Digital Protection of Power System

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Lecture - 12

Digital Protection of Transformer-II

Hello friends. So, in the previous lecture we have discussed digital relays. How it can overcome the problems that are faced by conventional electromechanical relay, and that is used by utility and that is biased or percentage differential protection scheme.

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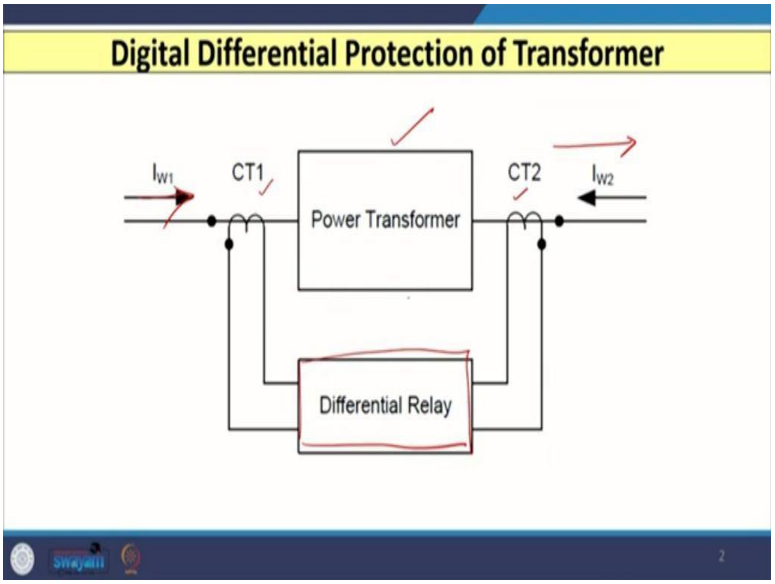

Digital Differential Protection of Transformer

Now, if I use digital relays or numerical relays for the protection of power transformer, then the digital relay is connected like this. So, if I have any power transformer which I wish to protect, then the CTs are connected on both sides; and secondary of CT signals are given to the digital relays or differential relay.

So, the arrangement remains the same. The only difference is that whatever currents we are going to give or that is going to enter to CT$_1$ and whatever currents that is going to leave the CT$_2$ here. And that currents, how we are going to provide, or how we are going to process inside the digital relay.

That process is entirely different when we consider the digital relay compared to the electromechanical relay. So, let us consider one example to understand the working principle of digital relay.

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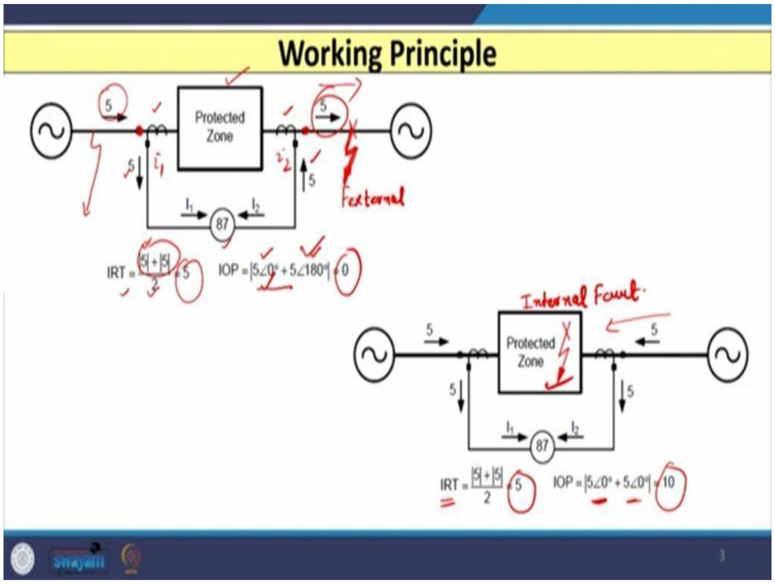

Working Principle

$$IRT = \frac{|5| + |5|}{2} = 5 \qquad IOP = |5\angle 0^\circ + 5\angle 180^\circ| = 0$$

$$IRT = \frac{|5| + |5|}{2} = 5 \qquad IOP = |5\angle 0^\circ + 5\angle 0^\circ| = 10$$

So, here I have considered the same figure, this is the binding of the power transformer; and I have considered CT on each side of the winding of the transformer. And I have connected one digital relay that is 87 number is given, if any external fault occurs here. This is my external fault, which is going to occur outside the range of the CTs, two CTs. So, in that case if I consider or if I calculate the operating current in case of biased or percentage differential relay, this is given by I_1 - I_2; whereas, in case of digital relay, this is given by the vectorial addition of the two currents that is I_1 and I_2.

So, if I consider this current as I_1 and this current as I_2 (as shown in above slide); then these currents that is given by one current is $5\angle 0^\circ$, and the other current that is again $5\angle 180^\circ$. Because, if I consider the dot here, then current entering and current leaving both are 180° out of phase. So, this current is $5\angle 0^\circ$ and this current that is $5\angle 180^\circ$, because both are out of phase. So, your operating current will be vectorial addition of two currents I_1 and I_2; and then you have to take the absolute value. So, this value comes out to be 0.

The restraining current in case of biased or percentage differential protection scheme; it will be $(i_1 + i_2)/2$. But, here in case of digital relay the restraining current I_{RT} that is nothing but the scalar addition of two currents I_1 and I_2; so, that is 5 and 5; so, that I am adding and divide by 2, so, again I will get the 5. So, as your operating current is 0 in case of external or through fault, maybe on this side, or maybe somewhere here. Then this relay is not going to operate. Now, let us consider the other case, that is when fault occurs inside the transformer.

So, this is the case of an internal fault which is going to occur inside the winding of the transformer. So, if fault occurs here inside the winding of the transformer, then the operating current that is nothing but $5\angle 0$; now in earlier case the direction is this. But, when the internal fault occurs, this direction reverses, so it is like this. So, both the values I_1 and I_2 both are $5\angle 0$; and your operating quantity comes out to be 10. Whereas your restraining quantity remains as it is in case of internal fault that is 5. So, as operating quantity is greater than restraining quantity, so this digital relay operates.

Now, if I represent this operating quantity and restraining quantity of digital relay, so, where the operating quantities the vectorial addition and the restraining quantity is the scalar addition.

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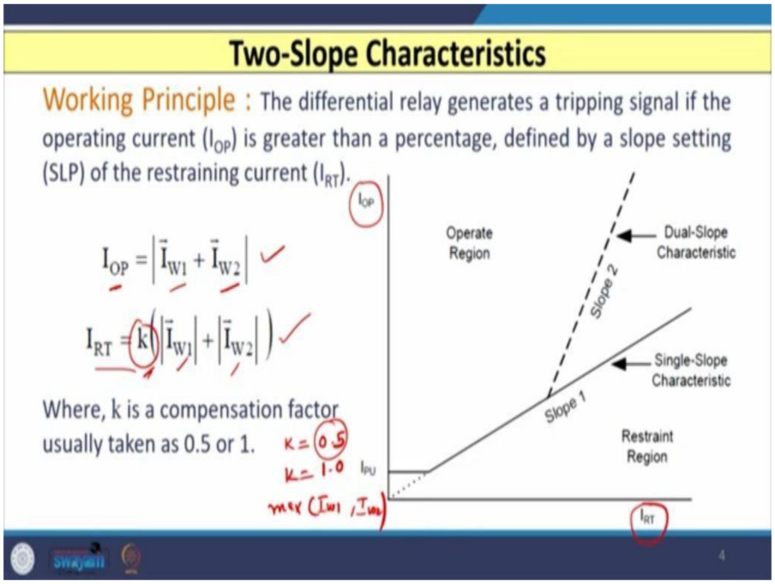


Two-Slope Characteristics

Working Principle : The differential relay generates a tripping signal if the operating current (I_{OP}) is greater than a percentage, defined by a slope setting (SLP) of the restraining current (I_{RT}).

$$I_{OP} = \left| \vec{I}_{W1} + \vec{I}_{W2} \right| ✓$$

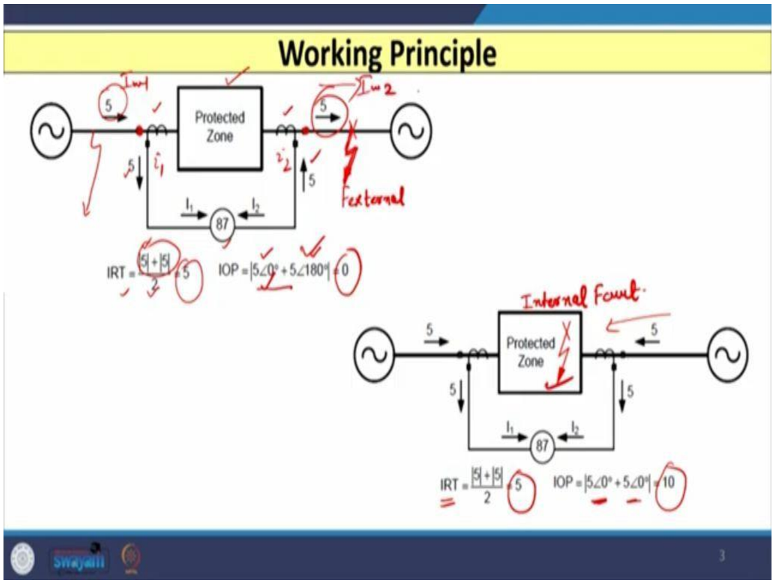
$$I_{RT} = k\left(\left| \vec{I}_{W1} \right| + \left| \vec{I}_{W2} \right| \right) ✓$$

Where, k is a compensation factor usually taken as 0.5 or 1.

$K = 0.5$

$K = 1.0$

$\max(I_{W1}, I_{W2})$



Working Principle

$IRT = \frac{|5|+|5|}{2} = 5$ $\quad IOP = |5\angle 0^\circ + 5\angle 180^\circ| = 0$

$IRT = \frac{|5|+|5|}{2} = 5$ $\quad IOP = |5\angle 0^\circ + 5\angle 0^\circ| = 10$

If I represent this in terms of relay characteristic considering restraining current on x-axis and operating current on y-axis; then we will have the characteristic like this. So, your operating current is nothing but the addition of two currents. So, here I consider this as I_{W1} and this as I_{W2}; so, this you can write down like this. And in generalized way, restraining current you can write down as the scalar addition of I_{W1} and I_{W2}. Now, instead of writing this 2, I have written the k; so, this k is nothing but the compensation factor.

And this k you can consider either 0.5, you can consider as 1; or you can also consider max of either I_{W1} and I_{W2}. So, three possibilities are there, but most of the utilities they will consider k as 0.5; so that is why this 2, one half that comes here, so that you can consider. However, 1 also can consider and the third case is also possible depending upon the application.

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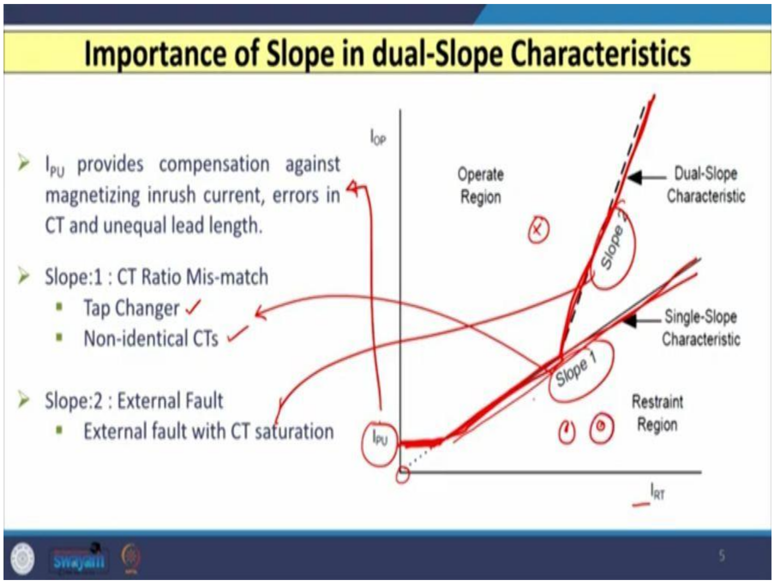

Importance of Slope in dual-Slope Characteristics

- I_{PU} provides compensation against magnetizing inrush current, errors in CT and unequal lead length.
- Slope:1 : CT Ratio Mis-match
  - Tap Changer ✓
  - Non-identical CTs ✓
- Slope:2 : External Fault
  - External fault with CT saturation

Now, if I consider this characteristic of differential relay on x and y axis with restraining and operating current, then the first point comes that is known as your i per unit (I_{PU}). And this I_{PU} provides compensation against magnetizing inrush current and errors in CT. And at the same time if there is an unequal lead length between the one side of the CT and the relay, where it is installed inside the control room; then that compensation is provided by this thing. So, instead of starting from origins, this graph is also going to start at some value; then the second is slope 1.

So, here I have considered slope 1. And if I use only this characteristic, then this is the single slope characteristic of digital differential relay. And this slope 1 is required to avoid CT ratio mismatch, because as I told you CT on both the side of the winding of the transformers are different; they have different CT ratio. If there is a tap changing mechanism or tapings are provided. And if your transformer is on other than the nominal or fixed tap, then those things are also compensated using slope 1. And if any non-idealities exist between the two CTs like CT saturation characteristic, then also that can be compensated using slope 1.

And slope 2, if I further add from here to here (as shown in above slide), then your slope 2 is required just to avoid the mal operation of digital differential relay, in case of heavy through fault. Particularly, when one of the CT saturates and other CTs working in the linear range; so, this is meant for this. So, if I use dual slope characteristic like this, and if any operating point comes here above this and the relay operates; otherwise for any point somewhere here relay does not operate.

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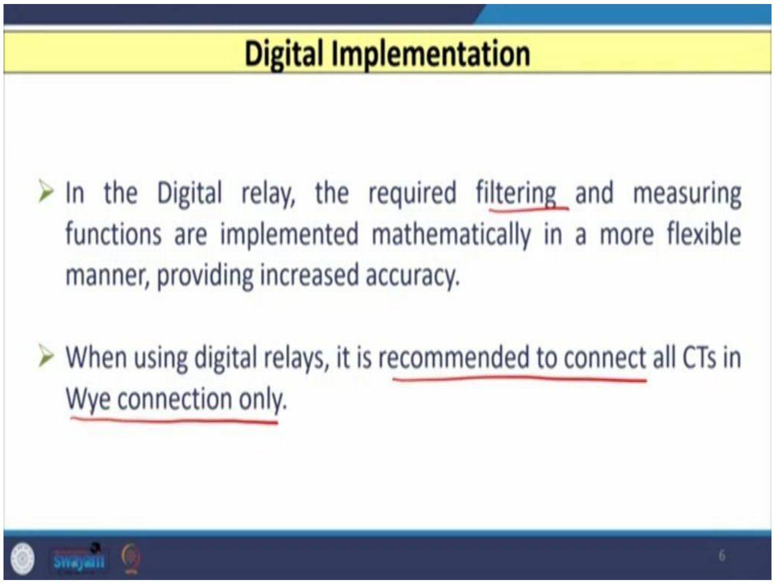

Digital Implementation

- In the Digital relay, the required filtering and measuring functions are implemented mathematically in a more flexible manner, providing increased accuracy.
- When using digital relays, it is recommended to connect all CTs in Wye connection only.

Now, if I consider the digital relay, which is used for the protection of power transformer. Then it is primarily important that how we are going to obtain the filtering and measuring functions; because that we need to implement mathematically inside the digital relay. And if we implement these functions mathematically inside the relay, then obviously the accuracy of the digital relay increases compared to the previous electromechanical relay, where we use biased or percentage differential protection scheme.

When we use digital relay, it is recommended by most of the manufacturers that all the CT connections are in the Wye fashion only. So, as I told you in the previous class, that if I correct the CTs in Delta fashion, then there are certain disadvantages like increase in burden, complex wiring, other things are also there. So, if we wish to avoid those disadvantages, then we have to go for Wye connection of CTs; and it is recommended for digital relay by most of the manufacturers.

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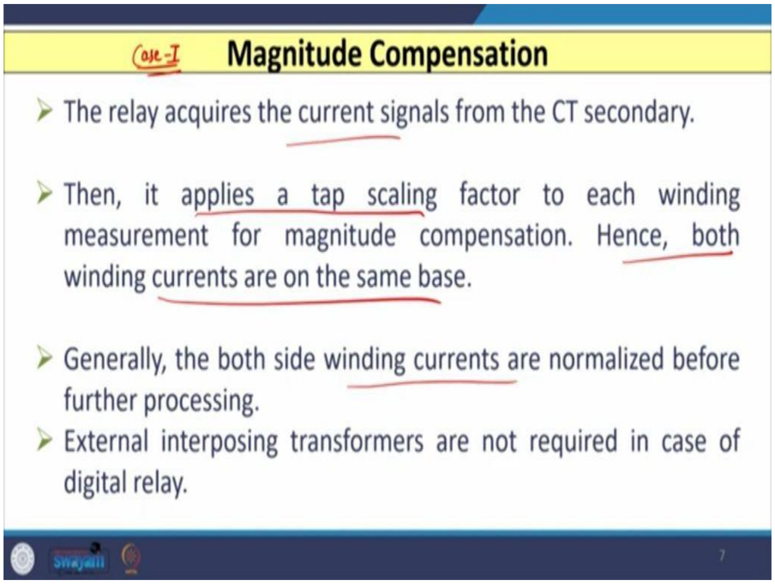

Case-I Magnitude Compensation

- The relay acquires the current signals from the CT secondary.
- Then, it applies a tap scaling factor to each winding measurement for magnitude compensation. Hence, both winding currents are on the same base.
- Generally, the both side winding currents are normalized before further processing.
- External interposing transformers are not required in case of digital relay.

Now, let us consider the first case where we can see how the magnitude compensation is possible, using some mathematical equation in case of digital or numerical relay. So, we know that relay acquires most of the current signals through CT and CT secondary signals, are given to the relay. And then when the CT secondary currents are available, these currents are applied some factor that is known as tap scaling factor for each winding. So, for each individual winding, we have this secondary current that is applied by this tap scaling factor. And that is the main logic for magnitude compensation inside the digital relay.

So, if we apply this tap scaling factor, then both winding currents, either on LV side and HV side, both are available at a common base or at common platform. So, generally both side winding currents are normalized before further processing. And if we do this, then external interconnecting transformers or ICTs are not required in digital relay, which are very essential in case of electromechanical relays which we have discussed earlier.

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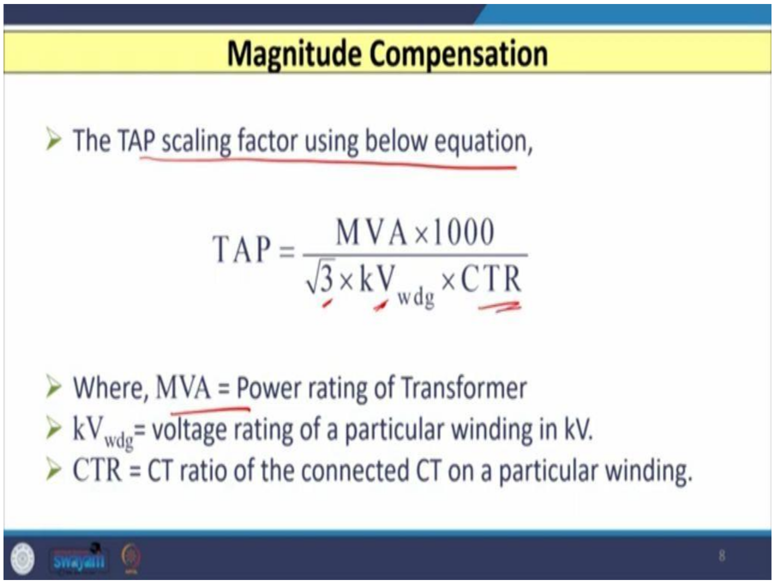

Magnitude Compensation

- The TAP scaling factor using below equation,

$$\text{TAP} = \frac{\text{MVA} \times 1000}{\sqrt{3} \times \text{kV}_{\text{wdg}} \times \text{CTR}}$$

- Where, MVA = Power rating of Transformer
- kV_{wdg} = voltage rating of a particular winding in kV.
- CTR = CT ratio of the connected CT on a particular winding.

So, now let us see what equation we can use in digital relay for magnitude compensation. So, tap scaling factor is given by this equation, $\text{TAP} = \frac{\text{MVA}\times 1000}{\sqrt{3}\times \text{kV}_{\text{wdg}}\times \text{CTR}}$

Where MVA is nothing but the power rating of the transformer, KV winding is the voltage rating of a particular winding in KV kilovolt and CTR is nothing but the CT ratio of the connected CT on a particular winding.

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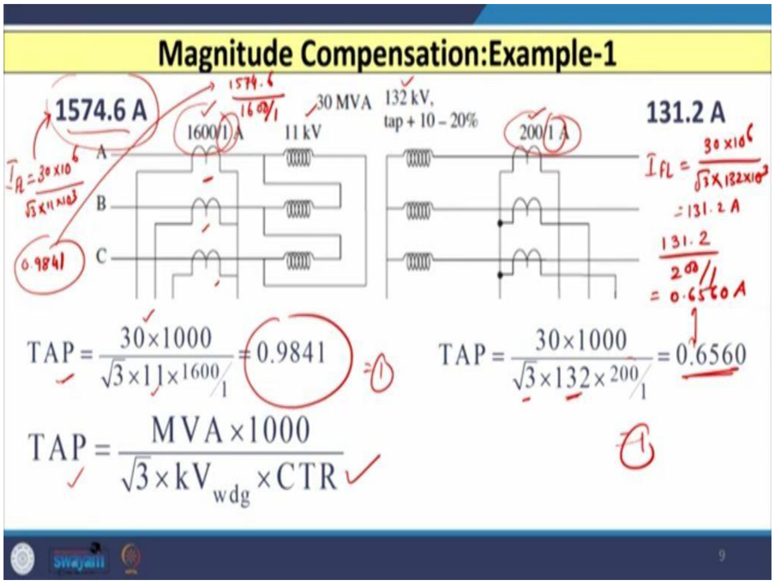

Magnitude Compensation:Example-1

$$TAP = \frac{30\times1000}{\sqrt3\times11\times\frac{1600}{1}} = 0.9841$$

$$TAP = \frac{30\times1000}{\sqrt3\times132\times\frac{200}{1}} = 0.6560$$

$$TAP = \frac{MVA\times1000}{\sqrt3\times kV_{wdg}\times CTR}$$

Now, to understand this magnitude compensation in a digital relay, let us consider two examples. So in the first example, I have considered one transformer which is 30 MVA rating; one side that is LV side is $\text{TAP} = \frac{30\times1000}{\sqrt3\times11\times\frac{1600}{1}} = 0.9841$ and HV side is $\text{TAP} = \frac{30\times1000}{\sqrt3\times132\times\frac{200}{1}} = 0.6560$.

So, if you calculate this, you will have a value that is 1574.6 ampere; this current is available on primary of the CT. So, if you convert this or if you transform or transfer this current on CT secondary side this side, then the current available that is 1500 and 74.6 divided by CT ratio that is 1600 by 1. So, if you solve this, you will have a value that is 0.9841.

So, in earlier case when we transform this primary current full load current on secondary side of CT on LV side, we will have the value 0.9841. And we if I use this equation, I will have the value 9841; so, if you divide these two, you will have the value that is 1. Same way on secondary side, if I calculate the full load current, then I full load current on secondary side is given by 30 MVA, divide by root 3 into 132 into 10 raises to 3.

So, if you solve this, you will have 131.2 A; and if you transform this current on secondary side, then 131.2 divided by 200 by 1, so you will have the value that is 0.6560 A. And if you use this equation of tap, then you will have the value 0.6560; and you can see if you divide this by these two values, you will have the value 1. So, this is how the magnitude compensation is obtained if we use the digital relay.

Now, here you can observe that primary of the CT that is here 1600 and here 200; these two values are different. However, the secondary of the CT on both the sides are same. Now, let us consider a second example when the secondary of the CTs are also different. So, primary and secondary values of the CTs on both sides are different; and in that case, let us see how we can obtain the magnitude compensation.

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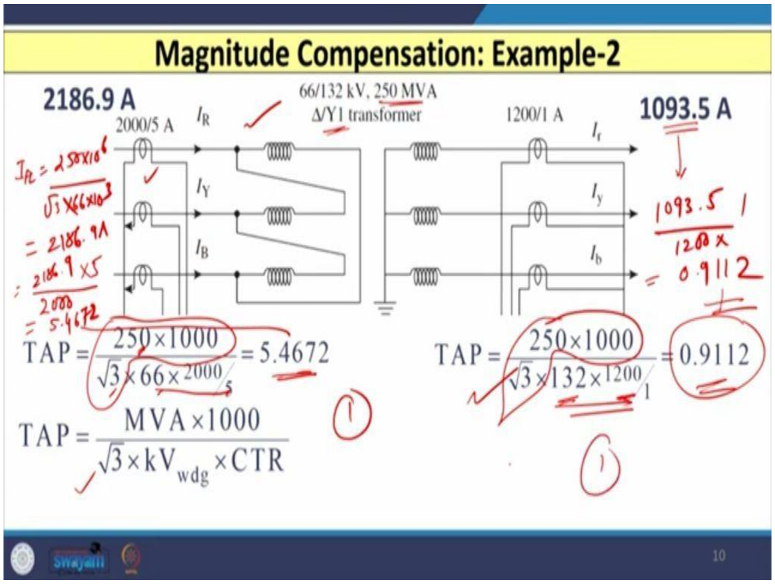

Magnitude Compensation: Example-2

$I_R = \frac{250\times10^6}{\sqrt{3}\times66\times10^3} = 2186.9A = \frac{2186.9\times5}{2000} = 5.4672$

$\frac{1093.5}{1200}\times 1 = 0.9112$

$$\text{TAP} = \frac{250\times1000}{\sqrt{3}\times66\times\frac{2000}{5}} = 5.4672$$

①

$$\text{TAP} = \frac{250\times1000}{\sqrt{3}\times132\times\frac{1200}{1}} = 0.9112$$

①

$$\text{TAP} = \frac{\text{MVA}\times1000}{\sqrt{3}\times\text{kV}_{wdg}\times\text{CTR}}$$

So, in that case, if I use let us say another transformer 250 MVA 66 by 132 kV; and this transformer is Delta Star 1. And if I use this if I calculate similar way the full load current, then on this side I will have the full load current that is nothing but $\text{TAP} = \frac{250\times1000}{\sqrt{3}\times66\times\frac{2000}{5}} = 5.4672$

So, you will have the value that is 5.4672. And if you divide these two (as shown in above slide), you will have again the 1 value. Same way on secondary side, if you calculate the full load current, you will have the current this; and if you transform this current you will have $\text{TAP} = \frac{250\times1000}{\sqrt{3}\times132\times\frac{1200}{1}} = 0.9112$

So, you will have the value that is 0.9112; and using tap also you will have the same value that is 0.9112. Because this value remains same, here also and here also; either you calculate or LV or HV side, the only difference is these two values.

So, if you change this, you will have the value this; and here also you will have same value. And if you divide, you will have the 1 value. So, either we consider the change in primary side of the current or secondary side of the current if both are entirely different, then also we will get the appropriate compensation in the magnitude in case of digital relay.

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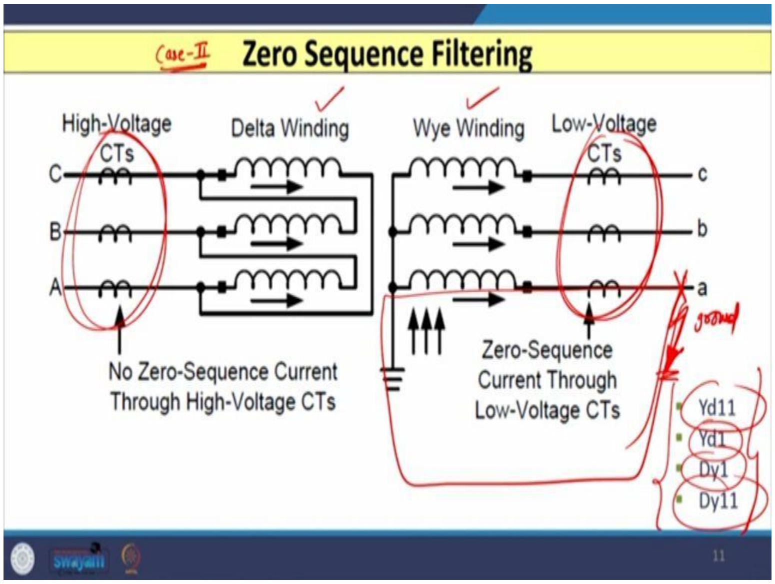

Case-II Zero Sequence Filtering

- Yd11
- Yd1
- Dy1
- Dy11

Now, the second case we need to consider is zero-sequence filtering or zero sequence compensation. Now to understand this, let us consider one Delta-Star transformer. So, this is your delta winding and this is your star winding, and I have connected three CTs here. I have also connected three CTs here. Now, if I use conventional scheme as this is the delta winding to this three CTs are connected in star; and then this is a star winding, so these three are connected in delta. But in the case of digital relay, we are connecting both these CTs in Star fashion to avoid the disadvantages of Delta winding.

So, in that case, we know that if there is a fault which is going to occur on Star side, and one of the phases which involves ground; this is fault which involves ground. So, in that case, the current will flow like this. So, this current, because whenever any fault occurs which involves ground, zero sequence current is always present. And that zero-sequence current will flow like this and that is also going to flow through these CTs. And as the CTs are connected with the relay, so those currents are reflected inside the digital relay.

On the Delta side, if you consider these currents are going to circulate inside the Delta winding, but it will not come out of the Delta winding. So, current through these CTs, there is no zero-sequence current. Hence, there is a mismatch. Because whatever currents you are going to give from this side to the digital relay; and here this side on one side zero sequence current are present, on another side they are absent; so, there is a mismatch. In digital relay, we have to compensate this also. And particularly this type of mismatch is going to occur, when we have a delta winding on one of the side of the transformer, like Star-Delta 11, Star-Delta 1, Delta-Star 1, Delta-Star 11.

So, these are the some common vector group we are using in case of power transformer; in all these cases we need zero sequence compensation.

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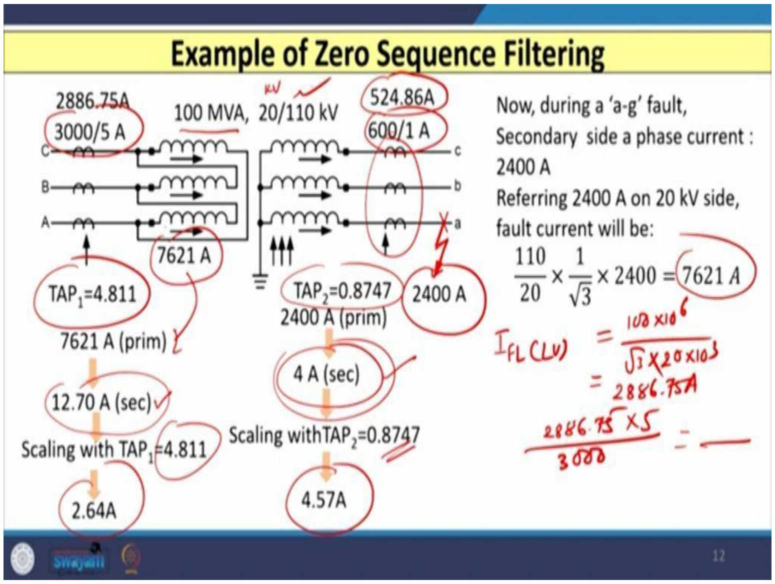

Example of Zero Sequence Filtering

Now, during a 'a-g' fault,
Secondary side a phase current : 2400 A
Referring 2400 A on 20 kV side, fault current will be:

$$\frac{110}{20} \times \frac{1}{\sqrt{3}} \times 2400 = 7621\,A$$

$$I_{FL(LV)} = \frac{100 \times 10^6}{\sqrt{3} \times 20 \times 10^3} = 2886.75A$$

$$\frac{2886.75 \times 5}{3000} = $$

Now, to understand the effect of zero sequence compensation, let us consider one example. So, here I have considered 100 MVA rating power transformer. The LV side rating is 20 kV and the HV side rating is 110 kV. Now, with this value if I calculate the full load current of the transformer on LV side, so I full load on LV side, we will have the $100 \times 10^6 / \sqrt{3} \times 20 \times 10^3$; so, you will have the value that is 2886.75 A. If I use the CT ratio on LV side that is 3000/5; because when current exceed 1000 A, the secondary should be 5 A (as shown in above slide).

So, if I use this and if I transfer this current on secondary side, then we have 2886.75 A divided by CT ratio that is 3000/5. Now, before we calculate this let us consider the other side also on HV side; if you calculate the full load current, then you will have the full load current that is 524.86 A. So, you have 100 MVA / $\sqrt{3}$ ×110 kV; and let us consider a 600/1 ampere that is the CT ratio on HV side. Now, let us say that some a to ground fault is going to occur on HV side, which is star grounded, with a fault current of 2400 ampere.

Obviously, these currents are going to flow through these CTs, which are connected on HV side. If I reflect this fault current on LV side which is delta connected, then that currents will be 2400 multiply by the turns ratio that is 110/20; and that is divided by root 3. Because when we move from this side to another side Delta, we have to divide by root 3; so, the current available that is 7621 that is this current. So, this is 7621, this current is 2400. Now, if I use this current that is 7621 ampere, and if you transform convert this current on secondary side using 3000 /5 ampere CT ratio; in secondary you will have the current 12.70 A.

So,

$$\frac{7621}{3000/5} = 12.7A$$

If you calculate now using the magnitude compensation using tap equation, which is given by:

$$\text{TAP} = \frac{\text{MVA} \times 1000}{\sqrt{3} \times \text{kV}_{\text{wdg}} \times \text{CTR}}$$

Then your tap value on LV side you will have 4.811. So, if you divide this secondary current by this value, you will have the current 2.64, which is not 1. Same way on the other side, if I use 2400 ampere current and if I convert it into secondary side using 600/1A CT ratio, we will have 4 amperes.

And if I calculate the tap on HV side we will have 0.8747; because again we have $\frac{\text{MVA}\times 1000}{\sqrt{3}\times \text{kV}_{\text{wdg}}\times \text{CTR}}$. So, your KV is 110 and CT ratio is 600/1A; so, you will have the tap value 0.8747. So, if you divide this secondary current by this tap on HV side, you will have the current 4.57 ampere.

So, see that these two currents are not on common base. So, that is why zero sequence filtering is a must when we use the digital relay. And specifically, when the vector group in the power transformer is delta connected or when delta winding is involved. Now, let us see how this zero-sequence compensation is achieved or obtained when we use digital relay.

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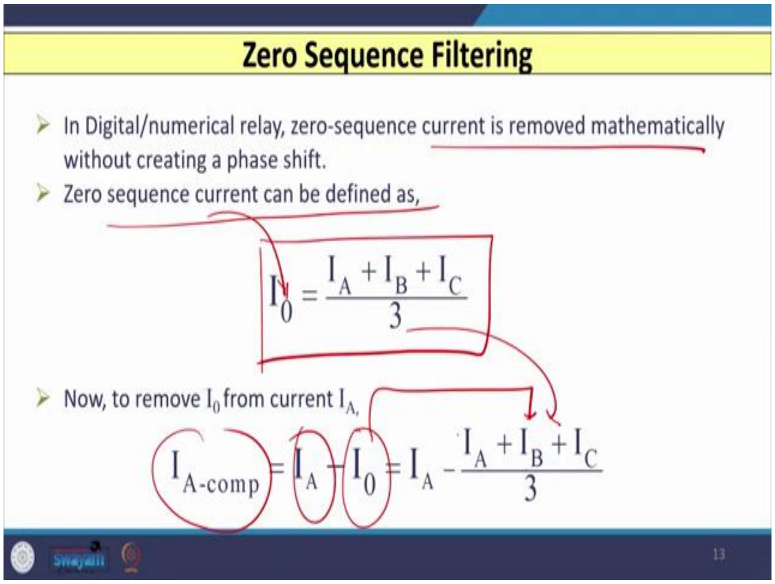


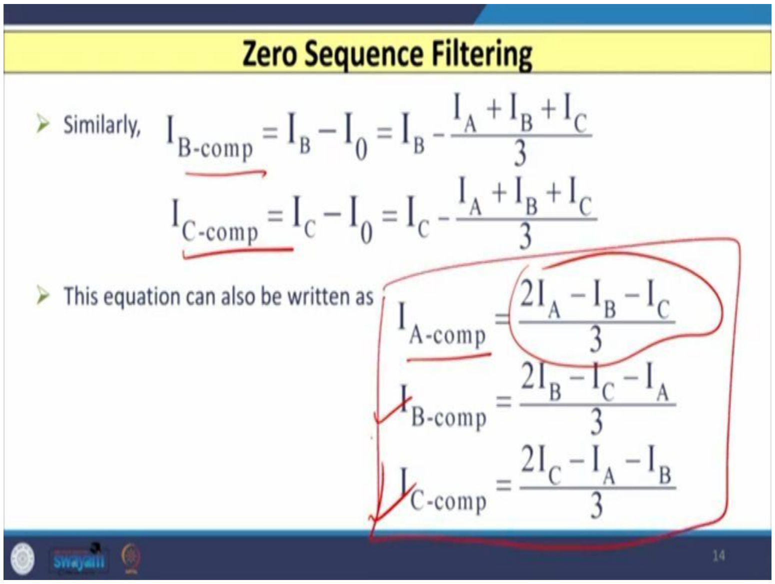
Zero Sequence Filtering

- In Digital/numerical relay, zero-sequence current is removed mathematically without creating a phase shift.
- Zero sequence current can be defined as,

$$\boxed{I_0 = \frac{I_A + I_B + I_C}{3}}$$

- Now, to remove I_0 from current I_A,

$$I_{A\text{-comp}} = I_A - I_0 = I_A - \frac{I_A + I_B + I_C}{3}$$



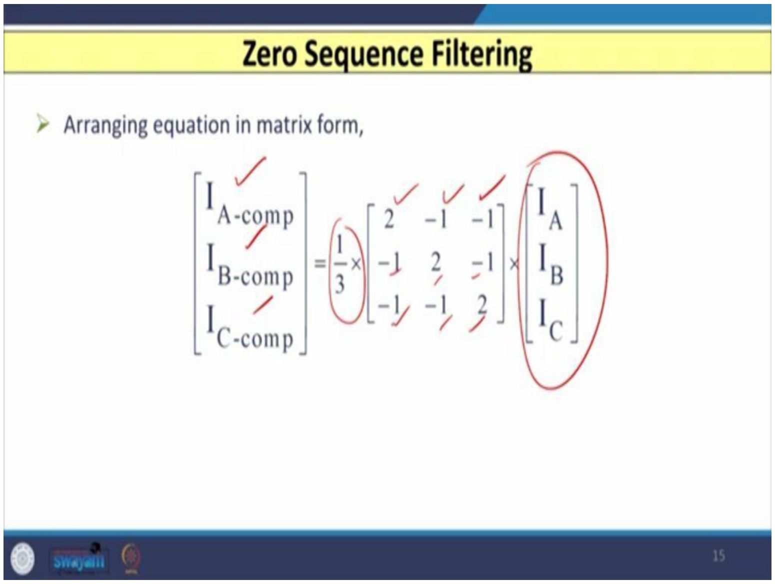
Zero Sequence Filtering

- Similarly, $I_{B\text{-comp}} = I_B - I_0 = I_B - \frac{I_A + I_B + I_C}{3}$

$$I_{C\text{-comp}} = I_C - I_0 = I_C - \frac{I_A + I_B + I_C}{3}$$

- This equation can also be written as

$$\boxed{\begin{aligned} I_{A\text{-comp}} &= \frac{2I_A - I_B - I_C}{3} \\ I_{B\text{-comp}} &= \frac{2I_B - I_C - I_A}{3} \\ I_{C\text{-comp}} &= \frac{2I_C - I_A - I_B}{3} \end{aligned}}$$



Zero Sequence Filtering

- Arranging equation in matrix form,

$$\begin{bmatrix} I_{A\text{-comp}} \\ I_{B\text{-comp}} \\ I_{C\text{-comp}} \end{bmatrix} = \frac{1}{3} \times \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \times \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

So, this can be achieved using some mathematical equation without creating any additional phase shift. So, we know that zero sequence current that can be defined or given by a very common equation $I_0 = \frac{I_A+I_B+I_C}{3}$

So, if I want any compensated value of current in any phase, let us say A phase, B phase and C phase, so then I want A phase compensated current $I_{A\text{-comp}}$, I want to B phase compensated current that is $I_{B\text{-comp}}$, and I want C phase compensated current that is $I_{C\text{-comp}}$.

Then in that compensated current let us say in A phase compensated current IA compensated, $I_{A\text{-comp}} = I_A - I_0 = I_A - \frac{I_A+I_B+I_C}{3}$

Same way, you have the compensated value of current in B phase and C phase.

$$I_{B\text{-comp}} = I_B - I_0 = I_B - \frac{I_A + I_B + I_C}{3}$$

$$I_{C\text{-comp}} = I_C - I_0 = I_C - \frac{I_A + I_B + I_C}{3}$$

So, these three questions IA compensated IB compensated, and IC compensated that can be written as IA compensated.

$$\mathrm{I}_{\text{A-comp}} = \frac{2\mathrm{I}_\mathrm{A} - \mathrm{I}_\mathrm{B} - \mathrm{I}_\mathrm{C}}{3}$$

$$\mathrm{I}_{\text{B-comp}} = \frac{2\mathrm{I}_\mathrm{B} - \mathrm{I}_\mathrm{C} - \mathrm{I}_\mathrm{A}}{3}$$

$$\mathrm{I}_{\text{C-comp}} = \frac{2\mathrm{I}_\mathrm{C} - \mathrm{I}_\mathrm{A} - \mathrm{I}_\mathrm{B}}{3}$$

So, if I write this equation in matrix form, then I have the three currents on left hand side; that is the compensated current in A phase, B phase and C phase.

$$\begin{bmatrix} \mathrm{I}_{\text{A-comp}} \\ \mathrm{I}_{\text{B-comp}} \\ \mathrm{I}_{\text{C-comp}} \end{bmatrix} = \frac{1}{3} \times \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \times \begin{bmatrix} \mathrm{I}_\mathrm{A} \\ \mathrm{I}_\mathrm{B} \\ \mathrm{I}_\mathrm{C} \end{bmatrix}$$

So, your compensated value of the equation that is given by this matrix; and using this you can easily compensate the zero-sequence current in case of digital relay.

In this class, we started our initial discussion with the digital relay. And we have seen how we can apply the principle of operating current and restraining current in the case of digital relay. And we have seen that operating current is given by the vectorial addition of two key secondary currents, whereas the restraining current is given by this scalar addition of the two currents.

Then, we have discussed about the how we can implement those things if I use the digital relay for the protection of power transformer. So, we have started our discussion with the magnitude compensation and how mathematically using an analytical equation, we can compensate the magnitude in the case of digital relay.

Then, we discussed that when any fault involved ground and if I have delta winding in any vector group of the transformer, then the zero-sequence path exists on one side; and it does not exist on the other side of the transformer winding. So, in that case we need zero sequence compensation also. And we have discussed that using again mathematical equation; we can easily compensate the zero sequence quantities in case of digital relay.

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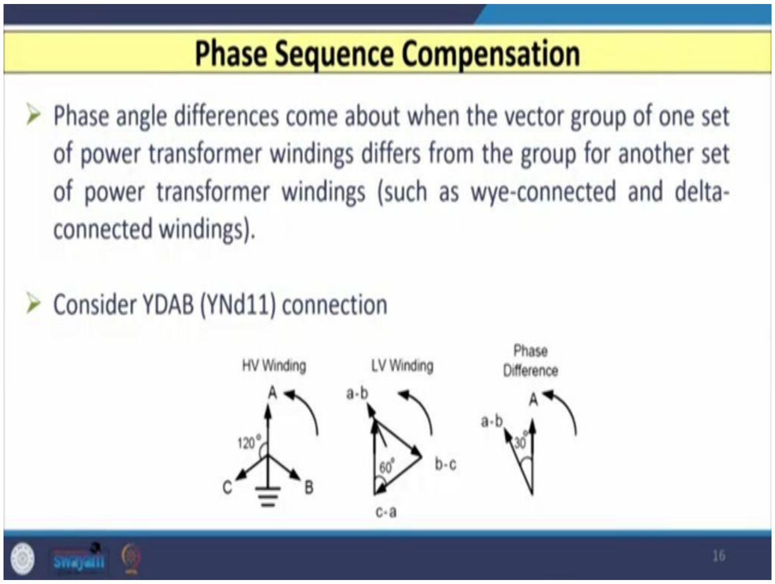

Phase Sequence Compensation

- Phase angle differences come about when the vector group of one set of power transformer windings differs from the group for another set of power transformer windings (such as wye-connected and delta-connected windings).
- Consider YDAB (YNd11) connection

The third case we have is the phase sequence compensation in digital relay; and this we will discuss in the next class. Thank you.