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, etc. 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, \( i_o \) between the CT secondary currents will flow through the relay for it to operate.

![Fig. 1. Current differential protection](image-url)

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.
The input current would be given as:

\[ i_{p1} = i_{p2} + i_f \]  

(1)

The CTs secondary currents will be:

\[ i_{s1} = \frac{n_p}{n_s} i_{p1} = \frac{n_p}{n_s} (i_{p2} + i_f) \]  

(2)

\[ i_{s1} = \frac{n_p}{n_s} i_{p2} + \frac{n_p}{n_s} i_f \]  

(3)

\[ i_{s2} = \frac{n_p}{n_s} i_{p2} \]  

(4)

The differential current is:

\[ i_d = i_k = \frac{n_p}{n_s} i_f \]  

(5)

If \( i_k \) 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., \( i_{s2} = i_{p1} \), and so there will be no differential current flowing through the relay, and hence no relay operation - ensuring correct fault discrimination.

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]:

\[(n_o i_d)^2 > \left(\frac{n_{RT}}{2} i_{s1} + \frac{n_{RT}}{2} i_{s2}\right)^2\]  

(8)

Where

- \( n_o \) = Number of turns on the operating coil
- \( n_{RT} \) = Number of turns on the restraining coil

If \( n_{RT} = k n_o \), \( 0 < k < 1 \)

\[(n_o i_d)^2 > \left(\frac{k}{2} i_{s1} + i_{s2}\right)^2, i_d > k i_{s1} + i_{s2}\]  

(10)

\[i_d > k i_{RT}\]  

(11)

Bias = \[\frac{i_d}{i_{RT}}\]  

(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.

![Operating diagram of biased differential scheme](image)

**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 a 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].

![CT equivalent circuit](image)

**Fig. 6. CT equivalent circuit**

$I_1$ = primary current

$V_1$ = primary voltage

$E_2$ = secondary induced (excitation) voltage

$E_2$ = 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

$X_L$ = leakage reactance referred to the secondary

$X_L$ = reactance of load (burden)

From Fig. 6, we write

$$\frac{I_1}{I_2} = \frac{N_2}{N_1}$$  \hspace{1cm} (13)

$$I_e = I_2 - I_2'$$  \hspace{1cm} (14)

$$\text{Ratio error} = \frac{I_2' - I_2}{I_2} = \frac{I_e}{I_2}$$  \hspace{1cm} (15)

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

$$E_2 = \frac{N_2}{N_1} E_1$$  \hspace{1cm} (16)

$$E_2 = j I_2 (X_e + X_L)$$  \hspace{1cm} (17)

$$E_2 = j (X_e + X_L) \left[ I_2' - I_e \right]$$  \hspace{1cm} (18)
Since all impedance elements are inductive,

\[ E_2 = \frac{N_1}{N_2} \left( X_L + X_m \right) \left( I_1 - I_e \right) \]  \hspace{1cm} (19)

Plotting equation (20) on the same coordinates as the magnetization curve (\( E_2 \) versus \( I_2 \)), we can predict \( I_2 \) for a given \( I_1 \) with known termination, \( X_L \). The solution for \( E_2 \) and \( I_2 \) 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.

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

\[ i_A = i_{AB} - i_{CA} \]  \hspace{1cm} (21)
\[ i_B = i_{BC} - i_{AB} \]  \hspace{1cm} (22)
\[ i_C = i_{CA} - i_{BC} \]  \hspace{1cm} (23)

It can be observed that the currents \(-i_A\) and \(i_c\) are in phase, likewise \(-i_{AB}\) and \(i_b\); \(-i_{BC}\) and \(i_c\).

\[ i_A = i_{AB} - i_{CA} = i_{AB} - i_{AB} \angle 120^\circ \]  \hspace{1cm} (24)

\[ i_A = i_{AB} \left( \frac{3}{2} - j \frac{\sqrt{3}}{2} \right) = \sqrt{3} i_{AB} \angle -30^\circ \]  \hspace{1cm} (25)

Thus \(i_A\) lags \(i_{AB}\) by \(30^\circ\) as shown in Fig. 10.

Similarly,

\[ i_B = \sqrt{3} i_{BC} \angle -30^\circ \]  \hspace{1cm} (26)
\[ i_C = \sqrt{3} i_{CA} \angle -30^\circ \]  \hspace{1cm} (26)

\[ i_{AB} = -\frac{N_s}{N_p} i_b \]  \hspace{1cm} (27)
\[ i_{BC} = -\frac{N_s}{N_p} i_c \]  \hspace{1cm} (27)
\[ i_{CA} = -\frac{N_s}{N_p} i_a \]  \hspace{1cm} (27)

\[ i_A = \frac{N_s}{N_p} (i_a - i_b) \]  \hspace{1cm} (28)
\[ i_A = \frac{N_s}{N_p} \sqrt{3} i_a \angle 30^\circ \]  \hspace{1cm} (28)

\[ i_A = \frac{N_s}{N_p} \sqrt{3} i_c \angle 30^\circ \]  \hspace{1cm} (28)

That is \(i_A\) leads \(i_a\) by \(30^\circ\) – the primary line current leads the secondary line current by \(30^\circ\) as shown in Fig. 10.

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

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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 Dyn1 transformer. 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, $I_s$ 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:

$$\Phi = \Phi_m \sin \omega t$$  \hspace{1cm} (30)

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

$$e = -N_i \frac{d\Phi}{dt} = -\omega N_i \Phi_m \cos \omega t = \omega N_i \Phi_m \sin \left( \alpha t - \frac{\pi}{2} \right)$$  \hspace{1cm} (31)

$N_i$ 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:

$$e = \frac{a_0}{2} + \sum (a_n \cos n \alpha t + b_n \sin n \alpha t)$$  \hspace{1cm} (32)

where

$$a_n = \frac{\omega N_i \Phi_m}{\pi} \left[ \int_{-\pi/2}^{\pi/2} \sin \left( \alpha t - \frac{\pi}{2} \right) \cos n \alpha t dt - \int_{3\pi/2}^{5\pi/2} \sin \left( \alpha t - \frac{\pi}{2} \right) \cos n \alpha t dt \right]$$  \hspace{1cm} (33)

$$a_n = \frac{\omega N_i \Phi_m}{\pi} \left[ \int_{-\pi/2}^{\pi/2} \left( \alpha t - \frac{\pi}{2} \right) \cos n \alpha t dt - \int_{3\pi/2}^{5\pi/2} \left( \alpha t - \frac{\pi}{2} \right) \cos n \alpha t dt \right]$$  \hspace{1cm} (34)

$$b_n = \frac{\omega N_i \Phi_m}{\pi} \left[ \int_{-\pi/2}^{\pi/2} \sin \left( \alpha t - \frac{\pi}{2} \right) \sin n \alpha t dt - \int_{3\pi/2}^{5\pi/2} \sin \left( \alpha t - \frac{\pi}{2} \right) \sin n \alpha t dt \right]$$  \hspace{1cm} (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.
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 is a 15MVA, 33/11kV, Dyn1 transformer. The relay is rated 1A. Transformer turns ratio is:

\[
a = \frac{N_1}{N_2} = \frac{\sqrt{3}V_1}{V_2} = \frac{\sqrt{3} \times 33}{11} = 5.2
\]
The primary full-load current is:

\[ i_A = \frac{15000}{\sqrt{3} \times 33} = 262.43 \text{A} \]

The secondary full-load current is:

\[ i_a = \frac{15000}{\sqrt{3} \times 11} = 787.3 \text{A} \]

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 = \[ 787.3 \times \frac{1}{2600} = 0.303 \text{A} \]

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 = \[ \sqrt{3} \times 0.303 = 0.525 \text{A} \]

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:

\[ i_a = \frac{N_1}{\sqrt{3} N_2} i_A \angle -30^\circ \] (39)

\[ i_s = \frac{i_a}{1600} = 0.492 \angle -30^\circ \] (40)

\[ i = \frac{n_1}{n_2} \sqrt{3} i_a \angle 30^\circ \] (41)

\[ = \frac{n_1}{n_2} \sqrt{3} \left(0.492 \angle -30^\circ\right) \angle 30^\circ = \frac{n_1}{n_2} \times 0.852 \text{A} \]

Fig. 17 shows ratio correction and phase-angle correction using one set physically-connected ICTs.

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

\[ I_{a1} = \frac{V_f}{Z_1 + Z_2} \]  \hspace{1cm} (42)

Where,

- \( V_f \): fault point voltage per unit.
- \( Z_1 \): positive sequence impedance per unit.
- \( Z_2 \): negative sequence impedance per unit.

It can be shown that \( I_{a2} = -I_{a1} \), and that the total fault current is:

\[ I_{bf} = a^2I_{a1} + aI_{a2} = (a^2 - a)I_{a1} \]  \hspace{1cm} (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:

\[ I_{bf} = -j\sqrt{3} I_{a1} \times I_{base} = -j6889A \]

\[ I_{base} = 787.3A \]

It is shown in Fig. 20 that the currents flowing in the secondary circuits of the CTs are equal (\( i_{a1} = i_{a2} \)). 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).

REFERENCES