GROUND FAULT DETECTION IN MULTIPLE SOURCE SOLIDLY GROUNDED SYSTEMS VIA THE SINGLE-PROCESSOR CONCEPT FOR CIRCUIT PROTECTION

Marcelo Valdes, PE.
IEEE Member
GE
Plainville, Connecticut

Greg Lavoie
GE
Plainville, Connecticut

Tom Papallo
GE
Plainville, Connecticut

Bill Premerlani, PHD
GE Research
Niskayuna, New York

Abstract – Modern power distribution systems often contain multiple power sources integrated within one system. A simple variant may be the common double-ended substation, which can be further complicated by additional emergency or alternate sources. This presents significant complexity to the designer attempting to design a protection system that will not be fooled by circulating neutral currents. The authors describe how the “Single Processor Concept for Circuit Breaker Protection and Control” [1] provides ways to address this sensing problem. One such method is described in further detail. Handling of resistance-grounded systems will be the subject of a related paper.

Index terms – ground fault, circulating neutral currents, double-ended substation, single-processor concept, multiple grounds.

I. INTRODUCTION

Detection and isolation of high-impedance arcing ground faults in solidly grounded low-voltage power distribution systems is an important part of over-current protection. Since the use of 480/277 V and 600/347 V systems became common in North America, the phenomenon of arcing ground faults has been well studied. The damage these faults create is greater than their magnitude would seem to indicate. The increased damage is, in fact, due to their lower magnitude. Normal over-current protectors (especially fuses) may not sense an arcing ground fault for several cycles, seconds, or even longer. In solidly grounded WYE systems, low-magnitude arcing faults are, however, relatively easy to detect with specific circuits created for that purpose. Modern ground-fault sensing methods allow detection of ground faults even when they are well below the magnitude of normal load currents in a system. GFCI residential protectors that detect 5 mA faults in 20 A circuits function on the same principle as higher-level ground-fault detectors designed for equipment protection. The National Electrical Code mandates ground-fault protection for solidly grounded WYE services of 1000 A and above. The pick-up level is limited to 1200 A maximum. Other code requirements for hospitals require a second level of coordinated ground-fault protection. Good engineering practice easily makes the case for even more levels of ground-fault protection in some situations. Ground-fault protection is an important consideration in the design of any power distribution system.

This paper reviews basic techniques of ground-fault detection in solidly grounded low-voltage systems and how they become increasing complex in systems with multiple sources and multiple grounds. Some of the commonly applied solutions that employ individual relays or circuit breaker trips are discussed. The concept of using a single processor to simultaneously process all circuit and circuit breaker information may provide for a new cost-effective way of solving the ground-fault detection problem for systems with multiple solidly grounded sources. A range of new solutions based on the single-processor-concept, described in IEEE paper PID-04-12, PCIC-03-28 “The Single-Processor Concept For Protection And Control Of Circuit Breakers In Low-Voltage Switchgear,” is presented.

II. NATURE OF THE GROUND-FAULT DETECTION PROBLEM

The electrical characteristics of ground faults in solidly grounded WYE systems allow for simple detection of ground currents by monitoring the phase and neutral currents for a simple unbalance in those currents. The principle is that the current going to the load on the normal phase and neutral conductors should return via those same conductors. Any missing current is deemed a fault to ground on the load side of the detector and, when that unbalance exceeds a set threshold, a ground fault is determined. The basic ways of measuring this unbalance for solidly grounded four-wire systems use one ground sensor surrounding the phase and neutral conductors, four individual current transformers connected in a WYE configuration, or four voltage sources connected in a delta configuration.

The ground-fault sensor shown in Figure 1 encircles all the phase conductors and neutral conductors, magnetically adding the flux vectors. The sensor is also called a zero-sequence current transformer. Net flux is caused by the net current unbalance of the ground-fault current flowing through the phase conductor. In Figure 1 the fault current is shown on phase B. The returning current vector is not sensed because the current is flowing from the fault to the transformer’s ground, bypassing the neutral conductor. This method is often used when separate ground-fault relays are applied.

The broken-delta method shown in Figure 2 employs four transducers, each monitoring one of the normal current-carrying conductors. Each produces a voltage vector proportional to the current through its respective conductor.

The net voltage in the circuit is proportional to the net unbalanced current flowing in the circuit plus error that is introduced by sensing and circuitry. The residual method also shown in Figure 2 employs four current transformers and places the trip coil of a relay in the common leg of the four transformers. The current flow through that leg is the net unbalance of the phase and neutral conductors.

Many modern electronic trips also use four sensors; however, the signals are digitized and summed in the trip electronics. All of these methods look for the unbalanced or residual current that results when the fault current finds a path back to the source via ground. Figure 3 demonstrates the simple equivalent circuit used for fault detection. The residual and broken-delta methods must also account for the error introduced by the four sensing devices and electronics. The zero-sequence method must consider the error introduced by conductor geometry within the single current transformer and sensor.

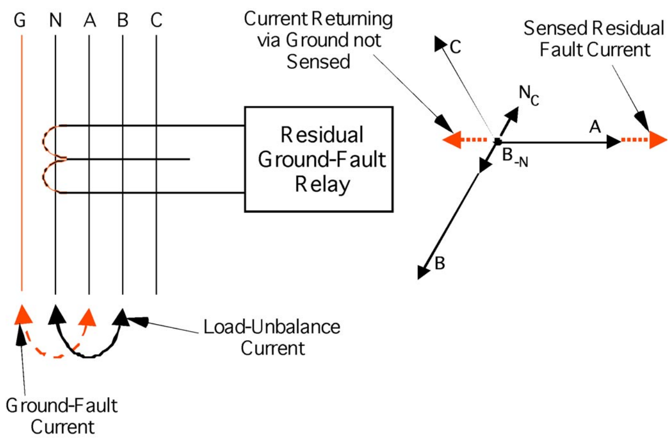

Fig 1. Ground-fault sensor.

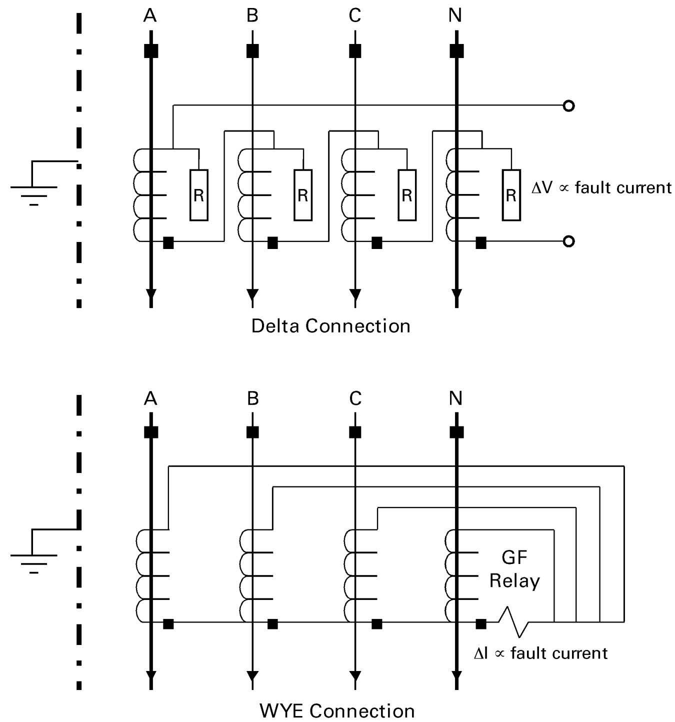

Fig 2. Broken-delta and residual methods of ground-fault detection.

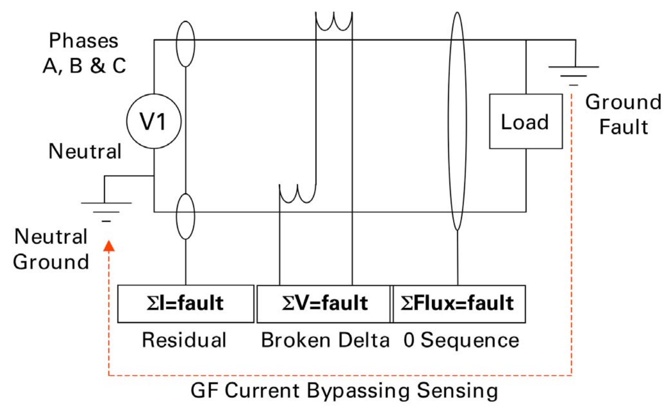

Fig 3. Equivalent circuit for fault detection.

III. COMPLICATIONS IN MULTIPLE-SOURCE SYSTEMS WITH MULTIPLE GROUND CONNECTIONS

As seen in the previous discussion, all the methods for detecting ground-fault current rely on comparing the phase and neutral currents for a particular circuit. Any unbalance that is sensed represents the fault current external to the expected circuit. Systems with multiple intentional grounds make these sensing methods difficult to implement because there are multiple paths that neutral and ground-fault currents can follow to the source. The most common situation where this problem is encountered is the double-ended substation with two transformers with solidly grounded secondary WYE windings. The common neutral connection between the transformers serves as a path for potential circulating neutral and ground currents. This causes significant complexity in confirming balanced currents during normal operation or detecting current imbalances due to ground-fault currents on the main bus, resulting in false detections or missed faults.

Figure 4 illustrates how a main breaker may be fooled by the alternate current path provided by the neutral and parallel ground connections between the transformers. In this case, the ground-fault detection circuit in the trip may miss the ground fault because the fault current is shunted back to the neutral of the left transformer (source 1) via the ground connection to source 2 and its connection to the common neutral bus. This could be caused by the source 1 ground connection having a higher impedance than source 2 ground connection. Figure 5 demonstrates a situation in which neutral current can return to the transformer neutral via the parallel ground path instead of the normal neutral connection. This can occur if source 1's neutral-to-bus neutral connection has higher impedance than the parallel ground path. This results in a situation in which the main circuit breakers could both sense current unbalance and indicate a ground fault that does not exist.

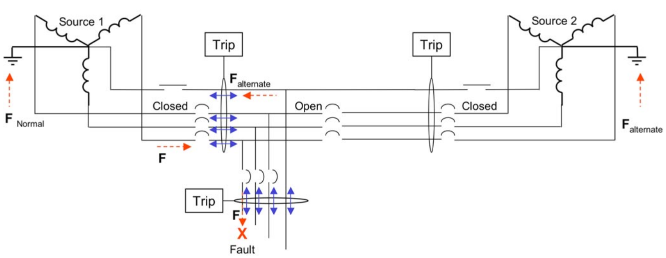

Fig 4. Alternate current path between transformers.

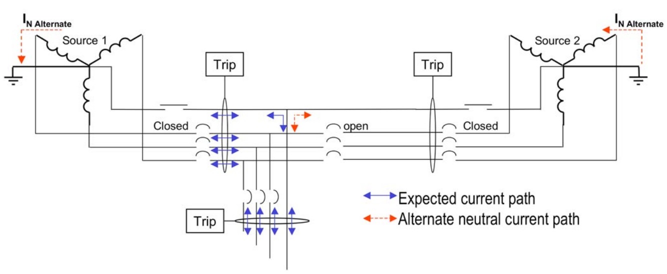

Fig 5. Neutral current returning to the transformer via a parallel ground path.

Figure 6 demonstrates circuit breaker trips based on the normal phase and neutral buses are not able to take into account all the possible currents because of the extra current loops that the interconnected neutrals provide. The one-line loop diagram facilitates analysis in terms of Kirchhoff's circuit laws. The various ground-fault sensors function by comparing the current on the positive bus (net three-phase line current) to the current on the negative bus (neutral current resulting from an unbalanced three-phase load). Any difference between the two buses should be proportional to the ground-fault current. However, the introduction of the second ground connection provides an alternative path for the negative bus (neutral) current, which may create circulating currents. The magnitude of the circulating currents is a factor of the various impedances in the negative bus, the ground connections, and the ground path. This renders the ground-fault protection for the source and tie circuit breakers inoperable. However, the load ground-fault protection is not affected. The reader may draw a third accidental ground and evaluate the loop circuits. It should be evident that the situation is worsened by the creation of additional ground loops, although the load ground fault will function in all situations.

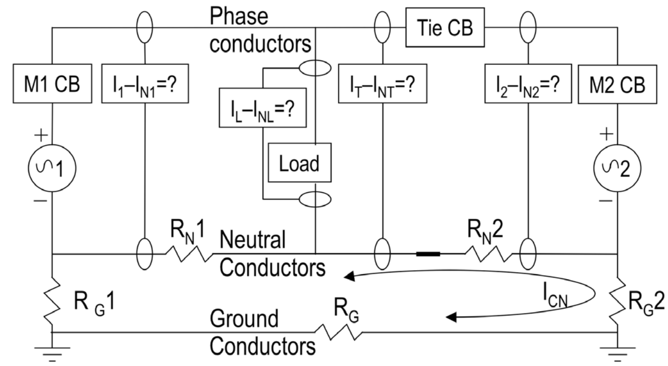

Fig 6. Second ground creates circulating neutral currents.

IV. TRADITIONAL SOLUTIONS:

In this situation, the best solution may be to use only a three-wire system in which the neutral is grounded but not connected and distributed. Without an interconnected neutral, circulating neutral currents are impossible and ground faults may be easily detected by individual circuit breakers or relays. This solution may often be very cost effective when the required 277 V or 347 V load is small or localized. However, this topology is not optimal for every power distribution system. Another solution for systems not designed for parallel operation is four-pole throw-over devices, with the fourth pole used to transfer the neutral bus. Typically, four-pole transfer switches or, more rarely, four-pole circuit breakers are used for this purpose. However, this requires expensive transfer switches and excludes applications requiring parallel operation of multiple grounded sources. Transitions must be open or closed for very brief periods. Four-pole circuit breaker solutions also exclude parallel operation of sources and are expensive and not universally available. There are various ground-fault sensing schemes that provide at least a partial solution to the problem.

One method applicable to double-ended substations that are grounded at a single point, as shown in Figure 7, employs ground-return sensors to detect the return current. This method of grounding does not permit circulating neutral currents. A double-ended substation can operate with the tie open or closed. Originally designed around electromechanical inverse-time over-current relays, a variation of this configuration is now commonly applied with relays specifically made for low-voltage ground-fault applications. This technique is suitable for applications requiring parallel operation of sources. The tie circuit breaker routes control power to the main circuit breaker relays so that the relays are energized only when the tie circuit breaker is open. Hence, the relays are insensitive to proper neutral currents that may be flowing from one bus to the other during closed-tie operation. When the tie is closed, its relay monitors ground-return current. The relay trips when it senses return current over its threshold. At that time the mains' relays are energized and each relay is then able to sense and react to the ground-return current, if present. The relay for the transformer feeding the fault will trip, while the other relay does not see fault current and so does not trip. This provides selective tripping of the tie and main circuit breaker. To allow for selectivity with the ground-fault function in the feeder circuit breakers, the relay settings must be sufficiently delayed to allow downstream devices to trip. Typically, this means the main circuit breakers are working with intentional delays of at least 300 ms or two delays above what is needed for the feeder circuit breaker to coordinate with load-side protective devices. This method requires relays separate from the circuit breakers' integral trips; dedicated sensors; and dedicated wiring for the sensors, relays, and auxiliary contacts required to properly operate the circuit.

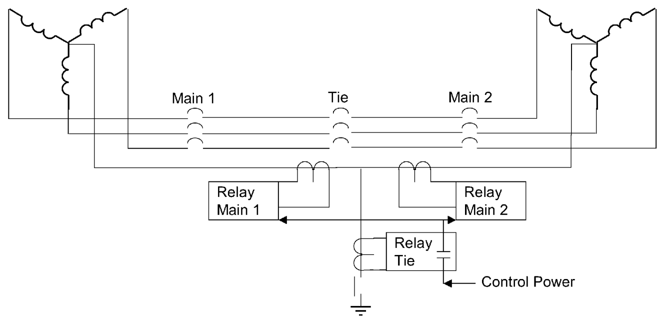

Fig 7. Double-ended substation grounded at a single point.

Another method is a summation scheme using loop-connected neutral sensors to detect circulating neutral currents. This method takes advantages of the integral trip units in modern circuit breakers. Auxiliary contacts in the circuit breakers guide circulating neutral currents out of the trip circuit for at least one of the circuit breaker trips. However, this method requires that at least one of the circuit breakers be open so that the associated neutral sensor forces the secondary circulating current to flow though the neutral sensor loop and all the sensors equally without entering a trip circuit. Figure 8 shows that the neutral unbalance current for the closed mains flows through the neutral sensor and into the respective trips. These sensors act as voltage sources. The neutral current that may be flowing from one transformer's ground to the other neutral flows through the tie circuit breaker's neutral current transformer. The current transformer secondary current is maintained in the neutral sensor secondary loop by the tie's sensor, which acts as a current source. The circuit works similarly if one of the mains is open and the tie is closed. All three circuit breakers may be closed only during short closed transition periods that should last less than the time delay set for ground-fault protection at any of the three circuit breakers.

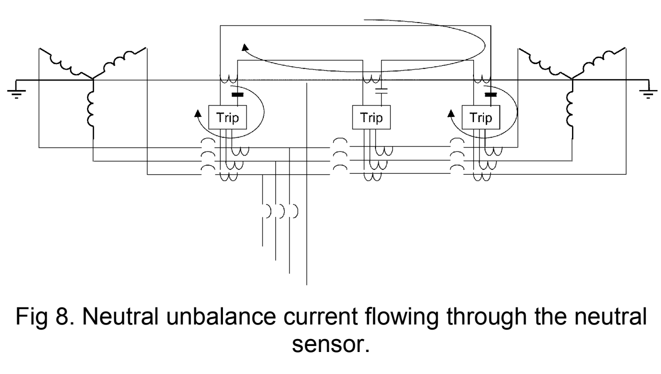

Fig 8. Neutral unbalance current flowing through the neutral sensor.

The summation scheme using circuit breaker integral trips is not easily suited for systems with more than three circuit breakers or for systems in which all three circuit breakers are closed simultaneously for extended periods. A more flexible and forgiving scheme is needed to handle one or more grounding points and more than two ties and main circuit breakers closed simultaneously.

Another available scheme is often called "modified differential ground-fault protection." This circuit may be used with residual circuits or single ground sensors. Figure 9 shows one form of this configuration using zero-sequence sensors around all the equipment conductors. The premise is that circulating neutral currents are kept in the secondary loop around the relay coils and, hence, the ground-fault relays are not sensitive to that current. This circuit works with ties open or closed and with sources in parallel. A disadvantage is that it only looks at mains and ties and it cannot differentiate between an in-zone fault and one below the zone. The time delay for the main and tie must be set slower than the feeder's ground-fault delay to maintain selectivity. Although this method provides for selective protection regardless of the combination of source circuit breakers that are closed, the protection must be delayed above the longest set-time delay of any feeder below the main buses. Selectivity is achieved, but protection at the main buses is slowed.

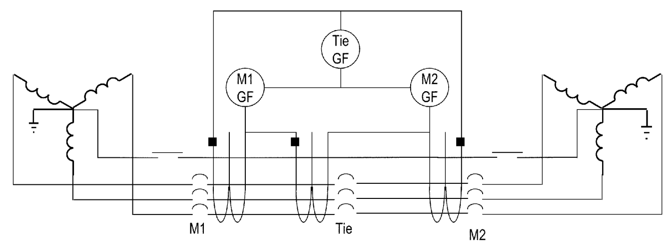

Fig 9. Modified differential ground-fault protection with zero-sequence sensor.

V. THE SINGLE-PROCESSOR CONCEPT

The single-processor concept for control and protection of low-voltage circuit breakers collects and simultaneously processes all substation current and voltage information in one central CPU. The CPU can perform multiple algorithms simultaneously using all the available information. The available information—current, voltage, and device status—is completely synchronized. All values may be considered instantaneously and simultaneously. Differential calculations that compare the relative values of current or voltage are possible because the synchronized data include correct magnitude and phase relations. Algorithms can take into account the open or closed status of each circuit breaker, recognizing which are sources and which are loads, and may make instant comparisons of the various currents because the data are fully synchronized. Redundancy in communication networks, processors, and backup-trip capability address potential reliability concerns.

Since all the information is available in one place, over-current protection may be based on zones. In other words, the location of a fault current may be specified within identified zones of protection. Furthermore, the magnitude of the identified fault is not limited by load currents normally associated with the zone or time-delay settings required to ride through inrush currents and achieve time-delay-based selectivity. The only limitation is imposed by the error considerations associated with current transformers, analog-to-digital converters, and other circuit components. This allows significantly better fault-magnitude resolution than cascaded protection and does away with the need for cascaded time delays to achieve selectivity.

It should be noted that the term “Single-Processor Concept” implies that all system information is available to one processor for consideration. It does not imply that system protection is entirely dependent on that one processor. Multiple redundant processors may be used and even local self-powered basic backup protection may be implemented for each circuit. This addresses concerns about reliance on a single device for protection of an entire system.

A. Basic Method

The obvious calculation method is ground-fault differential sensing. Once a zone is identified, all the residual currents into the zone are calculated and compared with all the residual currents flowing out of the zone. Any net residual current is proportional to the ground fault occurring within the zone. Any fault outside the zone is not sensed. This method is similar to bus-differential protection and is simple to understand; however, it has a significant drawback. Ground-fault currents in low-voltage systems may be low. Arcing ground-faults have an arc impedance that limits fault current. Code requirements also limit nominal settings to 1200 A and lower settings may be desirable. However, each residual calculation is subject to error caused by the nonlinearity and manufacturing tolerances of the current transformers and other circuit components. A full differential calculation has to account for the errors of all of the devices involved in the calculation. As the number of circuit breakers within a zone increases, the error increases. This is further complicated by the fact that error also increases as the load current through a current transformer increases. Normal transitory loads such as motor inrush currents and transformer inrush currents temporarily introduce increased error into a current-sensing circuit. Circuit breakers could have permissible short-time loads of up to 10 times the rated transformer current. If the current transformers at that point produce 5% error, a 2000 A circuit breaker with a 20,000 A current could be producing 1000 A of residual error current. Having several such errors in a full-differential calculation could produce significant cumulative error. Any relay, digital or analog, must accommodate this error without nuisance tripping and still provide reliable fault detection. How the algorithm handles error is discussed later.

Another way the system may be able to detect ground faults uses partial-differential calculations with restraint provided by circuit breakers in the zone excluded in the calculation. The premise is that the net residual current is only calculated for the source circuit breakers into a zone. The differential calculation including these source circuit breakers indicates a net residual current if there is a fault within the zone or fed by the zone. All circuit breakers fed by the zone have their own ground-fault calculation algorithms. If the net residual calculated for the zone is caused by a ground fault below the feeder, the system would know it. That information may be used to restrain the partial differential timing enough to allow downstream protectors to trip. This method of operation is similar to zone-selective interlocking. However, it does not rely on the individual mains and ties to recognize ground-fault current that, as discussed earlier, they would not be able to do reliably. Furthermore, it does not require additional wiring to send interlocking signals between circuit breakers, since all the calculations are performed in one processor.

Figure 10 shows that for a double-ended substation, three zones of protection may be considered. Two zones, each around one of the main buses, may be used for the differential-protection calculations. The third zone combines the other two smaller zones into one bus. In this case, we choose the two smaller zones, each of which includes the tie circuit breaker, a main, and the feeder circuit breakers on one bus or the other. The intent is to identify which zone has a fault and to trip the proper breakers to isolate the fault in minimum time with no loss of continuity in the other zone, if appropriate. The circuit breakers that are sources of power into the zone are identified and assigned a current direction. This defines whether the residual current calculated for that circuit breaker is added or subtracted. The source circuit breakers are also assigned a size to indicate the rating of the current transformers. Figure 10 shows the current flows assigned to each circuit breaker in the substation. The third zone only includes the main circuit breakers; it may be called the summation zone and used for backup protection.

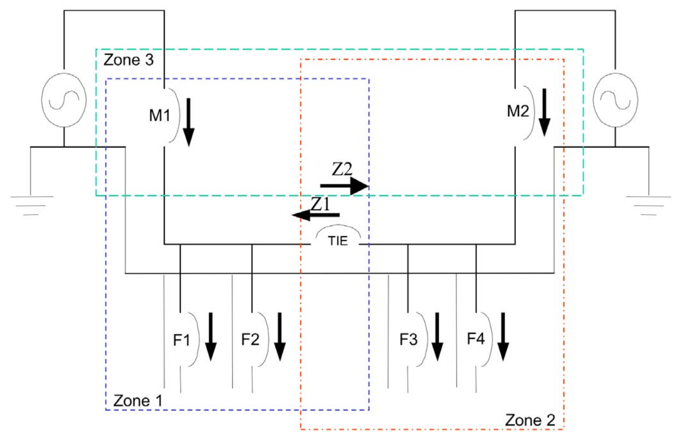

Fig 10. Current flows assigned to each breaker in the substation.

Since the system can detect which of the source circuit breakers are closed or open, the CPU can identify the power distribution system topology at any time. Each topology can be assigned a completely different range of fault-current settings and pickup delays. This is not expected for typical ground-fault applications, so in this explanation only one set of settings is discussed. However, the system should be able to change ground-fault settings or delete them completely based on the combination of source circuit breakers that is providing power at that time.

Pickup settings and time-delay settings may now be made for each zone, rather than for each of the source circuit breakers individually. The feeder circuit breakers may still be assigned settings in the traditional manner. In addition, each zone may be assigned backup devices to trip. This provides additional protection in case a circuit breaker fails to operate or fails to clear an arcing fault that has straddled a circuit breaker within the equipment. In a simple double-ended substation, the backup protector is the opposite bus main for either zone. In a double-ended substation with dual series ties, the backup protector could be the second tie or the opposite bus main.

The summation calculation for the zone includes the main circuit breaker for that zone and the tie circuit breaker between the buses. This calculation captures the phase and neutral currents whether the circuit breakers are open or closed. Circulating neutral current that flows through both the tie and main neutral sensors is cancelled out. Any fault detected by a feeder circuit breaker connected to the bus initiates the differential zone timing to a trip. However, a fault calculated for a downstream feeder would restrain the zone-protection timing long enough for the feeder circuit breaker to clear. If the feeder breaker does not clear the fault, the zone circuit breakers should quickly back up the feeder. If the differential calculation determines that a fault is present and feeder fault calculations have not resulted in a restraint, then the zone will time to a trip at its set delay. The zone will trip the tie and main simultaneously. Table 1 shows the settings that may be made for each of the zones. The feeder circuit breakers may have any pickup or time-delay setting, as long as the pickup setting is equal to or smaller than the zone setting above it. Time-delay settings at the feeder may be slower or faster than the setting for the zone providing power to the feeder circuit breaker.

TABLE 1.
CIRCUIT BREAKER SETTINGS FOR EACH OF THE ZONES.

Zone	**Primary PU**	**Primary Delay**	**Primary CB**	**Backup CB**	**Restraining Tier CBs**
1	1200A	Minimum	M1/T	M2	F1/F2
2	1200A	Minimum	M2/T	M1	F3/F4

B. Differential and Partial-Differential Calculations

Consider the fault scenario shown in Figure 11. In this case, the substation has all three source circuit breakers closed, both mains and the tie. Fault current to ground exists on bus 1 directly fed by main 1 and fed by main 2 through the tie.

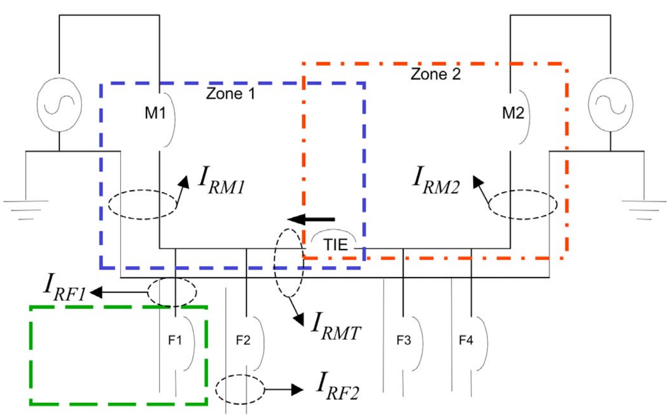

Fig 11. Fault with three source breakers closed.

The general algorithm equations are as follows:

$$\sum_{k}^{zone} I_{residual}[k] = 0 \qquad (1)$$

where *k* is the number of circuits contributing to the residual current. In this case, the equations for zone 1 and 2 are

$$\begin{aligned} I_{RM1} + I_{RT} &= I_{f1} + I_{f2} \\ I_{RM2} - I_{RT} &= I_{f1} - I_{f2} = 0 \end{aligned} \qquad (2, 3)$$

where I_{RM1} is the residual current through main 1, I_{RT} is the residual current through the tie, and I_{f1} and I_{f2} are the ground-fault currents fed from the respective mains.

The calculation for zone 1 identifies a fault in or below zone 1. The calculation for zone 2 yields a different result. In this case, the residual current flows in through the main and out through the tie, so the sum is zero, indicating that there is no fault on that bus or fed by the bus to the connected feeders. Since the source circuit breakers, mains and ties, are always included in the calculation whether they are open or closed, the neutral conductor may carry circulating current without affecting the result of the calculation. This allows the system to operate closed tie, in parallel or without a need for four-pole transfer or four-pole main devices.

The final determination of whether the fault is located at the bus or feeder is made by the individual feeder's ground-fault detection algorithm. If a feeder within the zone detects a ground fault, then the bus's differential calculation is delayed so that it acts as a backup to the feeder. The primary circuit breakers for the zone with the fault will trip at their set delay and the backup is delayed only in case they fail to operate or clear the fault. The same circuit breaker that is delayed in its backup role is not delayed when it is the primary protector for a zone. So, in all cases, all main and tie circuit breakers are able to operate for a fault within their respective zones at their set delay, which may be the minimum possible time delay. Feeder circuit breakers may also be set at minimum or higher delays. Selectivity need not be sacrificed to achieve optimum protection.

C. Calculation Method

AC current is normally represented as a phasor, in which each current is considered as a vector with a phase angle. Hence, the multiple currents being added are vectors with angular displacements with respect to each other. If all the currents in a three-phase system are evenly displaced, 120 degrees apart and with equal magnitudes, the sum of the vectors is like the average position of the moon around the earth: at the center of rotation or zero. An unbalance or a nonzero value indicates the presence of a fault current. In (4) and (5) the phase, neutral, and residual currents are treated as scalar values. The central processor in the system is able to analyze the data for all circuit breakers simultaneously. one sample at time. The mathematical operations use the raw data samples as instantaneous scalar values. The calculation accurately reflects the true rms magnitude, phase angle, and harmonic content of the current wave forms through the ($^n/_2$ – 1) harmonic. The full equation development for a zone for a set of 32 data samples encompassing one-half of an AC wave cycle is shown in equations 4 and 5. The *k*th sample of the residual waveform is given by

$$i_{residual,k} = i_{Ak} + i_{Bk} + i_{Ck} + i_{Nk} \qquad (4)$$

where *k = 0 to n and* i_{Ak}, i_{Bk}, i_{Ck}, and i_{Nk} are the *k*th samples of the phase A, B, C, and N currents, respectively.

The algorithm calculates the mean-squared residual current for the *M* breakers in the zone as

$$I^2_{residual,zone} = \frac{2}{N}\sum_{k=0}^{n/2-1}\left(\begin{array}{l}\frac{C_0}{C_{base}} i_{residual0,k} \pm \\ \frac{C_1}{C_{base}} i_{residual1,k} \\ \pm \cdots \pm \\ \frac{C_{M-1}}{C_{base}} i_{residualM-1,k}\end{array}\right)^2 \quad (5)$$

where N = 64 is the number of samples per cycle; $i_{residual0,k}$, $i_{residual1,k}$, and $i_{residualM-1,k}$ are the kth samples for each circuit breaker's residual current; M is the number of member breakers in the zone; C_0, C_1, and C_{M-1} are the current transformer ratios for each circuit breaker; and C_{base} is the base current transformer ratio used to normalize the data.

Whether a sample is added or subtracted depends on the current-flow direction programmed for that circuit breaker. The algorithm adjusts the residual current to account for the errors introduced by the measurement system. This creates a residual waveform. The residual waveforms can then be added or subtracted to generate the net zone residual waveform. This net residual waveform retains the magnitude, phase angle, and harmonic content of the original individual waveforms. This method also accounts for circulating third-harmonic currents that may be caused by differences between generators supplying the system.

The calculations for the zone residual current use I^2 rather than I. Because inverse-time curves for circuit breakers are functions of $t = k/I^2$, this eliminates one square-root calculation and the associated loss of bits and resolution.

D. Accounting for Current Transformer Error and Size

A digital calculation may easily account for the error caused by the nonlinearity and manufacturing tolerances in current transformers and for the various sizes of the current transformers that are used. (6) is used to calculate an error coefficient and (7) uses the coefficients to adjust the calculated residual current. The error in this digital process is similar to the error be experienced by a similar analog circuit employing multiple current transformers, as in any of the traditional ground-fault detection methods. However, this algorithm is able to treat the error in a more sophisticated manner and only needs to detune the ground-fault pick enough to account for the error at the particular time and current magnitudes used in the calculation. This is demonstrated in (6) and (7). The error coefficient is given by

$$\varepsilon_p = f(I^2_{max,p}, CT_p, CT_{base}) \quad (6)$$

where the ampere squared error, $\varepsilon_{p,t}$, is calculated for each half-cycle current sample as a function of the sampled current magnitude, $I_{max,p}$ the empirically known characteristics of the current transformer, CT_p, and the base current transformer size, CT_{base}, for the summation calculation. The error may then become part of the calculation for the residual current. This method optimizes the calculation for the specific current transformers, including their nonlinear characteristics, and the current magnitude affecting each individual current transformer. Equation (7) shows that the total error in the calculation is also a factor of how many circuit breakers are parts of the differential calculation. M is the number of member breakers in the zone. Using a differential calculation based on the zone's source circuit breakers and only incorporating the feeders as a restraint term allows the most accurate calculation of ground fault currents in the zone:

$$I^2_{residual,adjusted} = I^2_{residual,zone} - (\varepsilon_0 + \varepsilon_1 + \cdots + \varepsilon_{M-1}) \quad (7)$$

where $I_{residual,adjusted}$ is the adjusted residual current, $I_{residual,zone}$ is the measured residual current for the zone, and ε is the error term for each circuit being considered.

This adjustment is proportional to the total secondary current in any one phase current transformer of any circuit breaker in the zone. This automatically adjusts for the increased error inherent in looking for a small imbalance in what otherwise may be acceptable load current, such as during motor inrush or other temporary high-current conditions.

E. Adjusting for Current Transformer Saturation

Current transformers will, at some point, saturate and distort their apparent turns ratio. This results in an unmanageable level of error in calculating residual currents. The point varies at which each current transformer will saturate. Low-voltage current transformers used for fault-current sensing, metering, and self-powered trips tend to have saturation levels somewhat higher than 10 times the rated primary current. The calculation algorithm must turn off when a current signal included in the differential calculation exceeds an acceptable threshold, such as 10 times rated current. The chosen threshold must take into account the DC offset caused by downstream fault current or proper loads, such as motor starting. The threshold algorithm may use an rms value of current that would incorporate DC offset even while the actual differential calculation is made on a vector or point-by-point basis.

Fault currents of this magnitude engage the circuit breaker's normal over-current functions and hence the ground-fault detection circuit is no longer needed. Similarly, if one of the circuit breakers below the zone exceeds a defined current threshold at which that circuit breaker is no longer accurate, ground-fault sensing at that circuit breaker is no longer dependable. That circuit breaker's over-current protection should be engaged, hence its ground-fault algorithm should be disabled and the residual calculation for the zone could be restrained sufficiently to allow the feeder to clear the fault. In summary, selecting CTs with a high-enough saturation point and selecting the appropriate point at which to turn off or desensitize the differential calculation allows the system's ground-fault and over-current protection algorithms to provide protection over the range of possible fault-current values.

VI. SUMMARY

Using a single-processor-based method for sensing ground faults in multi-source, multiple-grounded systems may provide reliable location sensing of ground faults in a system with two to N possible sources. A specific implementation and practical considerations of processing power, software development, and realistic industry needs would limit N to a small number.

However, two, three, four, or more zones and grounds can easily be handled. Sources may be operated separately or in parallel. Neutrals may be connected or not. Even different settings for different operational characteristics may be incorporated. The single-processor concept allows simple implementation for primary protection without the need for cascaded delays. The concept also allows for layers of backup protection should devices not clear faults or a fault becomes multiple faults by arcing over tie circuit breakers.

Flexibility is provided by software algorithms capable of accommodating varying power distribution connections within one line-up of equipment. The sensors, communications, and processor are the same as those used for normal over-current protection and control of the circuit breaker. No incremental relays, wiring, or other hardware is required to perform these functions.

Normal current transformer error may be handled to minimize the level of detuning of the sensing algorithm and limit the effect of the error coefficients included in the calculations to a level proportional to the potential level of error for any given fault or load current. This may provide for a level of sensitivity as good as or better than most multi-sensor ground-fault protection systems.

The authors believe this method is a significant improvement over the current state of the art in ground-fault protection and provides an alternative suitable for simple or complex substation configurations.

VII. BIBLIOGRAPHY AND SOURCES

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VIII. VITAE

Marcelo E. Valdes, P.E. graduated from Cornell University in 1977 with a BS in electrical engineering. He has held various positions at General Electric since 1977. He has worked in the GE Installation and Service Engineer organization as a field engineer and service supervisor, and also has also worked in sales, application engineering, and marketing for GE Industrial Systems. He currently is the manager of application engineering for the Electrical Distribution Business in Plainville, Connecticut. Mr. Valdes is past chair of the IEEE Power Engineering chapter in San Jose, CA and also the Industrial Applications chapter in San Francisco, CA. He is a registered Professional Electrical Engineer in California. Mr. Valdes has co-authored three technical papers in IEEE forums and has various patents pending in the field of power systems protection.

Tom Papallo graduated from the University of Connecticut in 1986 with a BS and in 1989 with an MS, both in mechanical engineering. He started with GE in 1986 in the New Product Development department. He has also worked on circuit breaker and electrical distribution system projects for several other major manufacturers, returning to GE in 1997. He is currently the technical lead for a New Product Development project and an adjunct member of the Design Office for the New Product Introduction Department, Plainville, CT. He is the holder of 18 US and international patents and has co-authored three IEEE technical papers.

Dr. William Premerlani graduated from Rensselaer Polytechnic Institute in 1971, 1972, and 1974 with a BS, MS and doctor of engineering in electric power engineering. He has since worked at GE’s Global Research in Niskayuna, New York, exploring a wide range of technologies in the fields of parallel computing, power system protection, and software development. Dr. Premerlani holds over 35 patents and has co-authored numerous technical papers. His current research interest is in phasor measurements and advanced protection algorithms. He is a co-author of the popular textbooks *Object-Oriented Modeling and Design* and *Object-Oriented Modeling and Design for Database Applications*.

Greg Lavoie received a BSEE degree in 1987 and an MSEE degree in 1990, both from the University of New Hampshire. Mr. Lavoie also received an MBA in 1994 from Yale University. He began his career with GE in 1989 at the Meters business as a software developer. In 2001 he moved to the Consumer and Industrial business in, and is currently a project leader in the New Product Introduction department in Plainville, CT. He holds 22 US and international patents.