The Performance of Faulted Phase Selectors Used in Transmission Line Distance Applications

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***Abstract*-- The reliable performance of faulted phase selectors to identify the faulted phase or phases and appropriately block or permit tripping is critical to the application of distance protection. The most difficult fault type to identify correctly is a two-phase-to-ground fault. Incorrect detection methods of this fault type has lead to undesired overreaching and/or tripping for remote two-phase-to-ground faults beyond the underreaching zone reach setting. It is also important to provide accurate fault location and record correct faulted phase information after the fault has cleared to correctly access the fault type characteristics. This paper analyzes the issues related to two-phase-to-ground faults and discusses several methods used for faulted phase identification and the advantages and disadvantages of each. It also shows how different phase selection methods may be used to complement each other to provide more reliable faulted phase identification.**

***Index Terms*—Protective relaying, Distance measurement, phase selection**

I. Nomenclature

AB, BC, CA, AG, BG, CG, may indicate the fault type classification (i.e. CA fault) or the distance impedance unit measuring loop (i.e. AG unit measuring phase A to ground loop).

ABG, BCG, CAG, ABC, ABCG indicate the fault type classification.

Similarly ΦG, ΦΦ, ΦΦG indicates the generic form of either the fault type or measuring unit.

II. Introduction

THE primary function of distance protection is to provide dependable high-speed tripping for faults within the protected zone and security against unwanted operations for faults external to the protected zone. To accomplish this, a good understanding of microprocessor impedance measuring units and how they respond to different fault types and locations is required. Further, the implementation of single-pole tripping increases requirements for more secure faulted phase selectivity. Other protection associated functions affected by accurate faulted phase selection are fault location calculations and event recording.

An impedance zone is usually comprised of six phase comparator units, each measuring a fault loop of the three-phase system. There are three ground distance units for measuring the AG, BG, and CG loops and usually three phase distance units measuring the AB, BC, and CA loops. There are also other methods available for measuring phase loops that are not considered here, but the same discussion generally applies. The measuring units of the fault loops are not uniquely independent in that they may share the effect of common phase voltages and currents they measure. I.e. AB, CA, and AG all have phase A in common. Therefore, more than one measuring unit may operate for a single faulted loop due to a variety of system operating conditions. Additionally, when there are multiple faulted loops, the operation of one may affect the other. There have been many good papers written on the subject of phase selection that have identified many of the key issues. These are discussed in references [1] thru [5] and are summarized here:

1. The ΦΦ unit may operate for close-in reverse ΦΦ, ΦΦG, or ΦG faults.
2. The ΦΦ unit may operate for close-in forward ΦG faults.
3. The ΦG units may operate for close-in reverse ΦG faults.
4. The ΦΦ unit of a non-faulted loop may operate for ΦΦG faults with high fault resistance (e.g. CA unit for a BCG fault). The CA operation will occur with the expected BC operation giving the appearance of a three phase fault.
5. The ΦG unit of the leading phase will overreach for forward external ΦΦG faults with any measurable fault resistance. (e.g. BG unit for a BCG fault).
6. The ΦG unit of the lagging phase may underreach for forward internal ΦΦG faults near the reach setting with any measurable fault resistance. (e.g. CG unit for a BCG fault).

Items 1 - 4 are easily managed with appropriate directional or sequence current supervision to identify the correct faulted phase loop, and thereby fault type, to provide correct comparator unit operation. Items 5 and 6 are issues related the ΦΦG faults and present a far greater challenge for reliable high-speed operation. Therefore, the focus of this paper will be on:

- Analyzing the effects of ΦΦG faults on the six distance impedance measuring units of the impedance zone.
- Reviewing different methods used to address correct selection of the faulted phase loops and identifying the advantages and disadvantages of each.
- Investigating the synergistic effect of using multiple phase selection algorithms.

III. Two Phase-to-ground Fault characteristics

The system configuration of Fig. 1 was used to analyze the response of cross-polarized mho distance phase comparators to BCG faults. MathCAD© software is used to perform the analysis. System parameters values are in per unit and are shown in the appendix. The parameters were varied to determine the response of the phase and ground distance measuring units to fault resistance, fault location, load and source impedance to zone reach setting ratio, SIR_Z.

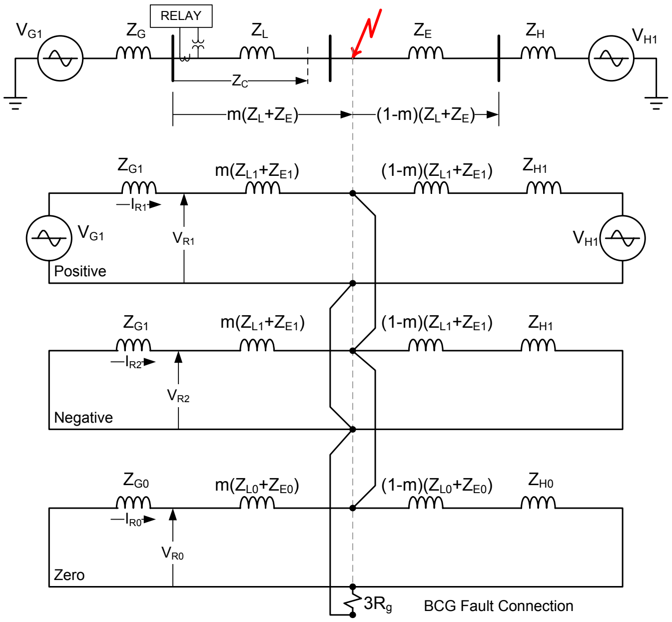

Fig. 1. Study System for BCG Fault. All impedances are in per unit. V_{G1}, is 1.0 and V_{H1}, is $1.0e^{j\alpha}$, where α is used to provide load flow. Fault location $m(Z_L+Z_E)$ is varied to measure results.

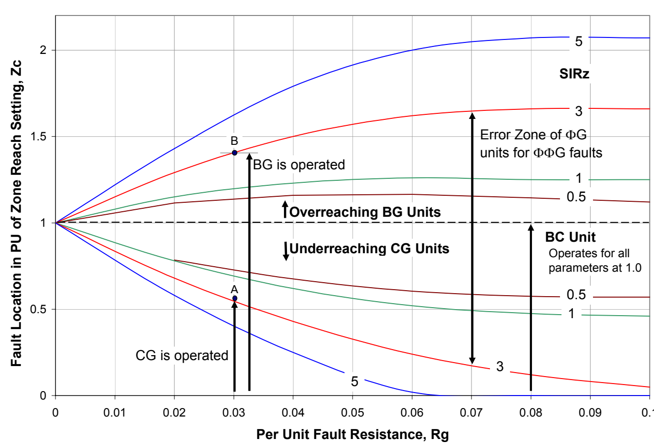

Fig. 2. Response of BC, BG and CG Phase Comparators to Fault Resistance, SIRz and Fault Location. $Z_G/Z_H = SIR_Z$. Operations of indicated units occur below their characteristic line. For example: For Rg =.03, SIRz=3, the operation of all units occur from a fault location at the bus of 0 up to point A on the line, 0.6 pu, where CG drops out. The BC unit drops out at the zone setting, 1.0 pu. BG unit operates up to point B, overreaching the setting 40%.

Fig. 2 shows the response of the BC, BG and CG units over a range of fault resistance, fault location and SIR_Z. Additional results are shown in the appendix that shows the effects of forward and reverse load and the remote source's contribution to the fault. In all cases the BC ΦΦ unit operates reliably providing the reach accuracy required. The BG (the leading phase) unit severely overreaches with increasing fault resistance, load and remote end contribution while the CG (the lagging phase) severely underreaches. These figures were plotted to visually show the relationship between the leading phase, BG, and lagging phase, CG, reaches during a BCG fault. The region between the upper overreaching and lower underreaching curves is the error zone where incorrect operation of involved ΦG units will occur. The error zone has the characteristic shape of a bullet pointed to the left. We call it the "ΦΦG Bullet." By reviewing these figures it is easy to see how the ΦΦG Bullet broadens with increasing fault resistance, load and remote end contribution. It becomes obvious the BG and CG units cannot be used for tripping and some form of BCG fault selectivity is required to release the BC unit for correct BCG tripping.

The response characteristics of the lagging CA ΦΦ unit are shown in Fig. 3. As observed, the BC unit operates correctly without fail. The CA unit undesirably operates from close-in faults with low fault resistance to overreaching for large fault resistances and higher SIR_Z. Such an operation will result in 3Φ in zone tripping with incorrect faulted phase identification. This figure also shows that there is also the possibility of incorrectly overreaching with the CA unit.

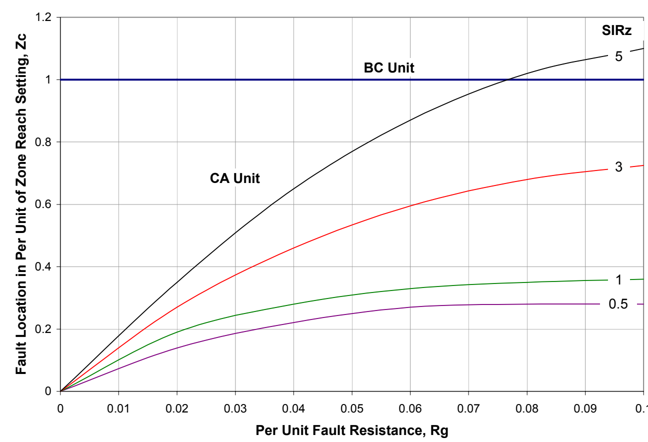

Fig. 3. Response of BC and CA Phase Comparators to Fault Resistance, SIRz and Fault Location. $Z_G/Z_H = SIR_Z$. Operations of indicated units occur below their characteristic line. No responses of AB unit observed.

From the analysis results and issues identified by other sources in Section II, the following may be concluded in regard to providing accurate operation of the phase comparator units:

- The singular operation of a ΦG unit cannot be assumed to be a single phase-to-ground fault.
- The ΦG units cannot reliably be used to trip for ΦΦG faults and must be blocked when ΦΦG faults are identified.
- The ΦΦ units must be blocked for faults that involve ground, but must be released for operation when ΦΦG faults are identified to assure reliable tripping.

The reader should keep in mind that using per unit calculations and system parameter values used for this analysis tend to dramatize the issue, but never the less, it is real.

IV. Fault Phase Selection Methods

There are many publications available that describe various faulted phase selection algorithms [2][3][4][8][8][9]. Some provide very high-speed (sub-cycle) approaches that are adequate for most applications, but may lack in accurate phase selectivity for the extreme system condition. Others provide accurate selectivity, but at the expense of speed.

There are also two basic types of faulted phase selection processes. The first is to identify the faulted phase loops prior to releasing the appropriate selected units for tripping. Using this method processing resources (CPU, RAM, etc.) are conserved by executing only the required measurement algorithms. The second method is to provide simultaneous running of all protection algorithms with the appropriate supervision to provide reliable three-phase or single-pole tripping and then provide the tripped phase information for single-pole reclosing, fault location and event reporting. This method may be a bit more process intensive and therefore require greater processing power.

The following reviews three faulted phase selection methods covering both the aforementioned approaches and identifies the advantages and disadvantages of each.

A. Overreaching Impedance

This method is the free-running approach where the faulted phases are identified, as opposed to selected, at time of tripping. Tripping supervision with overreaching impedance, hence correct phase identification, only applies to impedance measuring units. It must be complemented with correct directional and overcurrent supervision and will be accurate for applications where impedance units operate.

1) Application

It is not uncommon to use an overreaching zone to detect the operation of two ΦG units and use the developed signal to block zone-1's ΦG units and release the appropriate ΦΦ unit for operation [7]. Simplified logic is shown in Fig. 4.

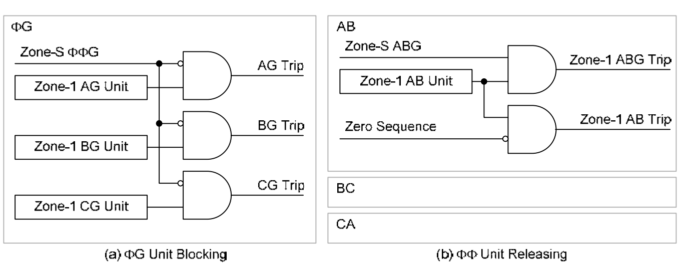

Fig. 4. Simplified Logic for Control of Zone-1 ΦΦ and ΦΦG Operation with Overreaching Zone-S.

The fundamental requirements for successful zone-1 tripping for ΦΦG faults are that the supervising overreaching zone, zone-S, ΦG units must operate before those of zone-1. Setting zone-S reach so that it can detect the lagging phase of a ΦΦG fault for all zone-1 faults requires study to assure correct operation. Following is an example.

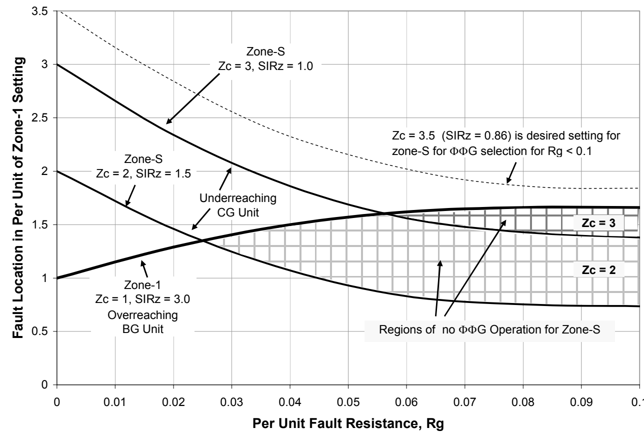

Fig. 5. Coordination of Zone-1 and the Overreaching Zone-S. The leading phase (BG) characteristic of zone-1 must not intersect with the lagging phase (CG) characteristic up to the value of Rg to be covered. The respective ΦG units operate for fault locations below the characteristic line.

The operation of zone-1's overreaching ΦG unit must be coordinated with zone-S's underreaching ΦG unit's operating characteristic. Consider a zone-1 reach setting, $Z_{C(1)}$, of 1.0 per unit and that its $SIR_{Z(1)}$ is 3.0. Next, consider a zone-S setting, $Z_{C(S)}$, of 2.0 per unit. The $SIR_{Z(S)}$ for zone-S is based on (1) and is 1.5.

$$SIR_{Z(S)} = SIR_{Z(1)} \cdot \frac{Z_{C(1)}}{Z_{C(S)}} \quad (1)$$

The characteristic are plotted in Fig. 5. It can be observed that with the zone-S setting of 2.0, that adequate supervision of zone-1's ΦG and ΦF units for a ΦΦG fault can only be provided where the fault resistance, R_g, is less than approximately 0.025 per unit. In this case, for Rg greater than 0.025 per unit, both involved ΦG units in zone-S do not operate to identify a ΦΦG thereby permitting a ΦG unit to overreach trip for fault locations greater than the set reach, 1.0 pu, or incorrectly identifying a necessary ΦΦG trip as a ΦG trip for fault locations less than the set reach. A larger zone-S setting is required to improve fault resistance coverage. In this case a zone-S setting of 3.5 per unit will assure correct operation.

2) Other Tripping Units

For free-running systems phase identification is not limited to impedance units; however they do impose the greatest challenge. Faulted phase identification based on high-set overcurrent tripping is straight forward because of the high currents involved. For weak infeed applications where the overcurrent and distance measurements are impractical, faulted phase identification based on voltage measurement is required, particularly for single-pole tripping.

3) Advantages

- Correct faulted phase identification for distance units is provided as part of tripping logic with correct directional, overcurrent and overreaching distance ΦΦG supervision.
- Well supervised measuring units naturally follows the fault condition, including evolving faults,

accurately tripping and reporting involved phases base on the latest system state.

- It is high-speed with ten years of in-service application experience providing sub-cycle tripping with correct faulted phase identification.

4) Disadvantages

- Although it is suitable for practical underreaching zone-1 applications, it does require careful study for correct implementation of ΦΦG supervision.

B. Delta Method

1) Application

The delta method for faulted phase selection is based on high-speed process that passes the transient component of system voltage and current changes (fault inception, breaker operations, etc.) while filtering out the steady-state pre-fault and fault components [8]. This is also referred to as a traveling wave component of the fault. A typical delta current signal is shown in Fig. 6.

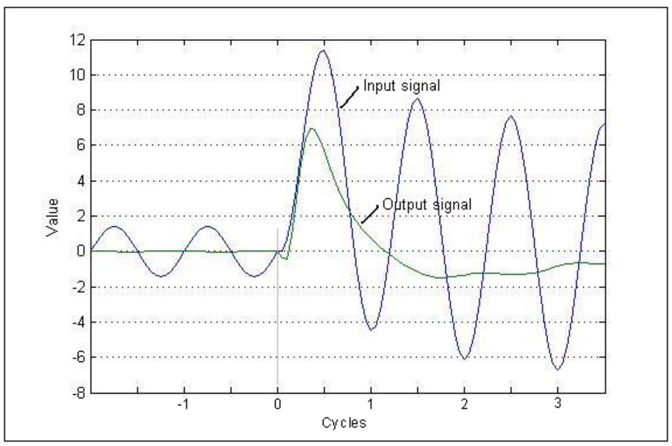

Fig. 6. Delta Current Transient Detector Showing Pre-fault and Fault Signal Input and Transient ΔI Output

Fig. 7 and 8 are used to explain the basics of the phase selection process. In Fig. 7 the Δ filter extracts the transients created by system faults or other disturbances from sampled phase current and voltage data. It measures the peak value and then uses a decaying memory function to delay the dropout of the Δ quantity after the transient has subsided. It outputs the values of ΔI_A, ΔI_B and ΔI_C when one or more of the Δ quantities are above a threshold value. This will produce delta quantities for faulted phases that are or are near maximum. These quantities are then input into the fault type selector where the fault type is determined with (2).

$$Fault\ \text{Type} = \frac{\Sigma(\Delta I_A, \Delta I_B, \Delta I_C)}{Max(\Delta I_A, \Delta I_B, \Delta I_C)} \tag{2}$$

Based on the fault type selected and the magnitude of the ΔI quantities the appropriate phases that are involved with the fault are identified. Ground involvement is determined externally by measuring ground current, 3I0.

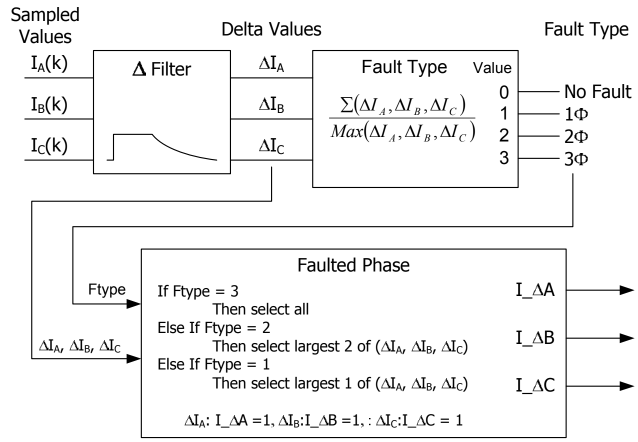

Fig. 7. Phase Selection With Δ Current Transient Detectors. A similar method is used with voltage data.

The ΔI currents are normally used for faulted phase selection evaluation. This is because there are more system conditions that cause voltage transients that are not fault related. Therefore, only in cases where there is insufficient current, e.g. weak infeed, to produce an output then the Δ voltages are used. In this case the relationship of V_0 and V_2 is evaluated to determine the involvement of ground.

Due to the fast calculation of the delta quantities it is likely to detect different phases of the fault at slightly different times. This is due to differences of fault incidence angles of the involved phase currents and voltage. Therefore, a fault type priority function is employed with the delta method to ensure dependable selectivity in optimum time. The basic concept is that with fewer phases or ground involved, phase selection is delayed sufficiently to allow evolvement of the fault to additional phases and/or ground. The fault type selection priority is: 3Φ and ΦΦG are released immediately, ΦΦ are delayed slightly to allow evolvement to 3Φ or ΦΦG. ΦG faults are delayed even longer to allow upward evolvement. The basic logic is shown in Fig 8.

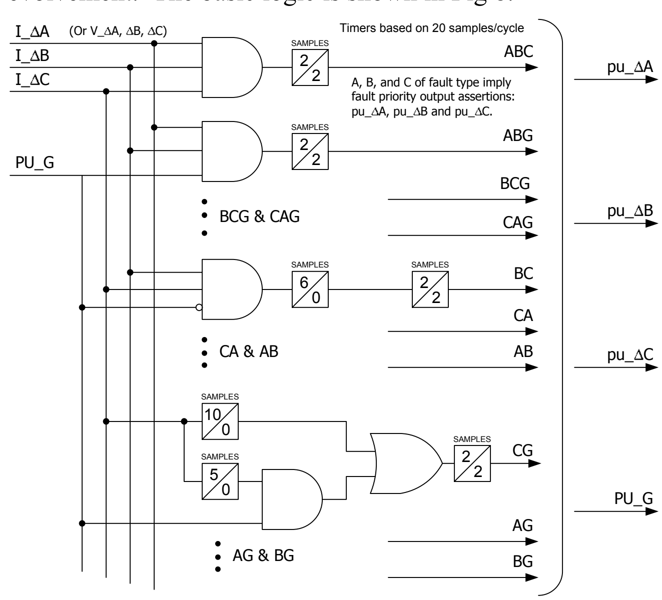

Fig. 8. Delta Method Fault Type Priority

2) Advantages

- The delta method is suitable for high-speed sub-cycle phase selection applications and is based years of in-service experience.
- It provides fast faulted phase selectivity based on fault type priority before releasing the appropriate tripping units thereby conserving processing requirements.

3) Disadvantages

- Phase selectivity is based on memory after a steady state fault condition is reached and transient subsides. This may result in incorrect phase selection for sequential or other time delayed tripping.
- Faults where there is little difference between pre-fault and fault quantities, e.g. large load and fault resistance, may not be detected.
- Slow evolving faults, i.e. low dI/dt and dV/dt, may not be detected

C. Symmetrical Component Method

1) Application

The symmetrical component method uses phase-A sequence quantities to determine the correct faulted phases. Since sequence components are calculated using a full or half cycle Fourier filter, this method will be slower than the delta method described above. It will, however, accurately calculate and sustain the phase selection information until the fault is cleared or there is a single-pole trip open phase condition. Phase selection is achieved by evaluating the angle of V_{A2}/I_{A0} and V_{A2}/V_{A1} as shown by Fig. 9.

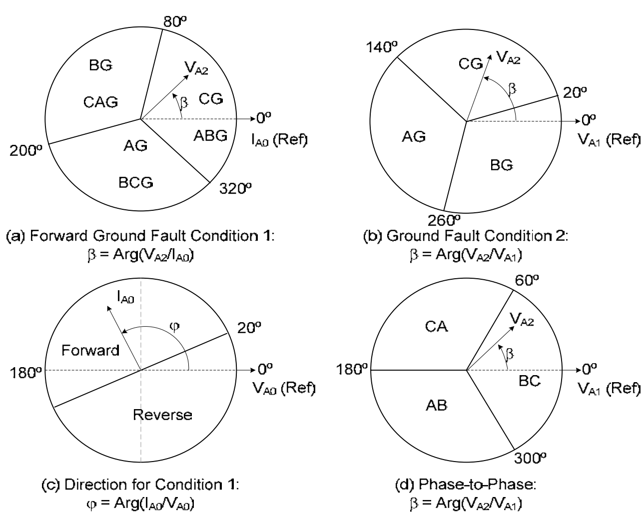

Fig. 9. Symmetrical Component Method for Faulted Phase Selection. Only Condition 1 (a) is affected by fault direction. For reverse ground faults the IA0 reference is at 180º. β = Arg(VA2/IA0) + 180º.

The absence of appreciable negative and zero sequence quantities indicates a three-phase fault condition. Also, having substantial negative sequence and no appreciable zero sequence quantities defines a ΦΦ fault. If a ΦΦ fault is identified then involved phases are identified by ΦΦ sector of Fig. 9(d), in which the angle of (V_{A2}/V_{A1}) occurs.

Two conditions that identify ground faults are also shown in Figure 9(a) and 9(b) [9]. Condition #1 evaluates the angle of (V_{A2}/I_{A0}) and condition #2 evaluates the angle of (V_{A2}/V_{A1}). If the results of both conditions agree for their respective ΦG sectors then it is a single ΦG fault of the indicated phase. If the results disagree then condition #1 indicates the correct ΦΦG fault.

Fig. 10 shows the basic logic using the results of Fig. 9 to release the appropriate faulted phase loops.

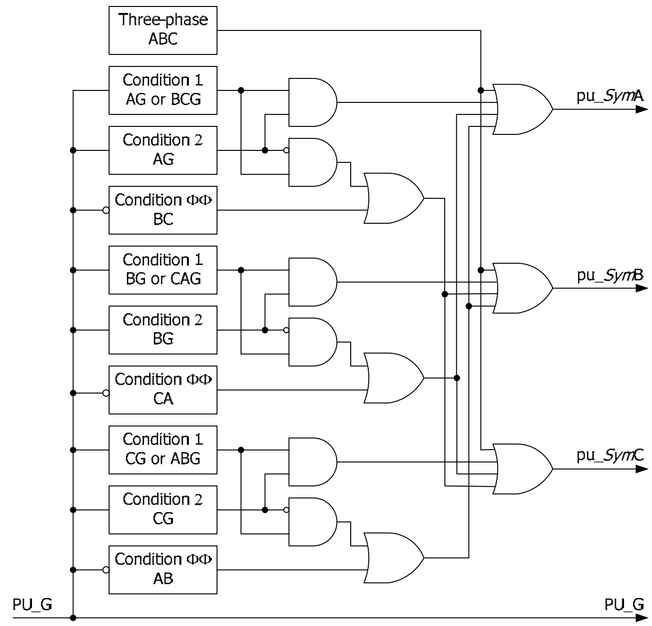

Fig. 10. Symmetrical Component Phase Selection Method

2) Advantages

- It is an extremely accurate over a wide range of system applications including, but not limited to, all the conditions studied herein.
- It is dynamic with the fault condition and can correctly identify slow evolving faults.
- It will easily address applications where there is little difference between pre-fault and fault voltage and current quantities.

3) Disadvantages

- It is slow generally requiring a minimum of 1.0 to 1.25 cycles of fault to reliably compute and, therefore, cannot provide sub-cycle faulted phase selectivity.

V. Complementary Approach Using Two Faulted Phase Selection Methods

The overreaching impedance method of faulted phase identification is fast and dynamic throughout the fault clearing period providing faulted phase identification upon tripping. It is therefore not considered in the complementary approach.

The complementary approach looks at combining the delta and symmetrical component methods discussed above. The logic to this approach becomes apparent after reviewing the advantages and disadvantages of both methods listed above. The delta method is very fast and reliable in the initial transient period immediately after fault inception providing quick release of high-speed tripping units. It becomes less dependable as the fault is sustained. The symmetrical component method is slower, but will handle the faulted phase selection for the aforementioned conditions that the delta method cannot reliably handle. Therefore, the combined use of the two methods will eliminate the disadvantages of each. The combined logic and operation sequence is shown in Fig. 11.

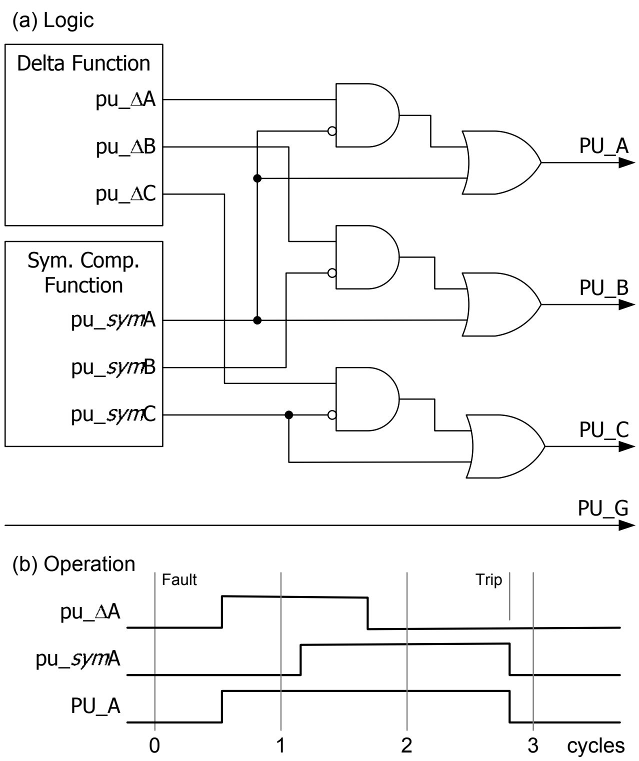

Fig. 11. Complementary Application of Delta and Symmetrical Component Methods of Faulted Phase Selection

VI. Conclusion

The effects of ΦΦG faults on distance impedance ΦG and ΦΦ measuring units were analyzed over a broad range of system parameters. The operating characteristics based on varying system parameters were plotted and compared to provide a visual understanding of operation issues. Fault resistance was shown to be the primary issue, i.e. no fault resistance, no problem. With the presence of fault resistance the issue is further exacerbated by forward load, SIR_Z, and remote source contribution.

Different methods for faulted phase selectivity or identification were also presented. The overreaching impedance method depends on effective directional, overcurrent and overreaching impedance supervision of the ΦG and ΦΦ units for reliable impedance tripping and identifies the faulted phases in the tripping process. Operation is reliable, but depends on an application study to determine the proper setting of the supervising overreaching zone. A coordination method to insure correct setting was presented.

The delta method provides very fast and accurate faulted phase selectivity allowing for sub-cycle tripping of impedance units. It, however, becomes less reliable with slow evolving faults, low fault current levels and time delayed or sequential tripping where the fault is sustained and the initial delta transient has subsided.

The symmetrical component method is too slow to allow sub-cycle tripping of the impedance units. Once operated, however, it is very reliable and can handle the slow evolving, low fault current and time delayed events with its dynamic response to the condition at hand.

Recognizing the positive aspects of the delta and symmetrical component methods the synergistic effect of their combined use is apparent and all the disadvantages of each are overcame.

Appendix

TABLE A-1
Test System Impedances

Positive Sequence	Zero Sequence
$Z_{G1} = (0\ .01 +\ j0.1)$ x SIR	$Z_{G0} = (0\ .03 +\ j0.3)$ x SIR
$Z_{H1} = (0\ .01 +\ j0.1)$ x Z_G/Z_H	$Z_{H0} = (0\ .03 +\ j0.3)$ x Z_G / Z_H
$Z_{L1} = 0\ .01 +\ j0.1$	$Z_{L0} = 0\ .03 +\ j0.3$
$Z_{E1} = 0\ .01 +\ j0.1$	$Z_{E1} = 0\ .03 +\ j0.3$
Rg = 0, .01, .02, .04, .06, .08, 0.1	

TABLE A-2
Phase Comparators

Operation: $0^o < Arg(S_1/S_2) < 180^o$		
Fault Loop	S_1 = Operating	S_2 = Polarizing
AG	$Z_C(I_A + K_0I_0) - V_A$	V_{BC}
BG	$Z_C(I_B + K_0I_0) – V_B$	V_{CA}
CG	$Z_C(I_C + K_0I_0) – V_C$	V_{AB}
AB	$Z_C(I_A-I_B) – (V_A-V_B)$	$-V_C$
BC	$Z_C(I_B-I_C) – (V_B-V_C)$	$-V_A$
CA	$Z_C(I_C-I_A) – (V_C-V_A)$	$-V_B$
$K_0 = (Z_{L0} – Z_{L1})/Z_{L1}$		

Table A-3 shows data results recorded for SIR = 5 and Z_G/Z_H = 5, no load curve of Fig. 2. This data shows the dropout values of the respective phase comparators and operation of symmetrical component faulted phase selector for the applied BCG fault of Fig. 1. Note the consistent and correct operation of the symmetrical component method of phase selection as BCG. Figs. A-1 and A-2 complement the curves of Fig. 2.

TABLE A-3
SAMPLE DATA RESULTS

	A	B	C	D	E	F	H	I	K	L	M	N	O	P	R	S	T	U	V	W
1	System Parameters						Fault Location		Phase Comparators						Symmetrical Component Cond					
2	SSIR	SIRz	Rg	Zc	ZL1	ZE1	m	m/Zc	AG	BG	CG	AB	BC	CA	AG	BG	CG	ABG	BCG	CAG
3	5	5	0	0.8	0.1	0.1	0.05	0.125		x	x		x						x	
4				0.8	0.1	0.1	0.4	1		x	x		x						x	
5				0.8	0.1	0.1	0.401	1.0025											x	
7			0.02	0.8	0.1	0.1	0.05	0.125		x	x		x	x					x	
8				0.8	0.1	0.1	0.142	0.355		x	x		x	x					x	
9				0.8	0.1	0.1	0.143	0.3575		x	x		x						x	
10				0.8	0.1	0.1	0.231	0.5775		x	x		x						x	
11				0.8	0.1	0.1	0.232	0.58		x			x						x	
12				0.8	0.1	0.1	0.399	0.9975		x			x						x	
13				0.8	0.1	0.1	0.4	1		x									x	
14				0.8	0.1	0.1	0.571	1.4275		x									x	
15				0.8	0.1	0.1	0.572	1.43											x	
17			0.04	0.8	0.1	0.1	0.05	0.125		x	x		x	x					x	
18				0.8	0.1	0.1	0.101	0.2525		x	x		x	x					x	
19				0.8	0.1	0.1	0.102	0.255		x			x	x					x	
20				0.8	0.1	0.1	0.26	0.65		x			x	x					x	
21				0.8	0.1	0.1	0.261	0.6525		x			x						x	
22				0.8	0.1	0.1	0.399	0.9975		x			x						x	
23				0.8	0.1	0.1	0.4	1		x									x	
24				0.8	0.1	0.1	0.715	1.7875		x									x	
25				0.8	0.1	0.1	0.716	1.79											x	
27			0.06	0.8	0.1	0.1	0.01	0.025		x			x	x					x	
28				0.8	0.1	0.1	0.349	0.8725		x			x	x					x	
29				0.8	0.1	0.1	0.35	0.875		x			x						x	
30				0.8	0.1	0.1	0.399	0.9975		x			x						x	
31				0.8	0.1	0.1	0.4	1		x									x	
32				0.8	0.1	0.1	0.799	1.9975		x									x	
33				0.8	0.1	0.1	0.8	2											x	
35			0.08	0.8	0.1	0.1	0.01	0.025		x			x	x					x	
36				0.8	0.1	0.1	0.4	1		x			x	x					x	
37				0.8	0.1	0.1	0.401	1.0025		x				x					x	
38				0.8	0.1	0.1	0.408	1.02		x				x					x	
39				0.8	0.1	0.1	0.409	1.0225		x									x	
40				0.8	0.1	0.1	0.827	2.0675		x									x	
41				0.8	0.1	0.1	0.828	2.07											x	
43			0.1	0.8	0.1	0.1	0.01	0.025		x			x	x					x	
44				0.8	0.1	0.1	0.399	0.9975		x			x	x					x	
45				0.8	0.1	0.1	0.4	1		x				x					x	
46				0.8	0.1	0.1	0.443	1.1075		x				x					x	
47				0.8	0.1	0.1	0.444	1.11		x									x	
48				0.8	0.1	0.1	0.827	2.0675		x									x	
49				0.8	0.1	0.1	0.828	2.07											x	

Test data was recorded for all figures shown and other extreme conditions. The symmetrical component method was unfailing in selecting BCG.

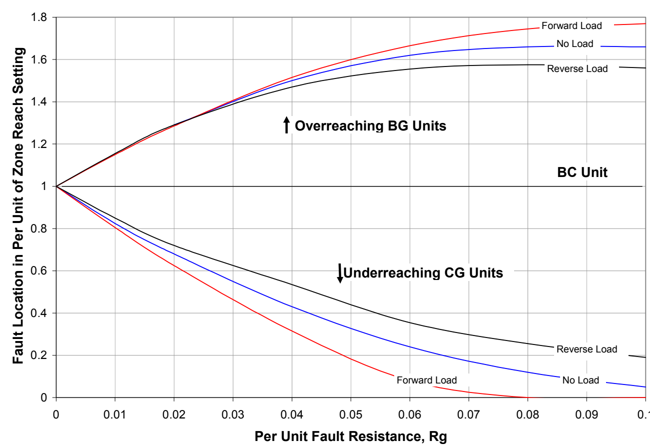

Fig. A-1. Response of BG and CG Phase Comparators to Fault Resistance, Fault Location and Load for SIRz = 3. $Z_G/Z_H = 3.3$.

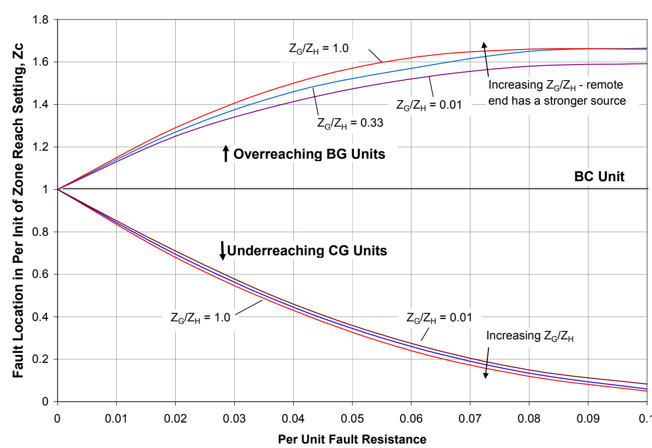

Fig. A-2. Response of BG and CG Phase Comparators to Fault Resistance, Fault Location and Effect of Remote End Source Impedance, Z_G/Z_H.

REFERENCES

[1] M. Akke," Fault Classification for Distance Protection," Transmission and Distribution Conference and Exhibition 2002. Asia Pacific. IEEE PES, Vol 2. pp 835 – 839.

[2] B. Kasztenny, B. Campbell, J. Mazereeuw, "Phase Selection for Single-pole Tripping – Weak Infeed Conditions and Cross-country Faults," 27th Annual Western Protective Relay Conference, Spokane, WA, Oct. 2000.

[3] A. P. Apostolov, D. Tholomier, S. H. Richards, "Superimposed Components Based Sub-cycle Protection of Transmission Lines", Power Systems Conference and Exposition, 2004. IEEE PES, Vol 1. pp 592 - 597.

[4] E. O, Schweitzer, III, J. D. Roberts, "New Developments in Distance Relay Polarization and Fault Type Selection", 16th Annual Western Protective Relay Conference, Spokane, WA, Oct. 1989.

[5] E. Stokes-Waller, "Distance Protection: Pushing the Envelope," Southern African Power System Protection Conference, Johannesburg, Nov. 2000.

[6] W, Elmore, Protective *Relaying Theory and Applications*, New York: Marcel Dekker, Inc., 1994, pp 26.

[7] S. Ward, E. Udren. "High Speed Single Pole Trip Logic for Use in Protective Relaying", U.S. Patent 5 838 525, Nov. 17, 1998.

[8] N. Brandt, T Einarsson, "Device for detecting faulty phases in a multi-phase electrical network," U.S. Patent 4 409 636, Oct. 11, 1983.

[9] L. Eriksson, M. Saha, K Svensson, "Phase selection for ground fault," U.S. Patent 5 390 067, Feb. 14, 1995.

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Torbjorn Einarsson received his MScEE degree in Electrical Engineering in 1972 from the Chalmers Technical University, Gothenburg, Sweden. He joined ASEA (becoming ABB after the merge with BBC), Sweden in 1973 as a Test Engineer for High Power testing. In 1977 he moved to Protective Relay Division as Development Engineer and is currently is a Development Project Manager for protective relays at ABB AB, Vasteras, Sweden. He has been appointed as Specialist in Line Protection. His areas of interest are communication for line protection systems and development and testing of line protection relays with special focus on line differential protection. Torbjorn's email address is torbjorn.einarsson@se.abb.com