Transformer Differential Protection

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***Abstract*—Overcurrent and earth fault protective equipment that employ time grading and directional detection cannot provide correct discrimination and speedy fault clearance on all power networks. In this case, differential protection is a better alternative. It protects individual sections of networks or pieces of equipment, such as transformers, generators, e.t.c. It is normally applied where protection co-ordination cannot be readily achieved with time delayed over current and earth fault protection, or where fast fault clearance is necessary. Kirchhoff's first law, which states that the sum of the currents flowing to a node is equal to the sum of the currents flowing out from it is the basic principle of the differential protection scheme. The difference between the current entering a section and that leaving it is detected by the differential protection scheme. If the operating condition is normal (i.e. there is no fault within the protected section), the current leaving it will always be equal to that entering it, and the protective equipment should not operate. If there is fault in the protected unit, the output current differs in either phase or magnitude from the input current, and the protection should operate. This paper investigates how power transformers can be protected using the current-differential protection schemes.**

***Index Terms*—Power transformers, current transformer, differential protection, relay, fault clearance.**

I. Introduction

Transformers are sized according to the voltage applied to them. Small single-phase units are available for low-voltage application. Large and extremely large three-phase units are used for high and ultra-high voltages associated with alternators and transmission lines in power system networks. [1]. Transformers that supply distribution networks are exposed to a greater number of through faults [2]. This exposure reduces the life expectancy of the transformer [3]. All transformers need protection from power system hazards. The size or cost of a transformer determines the complexity and cost of its protective equipment. In other words, the protective scheme should be proportional to the equipment being protected [4], [5]. When a fault occurs within the transformer, the protective equipment must disconnect that transformer from the network, to forestall any damaged to the transformer. Damage occurs if the fault current remains longer than necessary on the network [6]-[9]. If this happens, there will be loss of revenue since energy will not be supplied, and the transformer will have to be replaced or repaired. Safety of personnel working in the substation under pressure to restore supply will also be threatened [10]. So, protective relays are set to trip circuit breakers to clear faults, but the settings must allow for the normal range of currents due to energization and heavy temporary loading periods. Of course, every protection scheme should be selective in order to prevent unnecessary outages [11]-[13]. The withstand capability of transformers is specified according to the kilovolt-ampere rating of the transformer [14]. Differential protection provides the best overall protection-it is selective and speedy in fault clearing [4], [15]. Since it protects only the equipment between the current transformers (CTs), back-up protection to other parts of the network is lacking. The transformer is highly reliable because of its static nature. However, it can fail as a result of [1]:

(i) Failure of insulation of windings, laminations.
(ii) Oil deterioration.
(iii) Loss of oil by leakage.
(iv) Tap changer faults.
(v) Cooling system faults.
(vi) Heavy through faults.
(vii) Overloads.
(viii) Switching surges.
((ix) Lightning

II. Principle of Differential Protection

Since the primary current of a transformer is quite different from the secondary current, current transformers (CTs) are placed on the primary and secondary sides to compensate for this. These CTs must produce the same secondary currents. So, their ratios must be chosen accordingly. Their primary current ratings, however, make the magnetizing characteristics of the two CTs different from each other. As shown in Fig. 1 [1], the relay is connected to the centre point of a balanced system. If the currents in the two current CTs are not equal, the difference, i_d between the CT secondary currents will flow through the relay for it to operate.

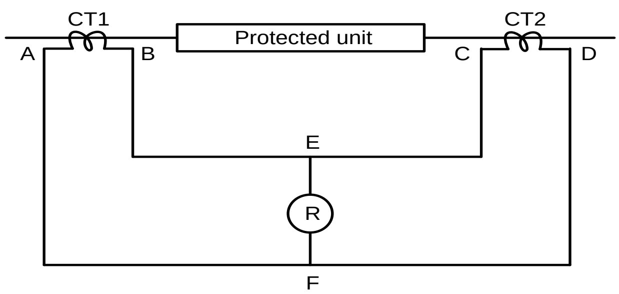

Fig. 1. Current differential protection

When a fault occurs on the protected unit, as shown in Fig. 2 [4], the output current would no longer be equal to the input current.

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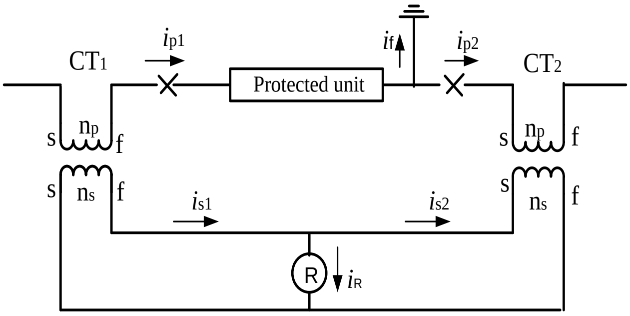


Fig. 2. Internal fault

The input current would be given as:

$$i_{p1} = i_{p2} + i_f \tag{1}$$

The CTs secondary currents will be:

$$i_{s1} = \frac{n_p}{n_s} i_{p1} = \frac{n_p}{n_s}\left(i_{p2} + i_f\right) \tag{2}$$

$$i_{s1} = \frac{n_p}{n_s} i_{p2} + \frac{n_p}{n_s} i_f \tag{3}$$

$$i_{s2} = \frac{n_p}{n_s} i_{p2} \tag{4}$$

The differential current is:

$$i_d = i_R = \frac{n_p}{n_s} i_f \tag{5}$$

If i_d flowing through the relay exceeds a certain minimum level, circuit-breaker operation would be initiated instantly. In the case of a fault occurring outside the protected unit, as shown in Fig. 3, the same primary current will flow through each CT, i.e. $i_{p2} = i_{p1}$, and so there will be no differential current flowing through the relay, and hence no relay operation - ensuring correct fault discrimination.

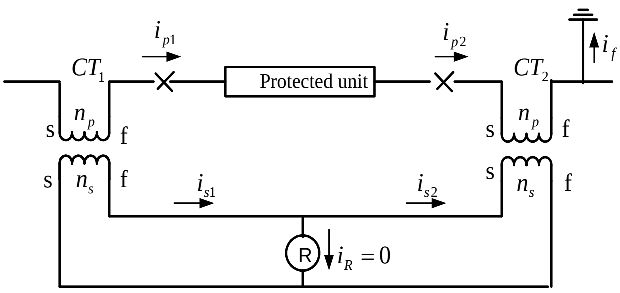


Fig. 3 External fault

However, some difficulties arise in the use of this scheme due to errors associated with current transformers.

A. Biased System

Protection schemes for large transformers must operate speedily when faults occur within the protected zones, but must be restrained when the protected transformer is healthy, hence the need for biasing arrangement. When high through current flows, biasing increases the current needed to operate the relay [4]. Differential elements compare a differential or operating current i_d with a restraining current. A restraining or bias coil is connected to carry a current proportional to the full system current and restrains the relay operation on large through-fault currents [16]. Fig. 4 [4] shows a biased protective scheme. The relay has two restraining windings (1 and 2), and one operating winding, 3. As currents flow, the force in the restraining windings opposes relay operation, while the force in operating winding causes operation.

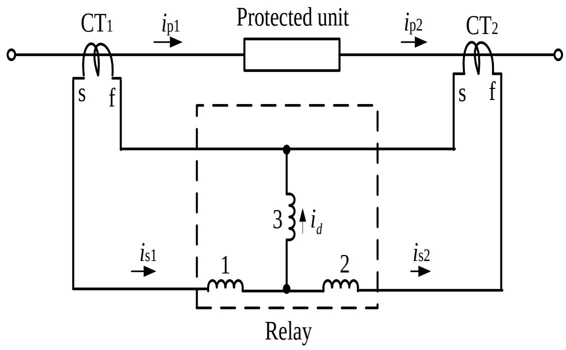


Fig. 4 biased protective scheme

$$Differential\ Current,\ i_d = i_{s1} - i_{s2} \tag{6}$$

$$Mean\ Through\ Current,\ i_{RT} = \frac{i_{s1} + i_{s2}}{2} \tag{7}$$

During through faults or stable operation, the restraining windings produce forces in the same direction when the currents in them are in phase with each other. The electromagnetic forces produced in the relay windings are proportional to the square of the magneto-motive forces. So, the condition for relay operation is [17]:

$$\left(n_o i_d\right)^2 > \left(\frac{n_{RT}}{2} i_{s1} + \frac{n_{RT}}{2} i_{s2}\right)^2 \tag{8}$$

Where

n_o = Number of turns on the operating coil

n_{RT} = Number of turns on the restraining coil

$$\text{If } n_{RT} = k\, n_o,\ \left(0 < k < 1\right) \tag{9}$$

$$\left(n_o i_d\right)^2 > \left(\frac{k\, n_o}{2}\left(i_{s1} + i_{s2}\right)\right)^2,\ i_d > \frac{k}{2}\left(i_{s1} + i_{s2}\right) \tag{10}$$

$$i_d > k\, i_{RT} \tag{11}$$

$$Bias = \frac{i_d}{i_{RT}} \tag{12}$$

The differential relay generates a tripping signal if the differential current, i_d, is greater than a percentage of the restraining current i_{RT} [18]. Equation (12) is plotted as shown in Fig. 5

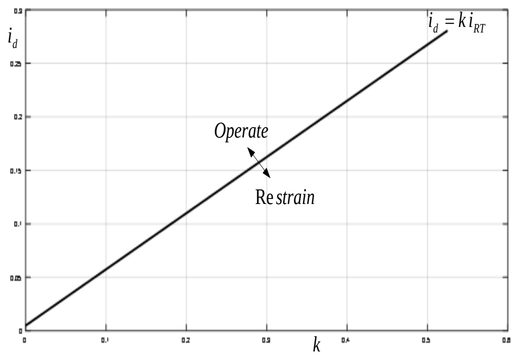


Fig. 5. Operating diagram of biased differential scheme

III. Factors Affecting Current-Differential Protection

A. Current Transformer (CT) Errors

The efficiency of current transformers plays vital role in the effective protection of equipment, just as the incorrect selection of current transformers can lead to the failure of a protective scheme to perform its function correctly. In other words, for a protection scheme to fulfill its obligation, current transformers must be carefully matched with the relays. Current transformers enable differential-protection schemes to compare the input and output currents of a protected unit, and also isolate the relays and interconnecting conductors from the high voltages associated with power systems. Because of transformation errors associated with CTs, it is necessary to have identical CTs at the input and output ends of a protected zone so that their errors during healthy and through fault conditions will always be the same [4]. Consequently, the secondary currents of the CTs would always be equal and zero current would flow in the relays except when internal faults occur. However, there will always be differences, no matter how small, in the magnetizing characteristics and this leads to instability in the scheme during through fault conditions. CTs are usually driven into saturation by transient during faults and this produces a high spill current. The transient disappears in about 20 cycles. So, time delay of, say 0.5s is needed to resolve the problem. If the core of one CT is saturated, while the other remains unsaturated the two CTs would be made to operate at different points on their excitation characteristics during a later external fault, causing sufficient unbalance current to flow in the relay and operate incorrectly [4].

1) Ratio Error (Current Error)

In a current transformer the whole of the primary current is not transformed into secondary current, a component of the primary current is used to magnetize or excite the core. In other words, the inductor X_e is such that it takes current equal to the exciting current of the CT [19], Fig. 6. The exciting current, I_e is part of I'_2 consumed in exciting the core. The remainder, I_2 is the true secondary current. Fig. 6 is the equivalent circuit of a CT [17], [20].

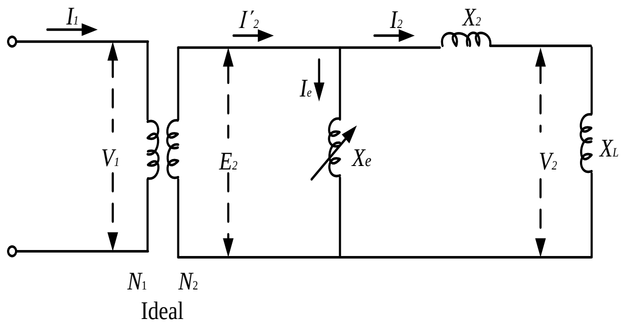


Fig.6. CT equivalent circuit

I_1 = primary current
V_1 = primary voltage
E_2 = secondary induced (excitation) voltage
V_2 = secondary terminal voltage
I'_2 = primary current referred to the secondary
I_e = secondary excitation current
I_2 = secondary current
X_e = excitation reactance referred to the secondary
X_2 = leakage reactance referred to the secondary
X_L = reactance of load (burden)

From Fig. 6, we write

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \tag{13}$$

$$I'_2 = \frac{N_1}{N_2} I_1 \,,\ I_2 = I'_2 - I_e \Rightarrow I_e = I'_2 - I_2 \tag{14}$$

$$\text{Ratio error} = \frac{I'_2 - I_2}{I'_2} = \frac{I_e}{I'_2} \tag{15}$$

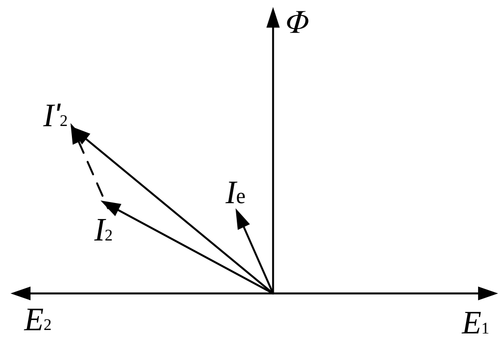


Fig. 7 Phasor Diagram

Equation (15) is the deviation of I_2 from I'_2 expressed as a percentage of I'_2.

$$E_2 = \frac{N_2}{N_1} E_1 \tag{16}$$

$$E_2 = jI_2 (X_2 + X_L) \tag{17}$$

$$E_2 = j(X_2 + X_L)[I'_2 - I_e] \tag{18}$$

$$E_2 = j\left(X_2 + X_L\right)\left[\frac{N_1}{N_2} I_1 - I_e\right] \quad (19)$$

Since all impedance elements are inductive,

$$E_2 = \left(X_2 + X_L\right)\left[\frac{N_1}{N_2} I_1 - I_e\right] \quad (20)$$

Plotting equation (20) on the same coordinates as the magnetization curve (E_2 versus I_e), we can predict I_2 for a given I_1 with known termination, X_L. The solution for E_2 and I_e is the intersection of the two plots, and I_2 can now be solved for.

2) *Phase angle error*

The phase angle error is the angle difference between the secondary current vector, when reversed, and the primary current [19]. This difference in phase angle between primary and secondary currents is due to the winding connections of the power transformer, e.g. star/delta or delta/star transformers.

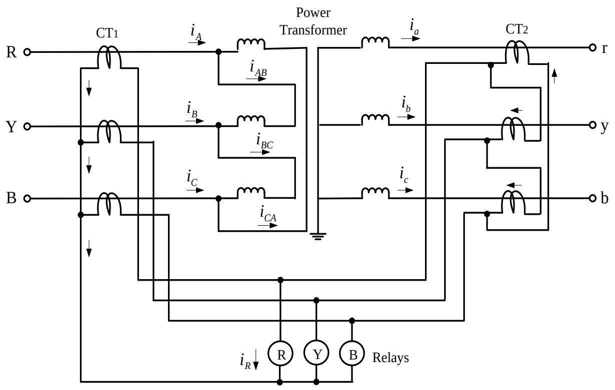


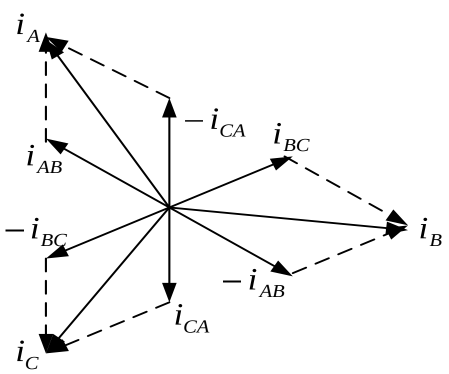
Fig. 8. Delta/Star transformer

For delta/star transformer, shown in Fig. 8 the currents in the primary winding of the transformer are:

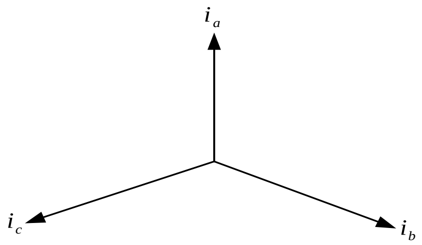
$$i_A = i_{AB} - i_{CA} \quad (21)$$

$$i_B = i_{BC} - i_{AB} \quad (22)$$

$$i_C = i_{CA} - i_{BC} \quad (23)$$



(a) Primary side currents



(b) Secondary side currents

Fig. 9 Steady-state phasor diagram of currents in a delta-star connected power transformer.

It can be observed that the currents $-i_{CA}$ and i_a are in phase, likewise $-i_{AB}$ and i_b; $-i_{BC}$ and i_c

$$i_A = i_{AB} - i_{CA} = i_{AB} - i_{AB}\angle 120^o \quad (24)$$

$$i_A = i_{AB}\left(\frac{3}{2} - j\frac{\sqrt{3}}{2}\right) = \sqrt{3}\, i_{AB}\angle -30^o \quad (25)$$

Thus i_A lags i_{AB} by 30º as shown in Fig.10
Similarly,

$$i_B = \sqrt{3}\, i_{BC}\angle -30^o$$
$$i_C = \sqrt{3}\, i_{CA}\angle -30^o \quad (26)$$

$$i_{AB} = -\frac{N_s}{N_p} i_b$$
$$i_{BC} = -\frac{N_s}{N_p} i_c \quad (27)$$
$$i_{CA} = -\frac{N_s}{N_p} i_a$$

$$i_A = \frac{N_s}{N_p}\left(i_a - i_b\right)$$
$$= \frac{N_s}{N_p}\left(i_a - i_a\angle -120^o\right) \quad (28)$$

$$i_A = \frac{N_s}{N_p}\sqrt{3}\, i_a\angle 30^o$$
$$i_B = \frac{N_s}{N_p}\sqrt{3}\, i_b\angle 30^o \quad (29)$$
$$i_C = \frac{N_s}{N_p}\sqrt{3}\, i_c\angle 30^o$$

That is i_A leads i_a by 30º – the primary line current leads the secondary line current by 30º as shown in Fig. 10.

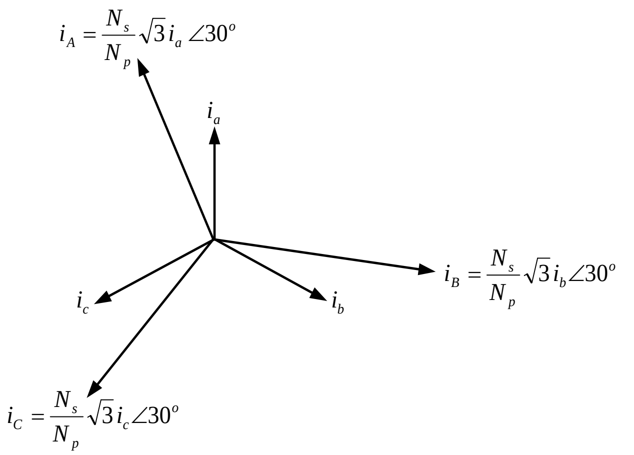


Fig. 10 Primary and secondary currents phasors for steady-state operation.

In other words the star-connected low-voltage line current lags the high-voltage line current by 30° i.e. the phase shift is -30°. It is a Dyn1transformer. Because of the phase shift, phase correction is necessary in order to prevent mal-operation of the relay.

B. *Mismatching caused by power transformer exciting current surges (magnetizing inrush current)*

The exciting current of power transformers is usually very small (2-5% of the rated current) when the operating condition is stable. At the time of energizing the transformer, the exciting current may rise to values many (8-30) times the rated current for significant period (typically 10 cycles) [4], [20]. Since these current flows in the primary winding only and in the operating windings of the relays used in the differential protection scheme, the relays would operate. Thus a time delay or effective biasing arrangement must be provided so as to prevent this mal-operation. The magnetizing inrush current saturates the CT iron core, and the waveform is much distorted. The second harmonic component of the inrush current is very high, and can be used to restrain relay operation when a time delay cannot be tolerated. The CT goes into saturation beyond the knee-point of the CT magnetization curve. In this region, the core flux is sustained by major part of the primary current. Thus, a disproportionate amount of the primary current is required to magnetize the core. There is drastic increase in the magnetization current, I_e while the secondary current, I_2 remains constant. In this condition, no matter the rise in primary current, the flux and secondary induced voltage remain constant. Hence, core loss increases; both the exciting and secondary currents become non-sinusoidal, since the shunt admittance is not linear. Ultimately, not all of the primary current transforms into secondary current

Let the instantaneous value of flux be:

$$\Phi = \Phi_m \sin \omega t \tag{30}$$

Fig. 11 shows the waveforms of the flux.

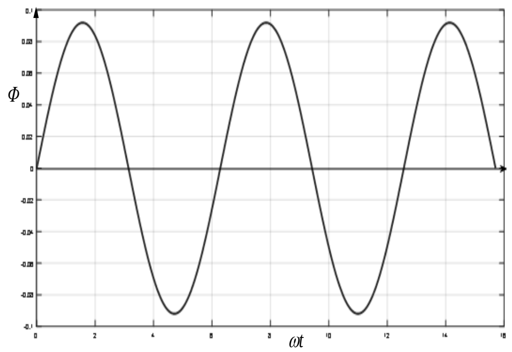


Fig. 11 Waveforms of flux

Then the instantaneous value of induced e.m.f is given by:

$$e = -N_1 \frac{d\Phi}{dt} = -\omega N_1 \Phi_m \cos \omega t = \omega N_1 \Phi_m \sin\left(\omega t - \frac{\pi}{2}\right) \tag{31}$$

N_1 is the number of turns on the primary winding

If the transformer is energized at the positive peak of the flux, the induced e.m.f. can be represented in Fourier series as:

$$e = \frac{a_o}{2} + \sum\left(a_n \cos n\omega t + b_n \sin n\omega t\right) \tag{32}$$

where

$$\frac{a_o}{2} = \frac{\omega N_1 \Phi_m}{\pi}\left\{\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} \sin\left(\omega t - \frac{\pi}{2}\right) d\omega t - \int_{\frac{3\pi}{2}}^{\frac{5\pi}{2}} \sin\left(\omega t - \frac{\pi}{2}\right) d\omega t\right\} \tag{33}$$

$$a_n = \frac{\omega N_1 \Phi_m}{\pi}\left\{\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} \sin\left(\omega t - \frac{\pi}{2}\right) \cos n\omega t \, d\omega t - \int_{\frac{3\pi}{2}}^{\frac{5\pi}{2}} \sin\left(\omega t - \frac{\pi}{2}\right) \cos n\omega t \, d\omega t\right\} \tag{34}$$

$$b_n = \frac{\omega N_1 \Phi_m}{\pi}\left\{\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} \sin\left(\omega t - \frac{\pi}{2}\right) \sin n\omega t \, d\omega t - \int_{\frac{3\pi}{2}}^{\frac{5\pi}{2}} \sin\left(\omega t - \frac{\pi}{2}\right) \sin n\omega t \, d\omega t\right\} \tag{35}$$

Fig. 12 shows the induced voltage waveform, and the magnetizing inrush current is shown in Fig. 13. Fig. 14 and Fig.15 show the harmonics of the inrush current during energization.

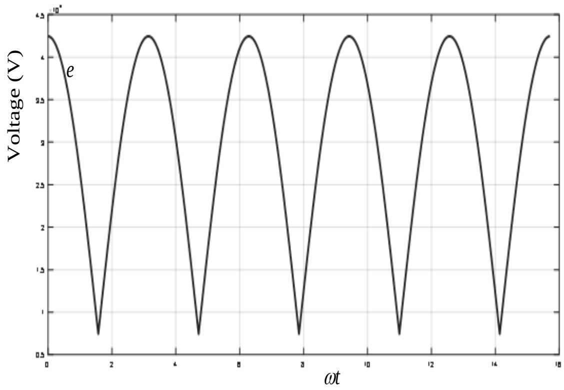


Fig.12 Induced voltage waveform

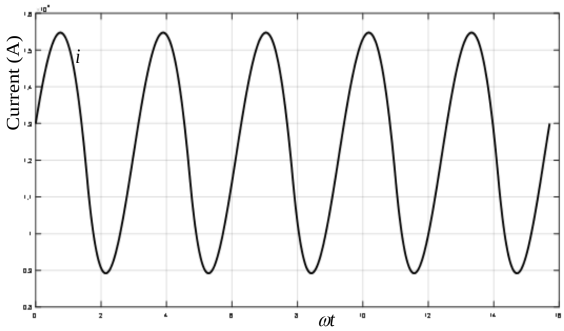


Fig. 13 magnetizing inrush current waveform

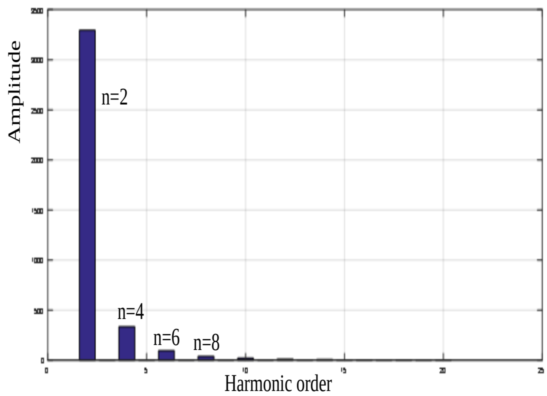


Fig. 14 magnetizing inrush current harmonics

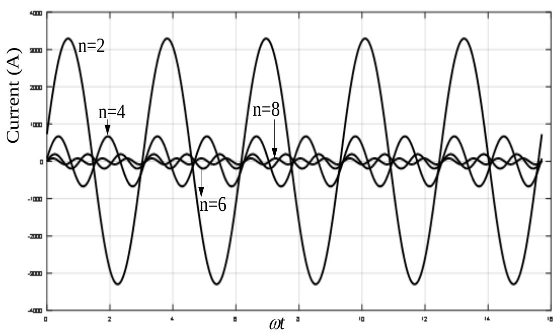


Fig. 15 magnetizing inrush current harmonics

Second harmonic component of the inrush current flow through sensitive restraining coils incoporated in the relays, and the relay is restrained from operating [16].

C. Mismatching caused by tap-changing

Tap-changing switches are used to select a particular number of turns in either the primary or secondary winding of a transformer, thereby varying the overall transformation ratio to obtain the desired output voltage. The associated CTs should also have tapped windings so as to maintain balance in current-differential schemes which compare the winding magneto motive forces. The CTs ratios must be changed in accordance with power transformer tap-changing. This scheme is complex, costly, and hardly practicable. Therefore, a biased scheme is needed because the differential relay will see out-of-balance, or spill current when a ratio other than the transformer nominal transformation ratio occurs [4].

IV. Implementation of the Differential Protection

Fig. 16 shows the basic differential scheme, [1], [4], where the CTs primary windings are in series with the primary and secondary windings of the protected transformer. The currents in the secondary windings of the CTs flow around the loop formed with the interconnecting conductors when the protected transformer is healthy. The operating windings of the relay are connected between the mid-points of the interconnecting conductors to form a symmetrical circuit. The currents into the differential element of the relay must balance to ensure correct operation when there is no abnormal condition. The HV and LV CTs primary ratings do not usually match the power transformer winding rated currents. This mismatch was traditionally compensated for by the provision of physical interposing current transformers (ICTs). However, CT ratio correction factors are provided in modern relays. When these factors are applied, the differential algorithm receives correct signals to achieve the desired relay operation. The correction factor can be adjusted from 0.05 to 2.0 in steps of 0.01 for each set of CT inputs [21].

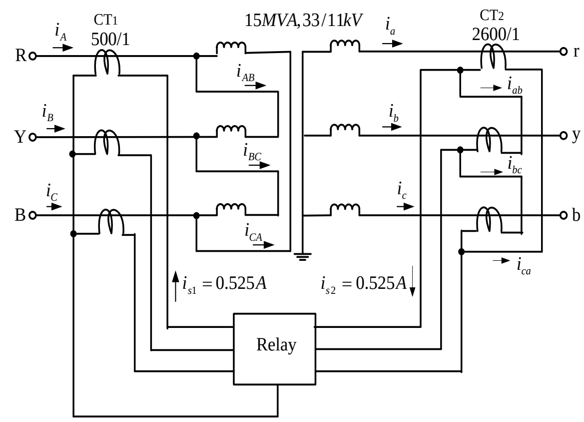


Fig. 16 ratio and phase-angle correction by delta connection of line CTs

Fig.16 is a 15MVA, 33/11kV, Dyn1 transformer. The relay is rated 1A.

Transformer turns ratio is:

$$a = \frac{N_1}{N_2} = \frac{\sqrt{3}V_1}{V_2} = \frac{\sqrt{3}x33}{11} = 5.2$$

The primary full-load current is:

$$i_A = \frac{15000}{\sqrt{3}\,x33} = 262.43A$$

The secondary full-load current is:

$$i_a = \frac{15000}{\sqrt{3}\,x11} = 787.3A$$

If CTs with ratios 262/1 for the primary side and 787/1 for the secondary side of the power transformer can be found, then there is no CT mismatch, and no need for ratio correction.

However, if the secondary side CT ratio is selected as 2600/1, then

LV CT secondary current $= \frac{787.3}{2600} = 0.303$A

Primary side CT ratio is to be determined. The secondary current rating of the CT to be connected in delta must be 0.5774 times the rating selected for the star-connected CT and for the rating selected for the relay [1].

Hence, primary side CT secondary current = $\sqrt{3}$ x secondary side CT secondary current= $\sqrt{3}$ x 0.303 = 0.525A

Primary side CT ratio = 262.43/0.525= 500/1

Because of the phase shift, phase correction is necessary in order to prevent mal-operation of the relay. This is achieved by connecting the CT secondary winding in star where the power transformer winding is connected in delta, and connecting the CT secondary winding in delta where the power transformer winding is connected in star as shown in Fig. 16 [1], [21]. From Fig. 16, we have:

$$i_a = \frac{N_1}{\sqrt{3}\,N_2} i_A \angle -30^o \tag{36}$$

$$i_{ab} = \frac{i_a}{2600} = 0.303\angle -30^o \tag{37}$$

$$\begin{aligned} i_{s2} &= \sqrt{3}\, i_{ab} \angle 30^o \\ &= \sqrt{3}\left(0.303\angle -30^o\right)\angle 30^o = 0.525A \end{aligned} \tag{38}$$

Ratio correction and phase correction can also be effected by using one set of physical interposing current transformers (ICT), connected as a replica of the power transformer winding arrangement, as shown in Fig. 17. Fig. 18 shows two sets of ICTs are in use. It can be noticed in Fig. 18 that both the CTs at the primary and secondary sides of the protected transformer are connected in star. However modern relays have software interposing CTs built into them for ratio correction, phase correction, and LV filtering of zero sequence current [21].

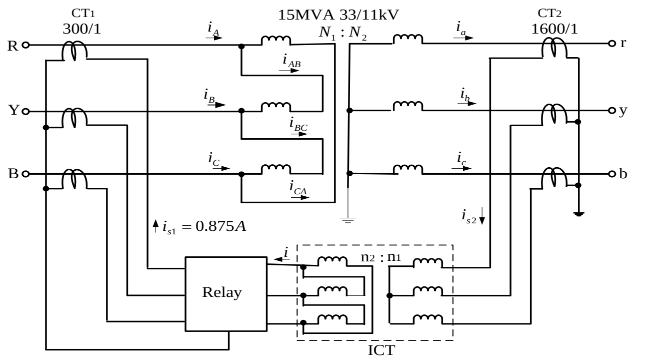


Fig. 17 Ratio correction and phase-angle correction using one set physically-connected ICT

From Fig. 17

$$i_a = \frac{N_1}{\sqrt{3}\,N_2} i_A \angle -30^o \tag{39}$$

$$i_{s2} = \frac{i_a}{1600} = 0.492\angle -30^o \tag{40}$$

$$\begin{aligned} i &= \frac{n_1}{n_2}\sqrt{3}\, i_{s2} \angle 30^o \\ &= \frac{n_1}{n_2}\sqrt{3}\left(0.492\angle -30^o\right)\angle 30^o = \frac{n_1}{n_2} 0.852A \end{aligned} \tag{41}$$

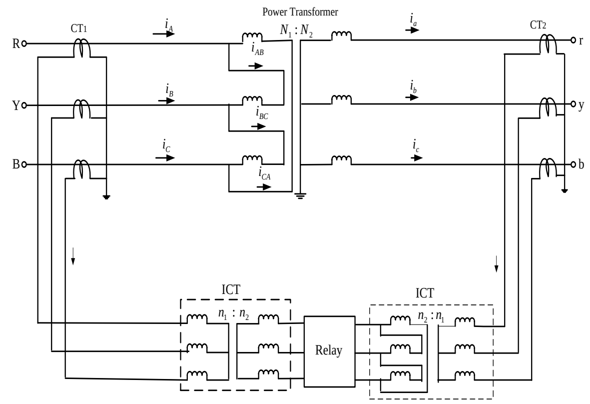


Fig. 18 ratio and phase-angle correction using two sets physically-connected ICTs

Fig. 19 shows relay in-built ratio correction factors and software ICTs [21]. Thus, from Fig 19:

HV ratio correction factor = $\frac{1}{0.875} = 1.14$ (setting applied to relay)

LV ratio correction factor = $\frac{1}{0.492} = 2.0$ (setting applied to relay)

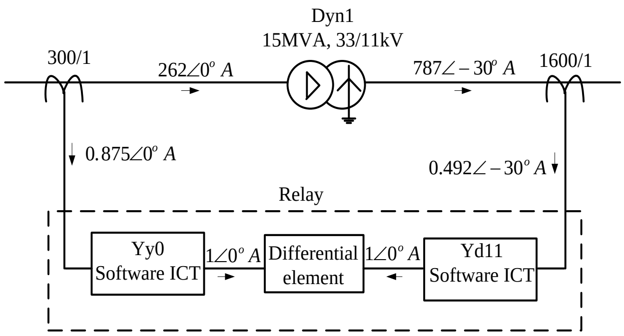


Fig. 19 Application of software ICTs

Fig. 20 shows the distribution of current in the transformer windings for a phase-to-phase through fault. It can be shown that the positive-sequence fault current is given by:

$$I_{a1} = \frac{V_f}{Z_1 + Z_2} \tag{42}$$

Where,

V_f= fault point voltage per unit.

Z_1= positive sequence impedance per unit.

Z_2=negative sequence impedance per unit.

Z_2=Z_1. Phases "y" and "b" are assumed to be shorted. It can be shown that $I_{a2} = -I_{a1}$, and that the total fault current is:

$$I_{bf} = a^2 I_{a1} + aI_{a2} = \left(a^2 - a\right) I_{a1} \tag{43}$$

where I_{a2} is negative sequence fault current.

The percentage impedance of the transformer is 9.898 %. Therefore, the fault current is given as:

$$I_{bf} = -j\sqrt{3}\ I_{a1} x\, I_{base} = -j6889\text{A}$$

$$I_{base} = 787.3\,\text{A}$$

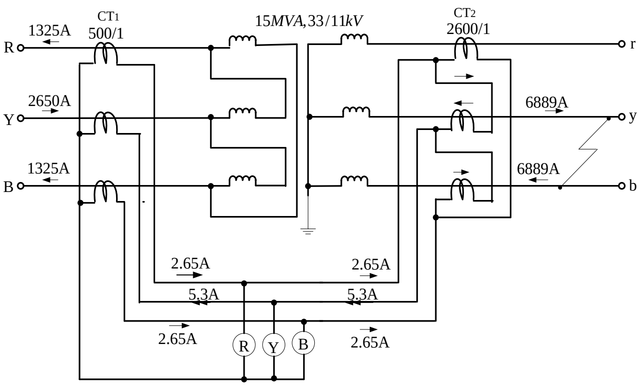


Fig. 20. Current distribution under phase-to-phase through fault condition

It is shown in Fig. 20 that the currents flowing in the secondary circuits of the CTs are equal ($i_{s1} = i_{s2}$). Thus, current through the relay is zero. It is obvious that, if the short-circuit fault occurred within the protected transformer, the current that would flow in the secondary-side CT would be much less than that in the primary-side CT, and so differential current would flow through the relay to cause operation.

V. Conclusion

In this paper, transformer differential protection has been presented. It protects a piece of equipment or a section of a network from faults. With proper selection of CTs, differential protection provides faster clearance of faults, and it is more effective in providing discrimination than simple overcurrent relays. CT ratio correction and phase correction, and zero sequence current filtering can be implemented by externally connected ICTs or software ICTs built into the differential relay. Biased differential schemes use restraining coils and second harmonic of magnetizing inrush current to prevent unnecessary operation of the relay during transformer energization, and through fault conditions. However, overall differential protection may only be justified for large transformers (typically > 5MVA)

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