UNDERSTANDING ZIG-ZAG GROUNDING BANKS

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***Abstract:* This is a treatise on understanding and protecting Zig-Zag grounding banks that are used to provide a fourth wire to serve phase-to-ground connected loads on distribution systems.**

The tertiary winding of a three winding transformer can be used to serve phase-to-ground connected loads by the installation of a Zig-Zag grounding bank. This paper explores how protective relays and current transformers are connected to provide adequate grounding bank protection and ground backup protection to all connected feeder breakers. The paper will also include a method that can be used to size the installation of one Zig-Zag grounding bank and/or two grounding banks in parallel to a site specific location.

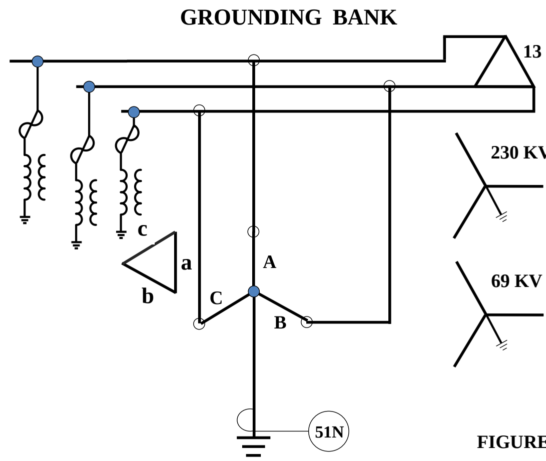

FIGURE 1

Before addressing the attributes of Zig-Zag grounding banks, it is appropriate to acknowledge that a conventional Wye-Delta transformer (Figure 1) can be used as a grounding bank. However, they are usually not as cost-effective as a zig-zag grounding transformer and require full voltage across all windings. The Zig-Zag design (Figure 2) is more efficient because each winding has less than the line to ground voltage by a factor of the $\sqrt{3}$. Therefore, the bank can be rated lower. $P = V_{LG} I_N / \sqrt{3}$

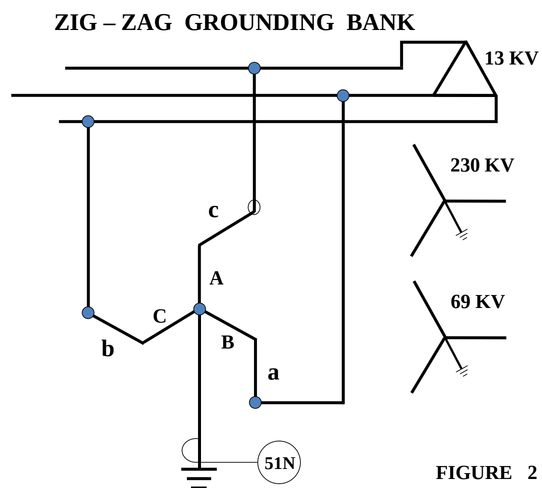

FIGURE 2

Figure 3 depicts a zig-zag grounding bank with over current relay protection (51) and backup ground protection (51N). The overcurrent relays are designed to provide sensitive protection to the zig-zag grounding bank and the backup ground relay coordinates with the residual ground relay (G) on all connected 13kv feeder breakers. However, there is obviously some confusion when attempts are made to coordinate Zig-Zag overcurrent relays (51) with the phase relays (ϕ) on 13kv feeder breakers. This paper attempts to clear up some of the ambiguity in setting the overcurrent protection scheme associated with grounding banks.

Overcurrent relays are commonly used to provide protection for grounding banks

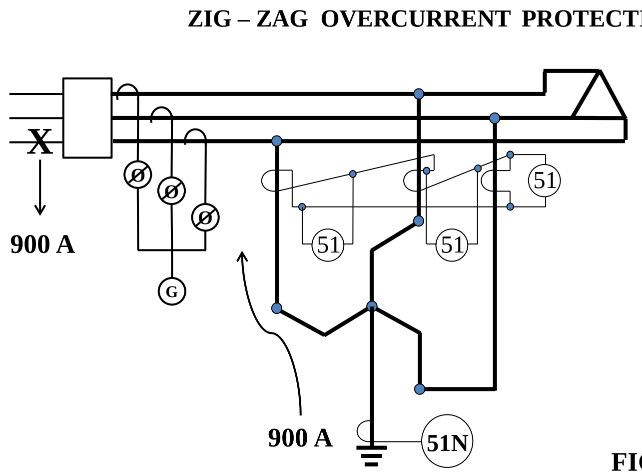

FIGURE 3

In order to analyze the **erroneous** assumption that overcurrent relays on a Zig-Zag grounding bank (51) coordinate with phase relays (ϕ) on feeder breakers, a low magnitude 900 ampere external phase-to-ground fault (figure 3), is **incorrectly** shown flowing thought only one phase of the Zig-Zag grounding bank. Figure 4 **incorrectly** depicts secondary current flows for a 900 ampere fault current. Note; all CT's are rated 300/5. Under these conditions a secondary current (15 amperes) will incorrectly flow in one of the overcurrent

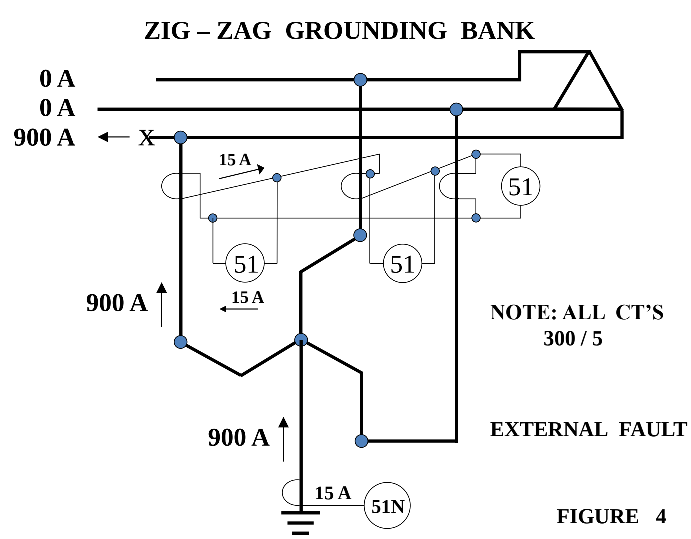

FIGURE 4

relays. Again, following this line of **incorrect** thinking, one might conclude that the (51) relays must be set to coordinate with the phase relays (ϕ) on the 13kv feeder breakers. This concept would seriously degrade Zig-Zag grounding bank protection because the overcurrent relays on feeder breakers must be set high to carry the total load current imposed on them.

Winding connections (Ratio 1/1)

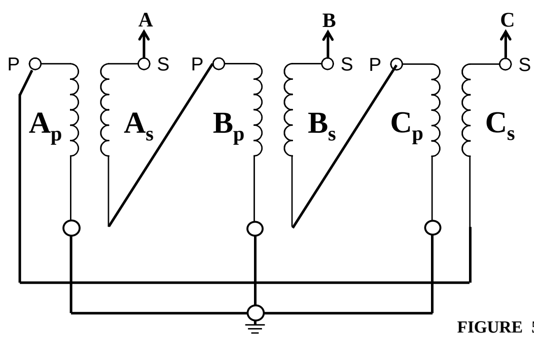

FIGURE 5

It is not uncommon for 13kv feeder breaker loads to exceed 1200 amperes. Therefore, for this condition, the pickup current of overcurrent relays (51) associated with a zig-zag grounding bank would have to be set above 1200 amperes. A setting of this magnitude would make the overcurrent relays (51) ineffective to protect the Zig-Zag grounding bank for small internal phase-to-ground faults.

Fortunately, this is not the way the system works. In actuality for any given 13kv phase-to- ground fault, the total fault current in the neutral of the Zig-Zag grounding bank divides equally between all windings.

Perhaps a simplified way to analyze the distribution of fault current in a zig-zag grounding bank is to review the internal connections of the transformers inside the zig-zag grounding bank.

ZIG – ZAG GROUNDING BANK

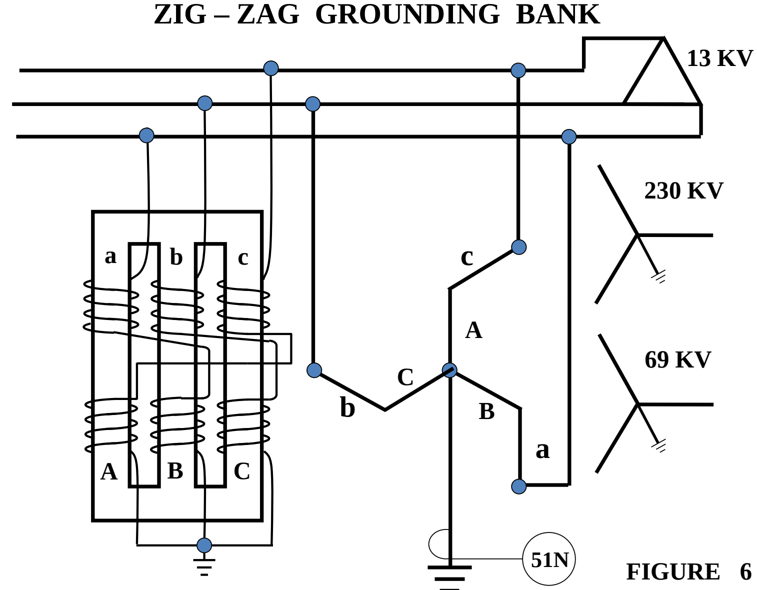

FIGURE 6

There are three sets of two winding transformers with one-to-one ratios. Refer to figure 5 for the transformer connections. The non-polarity side of the secondary of the A phase transformer (A_S) is connected to the polarity side of the B_P phase transformer. The non-polarity side of the secondary of the B phase transformer (B_S) is connected to the polarity side of the C phase transformer(C_P). In a similar manner the non-polarity side of the C phase transformer is connected to the polarity side of the A phase transformer (A_P). From these connections, one can readily see that if 100 A flows in one winding, 100 A will flow in all windings. The connections for all windings on a three legged core are shown in figure 6.

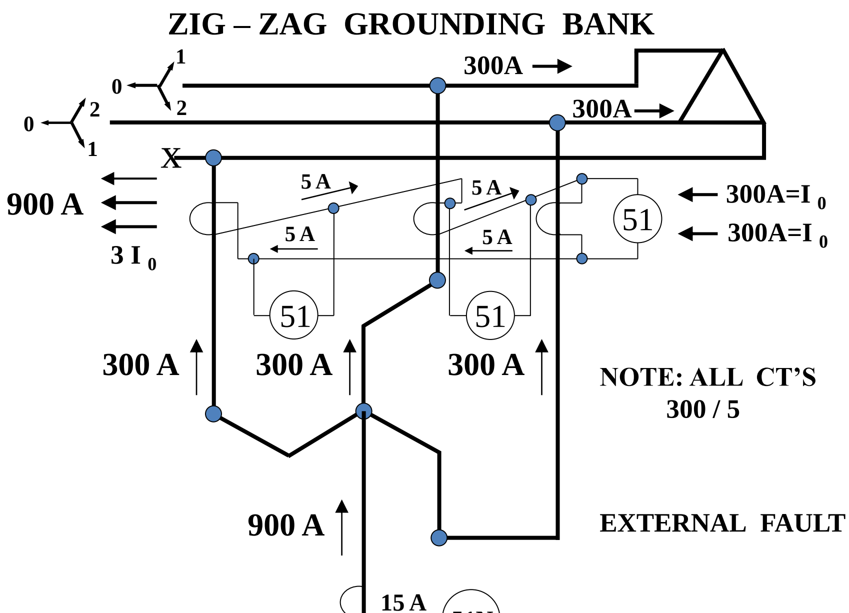

FIGURE 7

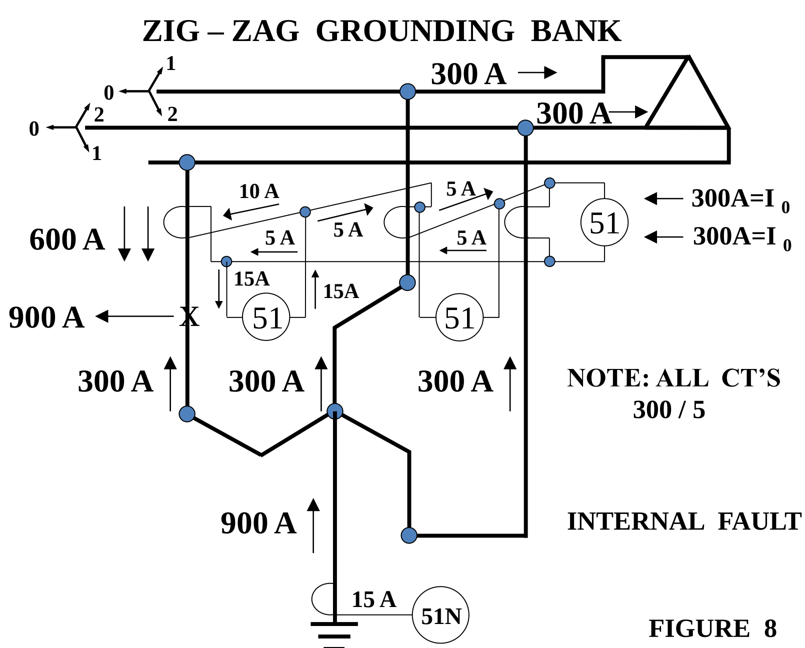

FIGURE 8

The current flow for an **external** 900 ampere fault is **correctly** shown in figure 7. An equal current of 300 A flows in each phase winding and, with current transformers connected as shown, 5 amperes flows between CTs and no current flows to the 51 relays. From symmetrical component theory the positive, negative, and zero sequence components are all equal at the fault.

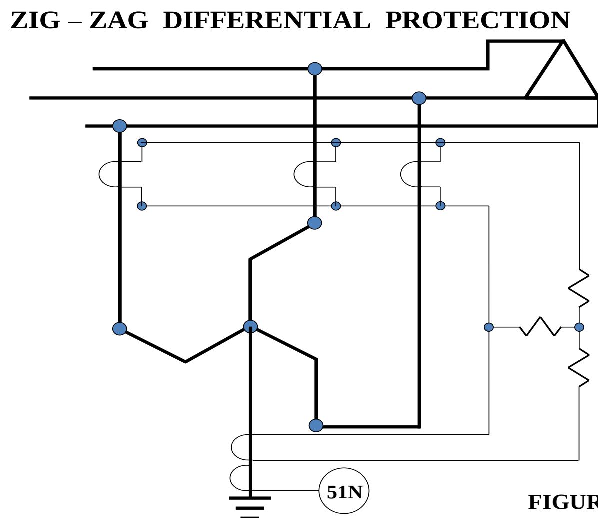

FIGURE 9

Assuming a radial feed, all sequence components will be equal in magnitude and in phase at the fault. The unfaulted phases will be zero. It should be noted that the two unfaulted phases in the zig-zag grounding transformer have zero sequence currents of equal magnitude flowing back to the Delta connected winding of the three-phase transformer. They return as two in-phase 300 ampere (600A total) sequence currents.

A view of an **internal** fault is shown in figure 8. It can be seen that 600 amperes flows in the reverse direction in one set of CTs. This does not balance the 300 amperes flowing in the other two phase CTs. This results in a 15 ampere current flow in one set of overcurrent relays. As a result of the way currents flow, the overcurrent protection is inherently directional and can be set fairly sensitively.

Differential relays can also be utilized to protect zig-zag grounding banks as shown in figure 9. Utilizing the same procedure as before, the secondary currents are shown in figure 10 for an **external** 900 ampere phase-to-ground-fault. As can be seen, the 15 ampere current in the phase CTs are offset by a 15 ampere current generated in the neutral CT resulting in zero current in the operating coil of the differential relays. The secondary currents in the phase CTs for an **internal** phase-to-ground fault are not balanced by the output current from the neutral CT, resulting in a current of 15 A through the operating coil of the differential relay (refer to figure 11).

Distributors should consider the installation of a grounding transformer even if only three phase distribution loads are served because line to ground faults can cause high phase-to-neutral voltages on the unfaulted phases and load imbalances can cause neutral shifts and over voltages.

ZIG – ZAG DIFFERENTIAL PROTECTION

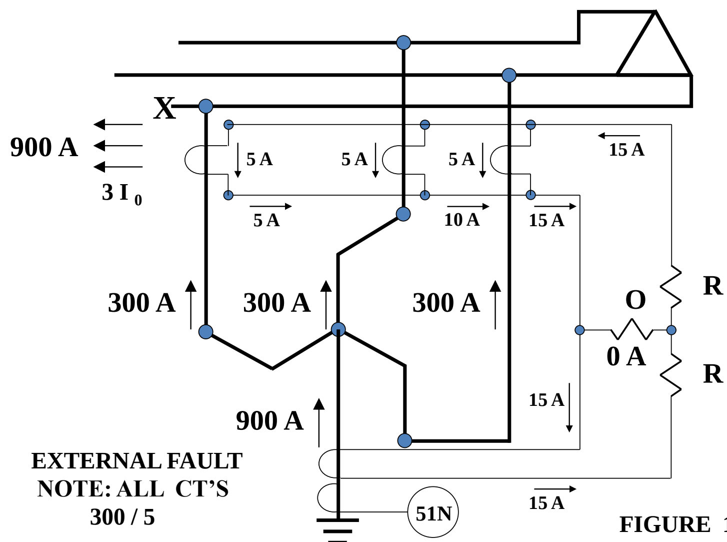

FIGURE 10

The loss of a grounding transformer that serves phase-to-ground connected loads and three phase loads will mean the loss of all connected loads. Therefore, it is highly recommended that two zig-zag grounding transformers be placed in parallel on a Delta connected system as shown in figure 12 so that the loss of one bank will not mean the loss of power while the failed transformer is being repaired. Each zig-zag grounding bank would still have to be protected by overcurrent relays (51) as shown in figure 12 or differential relays. The installation of differential relays would require an additional current transformer in the neutral connection of each grounding bank and additional CT secondary cables from the zig-zag grounding bank to the differential relays. However, only one station backup ground relay (51 N) connected between current transformers in the neutral of each grounding bank is required as shown in figure 12. The installation of two zig-zag grounding banks in parallel is a practice employed by many utilities. Contrast this to utilities that elect to install only one grounding bank. Their assumption is that connected loads can be served from an alternate source. However, over a period of time an alternate source may not be able to adequately supply power during peak load periods. This produces a conundrum for those utilities that have a philosophy of installing two grounding banks so that loads can continue to be served for the loss of one grounding bank. The problem occurs when the one grounding bank fails in a utility that has a philosophy of installing only one grounding bank. That utility may call a neighboring utility that has two grounding banks and request that it release one bank to supply its needs until it's damaged transformer can be repaired or replaced. For the length of time it takes to replace the damaged transformer, the (gracious) utility runs the risk of not being able to supply adequate service to its customers if it's remaining grounding bank fails. This begs the question; is the "gracious" utility obligated to supply its neighbor with one of its grounding banks and jeopardize its own system? It should be pointed out that most grounding banks are built to be "site" specific and may not be designed to work in a new environment. This will be covered in the following paragraphs.

ZIG – ZAG DIFFERENTIAL PROTECTION

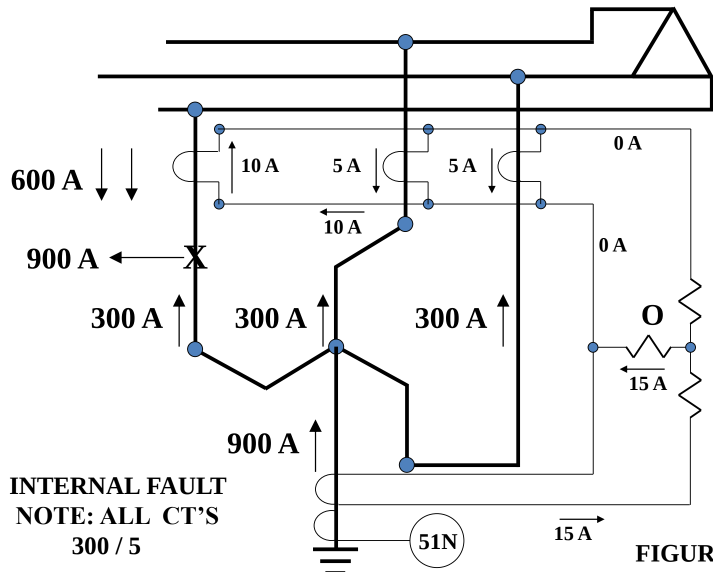

FIGURE 11

Calculations 1 and 2 represent one utilities approach to sizing zig-zag grounding bank installations. Calculation 1 is given for the installation of one grounding bank where $Z_0 / Z_1 = 3$. Calculation 2 is given for the installation of two grounding banks in parallel $Z_0 / Z_1 = 2$.

Therefore; during an emergency, when one (of two) banks is out of service because it failed, the remaining bank must supply all the grounding bank requirements. Under these conditions, $Z_0 / Z_1 = 4$.

TWO ZIZ-ZAG BANKS IN PARALLEL

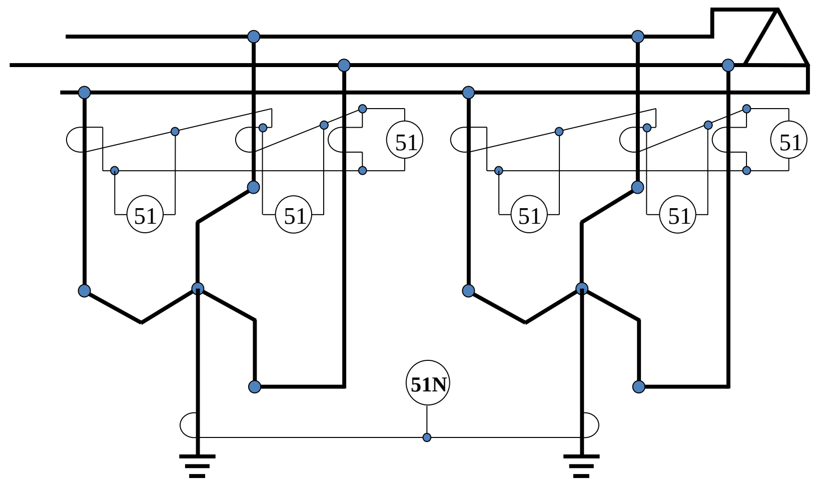

FIGURE 12

First, consider the installation of **one** zig-zag grounding bank whose source impedance (Z_1) is = 21% on 100 MVA base. Then I_g in per unit = 1.05. This is shown in Calculation 1. From these calculations the purchase of a zig-zag grounding bank with a 10 second rating is equal to 13,000 A.

ANSI/IEEE Standard 32-1972 requires a continuous rating of 3% for a 10 second rated unit. Therefore, the bank must be rated for 13,000 A (0.03) = 390 amperes continuously in the neutral of the zig-zag grounding bank. The power rating of the bank P = 7.62 x 390 / 1.732 = 1,716kva ($P = V_{LG} I_N / \sqrt{3}$). The zig-zag grounding transformer must be designed to handle the maximum fault current as well as a continuous unbalanced load on the circuit. The calculated continuous unbalanced current might suggest the specification of a “round off” current of 420 amperes neutral current (140 A per phase). If a utility can justify a lower continuous rating it would be able to save money on the purchase cost.

For those utilities, whose philosophy employs the installation of **two** grounding banks in parallel, a ratio of $Z_0 / Z_1 = 2$ might be considered. Again, to make a comparison, the example of using a source impedance of 21% on 100mva base is shown in Calculation 2. Notice, that while the total fault current has gone up to 15,620 A, the fault current and each zig-zag grounding bank is reduced to 7810 A. However, care must be taken to size the installation as if only one zig-zag grounding transformer is in service. Under these conditions the size of each zig-zag grounding bank, in a two bank system, is based on 10,414 A of current in the neutral.The sizing and installation of zig-zag grounding transformers can be complex. They are designed to be site specific, which does not lend itself to moving them from site to site.

On occasions significant voltage unbalances can occur when one phase voltage is opened upstream. This can occur when a single phase reclosure opens one phase and the zero sequence voltage approximates the line-to-neutral voltage. Under these conditions the zig-zag grounding bank will attempt to maintain normal voltage on the unfaulted phases which could produce damaging overload conditions on the grounding bank.

ONE Zig-Zag Bank (Calculation 1)

Assume Z_1 = 21% on 100 MVA Base

Then Z_0 = 3x21 = 63% (For One Grounding Bank)

Base Amperes = 100,000/13.2 (1.73) = 4374 Amperes

Therefore: $I_G = 4374/(Z_1 + Z_2 + Z_0)/3$ (Note: All “Z” in PU)

From Z_1 and Z_2 = 21% and Z_0 = 63%; the Sum = 105% (PU=1.05)

Therefore:

I_G = 4374 / 1.05 / 3 = 12,497 Amperes

This Current Magnitude would Suggest the Purchase of a

Zig-Zag Bank 10 Second Neutral Current Rating = 13,000 Amperes.

ANSI / IEEE Std. 32-1972 Requires a Continuous Rating of

3% for a 10 Second Rated Unit.

Therefore:

The Bank Must be Rated for a Continuous Neutral Current

Rating of 13,000 Amperes (0.03) = 390 Amperes

For the Case in Question Assume a Load Unbalance Not To

Exceed a Continuous Rating of 140 Amperes per Phase

Or 420 Amperes in the Neutral.

TWO Zig-Zag Banks (Calculation 2)

Assume Z1 = 21% On 100 MVA Base

Therefore: Z_0 = 2 x 21% = 42% For Two Banks

Two Banks @ 13.2 Kv

From: I_G = 4374 (Base Amperes) / (Z_1 + Z_2 + Z_0) / 3

4374 / 0.84 / 3 = 15,625 Amperes

Current in Each Bank = 15,625 / 2 = 7,810 Amperes

Assume one Bank Removed from Service

Then: $Z_0 = 4 \times 21 = 84\%$

Again: $Z_1 + Z_2 + Z_0 = 126\ \%$ (PU = 1.26)

I_G = 4374 / 1.26 / 3 = 10,414 Amperes

Notice: The 10 Second Rating For Each Bank In a

Two Bank System is Based on a One Bank Neutral

Current of 10,414 Amperes and Not 7,810 Amperes

Therefore: Each Bank Should Be Purchased with a

10 Second Neutral Current Rating of 10,400 Amperes and a Continuous

Rating of (0.03) x10,400 A = 312 A (Suggested Round Off 300 Amperes)

John Boyle, Bibliography

Professional Summary:

Electrical engineer retired Tennessee Valley Authority. Key positions included: Field Test Engineer, Area Protection Engineer, System Protection Engineer, Manager of Protection Section, Advisor to Manager of Operations, and Program Coordinator for the Power Equipment Facilities Transition Training Workshop of the Tennessee Valley Public Power Association.

Established an international consultant firm (Power System Analysts, PSA) with major clients being utilities, paper companies etc. Currently active in a variety of national electrical engineering groups such as IEEE, APPA, and EPRI. Teaches power system engineering courses and, on occasions, acts as an expert witness specializing in forensic diagnostic analysis of electrical problems.

Professional Activities

Member of Institute of Electrical and Electronics Engineers

Member of Power System Relaying Committee

Past chairman of the Power System Relaying Committee

Fellow, Life Member