# Zero Sequence Circuit of Three-legged Core Type Transformers

Jialong Wang — Basler Electric
Raluca Lascu — DTE Energy

## I. Introduction

Fault current estimation is essential in developing a proper protection scheme and setting protective elements. Positive, negative and zero sequence circuits have been developed and used widely in fault calculation.

In most literature, the sequence equivalent circuits are approximate due to the omission of transformer internal resistance and the magnetizing impedance [1][2][3]. There is rarely any problem with the negligence of the small transformer internal resistance in almost all fault calculations. In practical situations, it is a very good approximation to exclude the large magnetizing impedance in positive and negative sequence equivalent circuits. However, a more accurate zero sequence circuit may be needed, depending on both the transformer core structure and the winding connections.

This paper will introduce the core type and shell type core structures and their magnetic flux paths. The magnetizing impedance is small when the core is saturated and should be included in the zero sequence circuit in the following two cases:

1) <u>Three-legged core type transformer</u>
   There is no physical return path to the bottom core yoke, and the zero sequence flux has to go through the high magnetic reluctance through the air gap, structural steel and the tank. The magnetic impedance, which is inversely proportional to the magnetic reluctance, is typically in the range between 40% and 150%.

2) <u>Shell type transformer and four- or five-legged core type transformer</u>
   The lateral core leg(s) generally is sized to carry the flux of one phase. When zero sequence voltage approaches 33% of the rated voltage or higher, the core begins to saturate and the magnetic impedance drops dramatically.

As listed in IEEE C57.105-1978 [4], Y-YG connection is not recommended for three phase transformers. Y-YG connection is incapable of furnishing a stabilized neutral, and its use may result in phase-to-neutral overvoltage on one or two legs as a result of unbalanced phase-to-neutral load. Although it is not commonly seen, legacy or new installations of Y-YG transformers do exist. Analysis of unbalanced condition in the Y-YG transformer is not easily accessible in commonly used reference books. This paper compiles some information on transformer core structure and analysis of three-legged core type transformers. In order to study the Y-YG transformer in unbalanced condition, zero sequence circuit will be developed for common three-phase transformer connections. For a load side line-ground fault of a three-legged core type transformer, the fault current can be calculated, or at least estimated, if the exact zero sequence magnetizing impedance is not known. To verify the developed zero sequence circuit and the fault current calculated from it, a high impedance fault will be staged in the grounded side of a three-phase Y-YG transformer (18 MVA, 13.8kV/4160V), with the secondary neutral grounded through a 4 ohm resistor. A computer simulation also will be used to verify the calculation so fault current for other situations can be estimated without mathematical calculation or actual testing.

## II. Transformer Core Structures

A transformer core is made of magnetic material, serving as a path (or part of a path in some cases) for magnetic flux. Core construction can be either stacked or wound. Core type and shell type are the two basic types of core construction used in power and distribution transformers. In a core type transformer, a single core loop (path of magnetic circuit) links two identical winding coils. The core consists of legs and yokes. A leg, also called a limb, is the part of the core surrounded by windings. The remaining parts of the core, which are not surrounded by windings and are used to connect the legs (limbs), are called yokes. In a shell-type transformer, the laminations constituting the iron core surround the greater part of the windings.

### 2.1 Single Phase Transformer

A single phase core-type transformer is illustrated in Fig. 1. The windings on the two legs are identical. The windings on each leg consist of primary and secondary windings. Fig. 2 is a schematic of a single phase core, with the arrows indicating the magnetic path. Since the core has very high permeability, the magnetic flux is considered to be inside the core only.

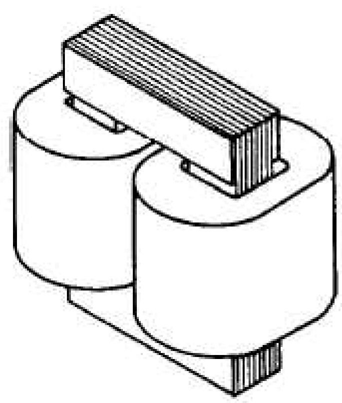


Fig. 1 Single phase core type transformer [4]

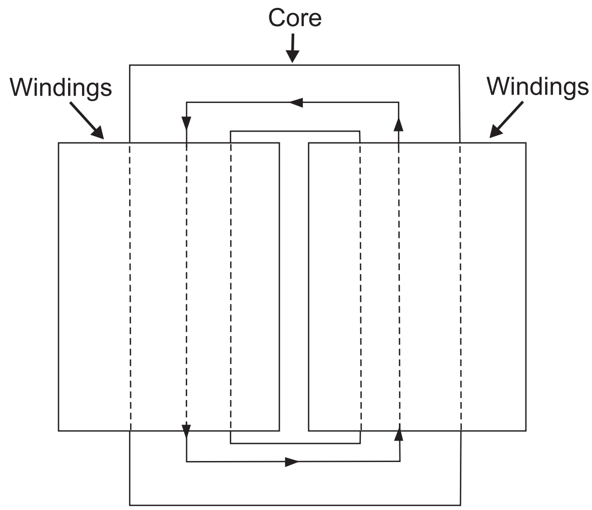



Fig. 2 Schematic of single phase core type magnetic path

A single phase shell-type transformer is illustrated in Fig. 3. In this core construction, a single winding links two core loops (paths of magnetic circuit), as illustrated in Fig. 4.

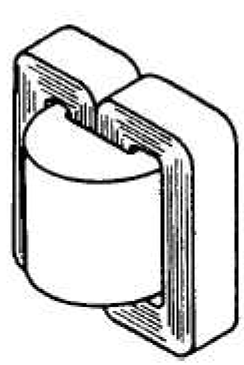


Fig. 3 Single phase shell type transformer [4]

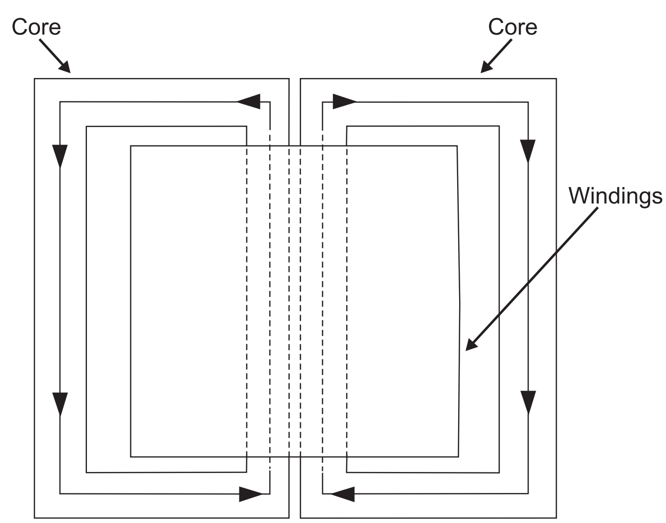



Fig. 4 Schematic of single phase shell type magnetic path

## 2.2 Three Phase Transformer

The majority of three phase transformers are mostly in the form of core-type construction. A small or medium rated transformer is usually of three-legged core-type, as illustrated in Fig. 5. The primary and secondary windings of one phase are on one core leg, which is different from a single phase core-type transformer. Fig. 6 illustrates the schematic of three phase core-type magnetic paths. Under balanced condition, the currents in three phases are equal in magnitude, with angles 120° apart. Accordingly, the vector form fluxes in three phases are 120° apart and summed to zero at the yoke. There is no need of a return path for the flux. If there is some unbalance in the terminal voltage, the residual flux, i.e., sum of the three phase fluxes, will not be zero and it has to return through a path out of the transformer magnetic core. This means the residual flux at the top yoke has to pass through a huge air gap and the tank to the bottom yoke. The path through the air gap and the tank has low permeability and, thus, high magnetic reluctance.

Let's assume the residual voltage is

$$v_{res}(t) = \sqrt{2}V\sin(\omega t) \tag{1}$$

We have the instantaneous flux

$$\phi_{res}(t) = \int v_{res}(t)\,dt = -\frac{\sqrt{2}V}{\omega}\cos(\omega t) \tag{2}$$

and its effective value

$$\Phi = \frac{V}{\omega} \tag{3}$$

Since the flux (in effective value) is equal to the magnetomotive force (MMF) divided by the total reluctance $\Re_{res}$, i.e.

$$\Phi = N \cdot I / \Re_{res} \tag{4}$$

we can get

$$I = \frac{\Re_{res}}{N}\Phi = \frac{\Re_{res}V}{N\omega} \tag{5}$$

and

$$Z = \frac{V}{I} = \frac{N\omega}{\Re_{res}} \tag{6}$$

We can see the impedance is inversely proportional to magnetic reluctance. For a three-legged core-type transformer, since the zero-sequence magnetic reluctance is high, the zero-sequence impedance is low. It is typically in the range between 40% and 150% per unit value. Under unbalanced condition, the zero sequence current will be large and the core and tank may be heated to an unacceptable temperature.

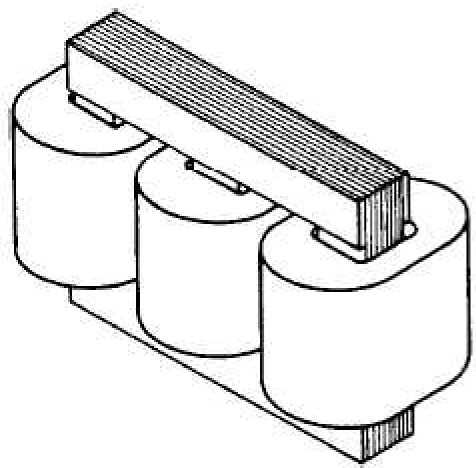


Fig. 5 Three-legged core-type transformer [4]

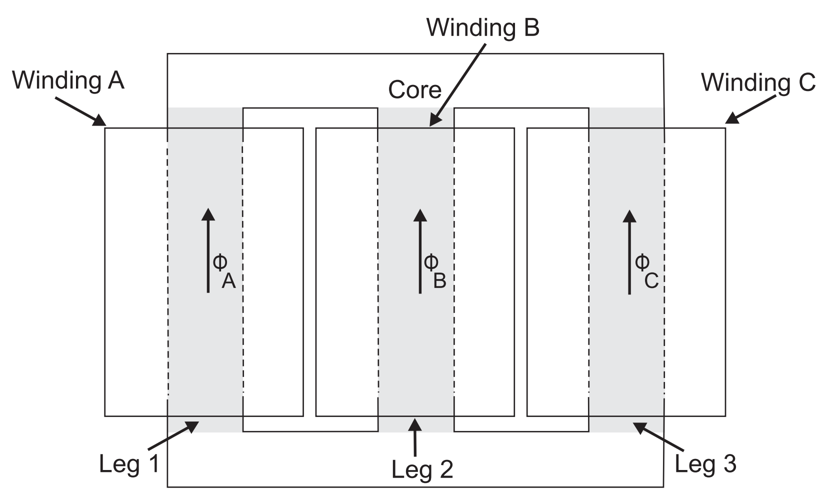



Fig.6 Schematic of three-legged core-type transformer magnetic paths

In order to overcome the shortcoming of three-legged transformers in unbalanced condition, a fourth leg is added to the transformer core. Fig. 7 illustrates a four-legged core-type transformer. The fourth leg provides a path for the zero-sequence magnetic flux, as shown in Fig. 8. For a four-legged transformer, the zero sequence magnetic reluctance is small and the zero-sequence impedance is large.

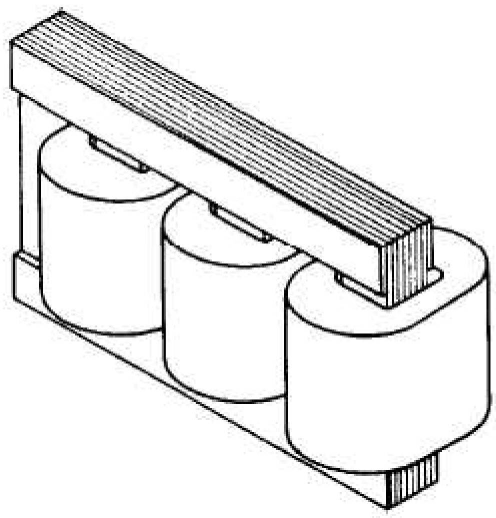


Fig. 7 Four-legged core-type transformer [4]

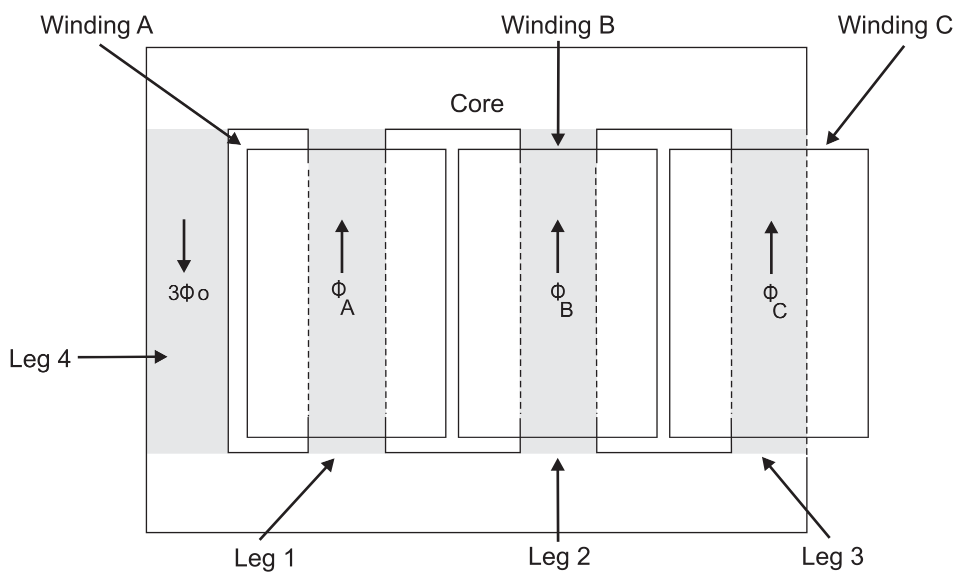



Fig. 8 Schematic of four-legged core-type transformer magnetic paths

The top and bottom yokes generally are designed to carry the full zero sequence flux in the fourth leg. In order to reduce the height of the yoke (thus the height of the transformer) on a large rated transformer for transportability, a fifth leg is added to the four-legged transformer. Fig. 9 shows a wound-type five-legged core type transformer. The schematic of four-legged core-type transformer magnetic paths is shown in Fig. 10. The zero sequence performance of a five-legged transformer is similar to that of a four-legged transformer, which is approximately the positive sequence leakage impedance between the windings until the applied voltage saturates either the yokes or the end legs.

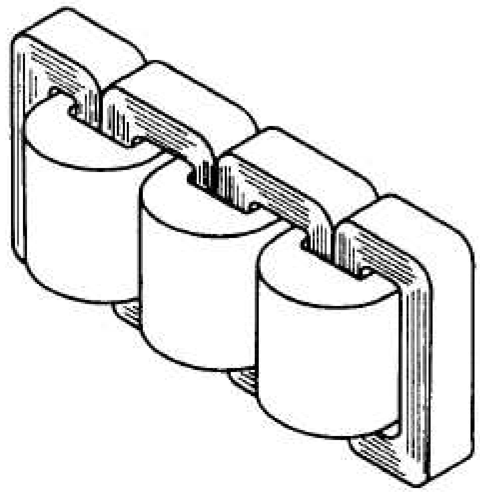


Fig. 9 Five-legged core-type transformer [4]

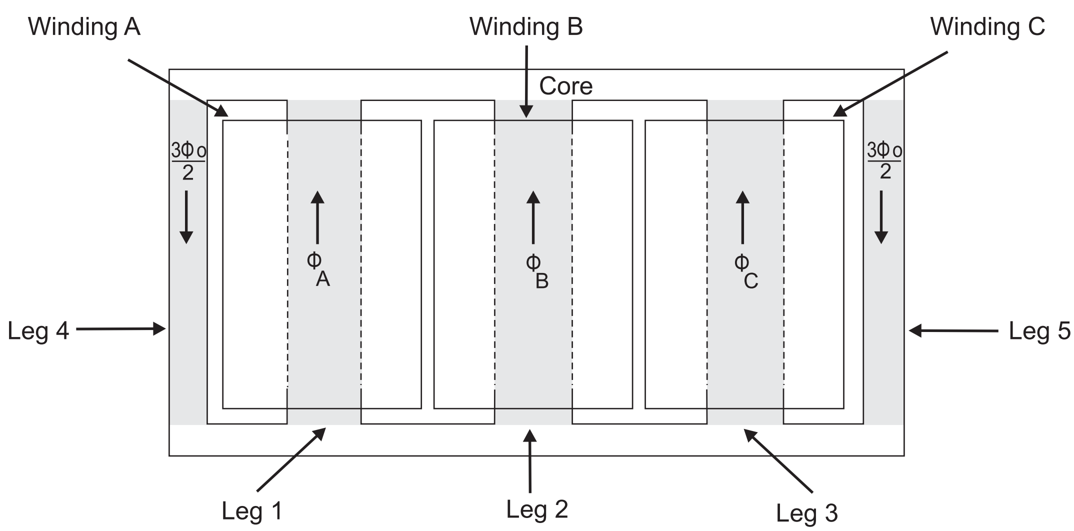



Fig. 10 Schematic of five-legged core-type transformer magnetic paths

The shell type design is different from the three phase core type design. In a shell type transformer, the windings are usually constructed from stacked coil spirals like pancakes. The windings can be wound, too. A three phase shell-type transformer is illustrated in Fig. 11. The shell type transformer is a variation of the five-legged core-type transformer.

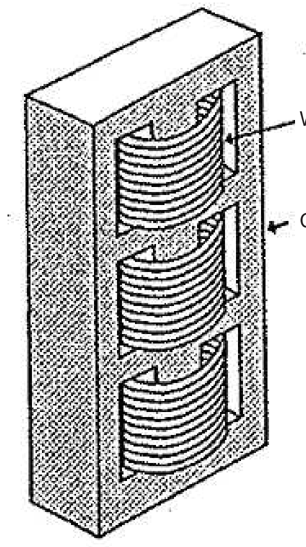



Fig. 11 Shell-type transformer [12]

Flux paths and its distribution in a shell type transformer are somewhat complicated. Fig. 12 illustrates the flux of three phases. The arrow in Fig. 12 represents the assumed positive direction and does not represent the actual direction of the flux. Fig. 12 illustrates that paths exist for zero sequence flux. Since the reluctance of the zero sequence flux path is low, the associated zero sequence magnetizing impedance is high. In unbalanced voltage or load condition, the zero sequence current is negligible unless the transformer core is overexcited to saturation.

If balanced voltage is applied to the three windings, the balanced three phase fluxes are

$$\Phi_A = \Phi\cos(\omega t)$$
$$\Phi_B = \Phi\cos(\omega t - 120 + 180) = \Phi\cos(\omega t + 60)$$
$$\Phi_C = \Phi\cos(\omega t - 240)$$

The fluxes in the shaded area can be calculated

$$\Phi_1 = \frac{\Phi_A}{2} - \frac{\Phi_B}{2} = \frac{1}{2}(\Phi\cos(\omega t) - \Phi\cos(\omega t - 120)) = -\frac{\sqrt{3}}{2}\Phi\sin(\omega t - 60)$$

$$\Phi_2 = \frac{\Phi_B}{2} - \frac{\Phi_C}{2} = \frac{1}{2}(\Phi\cos(\omega t - 120) - \Phi\cos(\omega t - 240)) = \frac{\sqrt{3}}{2}\Phi\sin(\omega t)$$

The maximum flux in the shaded area in Fig. 12 would be $\sqrt{3}$ times that in the top and bottom yokes.

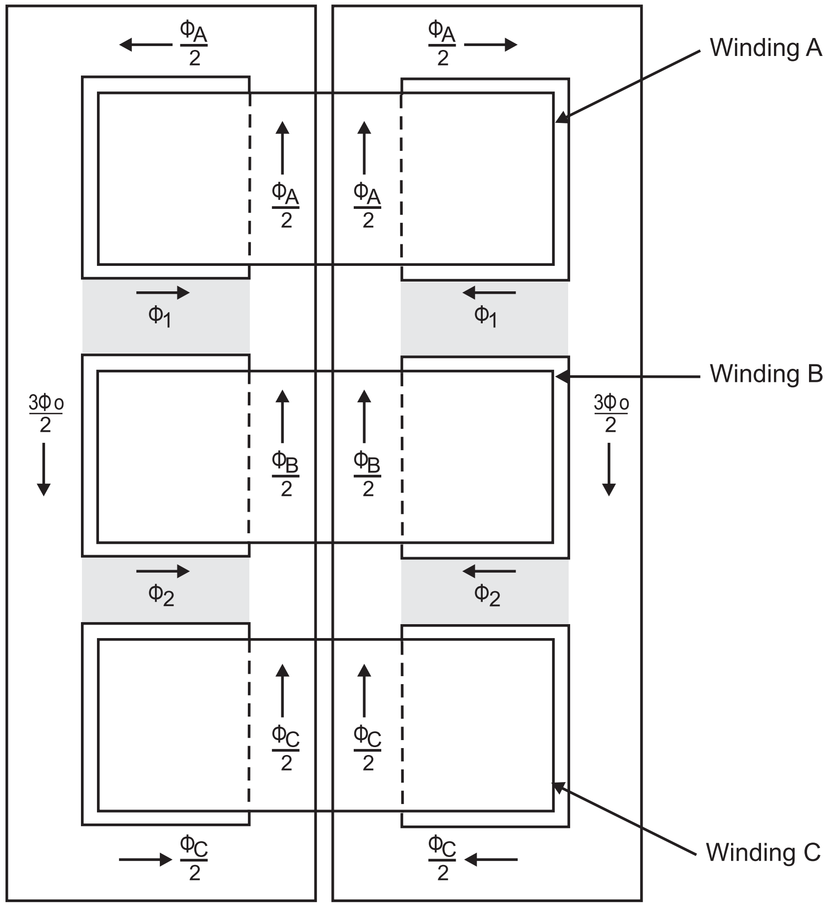



Fig. 12 Flux illustration in a three phase shell type transformer

In Fig. 11, if the winding direction of the coils on the middle leg is opposite that of the windings on the other two legs, the three phase fluxes are

$$\Phi_A = \Phi \cos(\omega t)$$
$$\Phi_B = \Phi \cos(\omega t - 120 + 180) = \Phi \cos(\omega t + 60)$$
$$\Phi_C = \Phi \cos(\omega t - 240)$$

And the fluxes in the shaded area would be

$$\Phi_1 = \frac{\Phi_A}{2} - \frac{\Phi_B}{2} = \frac{1}{2}(\Phi \cos(\omega t) - \Phi \cos(\omega t + 60)) = \frac{1}{2}\Phi \sin(\omega t + 30)$$
$$\Phi_2 = \frac{\Phi_B}{2} - \frac{\Phi_C}{2} = \frac{1}{2}(\Phi \cos(\omega t + 60) - \Phi \cos(\omega t - 240)) = \frac{1}{2}\Phi \cos(\omega t)$$

By reversing the direction of the middle winding, the maximum flux flowing in the shaded parts is the same as the maximum flux in the top and bottom yokes. To reduce the core size, the direction of the middle winding is reversed. With the middle winding reversed, at instant t=0, i.e., the instant when the top leg flux reaches its maximum, the flux distribution is illustrated in Fig. 13. It is to be noted that the arrow in Fig. 13 represents the actual flux direction. For clarity, the windings are not shown in Fig. 13.

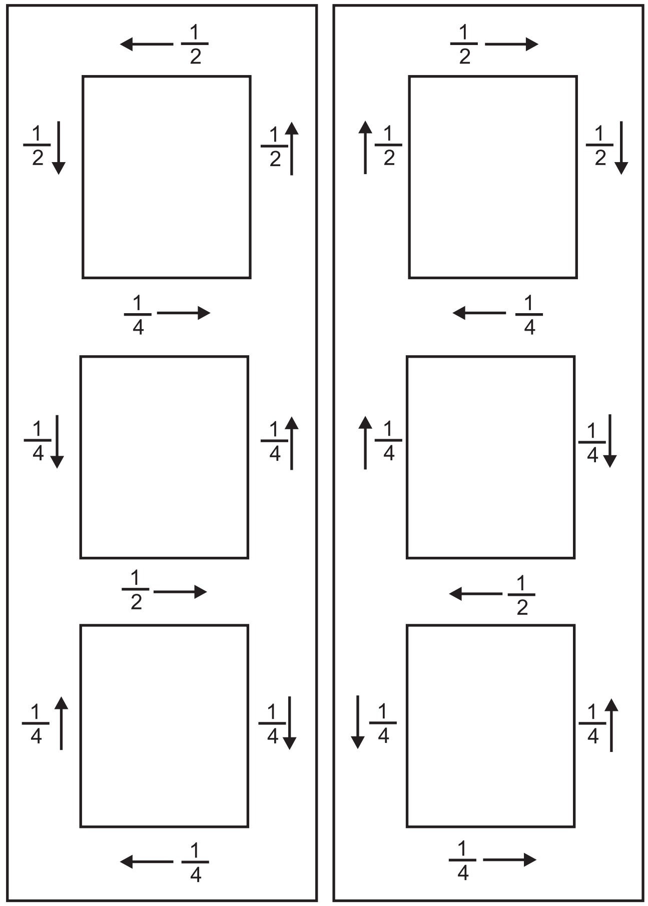



Fig. 13 Example of flux distribution in a three phase shell type transformer

### III. Equivalent Circuit of a Two-winding Transformer

For a single phase two-winding transformer, the equivalent circuit is given in Fig. 14. $R_H$ and $R_L$ are resistances of the primary and secondary windings respectively. $X_H$ and $X_L$ are leakage reactances of the primary and secondary windings respectively. $R_c$ represents no load (or core) losses due to the magnetic hysteresis loop and eddy current. $X_M$ represents the magnetizing reactance, which varies with the core saturation level.

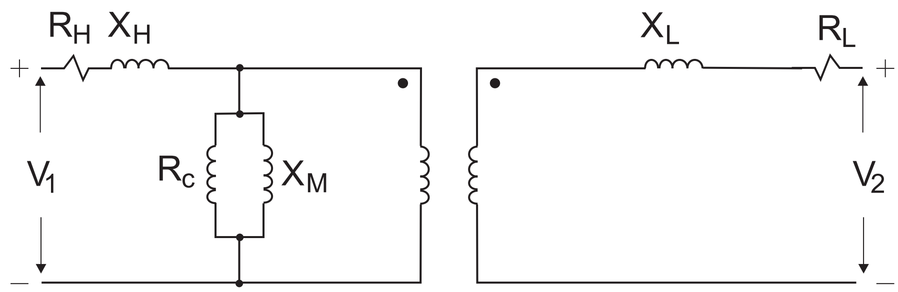



Fig. 14 Equivalent circuit of a two-winding transformer

When a transformer is under normal condition, the magnetizing reactance is typically at least 50 per unit value. $R_c$ is typically very large by design to reduce no load losses. Let

$$Z_H = R_H + jX_H,$$
$$Z_L = R_L + jX_L,$$
$$Z_M = R_C + jX_M.$$

$Z_L$ can be converted to a primary side value $Z_L'$ by the square of turns ratio. Fig.15 illustrates a simplified equivalent circuit of a single phase two-winding transformer. For simplicity, $Z_L'$ is replaced by $Z_L$ in Fig.15. Since $Z_M$ is much larger compared to $Z_H$ and $Z_L$, $Z_M$ is often omitted. With $Z_M$ omitted, $Z_H$ and $Z_L$ can be combined to be one impedance, i.e., Z = $Z_H + Z_L$. A simpler equivalent circuit is given in Fig. 16.

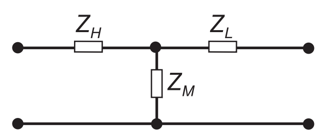



Fig. 15 Simplified equivalent circuit of a two-winding transformer

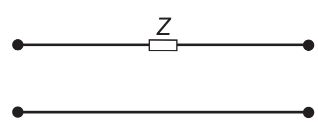



Fig. 16 Equivalent circuit of a two-winding transformer neglecting $Z_M$

For a three phase transformer, positive sequence, negative sequence and zero sequence networks are needed for fault analysis. Fig. 16 is good for positive and negative sequence networks. Zero sequence networks are usually different and depend on the transformer core structure and connections.

For most transformer core structure and connections, the zero sequence magnetizing impedance is very large, thus the zero sequence equivalent circuit can be considered an open circuit. Under this assumption, the zero sequence equivalent circuits are given in Fig. 17. Some variations of Fig. 17 can be found in most reference books [1][2] [3]. Solid grounded Y is not listed in Fig. 17 since it is a special case of impedance grounded Y with zero impedance.

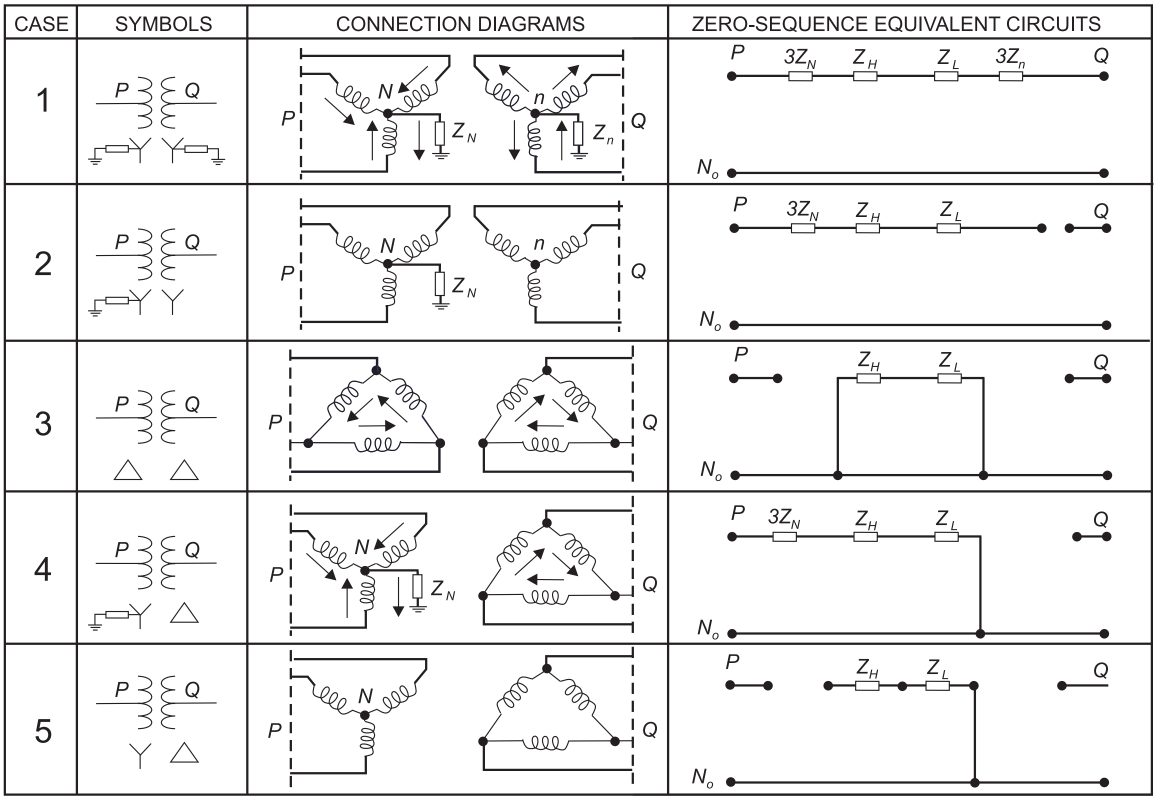
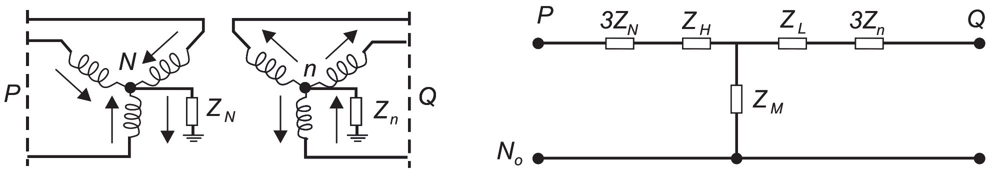



Fig. 17 Transformer zero sequence equivalent circuits with infinitive $Z_M$

The omission of the magnetizing impedance $Z_M$ is a good approximation in most cases, unless the core is saturated. If there is a grounding impedance in a Y-connected winding, the grounding impedance does not affect the positive or negative sequence circuit since the current flowing in the grounding impedance contains only zero sequence current component.

For a Y-YG transformer, since there is no zero-sequence path in the Case 4 in Fig. 17, there would be no zero-sequence current. However, this conclusion may not be true for a three-legged core type Y-YG transformer. As described in an earlier section, for a three-legged core-type transformer, the zero sequence impedance is relatively small and the magnetizing branch cannot be considered as an open circuit. The low zero sequence magnetizing impedance requires a modification in the zero sequence circuits given in Fig. 17 for Y-YG and YG-YG connected three-legged core-type transformers.

The equivalent circuit of a single phase transformer is given in Fig. 15. Fig. 15 also represents the zero sequence circuit of a solidly grounded YG-YG three phase transformer. For a more general case of a YG-YG connected transformer, the grounding impedance can be combined with the winding resistance and leakage impedance. Since the neutral current flowing in the grounding impedance is three times the zero sequence current, the grounding impedance needs to be multiplied by three in the zero sequence circuit. For the connection diagram in Case 1 in Fig. 17, the zero sequence circuit is given in Fig. 18, which can be derived from Fig. 13 by including the effect of grounding impedance.




(a) connection diagram (b) zero-sequence equivalent circuit

Fig. 18 A general zero sequence circuit of YG-YG transformer

For a YG-Delta connected transformer, zero sequence current can freely circulate in the delta winding. As long as zero sequence is concerned, the transformer acts as if it is short-circuited whether the winding is loaded or not. The delta connection suppresses the flow of zero sequence flux, and it does not really matter whether there is a flux return path or not. This explains that, for YG-Delta connection, the zero sequence circuit basically is the same whether the transformer is a three-legged core type or not.

Including the magnetizing impedance, the zero sequence equivalent circuits are given in Fig. 19 for common winding connections. A variation of Fig. 19 is available in a reference book [5]. It is to be noted that the magnetizing impedance $Z_M$ is not included in zero-sequence equivalent circuits when there is a delta connected winding.

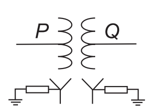
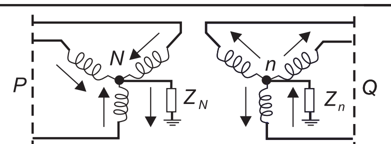
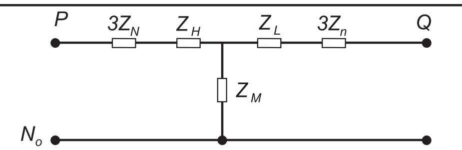
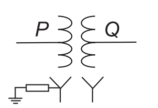
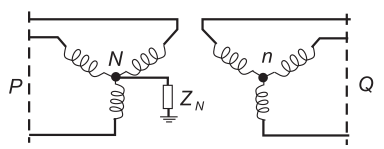
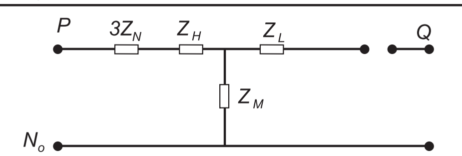
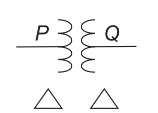
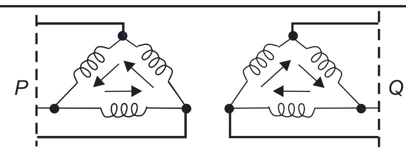
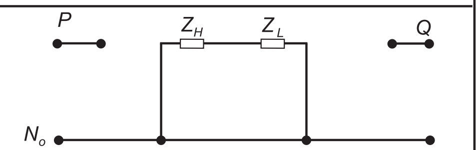
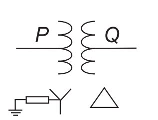
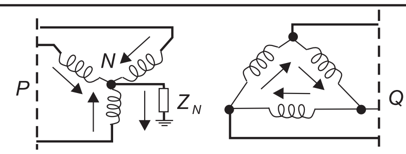
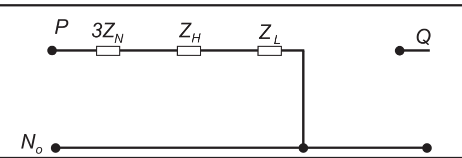
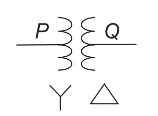
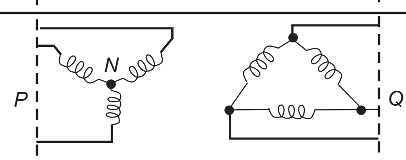
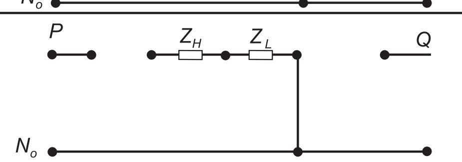
| CASE | SYMBOLS | CONNECTION DIAGRAMS | ZERO-SEQUENCE EQUIVALENT CIRCUITS |
|---|---|---|---|
| 1 |  |  |  |
| 2 |  |  |  |
| 3 |  |  |  |
| 4 |  |  |  |
| 5 |  |  |  |

Fig. 19 Transformer zero sequence equivalent circuits for all cases

## IV. Line-ground Fault Current Calculation of Y-YG Transformers

As we have discussed, the zero sequence impedance of a three-legged core type Y-YG transformer is small, and the magnetizing branch cannot be assumed to be an open circuit in the calculation of line ground fault current.

The connection diagram of Y-YG transformer, its positive, negative and zero sequence equivalent circuits are given in Fig. 20.

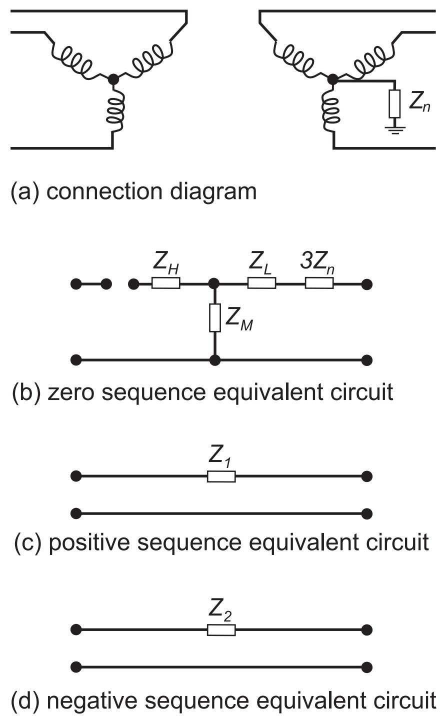



Fig. 20 Y-YG transformer connection diagram and sequence equivalent circuits

Fault current for a line-ground fault in the YG side of transformer will be studied. The Y side is connected to a generator, as is shown in Fig. 21.

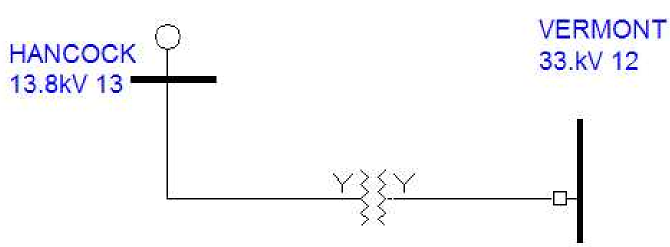



Fig. 21 Y-YG transformer connected to a generator

Assume both the generator and transformer have the rating of 100 MVA. The base impedance and base current are

$$Z_B = \frac{(base\ kV_{LL})^2}{base\ MVA_{3\phi}} = \frac{33^2}{100} = 10.89\ \Omega$$

$$I_B = \frac{base\ MVA_{3\phi} \times 1000}{\sqrt{3} \times base\ kV_{LL}} = \frac{100 \times 1000}{\sqrt{3} \times 33} = 1749.54\, A$$

For a fault resistor of 10 Ω,

$$R_F\,(pu) = \frac{R_F\ (\Omega)}{R_B} = \frac{10}{10.89} = 0.9183\ \ pu$$

Generally speaking, the generator synchronous impedance is larger and zero sequence impedance is smaller compared to its other impedances. For simplicity in this fault study, the generator synchronous, transient, subtransient, negative and zero sequence impedance are all assumed to be 0.1 pu. The transformer parameters are $X_0 = X_1 = X_2 = 0.14\, pu.$ The zero sequence magnetizing impedance of the transformer is assumed to be 0.5 pu for a three-legged core-type transformer and 100 pu for other types of transformers.

For a line-ground fault in the terminal of YG transformer, the generator positive and negative sequence impedance needs to be included in the Thevenin equivalent circuit at fault point. The generator zero-sequence impedance does not affect the Thevenin zero sequence equivalent circuit since the generator is connected to the ungrounded Y side.

Fig. 22 gives the positive, negative and zero sequence equivalent circuits at fault point.

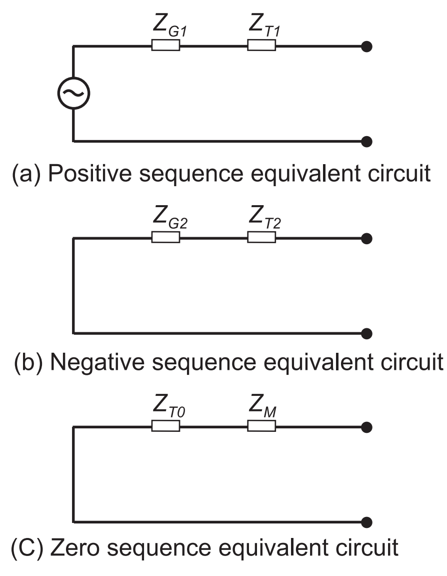



Fig. 22 Sequence equivalent circuits

For a line-ground fault, fault current can be calculated from a circuit in Fig. 23, which is formed by connecting the positive, negative and zero sequence circuits, with three times fault impedance.

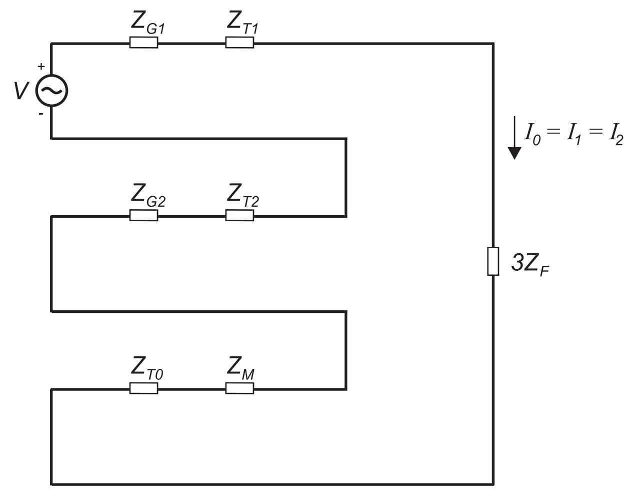



Fig. 23 Circuit to calculate line ground fault current

The zero, positive and negative sequence fault currents can be calculated using the following equation,

$$I_0 = I_1 = I_2 = \frac{V}{Z_{G1} + Z_{T1} + Z_{G2} + Z_{T2} + Z_{T0} + Z_M + 3Z_F} \qquad (7)$$

The fault current is

$$I_F = \frac{3V}{Z_{G1} + Z_{T1} + Z_{G2} + Z_{T2} + Z_{T0} + Z_M + 3Z_F} \qquad (8)$$

From equation (8), the fault current of a line-ground current in the ground side of Y-YG can be calculated.

### 4.1 Line-ground fault of Y-YG transformers (except three-legged core type)

For transformers except for three-legged core type (four- or five-legged core type transformers, shell type transformers) with YG-YG, Y-YG, YG-Y connections, $Z_M$ is very large. Assume $Z_M = 100\ pu$ and $V = 1\ pu$ for prefault condition, from equation (8), we can get the magnitude of the fault current

$$I_F = \left| \frac{3}{0.1i + 0.14i + 0.1i + 0.14i + 0.14i + 100i + 3*0.9183} \right| = 0.03\ pu$$

Since the fault current is so small, it generally is accepted that fault current cannot flow for a line-ground fault for a Y-YG transformer unless the transformer is of a three-legged core type.

### 4.2 Line-ground fault of three-legged core type transformers with Y-YG connection

For a Y-YG connected three-legged core type transformer, $Z_M$ is relatively small with a typical value between 0.4 and 1.5 pu. $Z_{T0}$ in equations (7) and (8) represents $Z_L$ in Fig. 19(b). $Z_L$ and $Z_M$ generally are unavailable and need to be estimated. Reference [6] describes a method to get these values by testing. Let $Z_M = 0.5\, pu$, $Z_{T0} = 0.1\, pu$ and $V = 1\, pu$ for prefault condition.

From equation (8), the fault current for the three-legged core type transformer is

$$I_F = \left| \frac{3}{0.1i + 0.14i + 0.1i + 0.14i + 0.14i + 0.5i + 3*0.9183} \right| = 1.01\, pu$$

We can see that the phase fault current can be large due to a low zero sequence magnetizing impedance $Z_M$ . From this example, we do see the big difference in line-ground fault current between a three-legged core type and other type of transformers.

For other fault types, based on the sequence equivalent circuits, formulae to calculate fault current can be derived easily from methods provided in almost any book on power system analysis.

## V. Fault Simulation

ASPEN OneLiner was used to simulate the same line-ground fault for the example system in Fig. 21. All parameters in section IV are kept the same.

### 5.1 Line-ground fault of Y-YG transformers (except three-legged core type)

Fig. 24 shows the transformer configuration in ASPEN OneLiner tool. The zero sequence magnetizing susceptance is the reciprocal of the zero sequence magnetizing impedance. Corresponding to $Z_M = 100\, pu$, the zero sequence magnetizing susceptance $B_0 = -0.01$ pu.

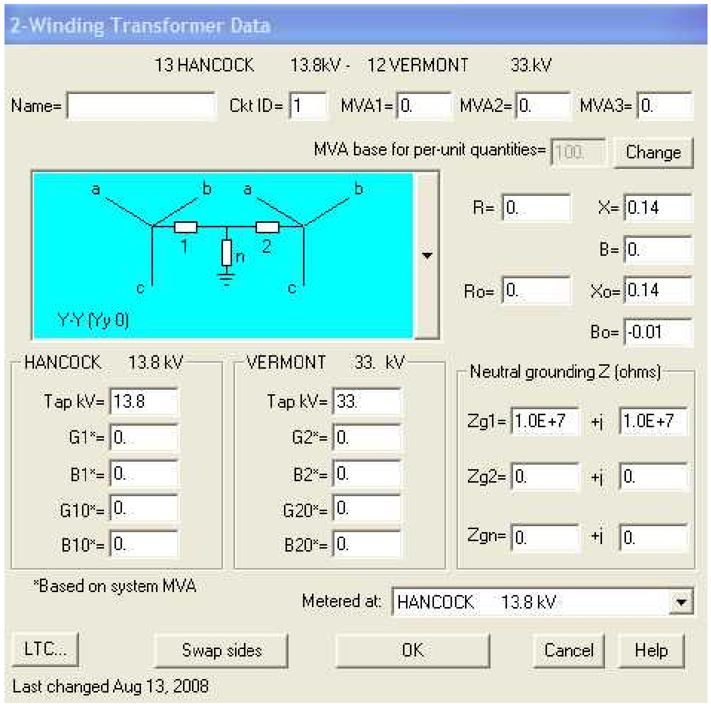



Fig. 24 Transformer with 100 pu zero sequence magnetizing impedance

The phase A ground fault is simulated at VERMONT bus. The result is shown in Fig. 25. Phase A fault current is 52 A (0.03 pu), which is negligible. This result matches the manual calculation based on sequence equivalent circuits in Section IV.

```
=====================================================================================================================
  3. Bus Fault on:         12 VERMONT      33.  kV 1LG Type=A R=10
                                                FAULT CURRENT (A @ DEG)
                 + SEQ            - SEQ            0 SEQ            A PHASE           B PHASE           C PHASE
                17.4@ -58.4      17.4@ -58.4      17.4@ -58.4      52.2@ -58.4        0.0@   0.0        0.0@   0.0
                                                THEVENIN IMPEDANCE (OHM)
                0.+j2.61359      0.+j2.61359   0.35632+j1090.19

                 SHORT CIRCUIT MVA= 3.0           X/R RATIO= 36.0849     R0/X1= 0.13633    X0/X1= 417.123
---------------------------------------------------------------------------------------------------------------------
BUS     12 VERMONT          33.KV  AREA   3  ZONE   1   TIER   0       (PREFAULT V=1.000@  30.0 PU)
                                     + SEQ           - SEQ          0 SEQ          A PHASE        B PHASE        C PHASE
VOLTAGE (KV, L-G)          >     19.007@  30.0   0.045@-148.4   18.954@-148.4   0.522@ -58.4   33.132@-119.1   32.613@-179.3
BRANCH CURRENT (A) TO      >
   13 HANCOCK        13.8  1T      17.4@ 121.6      17.4@ 121.6      17.4@ 121.6      52.2@ 121.6       0.0@   0.0       0.0@   0.0

CURRENT TO FAULT (A)       >       17.4@ -58.4      17.4@ -58.4      17.4@ -58.4      52.2@ -58.4       0.0@   0.0       0.0@   0.0
THEVENIN IMPEDANCE (OHM)   >     2.61359@  90.0   2.61359@  90.0   1090.19@  90.0
---------------------------------------------------------------------------------------------------------------------
```

Fig. 25 Simulation results of high zero sequence magnetizing impedance

### 5.2 Line-ground fault of low zero sequence magnetizing impedance

In this simulation, the zero sequence magnetizing susceptance $B_0$ in Fig. 25 is changed to $B_0 = -2$, which corresponds to 0.5 pu zero sequence magnetizing impedance for a three-legged core type transformer. Everything else stays the same as that in the simulation in Section 5.1. The phase A ground fault current from simulation is shown in

Fig. 26. Phase A fault current is 1764.4A (1.01 pu), which is significant and cannot be neglected. This result matches that from manual calculation in Section IV perfectly.

```
=======================================================================================================
  5. Bus Fault on:         12 VERMONT      33.  kV 1LG Type=A R=10
                                                      FAULT CURRENT (A @ DEG)
               + SEQ               - SEQ              0 SEQ            A PHASE            B PHASE            C PHASE
             588.1@   7.9        588.1@   7.9       588.1@   7.9      1764.4@   7.9        0.0@   0.0        0.0@   0.0
                                                      THEVENIN IMPEDANCE (OHM)
              0.+j2.61359        0.+j2.61359     0.0109+j6.96959

               SHORT CIRCUIT MVA= 100.8         X/R RATIO= 0.40641     R0/X1= 0.00417    X0/X1= 2.66667
-------------------------------------------------------------------------------------------------------
BUS     12 VERMONT         33.KV  AREA    3  ZONE   1   TIER   0        (PREFAULT V=1.000@  30.0 PU)
                                    + SEQ            - SEQ            0 SEQ          A PHASE         B PHASE         C PHASE
VOLTAGE (KV, L-G)         >      18.529@  25.6    1.537@ -82.1    4.099@ -82.2    17.644@   7.9   21.594@ -89.1   17.601@ 156.6
BRANCH CURRENT (A) TO     >
   13 HANCOCK        13.8  1T     588.1@-172.1     588.1@-172.1     588.1@-172.1   1764.4@-172.1       0.0@   0.0      0.0@   0.0

CURRENT TO FAULT (A)      >       588.1@   7.9     588.1@   7.9     588.1@   7.9   1764.4@   7.9       0.0@   0.0      0.0@   0.0
THEVENIN IMPEDANCE (OHM)  >     2.61359@  90.0   2.61359@  90.0   6.9696@  89.9
-------------------------------------------------------------------------------------------------------
```

Fig. 26 Simulation results of low zero sequence magnetizing impedance.

## VI. Testing of Line-ground Fault in a Three-legged Core Type Transformer

Field tests were staged and conducted at one of DTE Energy power plants of a three-legged core type transformer. The transformer size was 18 MVA rated 13.8 kV on the primary and 4160 V on the secondary. The primary was connected as wye ungrounded; the secondary was connected wye resistive grounded through a four ohm resistor. The transformer pu impedance on its own base was 7%. The value of zero sequence magnetizing impedance was unknown. The purpose of the multiple tests was to measure the value of a phase to ground fault current on the secondary of this type transformer. A 480 V voltage supply was applied to the primary side of the transformer.

**Case 1: One phase grounded, neutral in LV (low voltage) side connected to the tank through a 4 Ω resistor, tank grounded.**

This is a simplified test diagram of the first test that was run labeled Case 1. Currents in terminal X0, X1, H1, H2, H3 and in the 4Ω resister were measured.

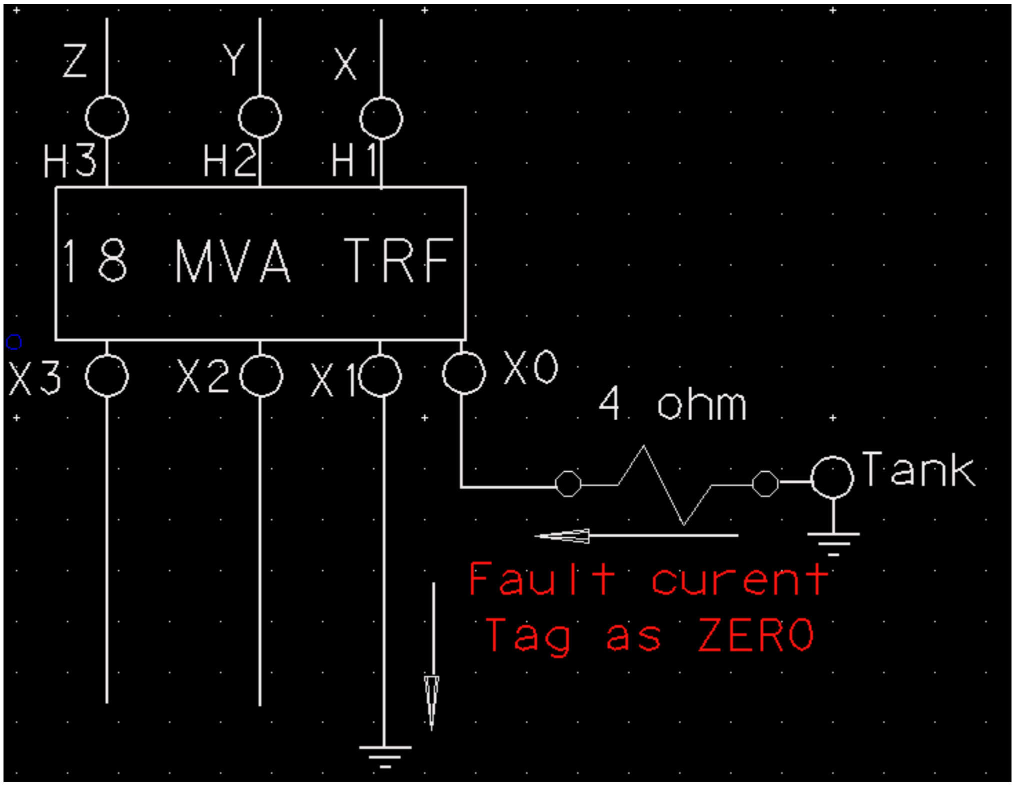



Fig. 27 Case 1 test diagram

Here are the test results of Case 1.

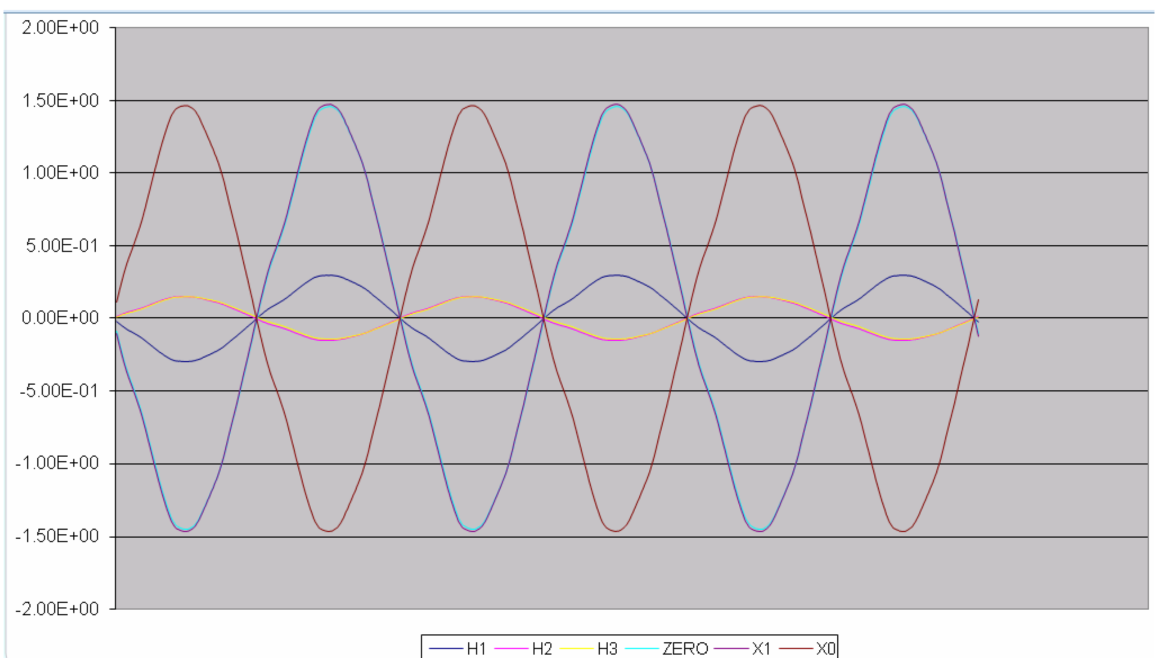



Fig. 28 Case 1 test results

In Fig. 28, the vertical axis is in the unit of volt, and 1 volt represents 20 Amps of current. As can be seen from the graph in Fig. 28, the value of the fault current measured at X1 is equal in magnitude and 180 degrees from the current at X0. This is expected, based on the sensing hookup in Fig. 27. The fault current measured was 20.7 Amps as illustrated in the graph.

The fault current can be calculated using the method developed in section IV. The line neutral voltage at the YG terminal (with normal voltage rating of 4160 V) is

$$V = 480/\sqrt{3} \times 4160/13800 = 83.54 \ volts$$

The transformer base impedance can be calculated,

$$Z_{base} = \frac{V_{LL}^2}{S} = \frac{4.16^2}{18} = 0.9614 \ \Omega$$

The positive and negative sequence leakage impedances of the transformer are

$$Z_{T1} = Z_{T2} = 0.07 \times 0.9614 = 0.0673 \ \Omega$$

Since the typical value of zero sequence magnetizing impedance is between 0.40 pu and 1.5 pu, the unknown zero sequence magnetizing impedance is assumed to be 0.95 pu,

$$Z_M = 0.95 \times 0.9614 = 0.9133 \ \Omega$$

Neglecting both the positive and negative source impedances, i.e., $Z_{G1} = Z_{G2} = 0$ . From equation (8), the calculated fault current is

$$I_F = \frac{3V}{|(Z_{T1} + Z_{T2} + Z_M)i + 3Z_F|} = \frac{3 \times 83.54}{|(0.0673 + 0.0673 + 0.9133)i + 3 \times 4|} = 20.81 \ Amps$$

The measured current, 20.7 Amps, and calculated current, 20.81 Amps, are very close and considered to match each other.

More tests were run with the same purpose of calculating the phase to ground fault current but with different connection points to ground. The test setups and results are shown as follows:

**Case 2. The neutral in LV side is grounded through a 4Ω resistor first and then connected to the tank.**

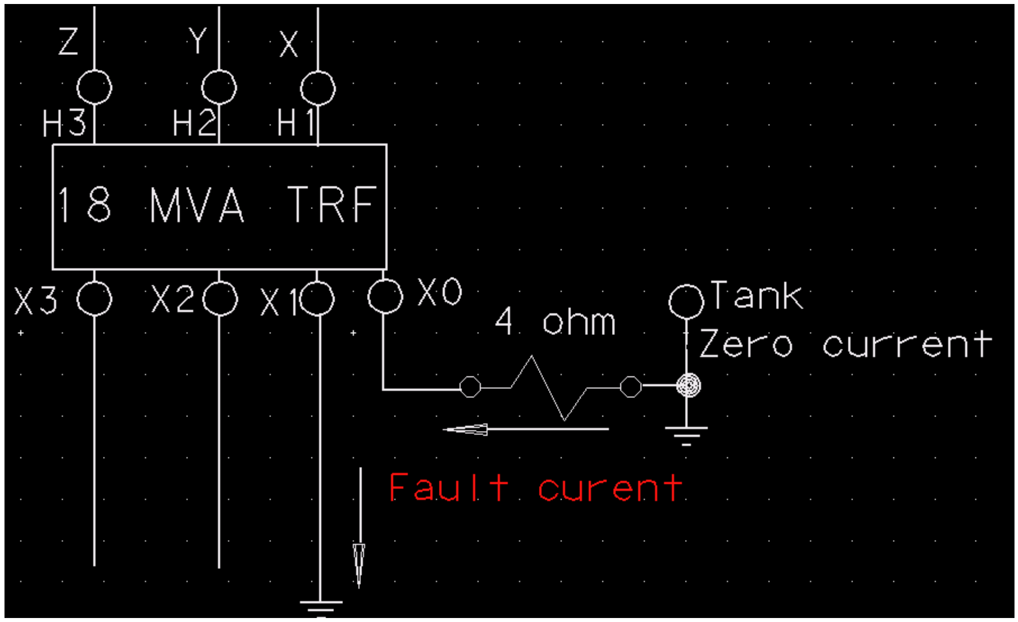



Fig. 29 Case 2 test diagram

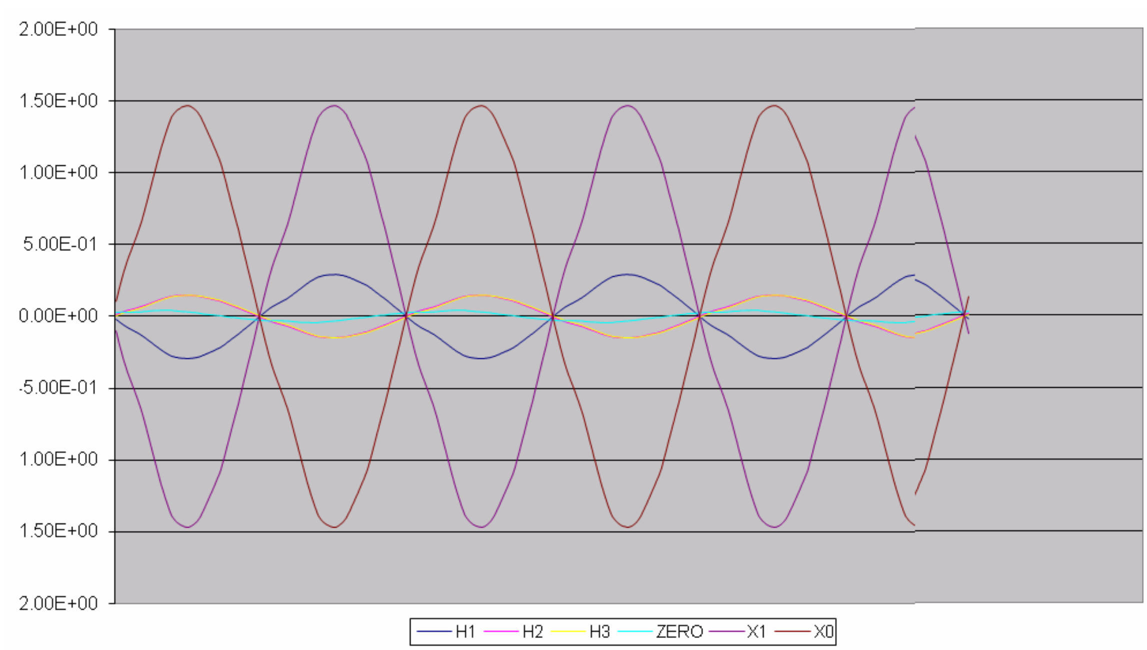



Fig. 30 Case 2 test results

**Case 3. One phase was connected to the tank, the tank connected to one end of the 4Ω resistor and then grounded.**

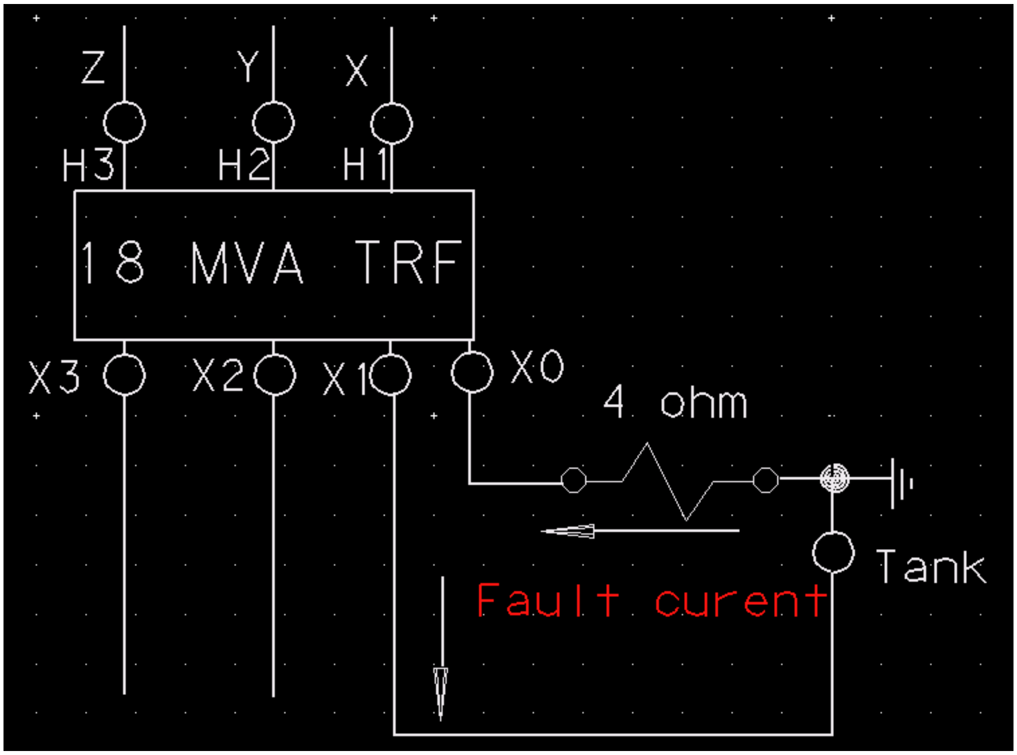



Fig. 31 Case 2 test diagram

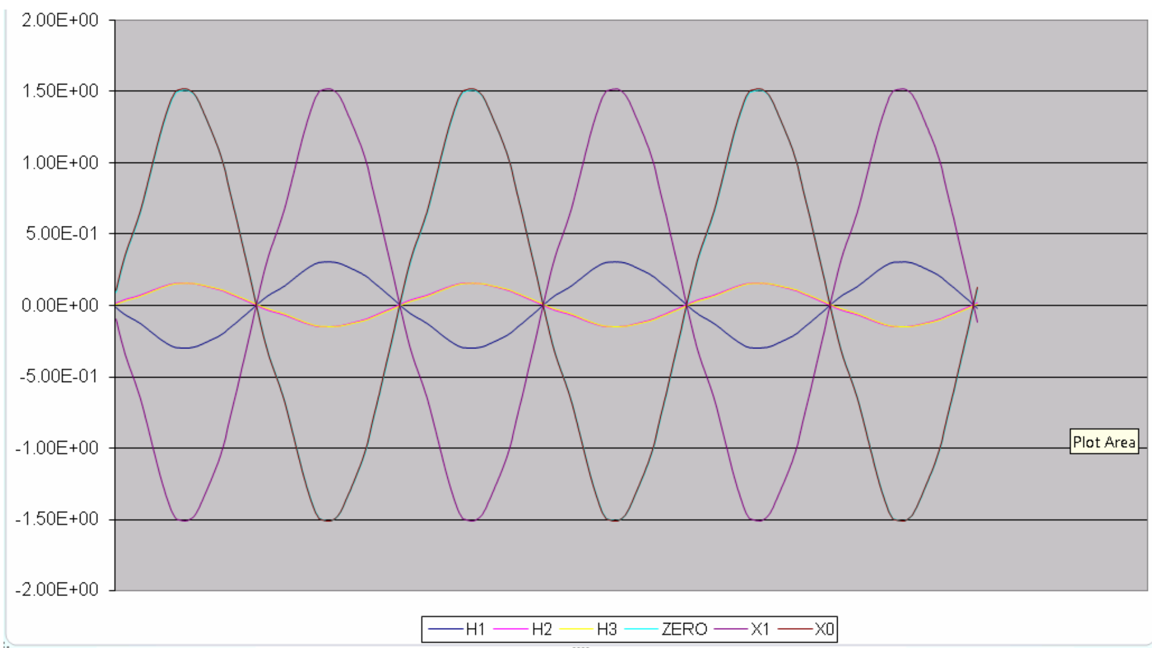



Fig. 32 Case 3 test results

The results are very similar, confirming that the three legged core transformer will produce a phase to ground current with a wye ungrounded wye grounded connection.

## VII. Conclusion

For three-legged Y-YG core type transformers, due to the high reluctance of zero-sequence magnetic return path, the zero-sequence magnetizing impedance is low. The low zero-sequence magnetizing impedance will allow fault current to flow for a line-ground fault in the YG side of a three-legged core type transformer. When calculating line-ground fault current of a three-legged core type transformer, the zero sequence equivalent circuit needs to include the zero-sequence magnetizing impedance. The zero-sequence equivalent circuit from most classic reference books does not take magnetizing impedance into account and needs to be modified. This paper gives the modified zero-sequence equivalent circuit for a three-legged core-type transformer. Theoretical calculation, computer simulation, and actual staged tests verify that fault current based on the modified zero sequence circuit matches the result from the simulation and actual test.

## Acknowledgement:

The authors would like to thank Dr. Thanh C. Nguyen of Advanced Systems for Power Engineering (ASPEN) for his valuable discussion on zero sequence equivalent circuit of three-legged core type transformers.

## References:

1. J. Lewis Blackburn, Thomas J. Domin, Protective Relaying Principles and Applications, 3rd Edition, CRC Press
2. Walter A. Elmore, Protective Relaying: Theory and Applications, 2nd Edition, Marcel Dekker, 2004
3. John J. Grainger, Power System Analysis, McGraw-Hill,1994
4. IEEE C57.105™-1978 (R2008), IEEE guide for application of transformer connections in three-phase distribution systems
5. J.C. Das, Power System Analysis: Short-Circuit Load Flow and Harmonics, Marcel Dekker, 2002
6. General Electric, GET-3388B, The Whys of the Wyes
7. B. A. Cogbill, Are Stabilizing Windings Necessary in All Y-Connected Transformers?, AIEE Power Apparatus and Systems, Vol. 78, Issue 3, 1959
8. John J. Winders, Jr., Power Transformers: Principles and Applications, Marcel Dekker, 2002
9. S.V. Kulkarni and S.A. Khaparde, Transformer Engineering, Marcel Dekker, 2004
10. James H. Harlow (Editor), Electric Power Transformer Engineering, 2nd Edition, CRC Press, 2007
11. T.A. Short, Electric Power Distribution Handbook, CRC Press, 2004
12. James J. Burke, Power Distribution Engineering, Marcel Dekker, 1994

Basler Electric®

www.basler.com

Highland, Illinois USA
Tel: +1 618.654.2341
Fax: +1 618.654.2351
email: info@basler.com

Suzhou, P.R. China
Tel: +86 512.8227.2888
Fax: +86 512.8227.2887
email: chinainfo@basler.com