one, the circulating current will be pointing to this reference. Now, this part is for the first stage, but the main transformer, if we see, Δ side to this collector bus side, the circulating current to this one. So, Z will be to this one. And the corresponding transformer was connected with the M bus here. So, if a fault happens to be there, it finds a path through the star grounded, it finds a path through this path and then circulating current goes through this side. So, that implies that for line to ground fault in grid side due to the arrangements of such transformer arrangements zero-sequence current flows.

So, zero-sequence current being not influenced by renewable plant, because it does not go to the renewable plant side, we see here from this path, only this corresponding main transformer impedance is not associate the grid side impedance. So it is not influenced by the renewable plan and the system follows homogeneous nature, as you can say that, already we have discussed in our earlier transmission system protection. So, this is only related to zero-sequence current perspective. However, this approach of protections like in a conventional synchronous generator, we see that involved with ground faults only. Therefore in case of ground fault zero-sequence current based protection schemes will not be affected even in the presence of renewable plants with such transformer connection and that is what the significance of transformer connection.

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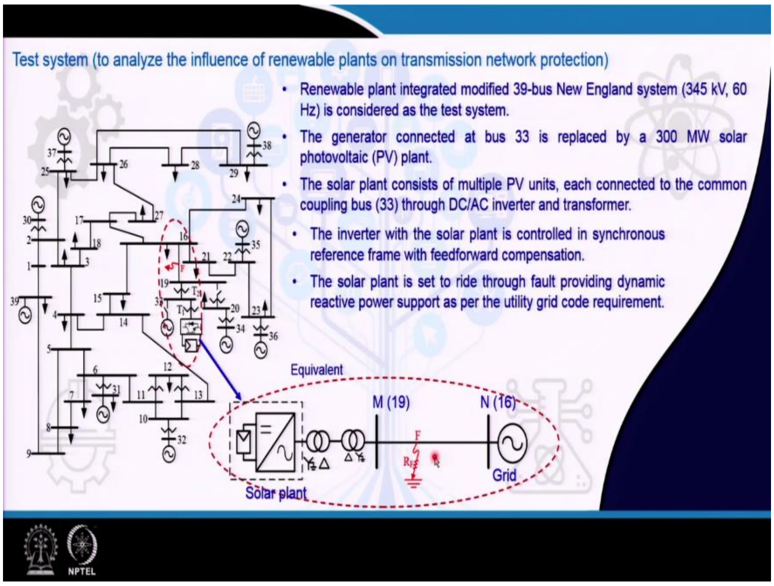

Now, will have a test systems, we were going to different network protection schemes. So, this is 39-bus New England systems. We have some modification here to integrate the corresponding renewable resource, 345 kV 60 Hz at bus number 33, here we replaced the corresponding a synchronous generator by PV plant with the inverter into interface and with adding to transformer perspective. The inverter with this solar plant is controlled in synchronous reference frame with feed forward compensation, this is what the scheme of control being used.

The solar plant is said to ride through the fault providing dynamic reactive power support as per the utility grid code requirement. So, that is what the reactive support is being provide. Now, this red dotted portion, we have taken the corresponding equivalence for this to have the test of the system. So, this is the solar plant perspective and then at this bus number 19, we have this M bus equivalent. And the bus number 16, we have this corresponding N. So, this network connections for this, how the corresponding line protection works, that we like to see. So for, faults in this particular line.

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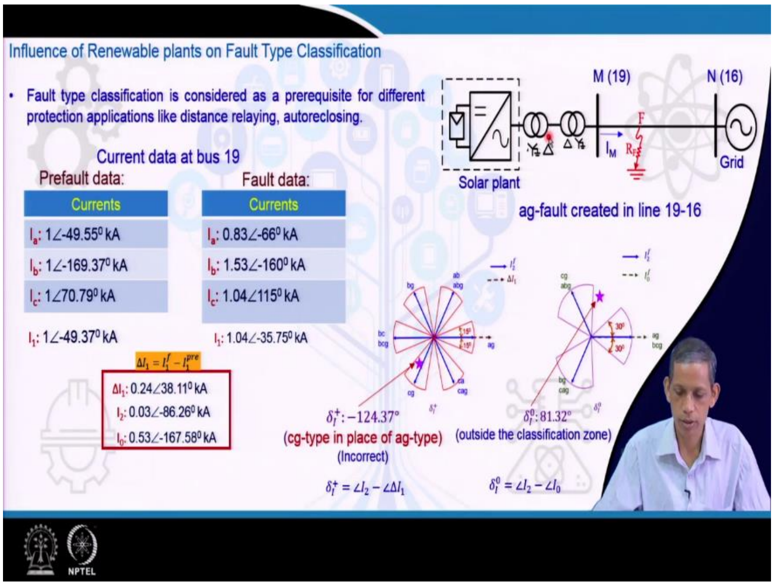

Now, same system equivalent we have considered here. So, consider that the distance relay is at bus N. So, whatever the associated issues and how does it function, correctly or not, that we like to check. Fault is at F, and phase-*a* to ground fault in this line with associated R_F. So first, we are talking about fault type classification. So, for fault type classification, if you remember, it primarily uses the current based approach. So, let us see the current data at bus number 19, here, for a fault in line 19 - 16. Pre fault current, you see here at a balance phase-*a* to ground fault. So, we can say here that the current nature here contributed by the solar plant through this current, through which flows this relay is contributed by the solar plant phase-*a* to ground fault, but the nature of fault current, we see here that is rather phase-*a* current has gone down. And it tried to balance the corresponding current even though phase-*a* to ground fault happens to be there. This leads to the δ_I^+ change in current from the fault current to a pre fault current.

So, this ΔI_1 happens to be 0.24 and the I_2 current happens to be 0.03 and I_0 current happens to be 0.53. Note, that this I_2 current is pretty small, insignificant here, as already mentioned. And the zero-sequence current finds a path, so that is why it is of significant value. Now, what happens that, when we translate the corresponding positive sequence and negative sequence and zero-sequence current into this classification plane, so we take the corresponding *ag* fault, the corresponding I, ΔI in this reference and with respect to the corresponding I_2. So, then the corresponding point, which we are getting for this case is at this star point mark here. Fault is *ag* type, but this happens to be the corresponding angle δ_I^+ happens to be -124.37^0 from this calculated one and that lies in this actual that, for the *cg* fault type. This area is marked for the fault type of phase *c* to ground and this angle falls in this one even though the fault is of *ag* type. Therefore, this current based classification approach fails here, looking at this perspective. And the duration, you see here that how the corresponding current modulation happens to be for the phase-*a* to ground fault. And also, the other one associate with the zero-sequence current with the reference and the corresponding I_2, that also falls, I think, the corresponding angle falls outside the zone of *cg*. So this also does not say about the type of fault *ag* type of fault or so. That means that the fault classification example here demonstrates that the fault classification approach may fail in the case of a transmission network connecting to a PV based power plant integrated with inverters.

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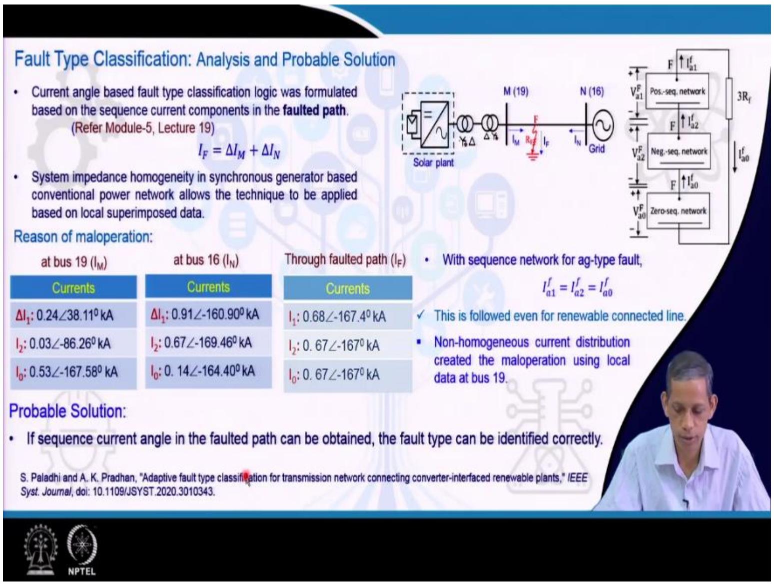

Now, we will try to analyse this. So, this is a current angle based fault classification logic, if we remember that started the associated current passing through the faulted path. And the corresponding positive sequence, negative sequence and zero-sequence network, let us say for a phase-a to ground fault, they happen to be series with 3 R_F. And then this faulted path current, the positive sequence, the zero sequence, and any sequence align with certain angle. And this sequence network from the sequence network for the faulted path current that reveals the corresponding, different angles for different types of fault.

So, our concern is based on the faulted path current. And in case of synchronous machine based approach, we see that the homogeneity angle of the corresponding throughout the M bus side and N bus side will be maintained. And from that angle, we consider that the local data also reveal the corresponding phase angle information for the application of fault classification. But now, the impedance angle of the solar plant being much different that of the grid side and that also that of the transmission system, so the homogeneity consideration is no more valid and that puts challenges. Now, let us see, what you have learned in lecture 19 of the reference, the model 5, that

$$I_F = \Delta I_M + \Delta I_N$$

System impedance homogeneity and synchronous generator based conventional approach allows these techniques to be using the local superimposed component. Now, let us see, bus 19 data and bus 16 data. So, during fault, so bus 19 data, ΔI_1, ΔI_2 and ΔI_0, we have already seen earlier slide. At the same, for the same fault, the bus 16 data, ΔI_1, ΔI_2 and ΔI_0, you see here the angles are almost same. But this is what we are talking about the homogeneity nature.

And if you see here, these angles are different, and that to say I_2 is of insignificance. But if we see this faulted path current, which is a summation of this current and this current, so this I_1 current, if we see here $0.68\angle{-167.4^0}$ kA and the angle is also same. So, this is for phase-a to ground fault, and that is what I can say that I_{a1}, I_{a0}, and I_{a2}, they are all same for the phase-a to ground fault, and that is what is valid here. Therefore, we observe that in such a situation also, the faulted path current maintains that current relation, the angle relations for the current for the fault classification business. But the local data at the converter side resource does not hold good because of the different converter control aspects. But grid side still is valid. So, that is the big difference with synchronous machine based approach and the renewable resource based approach. This non-homogeneity and all these things has been introduced relates because of this equivalent impedance of the solar plant and its associated angle. Now then, to overcome this, what is solution for the relay?

And the probable solution if the, if sequence current angle in the faulted part, sequence current angle in the faulted part, that what we are talking about here can be obtained by any means, then the fault type, that classification approaches, which we have used in transmission network protection earlier with, for the distance relay in different applications can be further used. And for that, the below reference provides that information.

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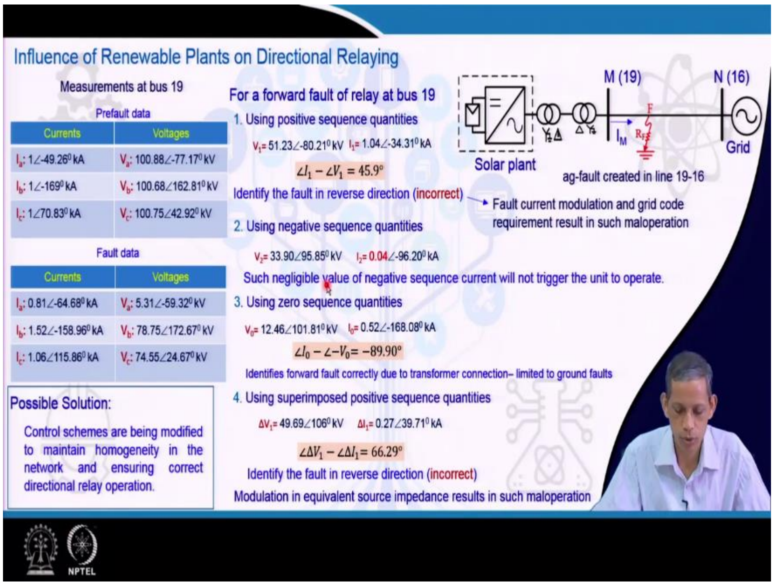

Next, we will go to the directional relaying application, directional relaying perspective in the presence of renewables. So for same fault that we are talking about *ag* fault here. The prefault data, fault data. So, for directional relaying, we use both voltage and current the prefault current sets and voltage sets are balance in nature. And fault data already enumerated phase-*a* to ground fault and the corresponding phase-*a* voltage goes down phase-b, phase-c voltage remains almost similar magnitude, though they are also affected as compared to the prefault voltages.

Now, for this for forward fault, for bus number 19 M, this what we are talking about, let us see, if we can apply the positive sequence quantities, negative sequence quantities and zero-sequence quantities based approach and superimposed and so and so. Using positive sequence quantities, we found the V_1 and I_1 for the fault using the fault data. And the

$$\angle I_1 - \angle V_1 = 45.9°$$

Which reveals the forward fault or reverse fault, this angle is coming to a positive, which means that this is a reverse fault. Reverse fault means, this side. Whereas the fault, actual fault is in the forward fault, so then, this is incorrect.

That is what due to the controlled actions provided by this the modulating current is creating problem. In terms of negative sequence current as you see here the negative sequence current is insignificant. We have already mentioned that the controller action does not allow negative sequence current because of the balance controlled approach. So, this small amount of current becomes unreliable, so it cannot rely on the negative sequence current. So, this is also rejected. Using zero-sequence quantities, this is a phase-*a* to ground fault, we say zero-sequence current will flow. So, significant current is flowing. And then the

$$\angle I_0 - \angle{-V_0} = -89.90°$$

And this is able to correctly identify the fault. And we have already reasoned it out that because of the transformer connections, significant zero-sequence current flows. And that has no relation with the solar plant site. So zero-sequence current based approach of fault classification will hold good. But why is that, this is limited to only ground faults. Using superimposed phase sequence quantities, we know that the corresponding positive sequence currents get modulated, we have already seen.

So, if we look back to the ΔV_1 and ΔI_1 superimposed quantities. So, we got this from this fault data. And then if we say,

$$\angle I_0 - \angle{-V_0} = -89.90°$$

Again, the superimposed component also identifies it incorrectly, this is a forward fault, but is identified as a reverse fault. So, from this, conclusion we made that negative sequence is not available, positive sequence or the superimposed component, they failed. Only the zero-sequence component based approach qualifies as a directional link approach provides the solution, but that has a limitation to the corresponding ground fault involvement and subject to the transformer connection as here. So, another generic solution for other types of fault and so, literature suggests about to have the control schemes embedded should modulated the current such that the conventional directional relaying can still hold good. So, that the corresponding angle during that fault situation, current, between voltage and current, still holds good, what you find for the normal synchronous generator based approach.

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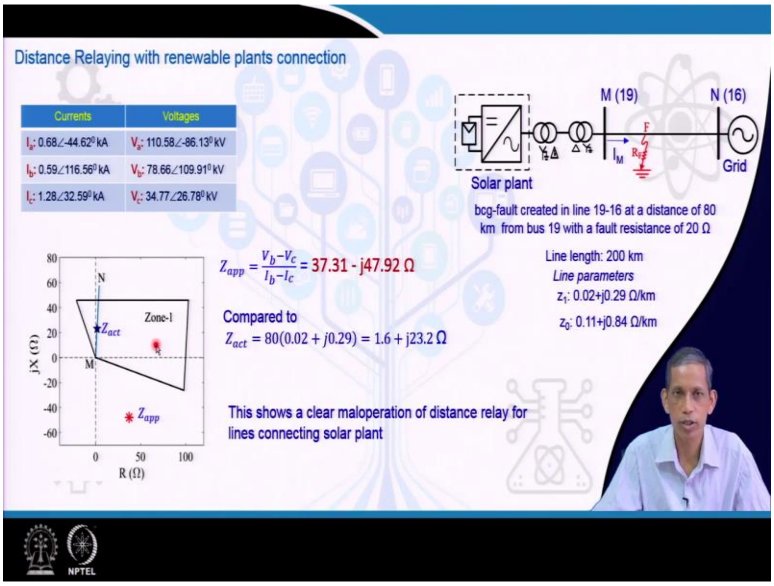

Now, we will see a third example on distance relaying with renewables. So, for the same system, equivalent system of the 39 bus system seal line number 19-16. So, we created fault at 80 km from the bus 19 with the fault resistance of 20 Ω. And the fault type is *cg* fault type. So, what we see here is that the line length is 200 km and line parameters are positive sequence, same as negative sequence, and zero-sequence provided here.

Now for this, you can say that *bcg* fault, the corresponding apparent impedance becomes

$$Z_{app} = \frac{V_b - V_c}{I_b - I_c}$$

And then if we put the corresponding fault data, that becomes equals to 37.31 - j47.92. So, the, this part is a negative, it means that the point corresponding, point becomes here. Whereas, the fault is at 80 km in the forward direction. So, the actual impedance become

$$Z_{act} = 80(0.02 + j0.29) = 1.6 + \mathrm{j}23.2\ \Omega$$

Whereas, the relay for this signal, getting Z_{app} to be this much. The Z_{app} seen by the relay becomes this, red point here as compared to the, which will be the ideal one, actual at this point on this line impedance on the RX plane. So, for this zone -1 protections, the corresponding distance relay will malfunction. It will not able to find the corresponding fault in the zone 1, that is the challenge.

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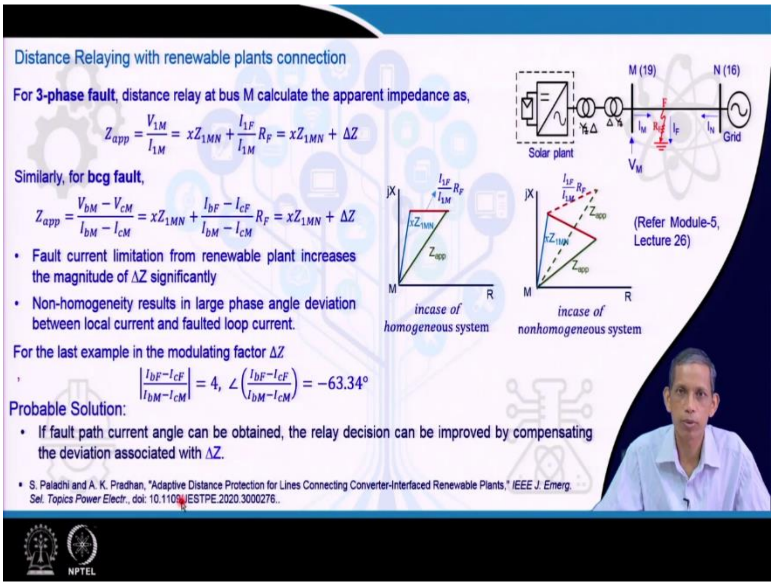

Now, we like, try to analyse, why that is happening in the distance relaying perspective. Solar plant connected to that same system, first considered for a clarity 3-ϕ fault. But for 3-ϕ fault,

$$Z_{app} = \frac{V_{1M}}{I_{1M}} = xZ_{1MN} + \frac{I_{1F}}{I_{1M}} R_F = xZ_{1MN} + \Delta Z$$

So the modulating factor of $(I_{1F} / I_{1M})R_F$ leads to deviation in impedance measurement from the original value xZ_{1MN}. Now, come to *bcg* fault. So, *bcg* fault, as we have seen in earlier example and last slide,

$$Z_{app} = \frac{V_{bM} - V_{cM}}{I_{bM} - I_{cM}} = xZ_{1MN} + \frac{I_{bF} - I_{cF}}{I_{bM} - I_{cM}} R_F = xZ_{1MN} + \Delta Z$$

So, fault current limitation from renewable plant increases the ΔZ significantly. We remember, current is limited, it means that impedance is more. Non-homogeneity is another issue for the large scale, phase angle deviation from the normal situation of, with synchronous generator or so. In the last example, and for this ΔZ, the modulating factor, there are two part R_F and this current angle current ratio part. So, the current ratio magnitude is, see here, for this case, the last, for the last example, data becomes 4 and its angle becomes -63.34^0. So, these angles show clearly that non-homogeneity is not maintained, and that is about that angle issue. And the, this magnitude of this 4 imply that, the, there is a large variation on the ΔZ part. And that is why we are dictating the on this perspective. So, we say that the relay malfunctions is due to this non-homogeneity, the angle interdiction, and then the angle ratio magnitude also may be of significant, because of the current limitation by the inverter based renewable resource. Then what are the probable solutions? A fault path current angle can be obtained like we saw in the classification perspective, the relay decision can be improved by compensating the deviation associated Δ Z. So, some perspective there, this reference reveals such an approach to mitigate the issue of distance relay performance in the presence of renewable resources.

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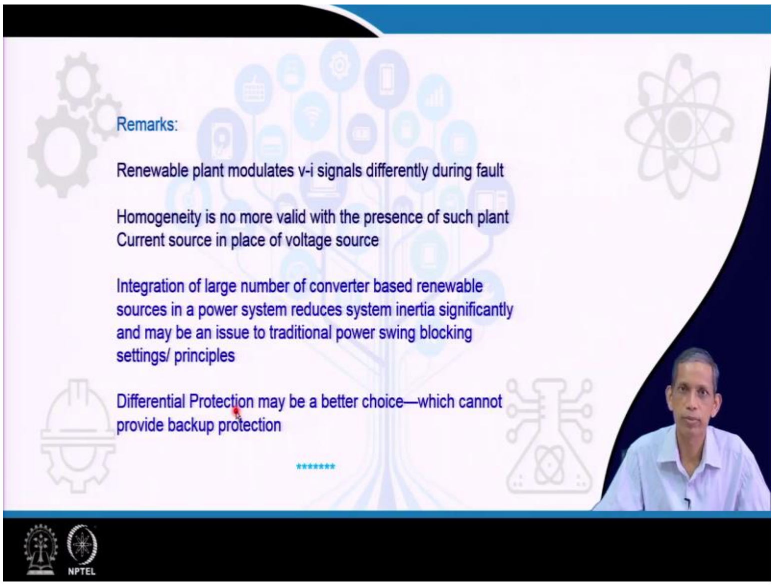

In overall, we see that renewable resource plants are being integrated in general with inverter interface and they modulate the voltage and current signal differently during fault as compared to the synchronous machine based approach. Homogeneity that the angle issue of the angle of that plant, equal end impedance of the plant, it is much different than that of the synchronous machine or the transmission system. This is a current source not, unlike the voltage source, which you can take for the synchronous machine based approach, non IED sequence current. Furthermore, important point is that integration of large number of such converter based approach, the inertia, non-rotating part here, the inertia becomes less if the penetration of such renewable resource becomes more and more, system inertia reduces accordingly. Therefore, what will happen that during a swing operation or so, the swing frequency will change, and therefore in that situation, the traditional power swing blocking settings and the principle associated, which you have learned in the distance relay are under scrutiny. Perhaps, differential protection maybe a better choice in this perspective. But we have already learned that line differential has limitations in terms of synchronization issue, line length, and associated communication cost and failure chance also. And furthermore, line differential cannot provide backup protections. So, with this, we conclude on this network protections with renewable resources. Thank you.