Grounded Wye-Delta Transformer Bank Backfeed Short-Circuit Currents

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***Abstract*—A common load on a distribution feeder consists of a combination single-phase lighting load and a three-phase load such as an induction motor. This combination load can be served by a wye-delta transformer bank. The question is whether the wye connection should be directly connected to ground, connected to ground through a grounding resistor or left ungrounded. During normal loading conditions, each connection has advantages and disadvantages. However, during a short-circuit condition, a grounded wye-delta bank will provide a "backfeed" short-circuit current for an upstream ground fault. This paper will develop methods for the analysis of the backfeed currents for an upstream line-to-ground fault.**

***Index Terms*—Capacitors, component model, distribution lines, loads, loop flow, regulators, test feeders, transformers.**

I. Introduction

The wye-delta transformer bank is the most common transformer connection used to serve three-phase loads or a combination of a single-phase lighting load and a three-phase load. With this connection, a decision has to be made as to whether or not to ground the neutral of the primary wye connection. The neutral can be directly connected to ground or grounded through a resistor or left floating (ungrounded wye-delta). When the neutral is grounded, the transformer bank becomes a grounding bank that provides a path for zero sequence fault currents. In particular, the grounded connection will provide a path for a line-to-ground fault current (backfeed current) for a fault upstream from the transformer bank. Various methods of the analysis of the upstream line-to-ground fault currents will be presented.

II. One Downstream Transformer Bank

A simple system consisting of one downstream grounded wye-delta transformer bank is shown in Fig. 1.

In Fig. 1, the substation transformer rating is kVA = 2500, 69 − 12.47 kV(LL), $Z = 0.005 + j0.06$ per-unit. The three-phase distribution lines are 336 400 ACSR phase conductors and 4/0 ACSR grounded neutral conductor. The 3 × 3 impedance matrix in Ohms/mile for the lines is

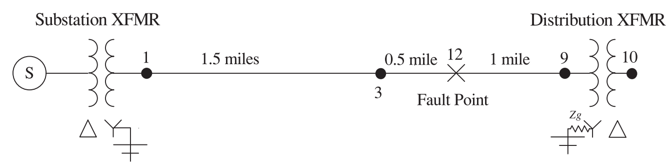

Fig. 1. One transformer system.

$$zp_{ABC} = \begin{pmatrix} 0.4576 + 1.078j & 0.1559 + 0.5017j & 0.1535 + 0.3849j \\ 0.1559 + 0.5017j & 0.4666 + 1.0482j & 0.158 + 0.4236j \\ 0.1535 + 0.3849j & 0.158 + 0.4236j & 0.4615 + 1.0651j \end{pmatrix}.$$

Three single-phase distribution transformers are connected grounded wye-delta with voltage ratings of 7200 LN wye – 240 delta volts.

The transformer banks are unbalanced with ratings:
Phase a: 50 kVA, $Z = 0.011 + j\,0.018$ per-unit;
Phase b: 100 kVA, $Z = 0.01 + j0.021$ per-unit;
Phase c: 50 kVA, $Z = 0.011 + j\,0.018$ per-unit.
The assumed value of the grounding resistance is $Z_g = 5\,\Omega$.

III. Three-Phase Circuit Analysis

A. Complete Three-Phase Circuit Analysis

The first method to calculate the short-circuit currents is to use basic circuit and transformer analysis to determine all voltages and currents. A three-phase circuit for the connection is shown in Fig. 2.

In Fig. 2, a node X has been installed to represent the fault at node 12. With the node X, there are four voltages defined as $Vf_{\mathrm{AX}}, Vf_{\mathrm{BX}}, Vf_{\mathrm{CX}}, Vf_{\mathrm{XG}}$ and three fault currents defined as If_A, If_B, If_C. The different types of faults are modeled by setting the appropriate voltages and currents to zero. For example, for an A–G fault, the following conditions are set:

$$Vf_{\mathrm{AX}} = 0,\ Vf_{\mathrm{XG}} = 0$$
$$If_B = 0,\ If_C = 0. \qquad (1)$$

The circuit of Fig. 2 is modified to represent the fault conditions as given in (1).

In Fig. 3, there are 28 unknowns which will require 28 independent equations. Without going into detail, the 28 equations are:

1) 13 KVL;
2) six basic transformer primary/secondary;

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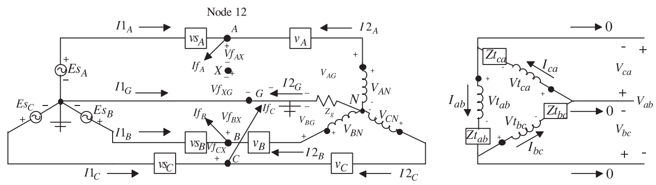

Fig. 2. Three-phase circuit.

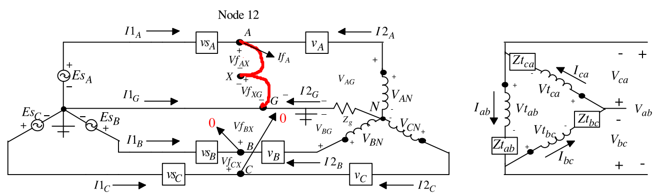

Fig. 3. A-G fault at node 12.

3) five KCL;
4) four from (1).

In this circuit, the source line-to-ground voltages are

$$[ELG_{\mathrm{ABC}}] = \begin{bmatrix} 7200\underline{/0} \\ 7200\underline{/-120} \\ 7200\underline{/120} \end{bmatrix} \text{ volts.} \tag{2}$$

With the grounding resistance of 5 Ω, the resulting short-circuit currents for a phase A to ground fault are

$$[If_{\mathrm{ABC}}] = \begin{bmatrix} 1298.3\underline{/-75.2} \\ 0 \\ 0 \end{bmatrix}$$

$$[I1_{\mathrm{ABC}}] = \begin{bmatrix} 1222.3\underline{/-77.6} \\ 91.7\underline{/137.7} \\ 91.7\underline{/137.7} \end{bmatrix} \quad [I2_{\mathrm{ABC}}] = \begin{bmatrix} 91.7\underline{/-42.3} \\ 91.7\underline{/-42.3} \\ 91.7\underline{/-42.3} \end{bmatrix}$$

$$I1_G = 1077.8\underline{/96.8} \qquad I2_G = 275.1\underline{/137.7}. \tag{3}$$

Note in (3) that $[I1_{\mathrm{ABC}}]$ and $[I2_{\mathrm{ABC}}]$ are directed into the faulted node 12. The results show that the three backfeed currents from the transformer bank are all equal. This is to be expected since there are no currents leaving the delta secondary there must be a circulating current in the delta windings which leads to three equal primary currents.

B. Reduced Three-Phase Circuit Analysis

The complete three-phase circuit analysis results in knowing all of the currents and voltages in the circuit. However, the primary concern in the short-circuit analysis is to know the currents that come from the source into the fault and the backfeed currents from the grounded wye-delta transformer bank. Recognizing that the three backfeed currents are equal and applying basic algebra manipulations, the 28 equations and 28 unknowns can be reduced to eight equations and eight unknowns. The resulting equations and unknowns are:

1) $Es_A = Vf_{\mathrm{AX}} + Vf_{\mathrm{XG}} + Z1_{1,1} \cdot If_A + Z1_{1,2} \cdot If_B + Z1_{1,3} \cdot If_C - Zx_1 \cdot I2;$
2) $Es_B = Vf_{\mathrm{BX}} + Vf_{\mathrm{XG}} + Z1_{2,1} \cdot If_A + Z1_{2,2} \cdot If_B + Z1_{2,3} \cdot If_C - Zx_2 \cdot I2;$
3) $Es_C = Vf_{cX} + Vf_{\mathrm{XG}} + Z1_{3,1} \cdot If_A + Z1_{3,2} \cdot If_B + Z1_{3,3} \cdot If_C - Zx_3 \cdot I2;$
4) $0 = \frac{1}{n_t} \cdot (Vf_{\mathrm{AX}} + Vf_{\mathrm{BX}} + Vf_{\mathrm{CX}} + 3 \cdot Vf_{\mathrm{XG}}) + Z_{\mathrm{eq}} \cdot I2;$
5) depends on fault;
6) depends on fault;
7) depends on fault;
8) depends on fault;

where

$[Z1]$ = total impedance matrix from the source to the fault node 12

$[Z3]$ = total impedance matrix from the transformer bank to node 12

for

$$\begin{aligned} i &= 1, 2, 3 \\ Zx_i &= \sum_{k=1}^{3} Z1_{i,k} \\ Zeq_i &= \sum_{k=1}^{3} Z3_{i,k} \\ Z_{\mathrm{eq}} &= \frac{9}{n_t} \cdot Z_g + n_t \cdot (Zt_{\mathrm{ab}} + Zt_{\mathrm{bc}} + Zt_{\mathrm{ca}}) \\ &\quad + \frac{1}{n_t} \cdot (Zeq_1 + Zeq_2 + Zeq_3). \end{aligned}$$

Solving these eight equations, the results match those of (3)

$$[If_{\mathrm{ABC}}] = \begin{bmatrix} 1298.3\underline{/-75.2} \\ 0 \\ 0 \end{bmatrix}$$

$$[I1_{\mathrm{ABC}}] = \begin{bmatrix} 1222.3\underline{/-77.6} \\ 91.7\underline{/137.7} \\ 91.7\underline{/137.7} \end{bmatrix} \quad [I2_{\mathrm{ABC}}] = \begin{bmatrix} 91.7\underline{/-42.3} \\ 91.7\underline{/-42.3} \\ 91.7\underline{/-42.3} \end{bmatrix}$$

$$I1_G = 1077.8\underline{/96.8} \qquad I2_G = 275.1\underline{/137.7}. \tag{4}$$

The backfeed fault currents flowing in the three transformers are 91.7 A. The rated primary current for the 100 kVA lighting transformer is 13.8 A. This means that the 91.7 A of backfeed currents is 564% of the rated current. The rated current for the 50 kVA transformers is 6.9 A which means the 91.7 A is 1.128% of rated current. Needless to say, the primary fuses on the transformers will have to blow in order to save the transformers from burning. This is a demonstration of the reason that it is typically recommended that the neutral of the wye should not be connected to ground. The magnitude of the backfeed currents can be limited by increasing the value of the grounding resistance. For example, if the grounding resistance is set to 50 Ω, the backfeed currents in the transformers are computed to be 19.3 A or 39.9% and 79.7% above rated currents. In the limiting case of an infinite grounding resistance, the backfeed currents will be zero and the transformer now is the recommended ungrounded wye-delta connection.

C. Ungrounded Wye-Delta Model

Neglecting backfeed currents can be simulated by modeling the transformer bank as ungrounded wye-delta. For this study, the 7×7 matrix was used which ignores the backfeed currents [1]. The fault circuit current flows are as follows:

$$[If_{\mathrm{ABC}}] = \begin{bmatrix} 1197.1\underline{/-78.2} \\ 0 \\ 0 \end{bmatrix}$$

$$[I1_{\mathrm{ABC}}] = \begin{bmatrix} 1197.1\underline{/-78.2} \\ 0 \\ 0 \end{bmatrix} \quad [I2_{\mathrm{ABC}}] = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}. \tag{5}$$

By ignoring the backfeed fault current, the error is computed to be

$$\text{Error} = \frac{1298.3 - 1197.1}{1298.3} \cdot 100 \quad \text{Error} = 7.8\%. \tag{6}$$

D. WindMil Solution

The distribution analysis program "WindMil" is a product of Milsoft Utility Solutions [2]. WindMil applies a method involving "loop flow" [3] for the solution of the one downstream transformer system of Fig. 1. The results are

$$[If_{\mathrm{ABC}}] = \begin{bmatrix} 1298.38\underline{/-75.6} \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

$$[I1_{\mathrm{ABC}}] = \begin{bmatrix} 1222.41\underline{/-77.6} \\ 91.72\underline{/137.7} \\ 91.65\underline{/137.7} \end{bmatrix} \quad [I2_{\mathrm{ABC}}] = \begin{bmatrix} 91.74\underline{/-42.3} \\ 91.72\underline{/-42.3} \\ 91.65\underline{/-42.3} \end{bmatrix}.$$

The WindMil results match those of (3).

E. Symmetrical Component Method

Another method of calculating the approximate short currents is to apply the method of symmetrical components. In the application of symmetrical components, it must be understood that all types of unbalances are eliminated. That is, all lines are assumed to be balanced as well as the transformer banks. This will lead to errors compared to the results when all unbalances are included. To first demonstrate this method, the one transformer system of Fig. 1 is used. For this system, the same line impedances and transformer ratings are used. The sequence impedances of the lines and transformers are required. The method used was to convert the phase impedance matrices to sequence impedance

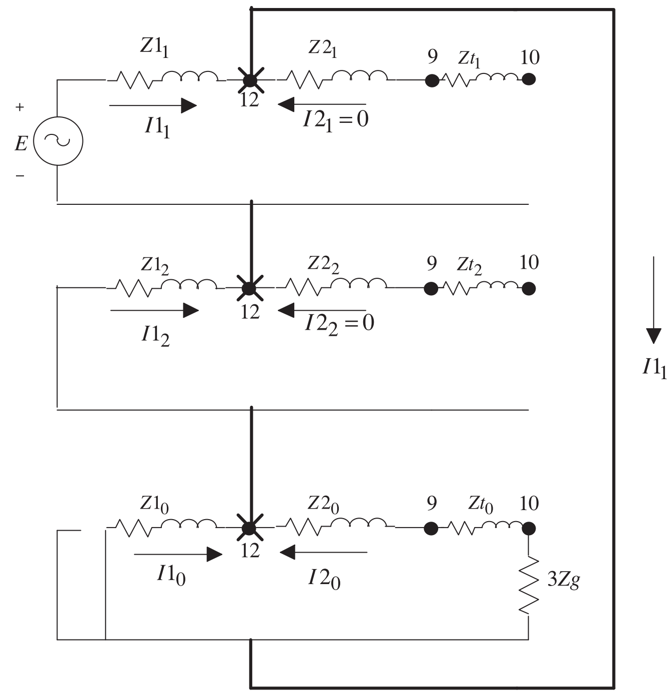

Fig. 4. One transformer sequence network connection for LG fault.

matrices using

$$[Z_{012}] = [A]^{-1} \cdot [Z_{\mathrm{ABC}}] \cdot [A]$$

$$\text{where } [A] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\underline{/-120} & 1\underline{/120} \\ 1 & 1\underline{/120} & 1\underline{/-120} \end{bmatrix}. \tag{8}$$

The sequence impedance matrices computed using (8) include the mutual coupling impedances between sequences. To apply the method of symmetrical components only the self-sequence impedances (diagonal terms) are used. The sequence impedances for the various components are computed to be

Substation transformer:

$$ZT_0 = ZT_1 = ZT_2 = 03110 + j3.732\,\Omega$$

Distribution lines:

$$Zl_0 = 0.7735 + j1.9372$$

$$Zl_1 = Zl_2 = 0.3061 + j.6270\,\Omega/\text{mi}$$

Distribution transformers:

$$Zt_0 = Zt_1 = Zt_2 = Zt_{\text{seq}} + 3 \cdot Z_g = 15.0415 + j0.0714\,\Omega. \tag{9}$$

For this one transformer system, the connection of the sequence networks is shown in Fig. 4.

Note in the connection that the grounded wye-delta transformer only supplies a zero sequence backfeed current. The analysis of the sequence network circuit gives the following

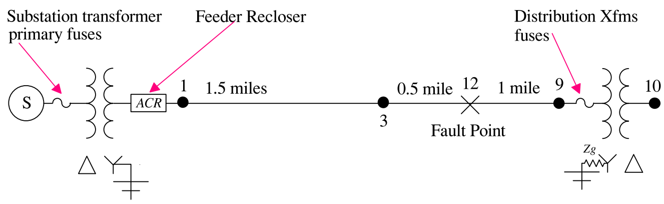

Fig. 5. Short-circuit protection.

results:

$$[I1_{012}] = \begin{bmatrix} 360.9/\underline{-83.1} \\ 434.5/\underline{-75.2} \\ 434.5/\underline{-75.2} \end{bmatrix} \quad [I1_{\mathrm{ABC}}] = \begin{bmatrix} 1227.5/\underline{-77.5} \\ 91.5/\underline{137.6} \\ 91.5/\underline{137.6} \end{bmatrix}$$

$$[I2_{012}] = \begin{bmatrix} 91.5/\underline{-42.4} \\ 0 \\ 0 \end{bmatrix} \quad [I2_{\mathrm{ABC}}] = \begin{bmatrix} 91.5/\underline{137.6} \\ 91.5/\underline{137.6} \\ 91.5/\underline{137.6} \end{bmatrix}$$

$$[If_{\mathrm{ABC}}] = [I1_{\mathrm{ABC}}] + [I2_{\mathrm{ABC}}] = \begin{bmatrix} 1303.4/\underline{-75.2} \\ 0 \\ 0 \end{bmatrix}. \quad (10)$$

Comparing the symmetrical component results of (10) with the exact solutions of (3), there is a small difference that is a result of the assumption of balanced lines and transformers used in the symmetrical component method. The major differences are

$$\begin{aligned} &\text{Exact: } If_A = 1298.3 \\ &\text{Symmetrical components: } If_A = 1303.4 \\ &\text{Difference = 5.1 Amps or } 0.4\% \\ &\text{Exact: } I1_A = 1222.3 \\ &\text{Symmetrical components: } I1_A = 1227.5 \\ &\text{Difference = 5.2 Amps or } 0.4\% \\ &\text{Exact backfeed: } I2_A = 91.7 \\ &\text{Symmetrical components: } I2_A = 91.5 \\ &\text{Difference: } 0.2 \text{ Amps or } 0.2\%. \end{aligned} \quad (11)$$

The summary results of (11) show that there are small differences in the calculated values of the backfeed currents based upon the exact method versus the method of symmetrical components. However, this demonstrates that the symmetrical component method of analysis is a very good test for the accuracy of the more exact unbalanced short-circuit analysis.

F. Short-Circuit Protection

Fig. 5 shows the protective devices that can be used to protect the system during a short-circuit condition.

A possible protection scheme for this system is shown in the time–current curves of Fig. 6. The substation transformer fuses are primarily there to open on faults inside the transformer. They also provide backup protection if the recloser fails to open on a permanent downstream fault. The recloser will typically have two "fast" operations where the recloser will open very quickly and stay open for a short period of time before closing. The

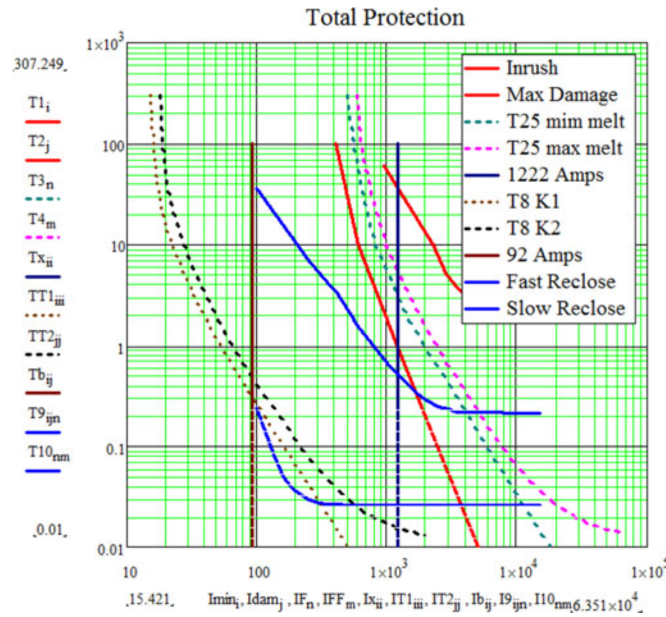

Fig. 6. Time–current curves.

theory is that the fault is assumed to be temporary and during the open condition the arcing will stop and upon closing the fault will be gone. The fast opening of the recloser will occur before the distribution transformer fuses blow. This sequence will happen twice. For a permanent fault upon closing the second time, the control for the recloser transfers to the slow allowing the distribution transformer fuses to blow and upon closing the fault will still exist and the recloser will open and not reclose.

For this system, of particular interest is how the system protection will respond to the 1222 A flowing from the substation transformer to the LG fault at node 12 and the 92 A backfeed currents from the distribution transformers back to the LG fault at node 12. In Fig. 6, the black vertical line displays the 1222 A and the brown vertical line displays the 92 A backfeed currents. The "fast" recloser curve is in dark blue at the bottom of the graph. For this case, the 1222 A seen by the recloser will cause the fast curve to open the recloser in approximately 0.025 s. Because the recloser opens quickly with the fast curve, there will not be any backfeed current flowing through the distribution transformer fuses since the minimum melt curve intersects the 92 A at approximately 0.3 s. After a short time, the recloser will close and if the fault is still present the fast curve will again open the recloser. At this time, the distribution transformer fuses may or may not blow. The fuses heat up when the 92 A flows and there is a possibility that the fuses will blow before the second fast opening of the recloser. Assuming that the fault is permanent and the distribution transformer fuses have not blown the control of the recloser is now the slow curve. The 92 A backfeed current is flowing and the fuses will blow on the minimum melt curve in approximately 0.3 s while the slow recloser curve will open the recloser in approximately 0.7 s. If the fault is temporary, there is a strong possibility that the distribution transformer fuses will blow resulting in a loss of service to the customers served by the transformer bank.

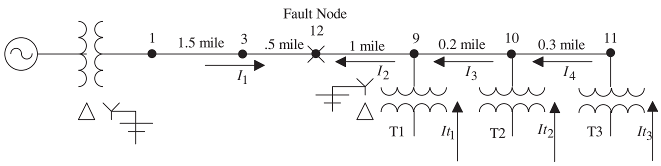

Fig. 7. Three transformer system.

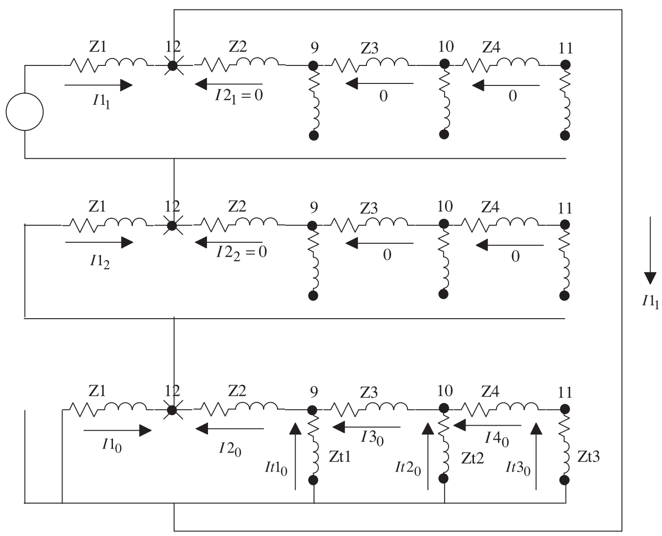

Fig. 8. Three transformer sequence networks connection.

It is not the intention in this paper to delve deeply into the protection scheme. What has been done is to demonstrate that the backfeed current does flow for an upstream LG fault and this will cause the distribution transformer fuses to flow.

G. Three Downstream Transformers System

The method using the 8 × 8 matrix works well when there is only one downstream transformer bank. If there are multiple banks, then an 8 × 8 matrix must be formed for each bank. This does not lend itself to a simple method of analysis of the backfeed currents. In order to determine the approximate values of the backfeed currents, the method of symmetrical components is applied for the system shown in Fig. 7.

The sequence impedances for the distribution transformers include the 5 Ω grounding resistance for each transformer bank. The symmetrical components connection of sequence networks for the A–G fault at node 12 is shown in Fig. 8.

The symmetrical component analysis gives the following results:

Fault current

$$[If_{012}] = \begin{bmatrix} 482.8\underline{/-73.8} \\ 482.8\underline{/-73.8} \\ 482.8\underline{/-73.8} \end{bmatrix} \quad [If_{\mathrm{ABC}}] = \begin{bmatrix} 1448.4\underline{/-73.8} \\ 0 \\ 0 \end{bmatrix}.$$

Line 1–12

$$[I1_{012}] = \begin{bmatrix} 303.9\underline{/-88.2} \\ 482.8\underline{/-73.8} \\ 482.8\underline{/-73.8} \end{bmatrix} \quad [I1_{\mathrm{ABC}}] = \begin{bmatrix} 1262.2\underline{/-77.2} \\ 203.1\underline{/128.1} \\ 203.1\underline{/128.1} \end{bmatrix}.$$

Line 9–12

$$[I2_{012}] = \begin{bmatrix} 203.1\underline{/-51.9} \\ 0 \\ 0 \end{bmatrix} \quad [I2_{\mathrm{ABC}}] = \begin{bmatrix} 203.1\underline{/-51.9} \\ 203.1\underline{/-51.9} \\ 203.1\underline{/-51.9} \end{bmatrix}.$$

Line 10–9

$$[I3_{012}] = \begin{bmatrix} 134.0\underline{/-52.3} \\ 0 \\ 0 \end{bmatrix} \quad [I2_{\mathrm{ABC}}] = \begin{bmatrix} 134.0\underline{/-52.3} \\ 134.0\underline{/-52.3} \\ 134.0\underline{/-52.3} \end{bmatrix}.$$

Line 11–10

$$[I4_{012}] = \begin{bmatrix} 67.6\underline{/-52.0} \\ 0 \\ 0 \end{bmatrix} \quad [I4_{\mathrm{ABC}}] = \begin{bmatrix} 67.6\underline{/-52.0} \\ 67.6\underline{/-52.0} \\ 67.6\underline{/-52.0} \end{bmatrix}.$$

Transformer 1

$$[It1_{012}] = \begin{bmatrix} 69.2\underline{/-51.1} \\ 0 \\ 0 \end{bmatrix} \quad [It1_{\mathrm{ABC}}] = \begin{bmatrix} 69.2\underline{/-51.1} \\ 69.2\underline{/-51.1} \\ 69.2\underline{/-51.1} \end{bmatrix}.$$

Transformer 2

$$[It2_{012}] = \begin{bmatrix} 67.6\underline{/-52.0} \\ 0 \\ 0 \end{bmatrix} \quad [It2_{\mathrm{ABC}}] = \begin{bmatrix} 67.6\underline{/-52.0} \\ 67.6\underline{/-52.0} \\ 67.6\underline{/-52.0} \end{bmatrix}.$$

Transformer 3

$$[It4_{012}] = \begin{bmatrix} 66.4\underline{/-52.6} \\ 0 \\ 0 \end{bmatrix} \quad [It4_{\mathrm{ABC}}] = \begin{bmatrix} 66.4\underline{/-52.6} \\ 66.4\underline{/-52.6} \\ 66.4\underline{/-52.6} \end{bmatrix}.$$

When these results are compared to those of the symmetrical component analysis of the one transformer system, it is noted that

1) the short-circuit current from the substation transformer to the fault has increased slightly (1262 A increased to 1277 A);
2) the backfeed currents from the distribution transformers are greatly reduced from the one transformer system (91.5 A to 69.2, 67.2, and 66.4 A).

H. WindMil Solution

Since the application of the 8 × 8 matrix for each grounded wye-delta transformer bank does not lend itself to an easy solution, WindMil applies a method involving "loop flow." This method gives good results but requires a considerable amount of computer time for a solution. To demonstrate the loop flow method, the three transformer system was modeled in with the following results:

$$[If_{\mathrm{ABC}}] = \begin{bmatrix} 1444.0\underline{/-73.8} \\ 0 \\ 0 \end{bmatrix} [I1_{\mathrm{ABC}}] = \begin{bmatrix} 1257.5\underline{/-77.3} \\ 203.8\underline{/-128.3} \\ 203.8\underline{/-128.3} \end{bmatrix}$$

$$[I2_{\mathrm{ABC}}] = \begin{bmatrix} 203.9\underline{/128.3} \\ 203.9\underline{/128.3} \\ 203.9\underline{/128.3} \end{bmatrix} [I3_{\mathrm{ABC}}] = \begin{bmatrix} 134.5\underline{/127.9} \\ 134.5\underline{/127.9} \\ 134.5\underline{/127.9} \end{bmatrix}$$

$$[I4_{\mathrm{ABC}}] = \begin{bmatrix} 66.7\underline{/127.5} \\ 66.7\underline{/127.5} \\ 66.7\underline{/127.5} \end{bmatrix} [It1_{\mathrm{ABC}}] = \begin{bmatrix} 69.4\underline{/129.1} \\ 69.4\underline{/129.1} \\ 69.4\underline{/129.1} \end{bmatrix}$$

$$[It2_{\mathrm{ABC}}] = \begin{bmatrix} 67.8\underline{/128.2} \\ 67.8\underline{/128.2} \\ 67.8\underline{/128.2} \end{bmatrix} [It3_{\mathrm{ABC}}] = \begin{bmatrix} 66.7\underline{/127.5} \\ 66.7\underline{/127.5} \\ 66.7\underline{/127.5} \end{bmatrix}.$$

Comparing the WindMil results with the symmetrical component results again shows that the symmetrical component method gives the same results. It should be pointed out that the symmetrical component method has the currents flowing from the transformer to the fault while WindMil directs all currents from the source to the end of the line. The only purpose of the symmetrical component method was to verify the "loop flow" method used by WindMil since forming 8 × 8 matrices for each transformer was not a feasible method of analysis.

IV. Conclusion

The first system studied in Fig. 1 assumed only one downstream transformer. The analysis of this system was done in three different ways. The first method was a complete three-phase analysis of the system using basic circuit and transformer theory. This method was used in order to accurately determine the voltages and currents everywhere in the system. Unfortunately, this method required the formation of a 28 × 28 matrix. With basic algebra, it was possible to reduce the 28 × 28 matrix to an 8 × 8 matrix that leads to the exact same results. This simply shows that it is possible to model the backfeed currents of one downstream transformer bank with the 8 × 8 matrix. The third analysis method was the application of symmetrical components. This method is used many times in order to verify that the true analyses results. Unfortunately when there are more downstream transformer banks, an 8 × 8 matrix must be formed for each transformer bank. This does not lend itself to an efficient method of analysis. What is most important is the backfeed currents greatly exceed the rated currents of the distribution transformers. This is the major problem of using a grounded wye-delta transformer bank. The backfeed currents at best will blow the fuses of the distribution transformers. Depending upon the protection system, this may lead to the loss of the transformer bank during a temporary upstream ground fault.

When more than one downstream grounded wye-delta bank is present, the 8 × 8 matrix method does not work. A method of analyzing such a system was first demonstrated using the method of symmetrical components for the one downstream transformer bank. The results of this method compared to the exact (8 × 8 matrix) showed that the backfeed currents were approximately equal. This demonstrates that the symmetrical component method can be used for the analysis. The method of symmetrical components was then used to analyze the three downstream bank system and the results showed that the backfeed currents from each transformer were reduced from those of the one transformer system. WindMil uses a "loop flow" method to analyze the multiple downstream transformer systems. The WindMil results show the backfeed currents to be approximately equal to the values using symmetrical components.

All of the studies have demonstrated that when there is a choice, the wye connection should not be grounded. Adding a larger grounding resistor limits the short-circuit and backfeed currents. When the backfeed currents for the one transformer system were ignored (ungrounded wye-delta), it showed a 7.8% error from that of the exact method. This is not enough error to warrant applying the "loop flow" method of analysis for short-circuit conditions.

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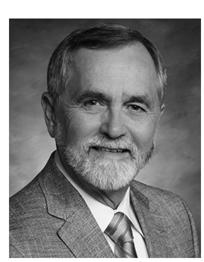

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