Digital Protection of Power System
Professor Bhaveshkumar Bhalja
Department of Electrical Engineering
Indian Institute of Technology, Roorkee
Lecture 14
Digital Protection of Transformer-IV

Hello friends. So, in the previous lecture, we have discussed regarding the digital implementation of the digital or numerical relay when we used in a power transformer.

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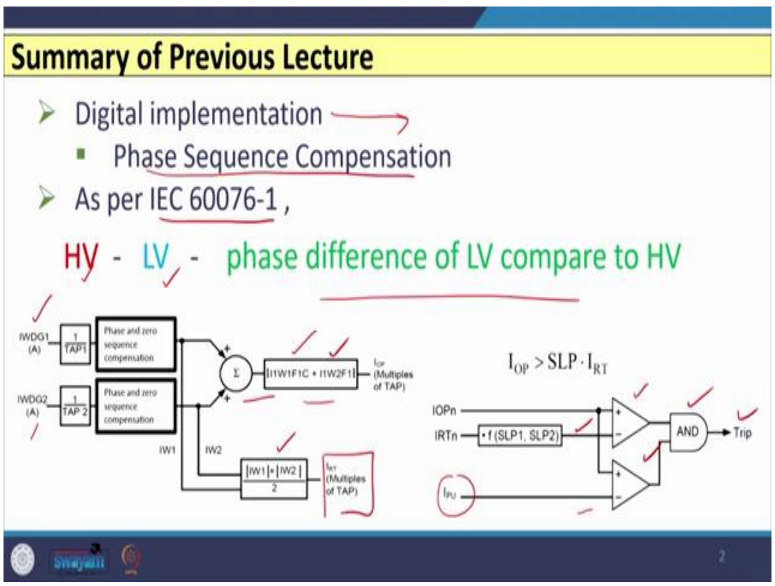

We have discussed that if we wish to achieve the inherent phase shift compensate, then we have to use different metrics depending upon what vector group or winding connections are used. And we have also seen that as per IEC 60076-1 we have to enter the winding connections first HV winding, then LV winding and then the phase difference of LV compared to the HV.

And then we have seen that depending upon each or specific vector group or winding connection specific metrics is available and that metrics is need to be multiplied with either delta or star depending upon what degree of phase shift we want to cancel. Then we have discussed the overall diagram of the digital or numerical relay applied in for power transformer.

So, we have seen that when we have the LV winding current and HV winding currents after the magnitude compensation, phase compensation and zero sequence compensation and after summing we will have the value of the operating current that is the vectorial addition of two currents or two winding currents.

Similarly, we can have the value of restraining current by just a scalar addition and multiplied with the compensation factor k. In this case it is 0.5, then once we have the value of operating current and restraining current, we can use this operational amplifiers and AND gate. And we can connect it in such a way that when operating current exceeds the restraining current, which is multiplied with some slope and second when operating current exceeds some I_{PU} value, then that Trip in command is initiated by the relay and circuit breakers can be tripped.

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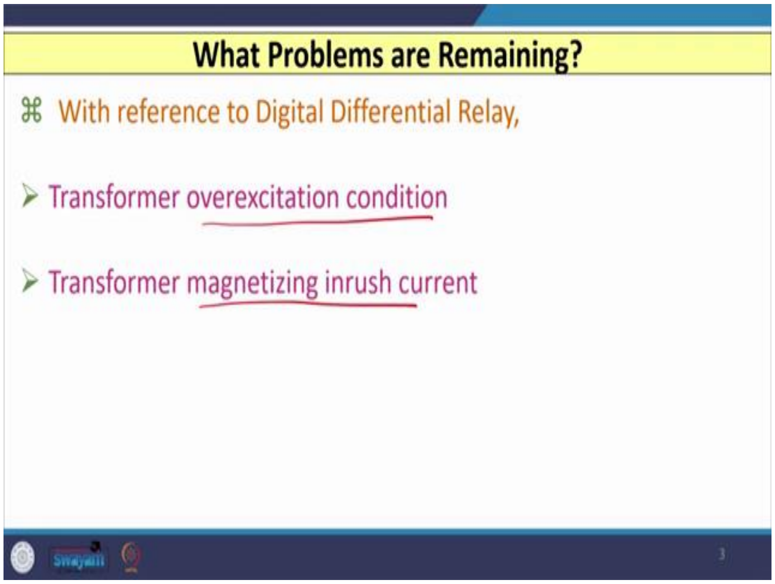

Now, in this class, we will discuss the two important problems that is phased by the digital relay or numerical relay that is the transformer overexcitation condition and second is the magnetizing inrush current when we switch on the unloaded transformer, then the magnetizing inrush current comes and transformer overexcitation condition comes specifically when there is a specific change in voltage and frequency or both. So, let us discuss first the over excitation condition.

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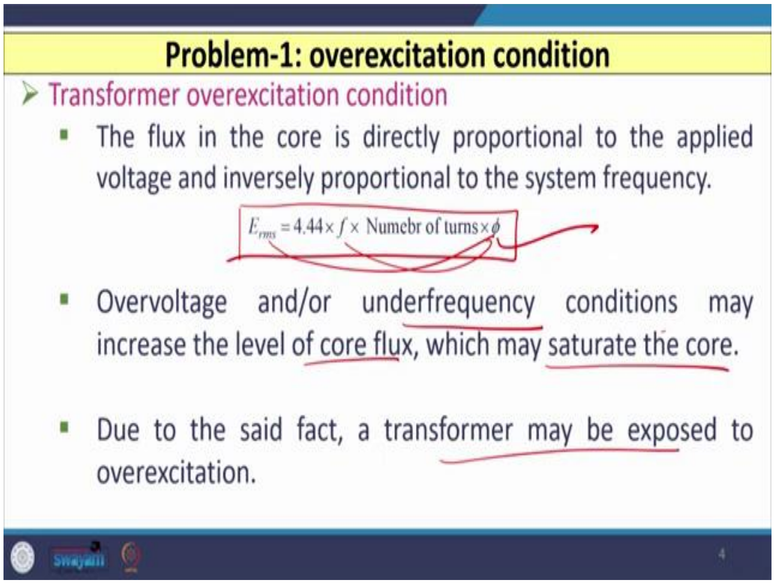

So, the flux in the core or transformer core is directly proportional to the applied voltage and it is inversely proportional to the frequency. And this can be seen using this equation. $E_{rms} = 4.44 \times f \times \text{ Numebr of turns} \times \phi$.

So, the flux in the core that is directly proportional to voltage and that is inversely proportional to the frequency. So, if there is an increase in voltage, so, in case of over voltage condition or in case of reduction in frequency or both over voltage and under frequency in that case the level of flux inside the transformer increases and there are fair chances of saturation of the transformer core and because of this fact transformer may be exposed to an overexcited condition.

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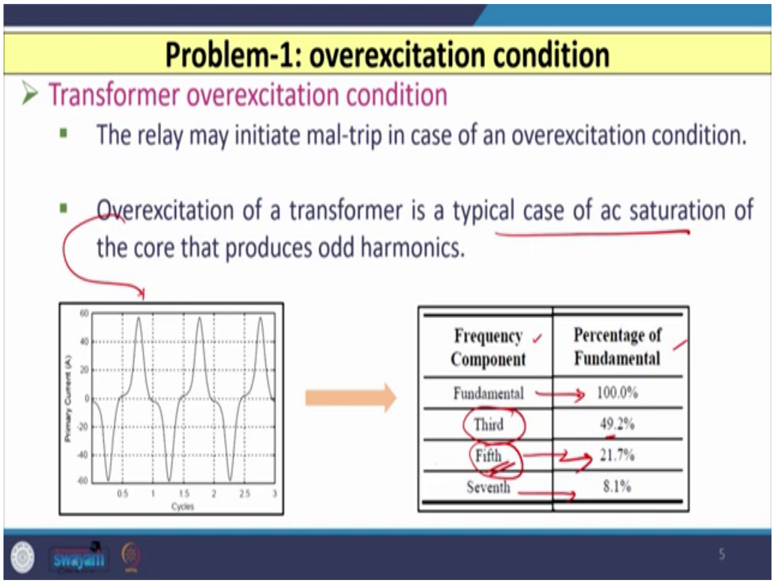

So, in this case relay may initiate a wrong trip in over excitation condition and this needs to be avoided by taking some precaution in the digital or numerical relay. Now, if I consider over excitation condition in a typical power transformer then if I look at the waveforms of this over excitation condition, then you can see I have shown the primary current waveforms with reference to the time in terms of cycles and if I take the harmonic contents of this current waveform, then you can observe that the over excitation condition is nothing but the ac saturation of the core which produces harmonics and more specifically odd harmonics.

So, here in the table you can see if I take the harmonic analysis of this waveform, then you can see (as shown in above slide) in the first column I have shown the frequency component and in the second column I have shown the percentage of fundamental for a specific frequency component. So, fundamental is obviously in the first row it is highest.

But if you consider the 3rd harmonic component, then its value is 49.2 percent with reference to the fundamental and 5th harmonic value is again 21.7 percent and 7th harmonic that is almost close to 8 percent. Now, third harmonic, we cannot use because if I have delta connected winding then that can be trapped inside.

So, we have to go for 5th harmonic. Normally, most of the manufacturers they provide the over excitation blocking condition with the help of 5th harmonic content. So, if this content exceeds some threshold value, then the blocking command is initiated and relay should not trip because this is not a fault condition, but it is an overexcited condition of the transformer.

The second problem that is faced by most of the digital or numerical relays is mal operation in case of magnetizing inrush current. So, we know that when we switch on or energize the transformer and this energization of power transformer is very frequent. So, when we energize it normally load is not connected.

So, when we energize unloaded power transformer or lightly loaded power transformer then in that case the wave shape of flux that is entirely different then it is in normal condition. So, when the wave shape of flux is symmetrical in nature.

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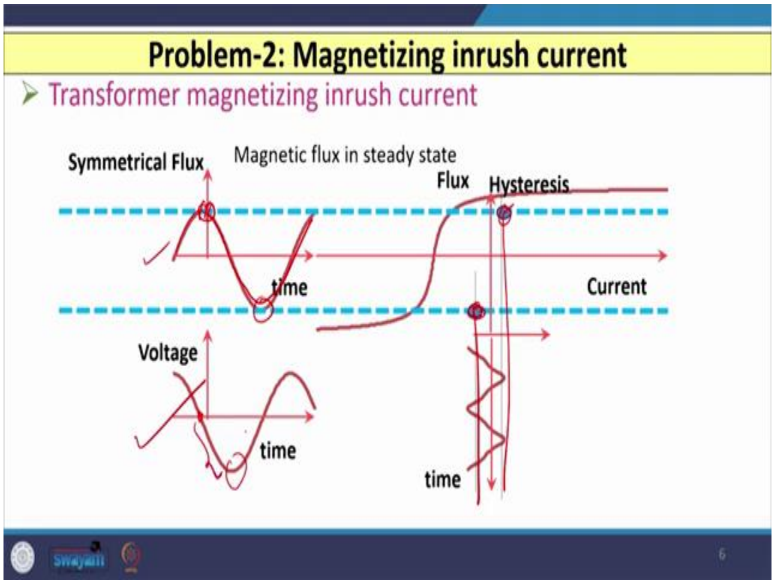

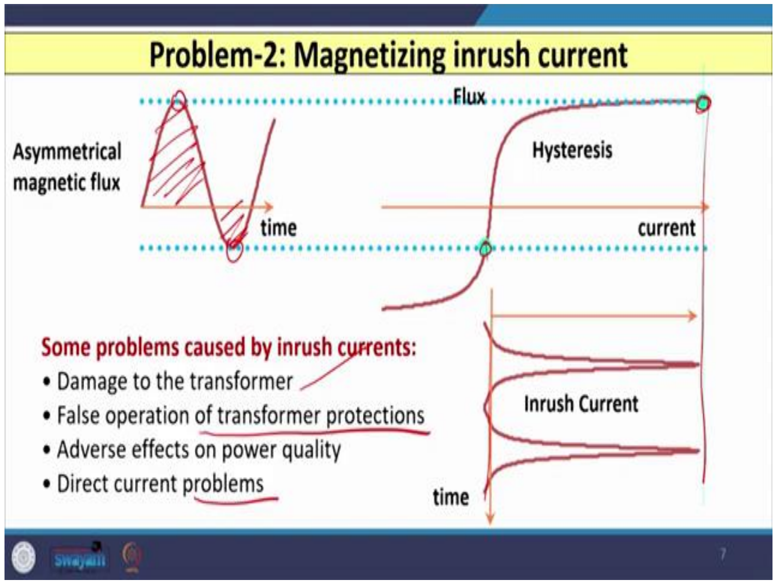

Because I have shown the flux waveform with reference to the voltage waveform because both are in quadrature. So, if your flux is symmetrical in nature, then this point (as shown in above figure) you can extend it here and this another point you can extended here and if you extend this two points, then you will have the value of current which is well within the range.

However, when your flux is not symmetrical, that means, when it is asymmetrical in nature, then you can see (as shown in above figure) that there is an asymmetry. So, in that case, you can see this point that will be extended here on the BH curve because in earlier case if you see I have shown the hysteresis curve, where this operating point remains in the linear region.

However, when your flux becomes a symmetrical in nature, then (as shown in above figure) this point that will extend it whereas, this point remains as it is. So, if you extend these two points, then the magnitude of current that increases suddenly with reference to the full load current of the transformer.

And this value of magnitude of current that is almost 5 to 6 times the full load current of the transformer. So, because of that your transformer may damage it may possible that your relay looks this as an internal fault and it may trip the circuit breaker. So, False operation of transformer that can be observed.

Sometimes power quality is also adversely affected and this inrush current contains significant value of DC component problems are also there because of this DC component. Those are also observed when we have magnetizing inrush current during switching off an unloaded or lightly loaded power transformer.

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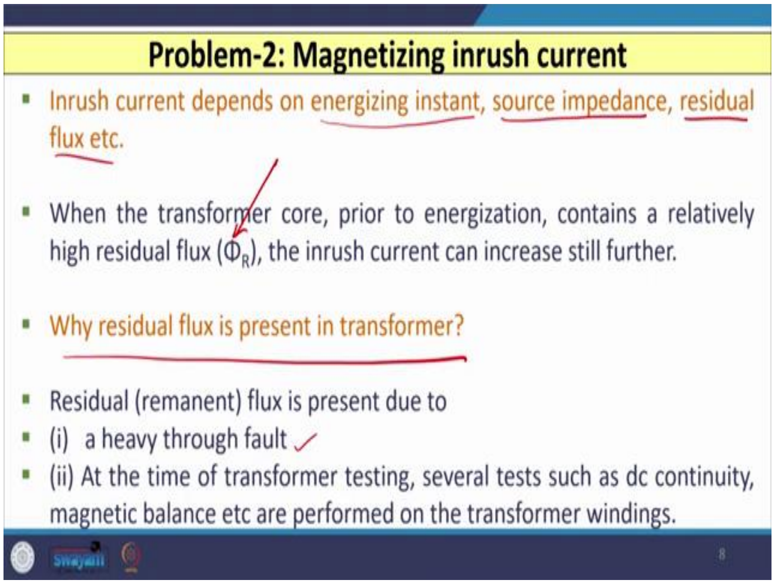

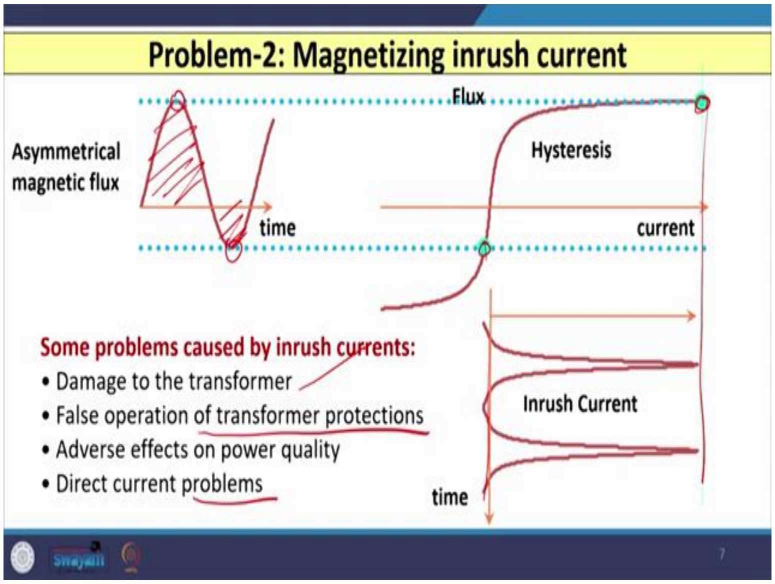

Now, when we consider the inrush current magnitude that depends on many parameters. The first parameter is the energizing instant at what instant you are energizing the transformer whether you are energizing the transformer when voltage wave is at 0 point or when voltage wave is at its peak value or the voltage wave is in between 0, and its peak value.

So, that instant is also going to decide the magnitude of inrush current. The second parameter which is going to decide the magnitude of inrush current that is the source impedance and the third point or parameter which is very important which is going to decide the magnitude of inrush current that is residual flux source impedance of course, it is not in our hand because that is a design parameter.

However, residual flux is a variable quantity when any transformer core that is prior to the energization of the transformer that contains a relatively high residual flux, which is normally indicated by Φ_R that is nothing but the residual flux if significant value of residual flux exists then that flux is going to again superimposed with your this flux (as shown in above slide), then again the magnitude of inrush current increases.

Now the question comes why residual flux is present in the transformer? So, the reason is residual flux is there inside the core of the transformer because maybe some heavy through fault is going to occur or when we test the transformer, then we know that several tests are to be carried out.

Like DC continuity test or magnetic balance test these tests are performed on the winding of the transformer for performing this test, we need to externally inject the DC current and because of that residual flux that is there inside the core of the power transformer that value is significant and that is going to increase the magnitude of inrush current.

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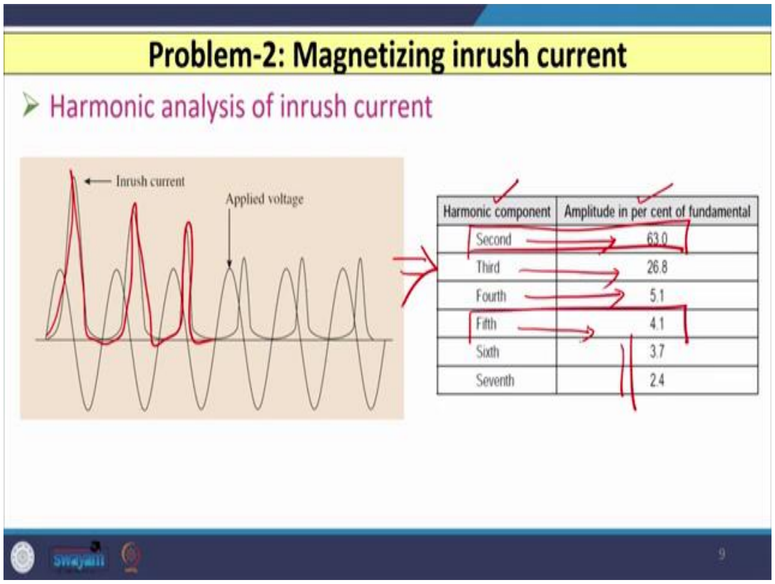

If I just observe the waveform of inrush current then you can see (as shown in above slide), that this are the waveform of inrush current. Because here I have shown the waveform of inrush current along with the voltage waveform. So, if I take the harmonic contents of this inrush current waveform, then you can see that I have shown in the table the first column is the harmonic component.

And second column is the percentage of the particular that particular component with reference to the fundamental component. So, you can see that your second harmonic content is almost close to 63 percent with reference to the fundamental and your third harmonic is also very high almost close to 25 percent however, we do not consider third harmonic.

Because if we have delta winding that can be easily trapped, fourth harmonic that is again all the even harmonics we are not even considering, fifth harmonic we can consider, but that is again for the over excitation condition and the other harmonics beyond fifth those magnitudes are not significant. So, to detect the magnetizing inrush current, we will use the second harmonic component and for the detection of over excitation condition, we will use the fifth harmonic component.

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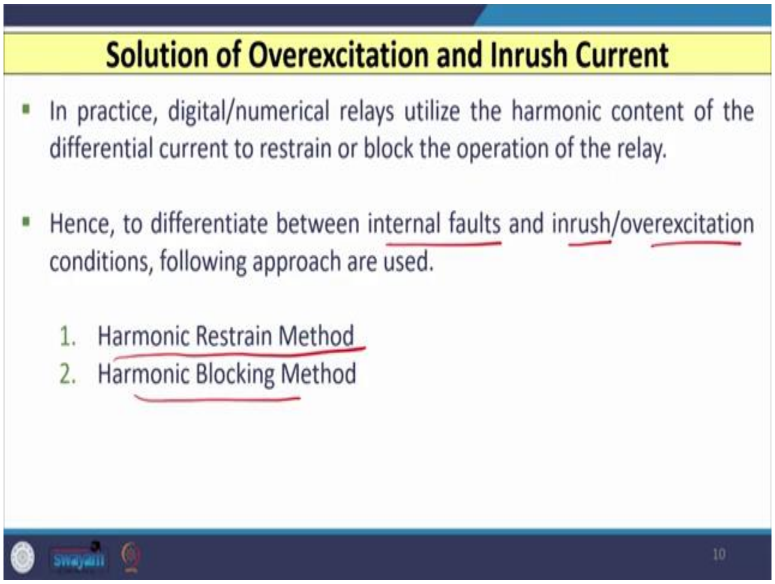

Now, with this background, let us see how the solution of over excitation problem and inrush current phenomena that can be achieved in a digital relay. So, in digital relay in actual practice, this relay utilizes the harmonic content of the differential current to restrain or to block the operation of the relay.

So, if we wish to differentiate between internal faults and or other non internal events like inrush or over excitation conditions, then most of the manufacturers they provide two approaches. The first approach is known as Harmonic Restrain Method and the second approach is known as Harmonic Blocking Method.

So, in both these methods, when such non internal events are detected like inrush or over excitation condition, then tripping command is either blocked so, that no further tripping is initiated. Now, to understand this, let us consider the first method that is Harmonic Restrain Method.

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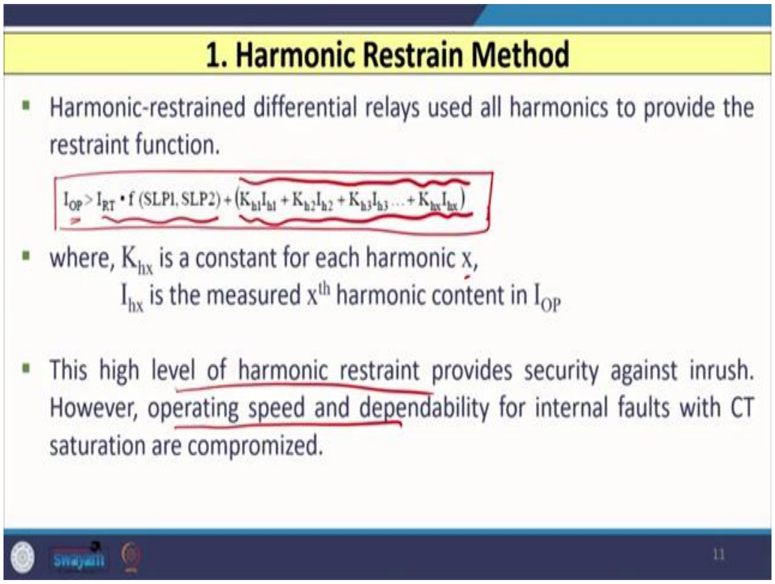

So, Harmonic Restrained differential relays used or utilize all the harmonics to provide or to achieve or to configure the restraint function and this is given by this equation.

$$I_{OP} > I_{RT} \bullet f\,(SLP1, SLP2) + \left(K_{h1}I_{h1} + K_{h2}I_{h2} + K_{h3}I_{h3} \ldots + K_{hx}I_{hx}\right)$$

So, here you can see that in this equation operating current that is greater than the restraining current multiply by the function of slum slope values that is slope 1 and slope 2, assuming we are utilizing dual slope characteristic.

But you can see that this another equation which we have added in that equation, we have the some constant K which is nothing but the specific value of constant for specific harmonic number where x indicate the harmonic number and I_{h1} to I_{hx} that is nothing but the measured X^{th} value of the harmonic content from the your operating current.

So, the high level of harmonic content obviously, that will provide the security against the inrush. So, if we use Harmonic Restrained Method, then when inrush condition is there, then relay is not going to operate however, when we consider the two important parameters, one is the operation speed and the second is the dependability specifically in case of internal fault and that is compromised because of these Harmonic Restraints Functions.

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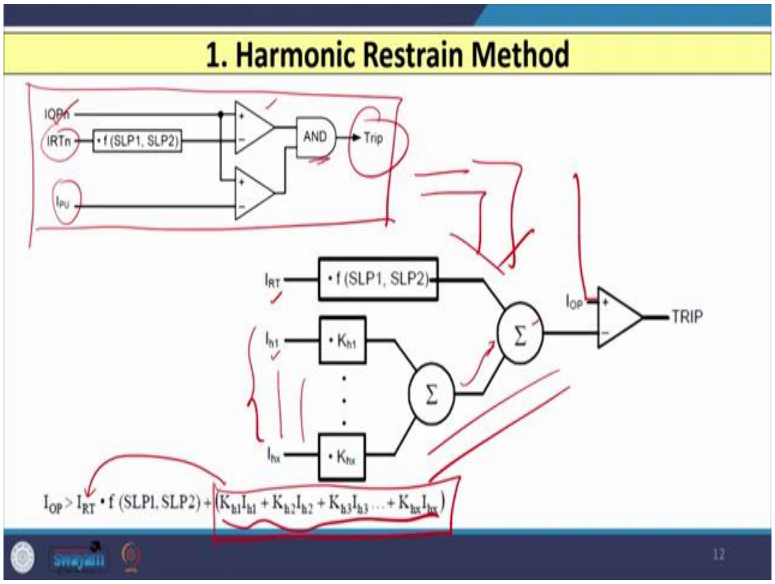

Now, let us see through the block diagram what change we need to do if I use Harmonic Restrain Method, so, that the operation of relay in case of the non internal events that can be restrained or blocked. So, our original block diagram is like this (as shown in above slide) where we have the operating current which is given to one operational amplifier and that is compared with restraining current.

And again in second operational amplifier operating current is compared with I_{PU} threshold and that is given to AND gate and finally, we obtained the Trip command. However, if I wish to obtain or use the Harmonic Restrain Method, then you can see that I have the one operational amplifier and one input is from operating current I_{OP}, the other input which is given from this whole logic.

So, in this case the restraining current is given to one summation block through this the slope values and the other two values you see it is added in the restraining current. So, you can see that specific content of harmonic multiplied with a specific constant those are added using the summing block and that is again added with I_{RT} because we need to add this complete this value into the I_{RT}. So, that, that will be again compared with the operating current. So, that is the change we need to do in the block diagram if we wish to use Harmonic Restrain Method.

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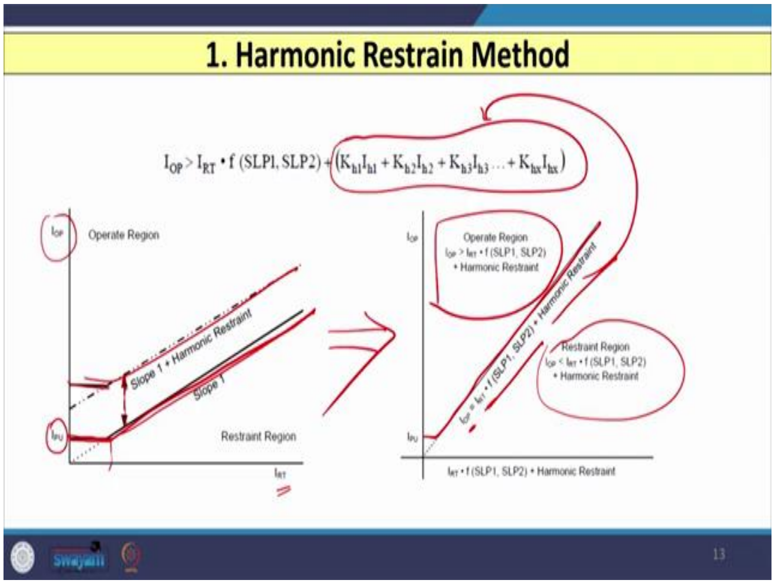

Now, if I use Harmonic Restrain Method, then let us see what will be the change in differential relay characteristic. So, we know that normally differential relay characteristic are plotted considering on x-axis restraining current and y-axis is the operating current. So, then we can see that the initial characteristic is like this assuming we have used only one slope or single slope characteristic.

So, this is your I_{PU} setting and then you have slope one setting. Now, if I just going to add this into the our original equation of restraining current, then you can see that the whole or entire characteristic that can be shifted (as shown in above slide). So, obviously, your operating region of the differential relay that can be reduced and you are deliberately increasing the restraining region of the differential relay.

So, if I consider operation wise on this slope, I have to connect the operating current which should be equal to the restraining current with slope values plus harmonic restraint values which is given by this equation.

$$I_{OP} > I_{RT} \cdot f\,(SLP1, SLP2) + \left(K_{h1}I_{h1} + K_{h2}I_{h2} + K_{h3}I_{h3} \ldots + K_{hx}I_{hx}\right)$$

And in this region, you can see that your operating coil current is greater than the restraining current multiplied with slope values plus harmonic restraint, whereas, in the lower region below this line, you have the operating coil current is lower than the restraining current multiplied with slope values plus harmonic restraint.

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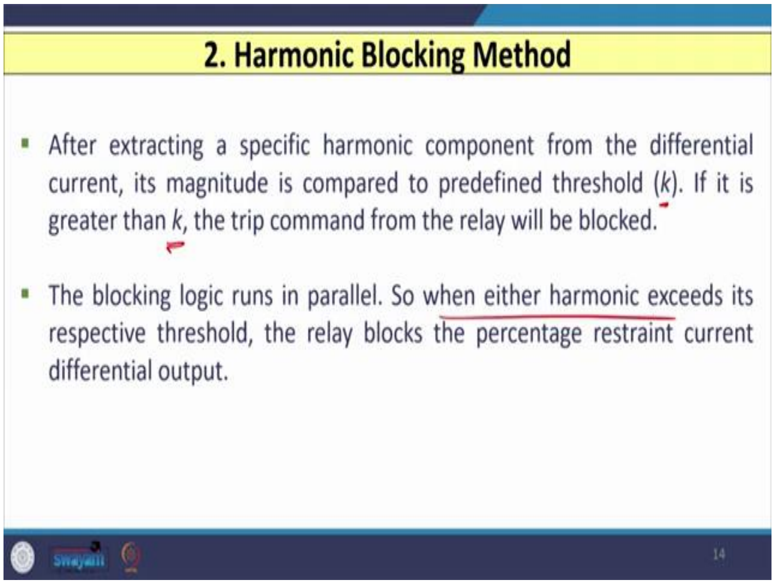

Now, let us see the second method that is known as the Harmonic Blocking Method. So, after extracting a specific harmonic component from the differential current the magnitude is compared with some threshold, predetermined threshold let us say k, and if this magnitude is greater than the threshold, then trip command from the relay that should be blocked this is the main logic of the Harmonic Blocking Method. Normally, blocking logic runs in parallel in the digital or numerical relay. So, when either harmonic exceeds the respective threshold, then the relay blocks the entire operation of the relay.

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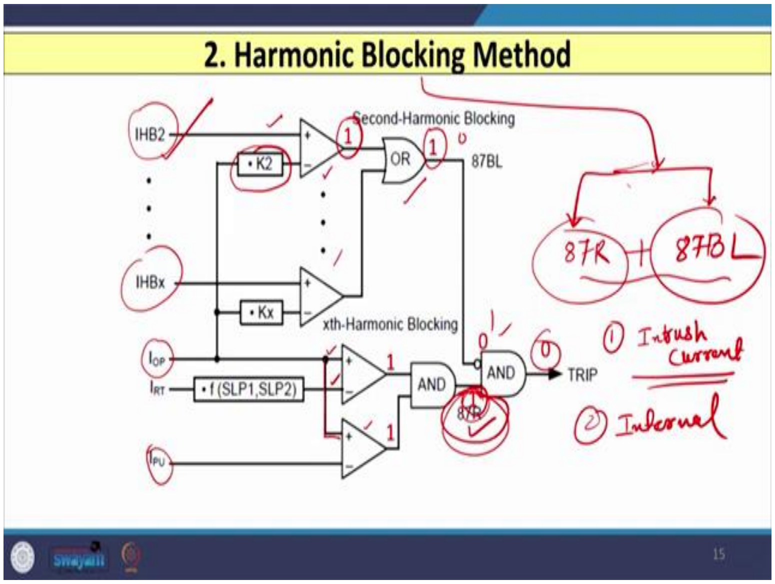

To understand this, let us consider a block diagram (as shown in above slide). So, here you can see that the lower portion of this block diagram remains as it is. So, harmonic blocking method block diagram that is divided in two parts, one is the operation of 87 R and another is the operation of 87BL, what is 87 R?

So, 87 R is nothing but our conventional two operational amplifiers where operating current is compared with the restraining current multiplied with slope values and in second one operating current is again compared with the I_{PU} setting and with AND logic you will have the values that is 1 if it is an internal fault.

Even though there are some non internal fault condition like inrush also you will have this value. Now, on the other side 87BL is nothing but your 87 blocking logic. So, in this case, you can see that I have considered again the number of operational amplifiers and the output of that is given to OR gate.

So, here you can see I have considered the different harmonic currents that is IHB2 to IHB_x and with that, I have given directly this current to one of the input to the operational amplifier and the other input from negative terminal is given from the operating point, let us assume that two conditions let us say the first condition is an inrush current. So, let us assume that in inrush current we want that if my percentage of let us say second harmonic exceeds 20 percent, then it is an inrush condition and relay should not TRIP.

So, in that case, if I consider this command then the, this value which is K2 is nothing but the 20 percent of your operating coil current. So, when IHB2 that is I is the current, HB is the harmonic blocking and we are using second harmonic. So, when this value exceeds K2 multiplied I operating then you will get a here the one logic and that is given to the OR gate.

So, anything given to the OR gate if any value is 1, you will have the output is 1, and that is connected with some NOT gate. So, you will have the zero logic. So, even though your lower logic given by 87R, if it is also 1 because we know that in case of inrush magnitude of current is 5 to 6 times. So, even though this is 1, AND gate output is 0.

So, no tripping command is initiated. However, on the other hand, in case of internal fault obviously, this you will get 1 87R and this you will also get 1 because the percentage of harmonics are always lower than 20 percent. So, this you will get 0, and this you will get 1. So, tripping command is initiated.

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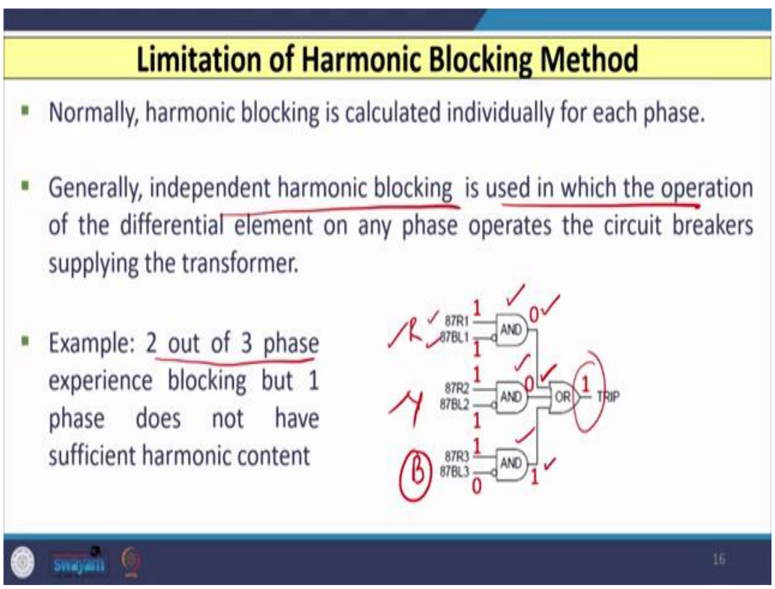

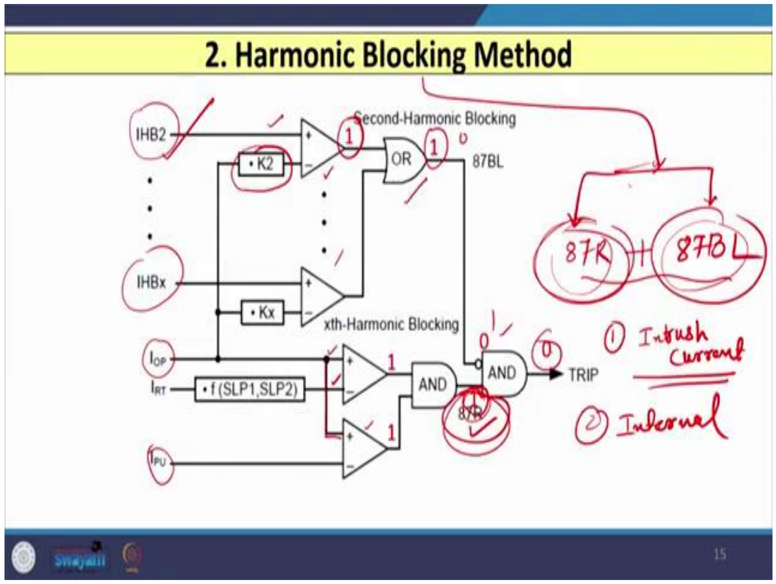

Now, if I consider the Harmonic Blocking Method, then harmonic blocking is calculated normally for each phase individually. So, generally independent Harmonic Blocking Method is used by most of the utilities that is given by the manufacturer and in this the operation of the differential element on any phase operates the circuit breaker supplying the transformer.

So, here you can see that I have seen the three different logics same as I have explained, we have two values, one is 87 R and another is 87 BL. So, that I have shown for each AND gate phase wise. So, if I consider one example, let us say it may possible that in the actual field when inrush current is present, it may be possible that in all the 3 phases, the content percentage of second harmonic may exceed 20 percent, it may possible that in 2 phase the percentage harmonics are greater than the threshold value, but in one phase it is lower or maybe any combination is possible. So, let us assume that 2 out of 3 phase experiences the blocking that means, in 2 phase.

Let us say we have the inrush current or percentage of second harmonic that is greater than the threshold value in 2 phase. Let us say in R phase and Y phase, but in B phase, the percentage value of second harmonic that is lower than the threshold value. So, when these 2 phase you have the sufficient value of percentage of second harmonic, then as discussed you will have the logic that is 0 here. So, that I have shown here, whereas, in the third phase where you have the percentage of second harmonic that is lower than the threshold.

So, you will get the 1 logic, so, here that is OR with 1. So, finally output will be given as 1 this is the main limitation of harmonic blocking method, that it may be possible that we do not know that whether the percentage of second harmonic exceeds the threshold value in 1 phase or in 2 phases or in 3 phases or any combination. So, that depends on application, what type of logic we want whether we want 2 out of 3 blocking or let us say 1 out of 3 blocking or we want per phase blocking, that depends on application.

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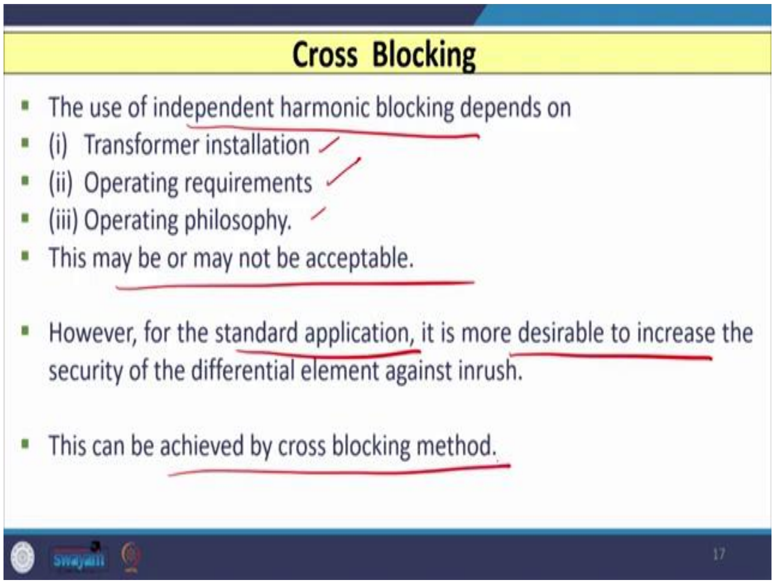

So, whether we want to go for independent harmonic blocking, then that depends on the let us say installation of transformer, operating requirements and operating philosophy of the transformer. And this may or may not be acceptable by each an individual utility person. However, for the standard application, normally, it is more desirable to increase the security of differential relay against the inrush current.

So, that unwanted operation of the transformer or differential relay that can be avoided. So, if we wish this, this can be achieved by cross blocking method. So, the question comes, why cross blocking method is required? So, the reason is the cross blocking method is required because of the different types of inrush we have seen that inrush is again available, when we switch on the unloaded or lightly loaded transformer. So, in that case, it may possible that the magnitude of inrush current or percentage of second harmonic that is greater than the threshold in all the 3 phases and maybe blocking command is initiated.

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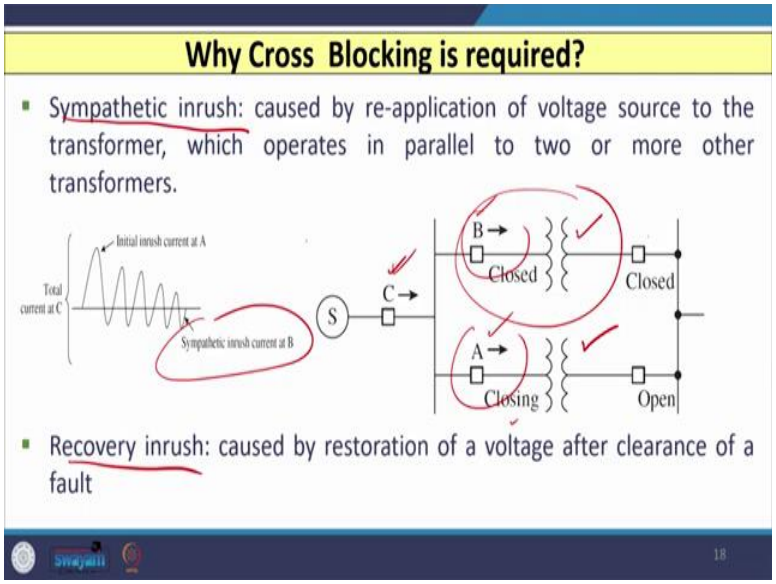

However, sometimes it may possible that if we have sympathetic inrush or if we have recovery type of inrush, then the percentage of second harmonic may not be higher than the threshold value in maybe 1 phase or 2 phases. So, in that case, your conventional harmonic blocking method fails. So, in that case, cross blocking must be used.

So, let us see first what is the sympathetic inrush how we can obtain the sympathetic inrush condition. So, for that, I have shown two transformers. And I have shown the three circuit breakers A, B and C. And the A and B circuit breakers are connected on one of the winding side of the transformer.

Whereas the other circuit breaker is connected with the utility that is generator and you can see that whenever let us say this transformer is already there inside the circuit and you are trying to again energize the another parallel connected transformer. So, when you want to try to energize it, obviously, this is going to have the inrush current.

But the another transformer which is already there, that is also going to have the inrush current or that is also going to seen the inrush current and that is nothing but the sympathetic type inrush current. Similarly, when if any fault occurs near the transformer, and if that fault is cleared, there also recovery type of inrush is observed. But keep in mind the magnitude of sympathetic inrush and recovery inrush in both the cases magnitude of current is always lower than the original initial inrush condition. So, in cross blocking method, four different methods are used.

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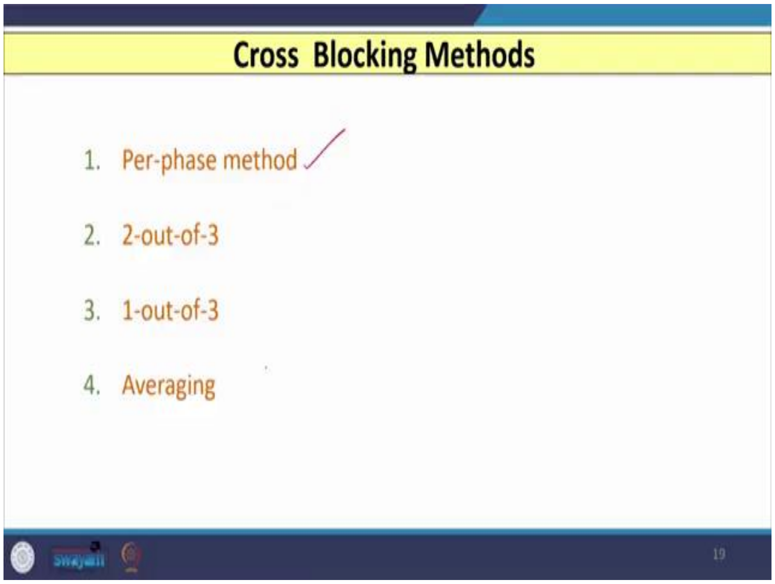

Those methods are Per-phase method, 2 out of 3, 1 out of 3 blocking and averaging concept. So, let us see the first method Per-phase method.

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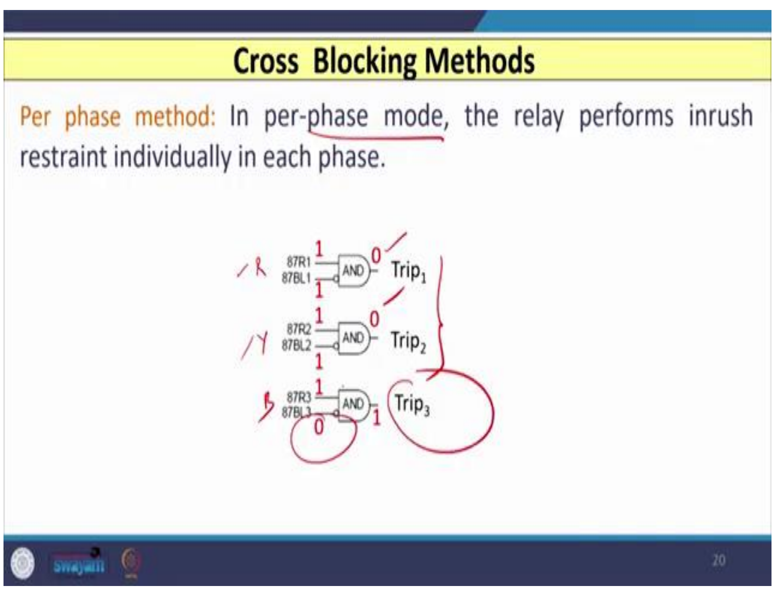

So, in this method, the relay performs the inrush restraint individually in each phase. So, here you can see that I have shown the 3 phases. So, you can see that when let us say in R and Y phases, let us say we have the blocking command is initiated and in other phases, let us say in B phase, you do not have these blocking command. So tripping is initiated only in B phase, here you have the Per-phase blocking.

So, that means if you have let us say in B phase, if percentage of second harmonic content is greater than the predetermined threshold value, let us say 20 percent, then only the B phase is blocked other 2 phases, they remain as it is.

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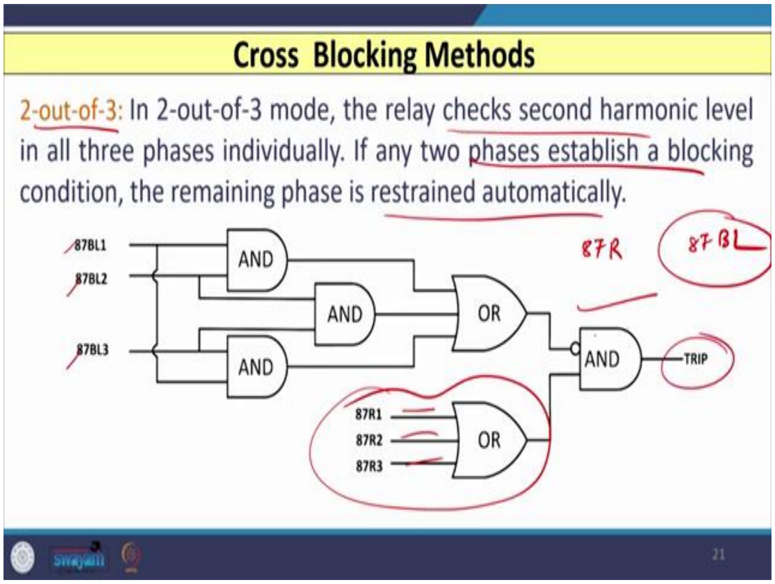

Similarly, let us consider the second method that is 2 out of 3 blocking method. So, here in 2 out of 3 blocking method relay checks the second harmonic level in all the three phases individually, and if the percentage of second harmonic that is greater than the predetermined threshold value in any of the 2 phases, then the blocking condition is established and the remaining phase is restrained automatically. So here you can see that I have considered this logic by considering again 87 R and 87 BL separately. So, this 87 R, I have considered are all with OR gate. So, this I am assuming that you will have the higher logic available.

Because this is always activated because even though you have inrush current then also magnitude is very high. So, your operating current is greater than the restraining current. However, in this blocking scheme, you have 87BL, 1, 2 and 3 for each phase. So, whenever in any of the 2 phases, if the harmonic contents are greater, then that thing is available here and that is ended with this AND gate. And finally, you will have the tripping command.

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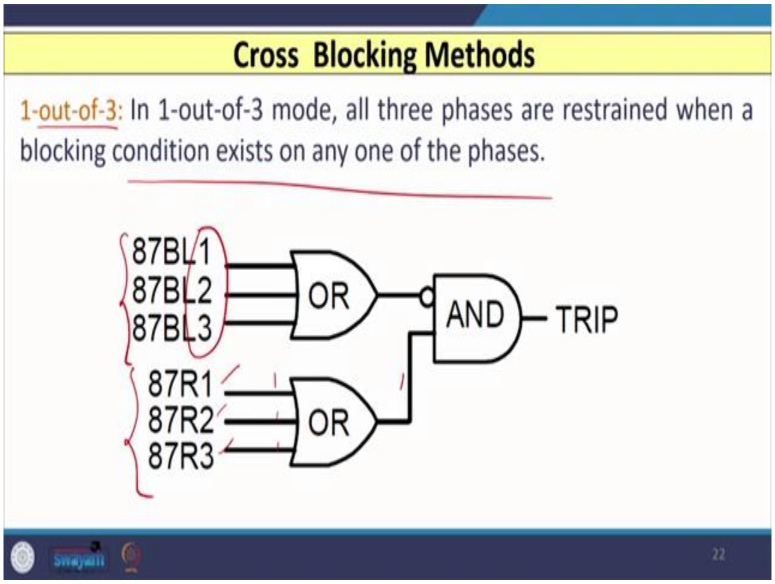

If I consider the third matter, which is 1 out of 3 blocking, then in 1 out of 3 mode, all the 3 phases are restrained when the blocking condition exists on any 1 of the 3 phases. So, here you can see that I have again considered the 87R and 87BL separately. So, you can see that I have the 87 in 3 phases 1, 2 and 3.

You have the one logic available, so, here you will get the 1, and in each phases of this if let us say in any of the phase, if the percentage of second harmonic exceeds the predetermined threshold value, then the blocking condition that is initiated and relay should not give the TRIP command. Whereas, in earlier case, if any of the 2 phases if the percentage of second harmonic is greater than the threshold value, then the blocking is given.

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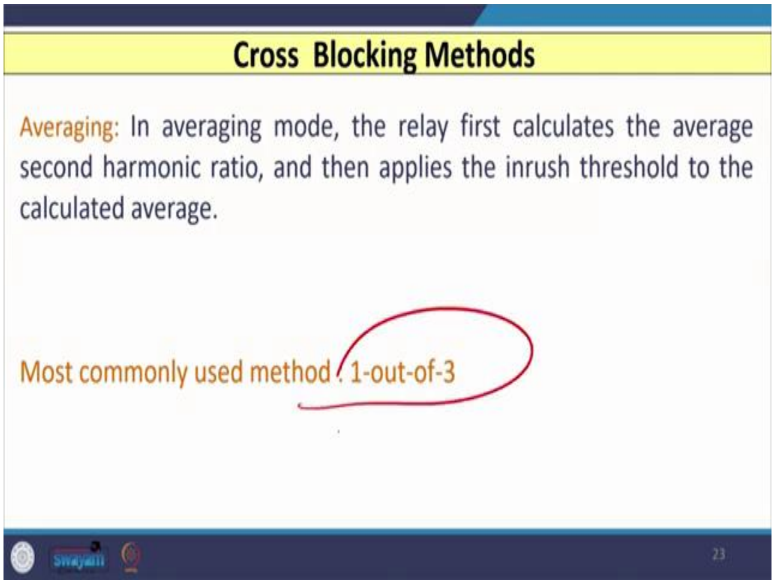

The fourth method is the Averaging method. So, in this case, the relay first calculate the average of the second harmonic ratio and then the it is applied to the inrush threshold. So, that average can be calculated and based on that the blocking is initiated. Now, out of all these 4 methods, which we have discussed that is the Per-phase blocking, 2 out of 3 blocking, 1 out of 3 blocking or averaging method, 1 out of 3 blocking is widely used by most of the utilities and that is also suggested by most of the relay manufacturers.

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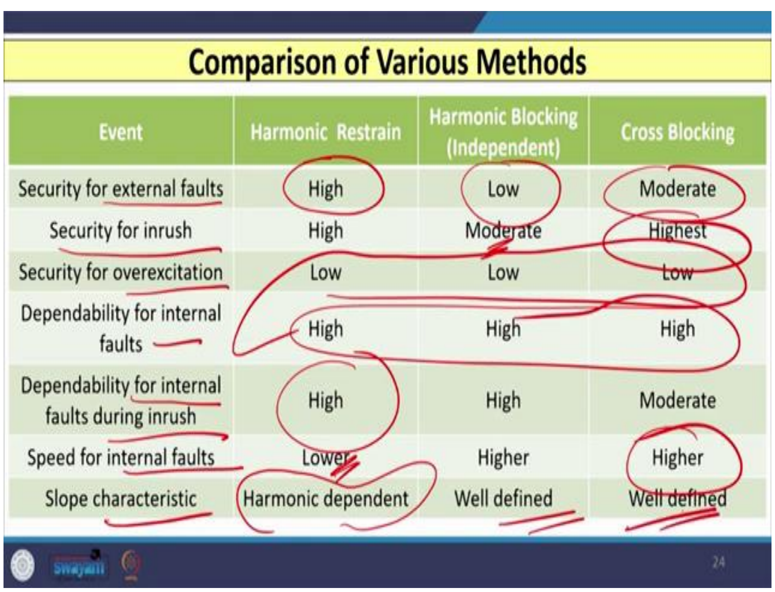

So, if I compare the Harmonic Restrain Method, Harmonic Blocking Method and Cross Blocking Method with considering several parameters, then if I consider security against external faults, so, if any heavy through fault is there, then the best method is the Harmonic Restrain Method.

Because they utilize all the different harmonics however, your cross blocking will give you moderate value whereas, the harmonic blocking gives low security against heavy through fault condition, if I want security again inrush then the highest security is provided by cross blocking whereas, moderate is given by independent harmonic blocking.

If I want security against excitation, almost all the 3 methods they will give low security because in that case, we have to use the fifth harmonic content and percentage of that content with reference to the fundamental. If I want dependability for internal faults, then again all the three methods will give proper dependability and if I want dependability for faulted energization of transformer, then again your Harmonic Restrain Method outperforms compared to all other methods. And if I want speed in case of internal fault means time of operation should be as low as possible, then the best output is given by cross blocking compared to the lowest output is given by Harmonic Restrain Method.

And if I consider the slope characteristic, then we have discussed that if I use Harmonic Restrain Method, then there is a shift in the characteristic because of the addition of harmonic contents that is $I \times k$ term along with the restraining term whereas, the this slope characteristic is well defined in case of cross blocking and independent harmonic blocking.

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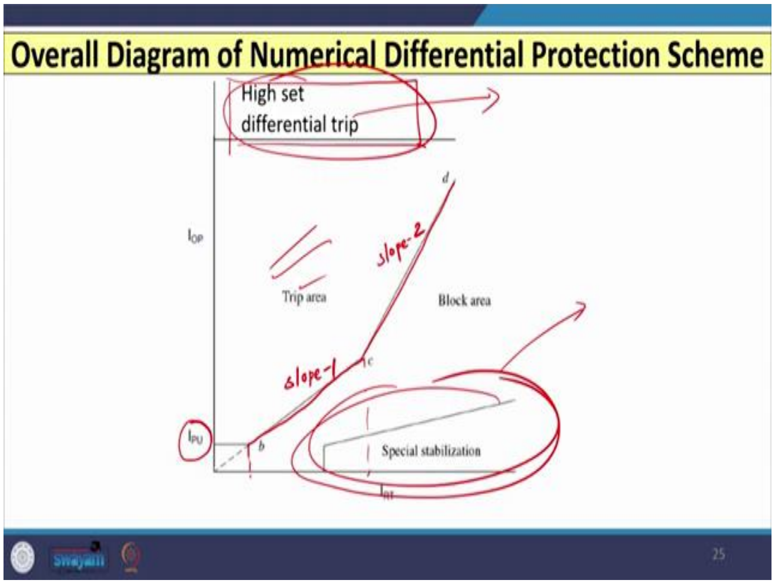

So, if I consider the overall diagram of digital differential relay which is used for the application of power transformer, then you can see (as shown in above slide) that we have the important point is the first setting is the I_{PU} setting which is considered as base threshold, then you have the first slope, so, we can say this is slope 1 and then we have the second slope.

So, you have again these values, you need on a restraining side axis and this is your tripping area and this is your blocking area. Now, along with this, nowadays most of the IDs are digital relays, they also provide two additional settings. The first setting is provided that is known as high set differential trip.

So, if the operating point falls in the upper side of the tripping area, then it indicates that your operating current is very, very higher compared to the restraining current. So, the magnitude of fault current is very high let us say 10-15 times. So, in that case, all the restraining will be by passed and immediately tripping command is given by the relay and the circuit breaker can be tripped.

The other type of setting is given for the restraining region. So, this is specially used in case of heavy through fault especially when CT saturates let us say Triple L fault if it occurs very near to the transformer and if one of the CT saturates and other side winding CT is working in linear region, then that is the case of a restraining condition and in that case to provide the stability against such condition this type of setting is also provided by manufacturer.

So, in this lecture, we started our discussion with the two important problems, one is over excitation condition and second is the magnetic inrush condition. Then, we have discussed that if we wish to avoid over excitation condition then we need to track or we need to use fifth harmonic content available in the operating current.

And if I wish to detect a magnetizing inrush condition, then I have to go for second harmonic content in the operating current. Then we have seen that we can go for either harmonic restraint or harmonic blocking method. And in that we have discussed that independent harmonic blocking method may fail when we have sympathetic inrush or recovery type of inrush.

In that case specifically, it is not possible to detect in one of the phases such type of percentage of second harmonics are lower than the predefined threshold. So, in that case, we may go for several cross blocking methods and we have discussed four important cross blocking methods starting from Per-phase method, where we want blocking of individual phase in which the percentage of second harmonic that is greater predefined threshold. The second method we have discussed that is 2 out of 3 blocking and third that is 1 out of 3 blocking and these two methods are based on whether the in 2 phases the percentage of second harmonics is greater than threshold and what we want whether we want blocking or not.

And similarly, 1 out of 3 blocking means, in any of the out of the 3 phases, if percentage of second harmonic is greater than threshold, then we have to go for blocking command. And for last method that is averaging method that is in which averaging of the different phases that is to be carried out and then final tripping is given.

And then we have discussed the overall block diagram of the digital relay and we have discussed that if we consider the differential characteristic, then the IPU slope 1, slope 2 and along with those two important additional settings high set differential trip and civilization against heavy through faults, especially in case of CT saturation that is provided by the relay manufacturer. Thank you.