Application Note

The 59N and Broken Delta Applications

On an impedance grounded system, phase-to-ground faults are detected by monitoring the zero sequence components of the line voltages and tripping with a 59N function (high 3V0).

Two ways relays determine $3V_0$ are:

1. Digitally calculating $3V_0$ from phase to ground voltage inputs. A relay monitors the phase-to-ground voltages from a set of 3 VTs connected wye-ground/wye-ground. The relay calculates $3V_0$ using the equation:

   $3V_0 = (V_{AG} + V_{BG} + V_{CG})$.

2. Measuring $3V_0$ from wye-ground/broken delta VTs. A relay with a single voltage input monitors the voltage across the broken delta derived from a set of 3 VTs connected wye-ground/broken delta. The voltage across the broken delta is simply the sum of system phase-to-ground voltages, or $3V_0$. The wye side of the wye-ground/broken delta VT can be directly connected to either the high voltage terminals or to the secondary of a main step-down VT.

Method 1 is used by digital multifunction relays, such as the BE1-FLEX Protection, Automation and Control System.

Most applications of these products need (or work best with) line-to-ground voltages. Therefore, no additional inputs are required to calculate the $3V_0$ quantity for the 59N application.

Method 2 was developed before the era of digital relays, but is still widely used. This is because users are familiar with past practices, it adds a small zero sequence load to help stabilize the system neutral, and it allows a simple relay to be used. The BE1-59N relay was designed for this application and is easy to use and set.

The BE1-59N and BE1-FLEX monitor a broken delta voltage via the V_x input. Digital multifunction products provide flexible, easy to apply protection elements, and include ancillary features as expected in modern digital multifunction products such as fault location, oscillography, sequence of events (SER), metering, power quality, and a variety of communication protocols.

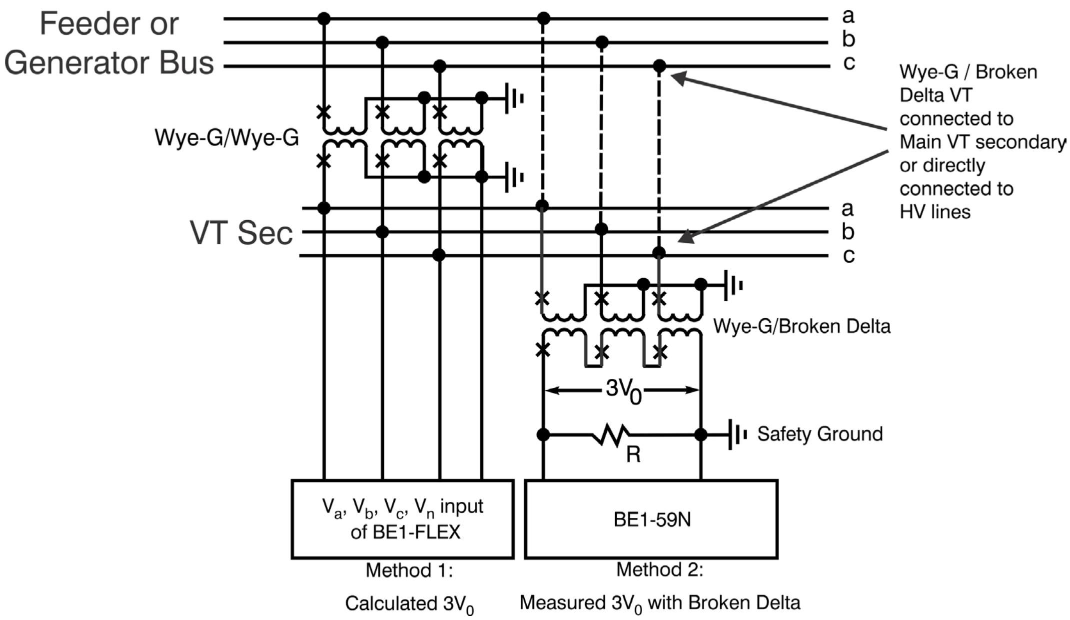

Figure 1 - 59N Broken Delta Schematic

In addition, BE1-FLEX protection includes all of the protection functionality required for nearly any Power System application. The BE1-FLEX is easily programmed with Basler's BESTCOMS*Plus*® interface software and includes many time saving features such as preprogrammed settings templates.

In method 2, it is common to place a resistor in the broken delta as shown in Figures 1 and 2, because the resistance stabilizes the measured voltage. It does this by a) reducing the risk of ferroresonance and b) allowing the VT to act as a very small ground bank.

The ground bank effect helps to hold the system neutral voltage closer to ground to prevent small leakage impedance to ground from causing high neutral shifts. The ground bank effect also provides a way to bleed off the capacitive voltage buildup associated with arcing ground faults on high impedance grounded systems. The ability of the VT and resistor to act as a ground bank and stabilize the neutral is fairly limited and will be covered later.

The question of whether an unloaded VT is at risk of entering into ferroresonance is difficult to answer. One circuit for ferroresonance is possible if the delta presents a path for a phase-to-ground voltage on one phase to energize another phase via the delta, which in turn has a capacitance to ground, creating an LC network where the L is saturable. If the circuit is lossy due to the resistance in the circuit, then resonance of the LC network is less likely but, on the other hand, leaving the delta completely open removes the resonant path. An argument could be made to leave the resistance out entirely if this is the circuit of concern. However, past practice by engineers indicates that including the resistance is advisable.

This application note does not attempt to analyze the matter any further than what is provided below.

Voltages During a Ground Fault

Refer to the phasor diagrams in Figure 2. During ideal normal operation with no ground fault or line-to-ground current:

$$
\begin{aligned}
V_{NG} &= 0 \\
V_{AG} &= V_{AN} + V_{NG} = 1\angle 0 + 0 \\
V_{BG} &= V_{BN} + V_{NG} = 1\angle -120 + 0 \\
V_{CG} &= V_{BN} + V_{NG} = 1\angle 120 + 0
\end{aligned}
$$

During a ground fault, virtually all of the faulted phase's voltage is impressed upon the neutral impedance. For a phase-A-to-ground fault, VAN=0, and the voltage across the neutral resistor is essentially the negative of the Phase-A-to-neutral voltage. Mathematically:

$$V_{AG} = 0 = V_{AN} + V_{NG}$$

which means:

$$V_{NG} = -V_{AN} = 1\angle 180$$

which therefore means:

$$
\begin{aligned}
V_{BG} &= 1\angle -120 + 1\angle 180 = 1.732\angle -150 \\
V_{CG} &= 1\angle 120 + 1\angle 180 = 1.732\angle 150
\end{aligned}
$$

A broken delta sums the three phase voltages, thus:

$$
\begin{aligned}
V_{Broken\ Delta} &= V_{AG} + V_{BG} + V_{CG} \\
&= 0 + 1.732\angle -150 + 1.732\angle 150 = 3\angle 180
\end{aligned}
$$

From this line of reasoning, it is evident that the worst case steady state functional frequency voltage at the broken delta is:

$$V_{Broken\,Delta} = 3 * \frac{V_{SYS,LG,NORMAL}}{VTR} \angle(V_{Unfaulted\,Phase\,Angle} + 180)$$

The VTR in the above equation is best considered in terms of the winding turns ratio, rather than voltage ratios. This is highlighted because the question of whether one should use V_{L-L} or V_{L-N} to calculate VTR is avoided if one thinks in terms of winding turns ratio.

For example, if normal system voltage is 13.8 kV_{L-L} and 7.97 kV_{L-G}, and a VTR of 115 is used, for a phase A fault, the worst case broken delta voltage would be:

$$
\begin{aligned}
V_{Broken\,Delta,\,Phase\,A\,Fault} &= 3 * \frac{7970}{115} \angle(0 - 180) \\
&= 207.9\angle 180
\end{aligned}
$$

With a VTR of 115, the normal secondary voltage during unfaulted conditions on each leg of the delta would be:

$$V_{LL,Delta\,Sec,\,Normal} = \frac{V_{VT\,Primary}}{VTR} = \frac{7970}{115} = 69.3V$$

During a fault, secondary voltage on the two unfaulted phases rises to 120 V (=13800/115). Note that 69.3 * 3 = 207.9 V, which agrees with the earlier calculations for the maximum broken delta voltage during the fault.

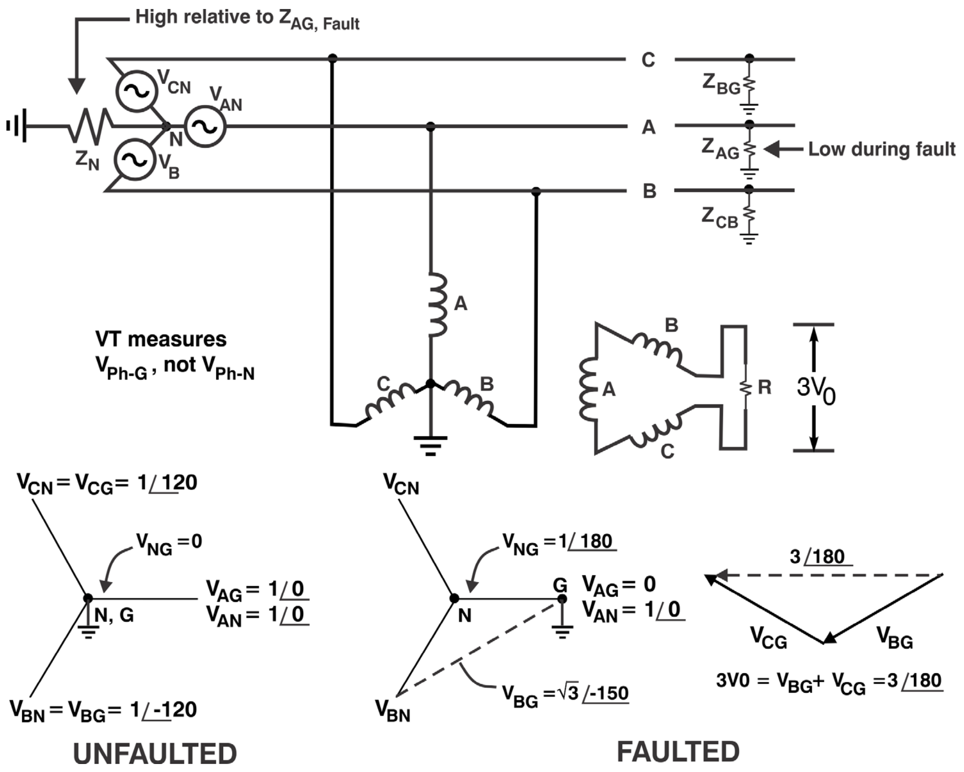

Figure 2 - Phasor Diagrams During Line-to-Ground Fault

If the ground fault impedance is high or the source ground impedance is low, the voltage that will arise during a ground fault will be less than 3 per unit. The calculation of what will occur can be analyzed using a set of simultaneous equations.

VT Voltage Rating

It is important to note that, during a ground fault, two of the VTs must withstand and reproduce full line-to-line voltage. It is incorrect to use a VT rated only for line-to-ground voltage. For instance, in the wye-broken delta system described above, the normal system voltage is 13.8 kV_{L-L} and 7.97 kV_{L-G}, and secondary voltage is 69.3 V under normal operating conditions but rises to 120 V during a fault. In this case, the VT should be rated for 13.8 kV/120 V.

Resistance Selection

To utilize the resistor's maximum capability to dampen system transients and ferroresonant circuits, a typical approach to sizing the resistor is to select one that can handle all the power that the VTs can supply during a full neutral offset. Fully loading the VT causes some voltage drop and error in the secondary, but if the VT is dedicated to the broken delta configuration, the voltage drop that results causes no ill effects. However, if the aux VT approach in Figure 1 is used, then one should determine if the fully loaded aux VT will pull down the main VT secondary voltage and affect other relaying in the system. Ignoring the voltage drop issue, sizing of the resistor to bring the VTs to a high loading level results in two approaches to sizing the resistor:

Approach 1 - Base resistance on VT continuous current rating: Size the resistor so that the amperes drawn are equal to the continuous current rating of the transformer bank or

Approach 2 - Base resistance on VT 3-phase VA rating: If the fault will be cleared quickly, size the resistor so that power in the resistor is equal to the full 3-phase VA of the transformer bank, which overcurrents the bank by a factor of sqrt(3), as seen below.

Approach 1 Considerations

This approach should be used if the fault could be in place for an extended period. Recall the previous example where V_{SEC} is 69.3 V normally but rises to 120 V during a fault and assume a VT rated at 500 VA per phase and 13.8 kV/120 V.

$$I_{VT\ Sec,Rated} = \frac{VA_{VT,\ 1phase}}{V_{Sec}} = \frac{500}{120}$$
$$= 4.167A$$

During a ground fault, ignoring voltage drop in the VT when fully loaded, the resistor measures 207.9 V per the previous example. To limit current to 4.167 A,

$$R_{\Omega} = \frac{V}{I} = \frac{207.9V}{4.167A}$$
$$= 49.9\Omega$$

The power in the resistor will be:

$$P_W = V \cdot I = 207.9 \cdot 4.167$$
$$= 866W$$

Because it is anticipated that the fault could be held for an extended period, the resistor must be sized to handle this heat dissipation continuously.

Approach 2 considerations:

This approach overloads the VTs and is appropriate only if the fault will be cleared before the overload can affect the VTs. Again, assume a VT rated at 500 VA per phase for a total of 1,500 VA for all three phases. Ignore the voltage drop in the fully loaded VT and assume that the full 207.9 V from the previous calculations is measured across the resistor. The resistance required to load the transformer bank to 1,500 VA is:

$$R_{\Omega} = \frac{V^2_{Sec,Faulted,}}{VA_{VT,3ph}} = \frac{207.9^2}{1500}$$
$$= 28.8\Omega$$

The current drawn during the fault would be:

$$I_{VT\ Sec} = \frac{V_{Sec,Faulted}}{R} = \frac{207.9}{28.8}$$
$$= 7.22A$$

This current is sqrt(3) times the continuous current rating of the VT, calculated previously. The power in the resistor would be:

$$P_W = V \cdot I = 207.9 \cdot 7.22$$
$$= 1500W$$

The VT is overloaded in this case, so it is recommended that the fault be cleared quickly. Assuming the fault will be cleared quickly, the short time rating of the resistor should be considered, which allows a smaller resistor to be used.

Resistor Short Time Power Rating

The power calculated in the previous examples is rather large. However, if the fault will be cleared quickly, then the short time rating of the resistor can be used to allow a smaller resistor wattage rating. As a general guideline, a wire-wound power resistor can handle a short time overload of:

where t_s = time in seconds. Solving for the required continuous rating:

$$P_{W,\ Short\ Time} = P_{W,\ Continuous} \cdot \frac{50}{t_S} \quad \text{for } 1 < t_s < 25$$

In the equation above, if t is less than 1 s, use t = 1, and if t > 25 s, it is best to consider using a fully rated resistor. For this example, if using a 28.8 Ω resistor, a 5-second fault clear time, and a x2 safety margin, then a 300 W resistor should be used (1500*(5/50)* (2) = 300).

$$P_{W,\ Continuous} = P_{W,\ Short\ Time} \cdot \frac{t_S}{50}$$

Ground Bank Effect of a VT

The ability of a VT to act as a small grounding bank and limit neutral voltage shift is fairly weak, but it may be applied in cases where ground impedances are very high. As a comparison, the 28.8 Ω resistor in the previous example reflected to the primary by VTR2 (1152) is 381 kΩ. This may help stabilize a substation bus or a short transmission line with only minor phase-to-ground capacitance or leakage resistance. Directly related to this concept, the current flowing in the delta will flow through the faulted phase VT, which tends to push some current from the VT back into the ground fault. If the ground fault impedance is large, the VT may sustain voltage on the faulted phase.

For More Information

Visit our website at www.basler.com to access product documentation, the technical paper, A Review of Ferroresonance, and Application Notes on other topics.

To discuss your specific application, contact Basler's Technical Support or Application Specialists at (618) 654-2341.

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