The use of simple drawings to determine fault currents

Er. Lee Wai Meng outlines an easier alternative to the complicated calculations normally used.

Introduction

The method of symmetrical components is used to analyse the behaviour of electrical power systems during unbalanced conditions. Typical unbalanced conditions include single phase to ground fault, double phase to ground fault, and double phase fault. The calculation of these fault currents needs cumbersome mathematics involving phasors. This can lead to the situation where one can 'see the trees but not the forest'. A better overall understanding of the magnitude and direction of these fault currents is obtained from simple drawings.

Single phase to ground fault

Assuming a single phase to ground fault at the red phase, the boundary conditions are:

- $I_{fault} = I_R$
- $I_Y = 0$
- $I_B = 0$

The 3 conditions can be written as:

- $I_R = I_{R1} + I_{R2} + I_{R0} = I_{fault}$
- $I_Y = I_{Y1} + I_{Y2} + I_{Y0} = 0$
- $I_B = I_{B1} + I_{B2} + I_{B0} = 0$

where

I_{R1}, I_{Y1}, I_{B1} are the positive sequence currents

I_{R2}, I_{Y2}, I_{B2} are the negative sequence currents

I_{R0}, I_{Y0}, I_{B0} are the zero sequence currents

The use of phasors is not required, to solve these equations. Instead, the equations can be solved using simple drawings. Intuitively, the solution to the equations is represented by drawing 1A and 1B.

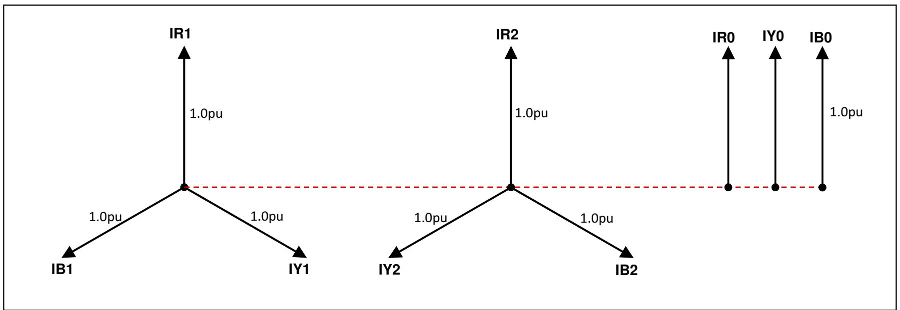
The key to arrive at drawing 1A is the zero value of the boundary condition: $I_Y = 0$ and $I_B = 0$

This is equivalent to:
$(I_{Y1} + I_{Y2}) = - I_{Y0}$ and
$(I_{B1} + I_{B2}) = - I_{B0}$.

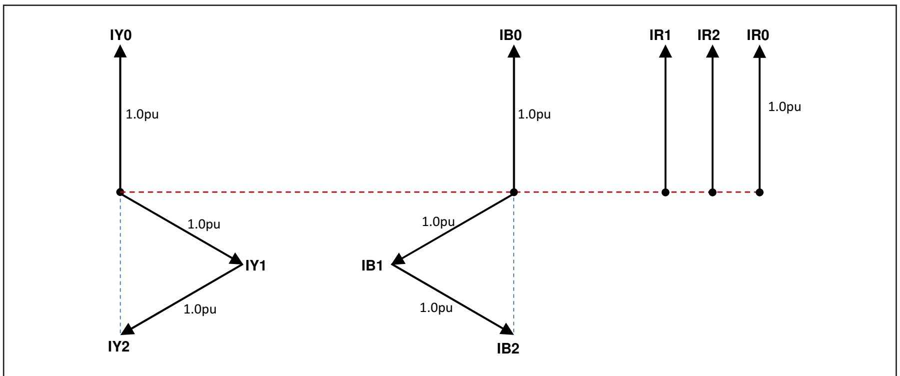
The magnitude of $(I_{Y1} + I_{Y2})$ is equal and opposite to I_{Y0}. $(I_{Y1} + I_{Y2})$ is at the position of 6 on a clock. I_{Y0} is at the position of 12 on the clock. This is illustrated in drawing 1B. The same reasoning will apply to the non-faulty blue phase. As a result, the magnitude and direction of the faulty red phase will be fixed. From drawing 1A, it can be concluded that the single phase to ground fault current at the red phase consists of positive, negative, and zero sequence currents, of equal magnitude and in the same direction, with their summation equalling the single phase to ground fault current. It can also be concluded that there must be a series connection between the positive, negative, and zero sequence network, as illustrated in drawing 1C. Drawing 1C describes the faulty red phase.

The individual magnitude of I_{R1} or I_{R2} or I_{R0} is V divided by $(Z_1 + Z_2 + Z_0)$.

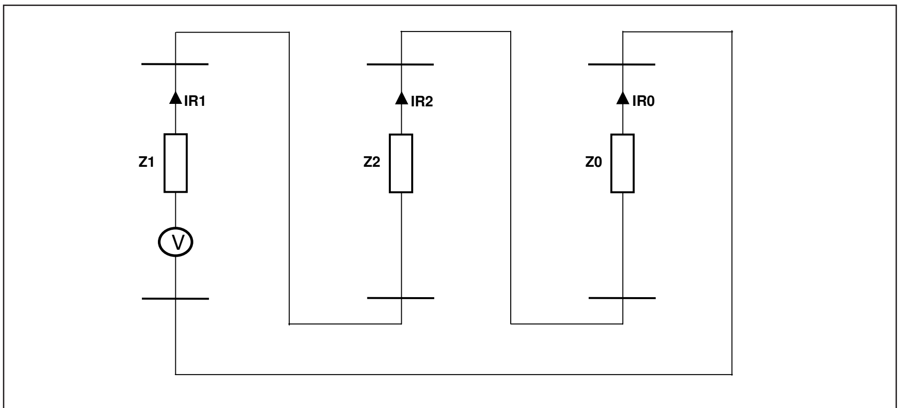
- V is the phase to neutral voltage
- Z_1 is the positive sequence impedance
- Z_2 is the negative sequence impedance
- Z_0 is the zero sequence impedance



Drawing 1A: Single phase to ground fault-positive, negative and zero sequence currents.



Drawing 1B: Single phase to ground fault – phase current.



Drawing 1C: Single phase to ground fault - positive, negative and zero sequence impedance for the faulted red phase.

- The fault current at the red phase will be:

$$I_R = I_{R1} + I_{R2} + I_{R0}$$

$$= \left(\frac{V}{Z_1 + Z_2 + Z_0}\right) + \left(\frac{V}{Z_1 + Z_2 + Z_0}\right) + \left(\frac{V}{Z_1 + Z_2 + Z_0}\right)$$

$$= \frac{3V}{Z_1 + Z_2 + Z_0}$$

It can be assumed that V=1 pu and Z_1 = 1 pu. In most applications, Z_2 will also be 1 pu. The value of Z_0 is usually larger than Z_1 and is assumed to be 1.5 pu. With these values, the single phase to ground fault current will be 0.86 pu.

Double phase fault

Assuming a double phase fault at the yellow and blue phases, the boundary conditions are:

- $I_R = 0$
- $I_{fault} = I_Y = I_B$

The 3 conditions can be written as:

- $I_R = I_{R1} + I_{R2} = 0$
- $I_Y = I_{Y1} + I_{Y2} = I_{fault}$
- $I_B = I_{B1} + I_{B2} = I_{fault}$

The zero sequence current does not exist for a double phase fault. It exists only for faults that involve a ground. Intuitively, the solution to the equations is represented by drawings 2A and 2B. The key to arrive at drawing 2A is the zero value to the boundary condition of the non-faulty red phase $I_R = 0$. This is equivalent to $I_{R1} = - I_{R2}$. The magnitude of I_{R1} is the equal and opposite to that of I_{R2}. I_{R1} is at the position of 12 on the clock and I_{R2} is at the position of 6 on the clock. Owing to the fixed magnitude and fixed direction of the non-faulty red phase, the magnitude and direction of the faulty yellow phase and faulty blue phase will be as illustrated in drawing 2B.

The yellow phase fault current is equal and opposite to the blue phase fault current. The magnitude of the yellow phase fault current is $\sqrt{3} \times I_{R1}$ and is at the position of 3 on the clock. The magnitude of the blue phase fault current is $\sqrt{3} \times I_{R1}$ and is at the position of 9 on the clock. From drawing 2B, the positive sequence current of the non-faulty red phase is equal and opposite to the negative sequence current of the non-faulty red phase. For this to happen, the non-faulty red phase positive sequence network must be series connected to the non-faulty red phase negative sequence network, as illustrated in drawing 2C.

The value of $I_{R1} = \frac{V}{Z_1 + Z_2}$

The fault current at the yellow phase will have a magnitude $\frac{\sqrt{3}\ V}{Z_1 + Z_2}$ and is at the position of 3 on the clock. The fault current at the blue phase will have the same magnitude of $\frac{\sqrt{3}\ V}{Z_1 + Z_2}$ and is at the position of 9 on the clock. This is expected for a double phase fault as the fault current is expected to flow to the fault location by one phase, and return by the other phase. If $Z_1 = Z_2 = 1$ pu, then the double phase fault current will be 0.87 pu.

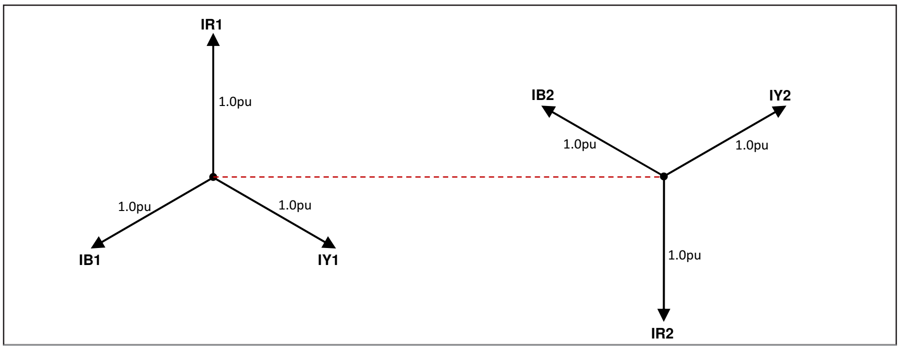
Double phase to ground fault

Assuming a double phase fault at the yellow and blue phases. The boundary conditions are:

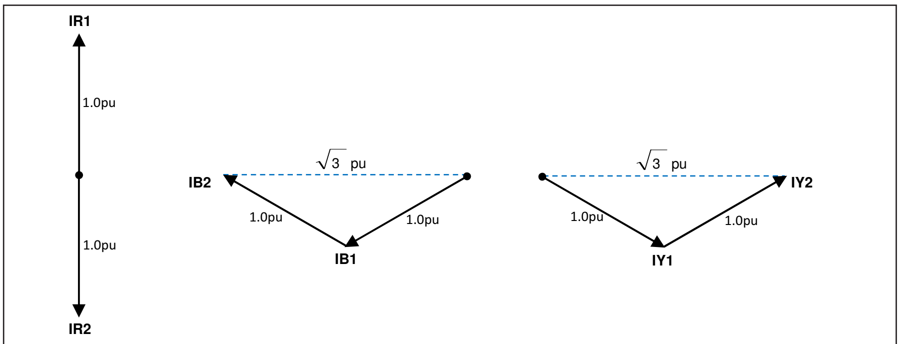
- $I_R = 0$
- $I_{fault} = I_Y + I_B$

The above conditions can be written as:

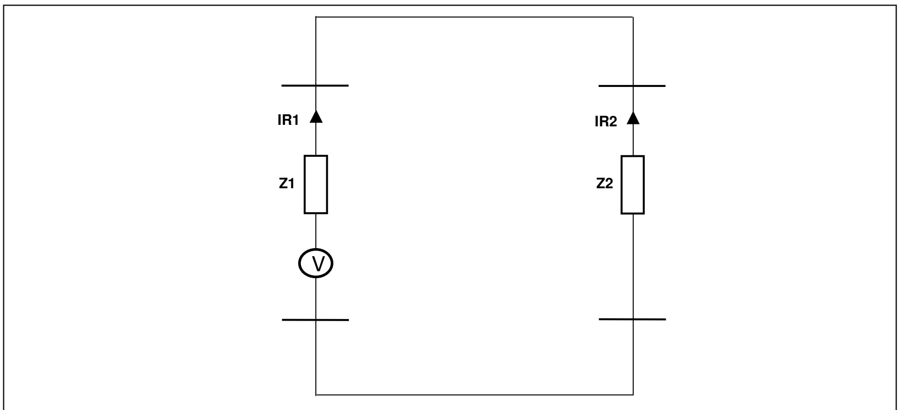
- $I_R = I_{R1} + I_{R2} + I_{R0} = 0$
- $I_Y = I_{Y1} + I_{Y2} + I_{Y0}$
- $I_B = I_{B1} + I_{B2} + I_{B0}$



Drawing 2A: Double phase fault – positive and negative sequence currents.



Drawing 2B: Double phase fault – phase current.



Drawing 2C: Double phase fault – positive and negative sequence network for the unfaulted red phase.

There are 3 fault currents - I_Y, I_B, and $(I_Y + I_B)$. Fault current $(I_Y + I_B)$ will be detected by protection CT located at the neutral of the transformers or generators. Fault current I_Y or I_B will be detected by protection CT located at the line side. The 3 equations for the double phase to ground fault, do not have a unique solution, as in the case for the single phase to ground fault, and the double phase fault. One possible solution is represented by drawing 3A and 3B. There will be infinite solutions to satisfy $I_{R1} = -(I_{R2} + I_{R0})$. Intuitively, the positive, negative, and zero sequence network is illustrated in figure 3C, where the I_{R1} current is split into I_{R2} and I_{R0}. The magnitude of I_{R2} and I_{R0} is determined by the impedance dividers Z_2 and Z_0. The positive sequence network has a driving voltage in series with the positive sequence impedance Z_1. There is no driving voltage for both the negative and zero sequence network. With this in mind, we arrive at the drawing 3C.

- $I_{R2} = \left(\frac{Z_0}{Z_0 + Z_2}\right) I_{R1}$
- $I_{R0} = \left(\frac{Z_2}{Z_0 + Z_2}\right) I_{R1}$
- $I_{R1} = \frac{V}{Z_1 + Z_0//Z_2}$

Where $Z_0//Z_2 = \frac{Z_0 Z_2}{Z_0 + Z_2}$

Assume $Z_1 = Z_2 = 1$ pu and $Z_0 = 1.5$ pu, then we have:

- $I_{R1} = 0.625$ pu
- $I_{R2} = 0.375$ pu
- $I_{R0} = 0.25$ pu

The fault current $I_Y = I_{Y1} + I_{Y2} + I_{Y0}$ or $I_B = I_{B1} + I_{B2} + I_{B0}$ cannot be obtained by simply adding (0.625 + 0.375 + 0.25) pu, to get 1.25 pu. This is obvious from drawing 3B. The fault current I_Y is the length AB, and fault current I_B is the length CD.

- Fault current I_Y = 0.94 pu.
- Fault current I_B = 0.94 pu.

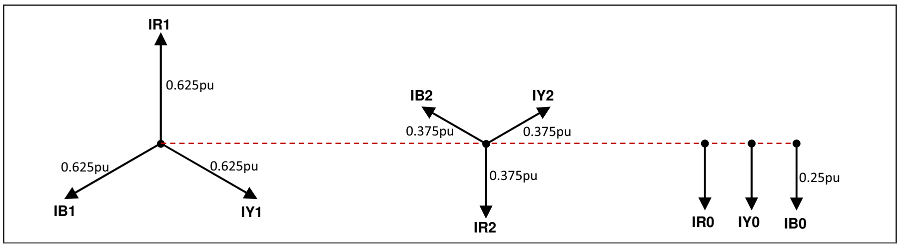
Single phase to ground fault with transformer

Analysing a single phase to ground fault at the red phase, of magnitude 3 pu, with an upstream delta/star transformer, as illustrated by drawing 4A, it is necessary to determine the magnitude of the fault current at the delta and star sides of the transformer. A delta/star transformer will introduce a 30º phase angle difference for the delta current and star current. The positive sequence current at the star side will be 30° phase shifted in the anticlockwise direction when reflected to the delta side of the transformer. The negative sequence current at the star side will be 30° phase shifted in the clockwise direction when reflected to the delta side of the transformer. The zero sequence current at the star of the transformer will have zero phase shift when reflected to the delta side of the transformer. These reflected zero sequence currents will be trapped by the delta windings and will not appear at the line side of the delta windings which will contain only positive and negative sequence currents. From drawing 4A, the yellow phase fault current at the delta side of the transformer is zero. The red phase fault current at the delta side of the transformer has a magnitude √ 3 pu at the position of 12 on the clock. The blue phase fault current at the delta side of the transformer has a magnitude √ 3 pu at the position of 6 on the clock.

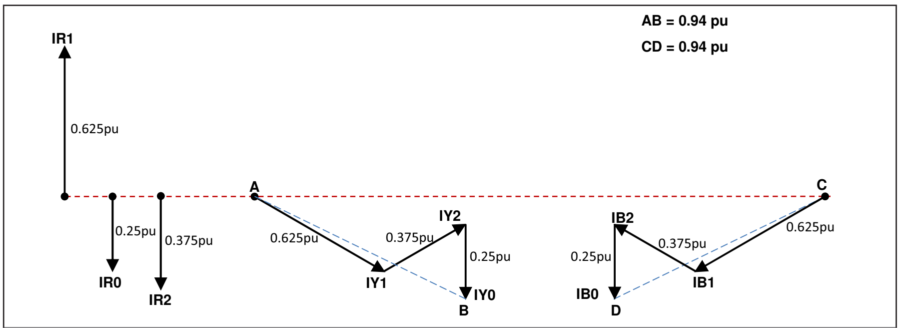
A single phase to ground fault of magnitude 3 pu at the star side of the transformer is seen as a double phase fault of magnitude √ 3 pu at the delta side of the transformer.

Double phase fault with transformer

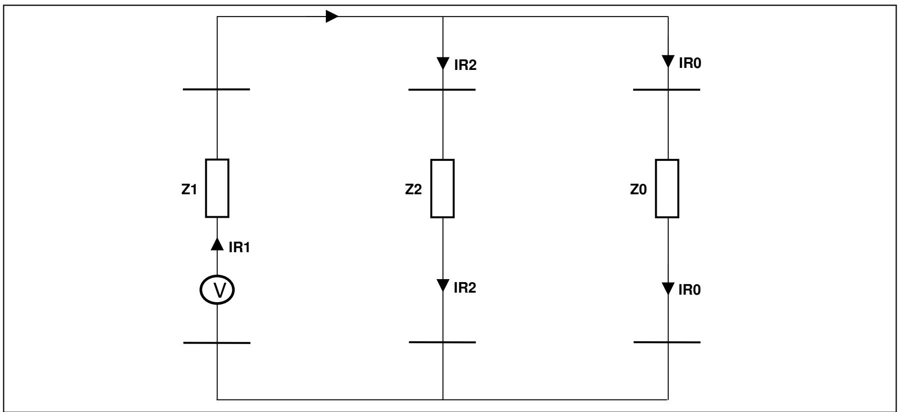
Drawing 5A illustrates a double phase fault of magnitude √ 3 pu with an upstream delta/star transformer. The positive sequence fault current at the star side will be 30º phase shifted in the anticlockwise direction when reflected to the delta side of the transformer. The negative sequence fault current at the star side will be 30°



Drawing 3A: Double phase to ground fault - positive, negative and zero sequence current.



Drawing 3B: Double phase to ground fault – phase current.



Drawing 3C: Double phase to ground fault - positive, negative and zero sequence network for the unfaulted red phase.

phase shifted in the clockwise direction when reflected to the delta side of the transformer. There is no zero sequence current for double phase fault. The yellow phase fault current at the delta side has a magnitude of 2 pu at the position of 3 on the clock. The blue phase fault current at the delta side has a magnitude of 1 pu at the position of 9 on the clock. The red phase fault current at the delta side has a magnitude of 1 pu at the position of 9 on the clock. A double phase fault of magnitude √ 3 pu at the star side of the transformer is seen as a three phase fault of magnitude with a ratio of 1:1:2 at the delta side of the transformer.

Double phase to ground fault with transformer

Drawing 6A illustrates a double phase to ground fault with an upstream delta/star transformer. The positive sequence fault current at the star side will be 30º phase shifted in the anticlockwise direction when reflected to the delta side. The negative sequence fault current at the star side will be 30° phase shifted in the clockwise direction when reflected to the delta side. The zero sequence current at the star side will have zero phase shift when reflected to the delta side. These zero sequence currents will be trapped by the delta windings and will not appear at the line side of the delta windings. Only positive and negative sequence currents will appear at the line side of the delta windings. Drawing 6B illustrates the use of simple drawings to determine the fault current. The yellow phase fault current is 1 pu. The blue phase fault current and red phase fault current are 0.55 pu.

Conclusion

The article illustrates the use of simple drawings to determine the magnitude and direction of unbalanced fault currents. Once the method is understood, there is no need to use phasors to calculate single phase to ground faults, double phase faults, and double phase to ground faults.

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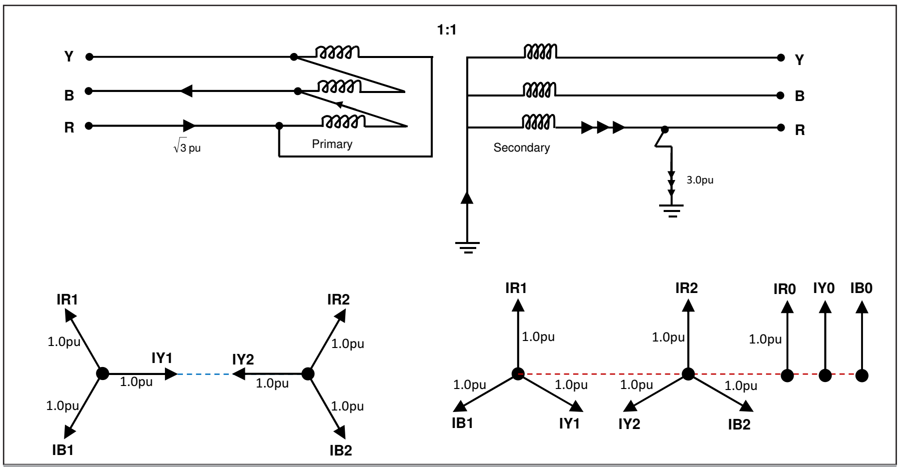
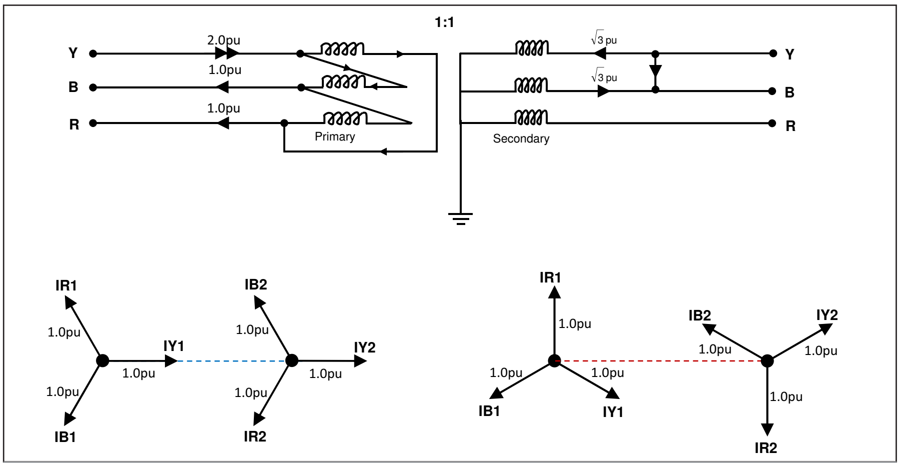
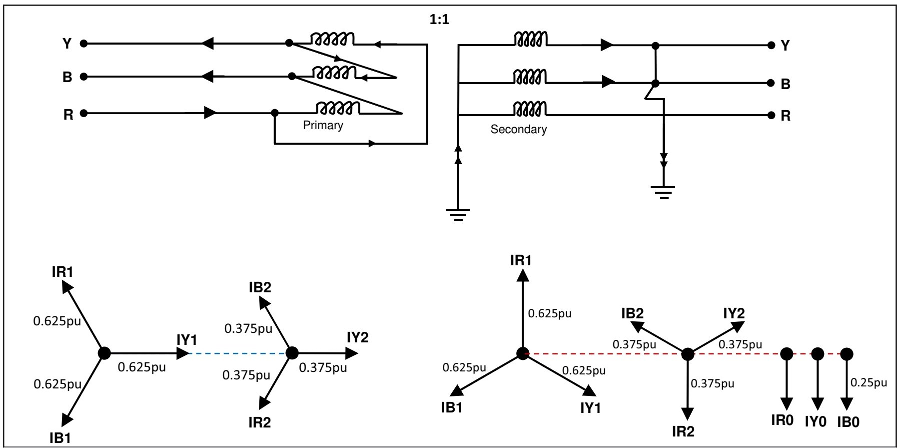


Drawing 4A: Single phase to ground fault with transformer.



Drawing 5A: Double phase fault with transformer.



Drawing 6A: Double phase to ground fault with transformer.

Drawing 6B: Double phase to ground fault with transformer – phase current.