Some Thoughts on Single-Pole Tripping

by:

Walter A. Elmore
ABB Power T&D Company Inc.
High Voltage Relay Division
Coral Springs, Florida

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Walter A. Elmore
Consulting Engineer
High Voltage Relay Division

Introduction

Historically, the relaying equipment associated with single-pole tripping has been complicated, expensive and space consumptive. While the root technology is still complicated, the incremental expense over 3-pole tripping is small and the panel space requirement is the same as for 3-pole tripping in modern single-pole relaying systems.

Another deterrent to single-pole tripping has been the fact that breakers have traditionally been equipped with 3-pole mechanisms. Today EHV breakers, due to the very wide pole separation, have been forced to use separate mechanisms, even for 3-pole applications, and independent pole operated breakers are now available from 72.5 kV to 800 kV (though with considerably higher cost below 345 kV).

This paper describes: 1) The advantages of single-pole tripping including stability considerations, 2) Phase selection methods to assure proper faulted phase identification, 3) The difficulty of subsequent fault identification, as for example a "B-G" fault after tripping for an "A-G" fault, 4) The symmetrical component representation of a system following single-pole tripping. 5) The influence on rotating machinery of the transmission line single-phasing, following single-pole tripping, 6) The near-certainty of increased use of single-pole tripping as a result of decreasing availability of rights-of-way.

Single-Pole Tripping Concept

Single-pole tripping, often called, somewhat erroneously, single-pole reclosing, provides some interesting benefits, but also some technical challenges. The strategy for single-pole tripping is to isolate only the faulted phase upon the occurrence of a transmission line single-line-to-ground fault, and to isolate all three phases for all other faults. The benefit to power system stability is obvious when we consider the fact that the two system segments which the transmission line interconnects, remain metallically interconnected by the two unfaulted phases during the single phasing period and as a result, a substantial amount of synchronizing power can flow. Also the impact of voltage variation throughout the power system is reduced as a consequence of single-pole tripping.

Following a dead period of sufficient time for the arc to become deionized, the open pole is reclosed. For temporary faults, the circuit is restored with relatively minor impact on the power system. For more persistent line-to-ground faults, the circuit breaker is then tripped 3-pole, with subsequent action being of the nature of conventional tripping and reclosing as dictated by the particular utility's practice or to allow the two systems to remain separated until re-synchronized.

Difficult Problems

While intuition may indicate that the selection of the faulted phase should be a simple matter, it is not. Fault current in one phase only, is obscured by the presence of load current. Load current may add to or subtract from the fault current, and certainly balanced load will produce current in the unfaulted phases. Also inequitable distribution of symmetrical component sequence quantities will generate unfaulted phase currents for a phase-to-ground fault even though there be no load current. Once a fault is identified as being on a particular phase, and single-pole tripping has been initiated, there will be a strong tendency for relays to trip incorrectly as a result of the unbalanced loading condition that remains. Zero sequence and negative sequence currents will flow in the protected circuit and, perversely, with such a relationship as to cause undesired operation of directional units using those sequence quantities ***at both transmission line terminals.***

At the same time, the relaying system must be able, during the single phasing period, to recognize a fault that occurs on one of the sound phases and to initiate three pole tripping at high speed. It must also be secure during this period against false tripping in response to **all** varieties of external faults or severe swing conditions.

To accomplish all of this requires a high order of relaying refinement and serious attention to all of these constraints.

Equivalent Diagram

The symmetrical component representation of a system, with a line operating with one pole open after single-pole tripping, is shown in Fig. 1. X1S, X2S and X0S are equivalent source positive, negative and zero sequence impedances X1L, X2L and X0L are line impedances and X1U, X2U and X0U are component impedances beyond the open. Fig. 2 shows a reduction of Fig. 1 to two machines and a single interconnecting reactance per phase. The power transfer associated with the open phase condition is determined by the equation shown in Fig. 2.

Stability

Single-phase-to-ground faults do not seriously impair the ability of a transmission line to carry power, but 20% reduction in the power transfer curve is typical. Tripping 3 pole in a complex network may hamper little the power transfer capability (particularly if the source/line impedance ratio is large). However, in applications involving the interconnection of a generating plant to a power system through a single transmission line, single-pole tripping may be the **only** way to maintain synchronism of the plant with the system, and then only for temporary single-line-to-ground faults.

Fig. 3 shows the substantial influence on stability that single-pole tripping can provide where one interconnecting line exists between a generating plant and a power system, or between two power system segments. Fig. 3b describes the trajectory on the power swing curves from normal to that with a phase-to-ground fault. When three-pole tripping occurs, all synchronizing power is lost until reclosing takes place. If reclosing is successful, swinging continues. If areas 2 + 4 above the original power line can equal areas 1 + 3 which are below the line, stability may be possible. Much depends on trip time, the H constants, the actual levels of accelerating and decelerating power, reclosing time and the actual system reactances.

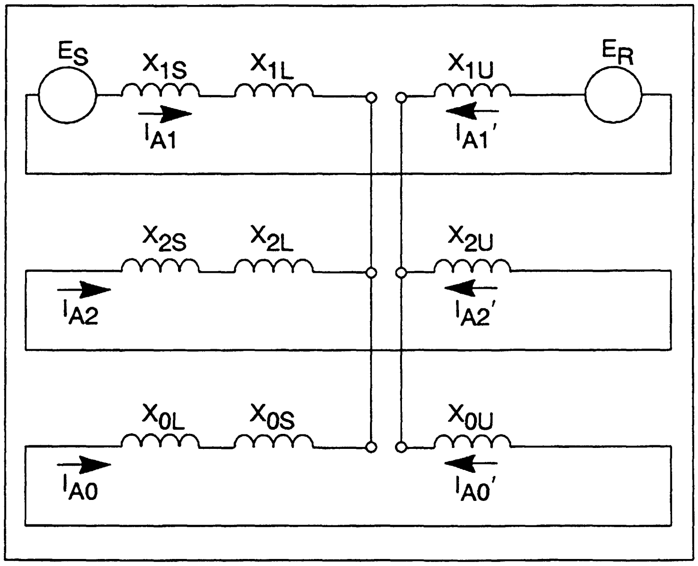


Figure 1: Symmetrical Component Network Interconnection for Open Phase Condition

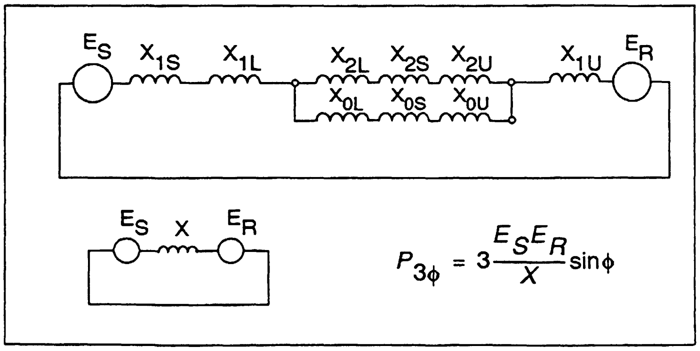


Figure 2: Reduction of Figure 1

Fig. 3c describes the similar process accompanying single-pole tripping. The likelihood of retaining stability with this strategy is very much greater. The obvious benefit that can be seen in this diagram is from the vast reduction in the accelerating power to which the sending-end is subjected during the single-phasing period.

Though these curves are only typical and based on the assumption of convenient system reactances, comparable results occur with other reasonable parameters.

Fig. 4 shows the circumstances accompanying a two-line case with a fault on one. Again the power transfer curve dips to approximately 80% of the non-fault level. With single-pole-tripping of the faulted circuit, the power transfer curve is elevated only slightly when that pole clears. Whether single-pole tripping is used or not, stability is never in question with only single line-to-ground faults being considered, however, it must be recognized that with one line out of service for maintenance the system and the stability considerations revert to the single-line case of Fig. 3.

Selective Pole Relaying

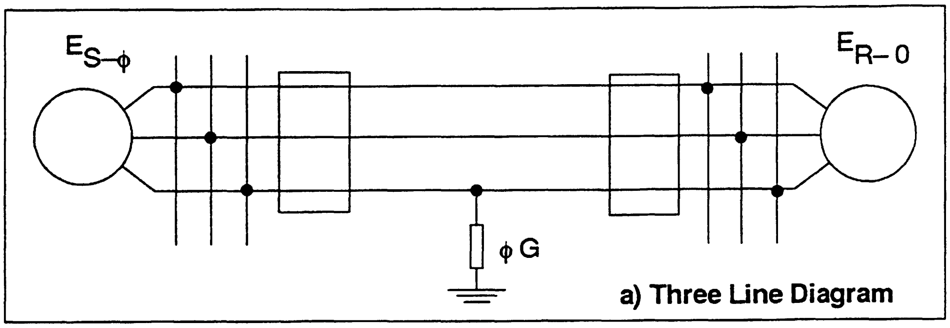
While single-pole tripping is considered as particularly beneficial for systems such as that of Fig. 3 or those such as that of Fig. 4 which can degenerate to that of Fig. 3 during an outage, some thought might be given to selective pole tripping. Selective pole tripping would isolate only those phases which are involved in a fault. This would extend the benefit previously described for single-pole tripping to phase-to-phase faults (and phase-to-phase-to-ground faults if desired). For a $\phi\phi$ fault, for example, only the breaker poles associated with the fault are tripped. Actually, only one pole at each end of the transmission line need be tripped to clear a temporary fault. Phase selection would be of no difficulty whatever using segregated phase relays (such as REL 350). Tripping two poles at each end for a $\phi\phi$ fault would require only minor adjustment of the standard scheme. Roughly 20% of the original power transfer capability is retained for two phase tripping compared to zero when all three poles are tripped in Fig. 3. With all combinations of pole tripping, close examination of circuit breaker recover voltage characteristics would have to be made. Standard breakers are compatible with single-pole tripping, but may not be for some types of selective-pole tripping.

Phase Selection

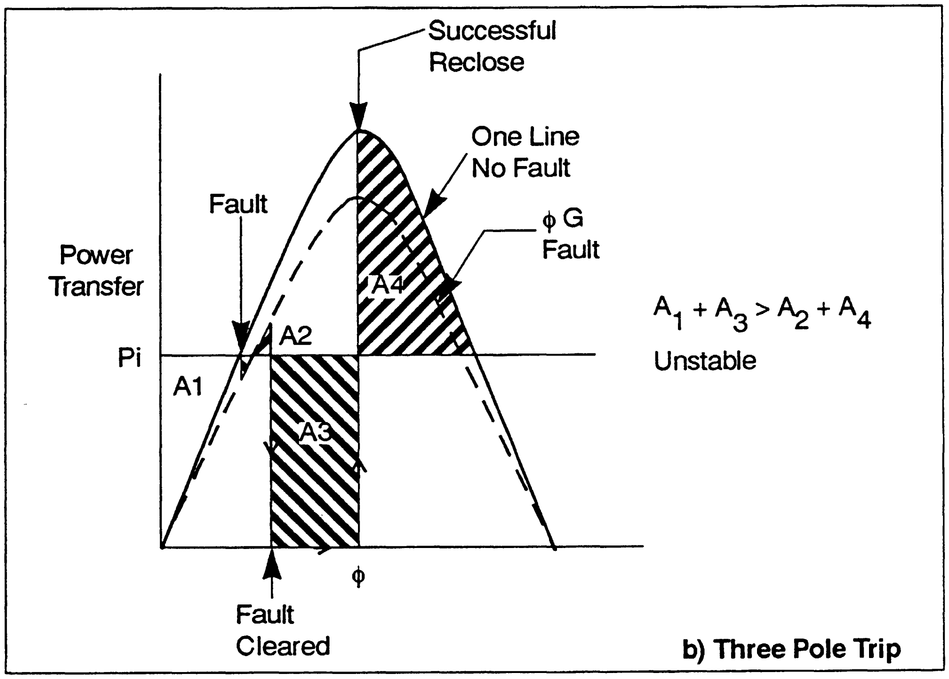
The proper selection of the faulted phase, or phases, on a protected transmission line is imperative, if the relays are to perform their function correctly. Proper operating and restraining quantities must be paired to properly identify fault type.

Many methods have been used for identifying fault type, some more successful than others. One obvious implementation uses individual phase overcurrent. Overcurrent in one phase would presumably indicate a phase-to-ground fault. In general, it doesn't. The use of overcurrent for faulted phase identification has severe shortcomings. Unequal symmetrical component distribution or large load component can produce substantial current in the unfaulted phases, obscuring the character of the fault. The use of distance relays has some appeal, but may fall short because of the tendency for more than one phase unit to operate for some single-phase-to-ground faults.

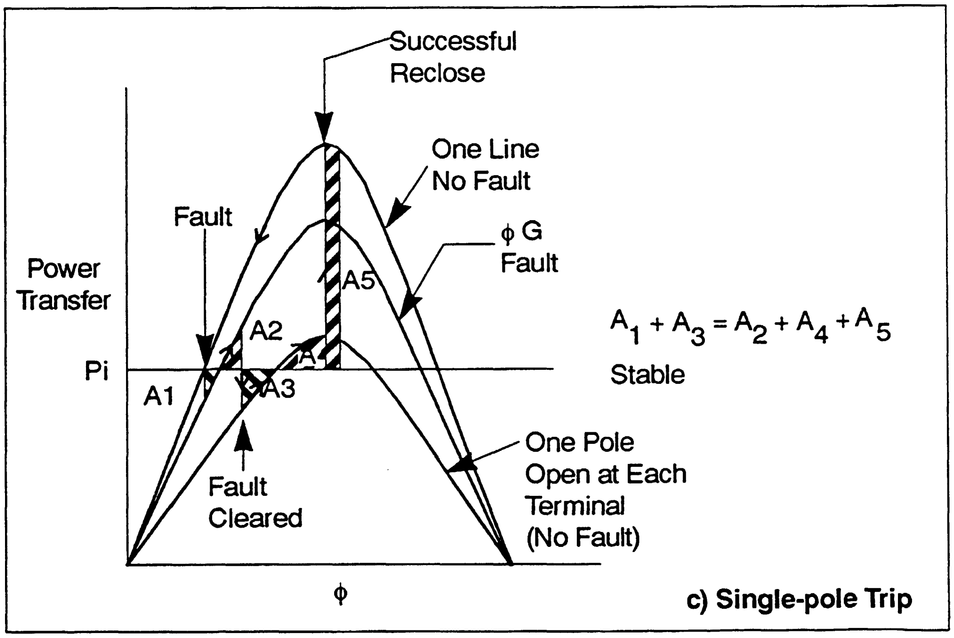
One scheme that has been used successfully for identifying the faulted phase involved in a line-to-ground case compares the phase relationship of individual phase negative sequence current with zero sequence current. This scheme, without help, falls short (see Fig. 5). For example, phase A negative sequence current aligns with zero sequence current for a phase-A to ground fault. Unfortunately similar alignment occurs for a B-C ground fault. This can be overcome by the patented scheme shown in Fig. 6, which adds to the logic a phase shifted voltage (shifted by a small angle to accommodate the angle of lag expected for ϕG faults). The 4.0 ms coincidence timer imposes the requirement that all three phasor quantities in the comparison fall within a 90° band. This minimizes the likelihood of a false identification of fault type with a high value of ground fault resistance. Fig. 7 shows the relationship between I_0 and I_2 for various fault types.



a) Three Line Diagram



b) Three Pole Trip



c) Single-pole Trip

Figure 3: One Interconnecting Circuit

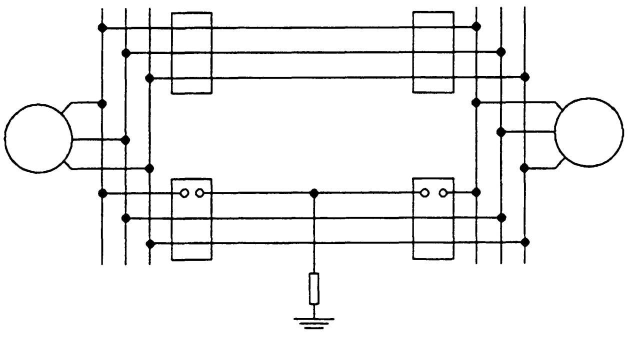
Another variation of this scheme for faulted phase selection also places dependence on I_0 and I_2 coincidence for each phase, but excludes $\phi\phi G$ faults by identifying them in terms of the extent of voltage reduction in the individual phases and blocks tripping. Blocking of the ground elements places partial dependence for $\phi\phi G$ tripping on the ***phase*** relays, requiring in some instances, special compensation (such as I_A-$3I_0$) for the phase elements designated to detect 3f faults.

Another important scheme utilizes $I_{A1} + I_{A2}$. These two quantities are well behaved with respect to one another and fault resistance does not influence their phase nor magnitude relationship. Pre-fault load flow can, however, affect the positive sequence current phase and magnitude. To eliminate this effect and to simplify the process for a microprocessor implementation, positive sequence current produced by the fault plus negative sequence current can be obtained by:

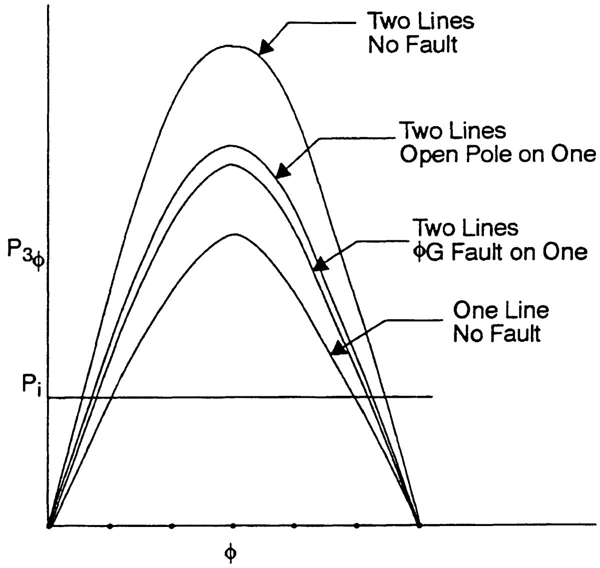
$$I_{A1} + I_{A2} = I_A - I_{AL} - I_{A0}$$

$$I_{B1} + I_{B2} = I_B - I_{BL} - I_{B0}$$

$$I_{C1} + I_{C2} = I_C - I_{CL} - I_{C0}$$



a) Three Line Diagram



b) Power Transfer Curves

Figure 4: Two Interconnecting Circuits

This comes about because I_A, for example, is total current during the fault including the pre-fault load current, and also the fault component of I_A is $I_{A1} + I_{A2} + I_{A0}$. Removing the pre-fault load current and I_{A0} from the measured phase current during the fault leaves only $I_{A1} + I_{A2}$, the positive and negative sequence fault components of A phase current. Comparing the magnitudes of the RMS values of the 3 phase component sums, the type of fault and phase(s) involved is apparent (see Fig. 8). The criterion used is based on a comparison of the phase sum with 1.5 times the phase sum of the other two phases.

For example:

$$|I_{A1} + I_{A2}| > 1.5\,|I_{B1} + I_{B2}|$$

and $$|I_{A1} + I_{A2}| > 1.5\,|I_{C1} + I_{C2}|$$

identifies a "phase-A" to-ground fault.

$$|I_{B1} + I_{B2}| > 1.5\,|I_{A1} + I_{A2}|$$

and $$|I_{C1} + I_{C2}| > 1.5\,|I_{A1} + I_{A2}|$$

identifies a BC or BCG fault.

This method has the interesting quality of utilizing symmetrical component quantities without having to generate any but zero sequence current and, of course, having that available from the sum of the individual phase currents.

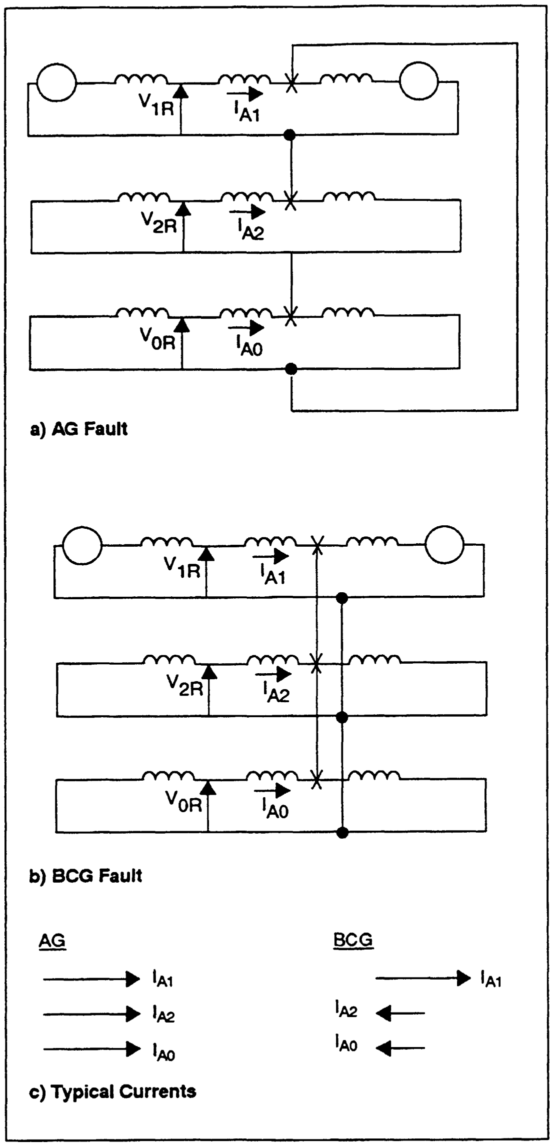
From Fig. 8, it is apparent that comparison of these sums will allow a clear identification of a phase AG fault, for example. Similar comparisons of other fault types show that all of them are identifiable using this method except for 3-phase faults which contain no negative sequence current (except in the practical case involving unequal phase impedances, where the level would be expected to be quite small).

The absolute method for identifying the type of fault and which phases are involved utilizes segregated phase comparison. The currents at each end of the transmission line are compared via a communication channel ***for each phase***. Current-in equals current-out for a sound line. Any difference other than that caused by uncompensated distributed capacitance is fault current. Even "cross country" faults, those involving more than one 3-phase transmission circuit, are clearly identified as to which phases are involved and on which circuits they exist in spite of the presence of distorted voltages for one circuit with a fault on the other. Voltage is not used in this scheme. The need for single-pole or three-pole tripping is clearly identified immediately without the complexity or time delay of other methods. Essentially simultaneous tripping occurs at both transmission line terminals even though a strong source exists behind only one of them.

During Single Phasing

Following single-pole tripping, a small secondary arc will be sustained as a result of capacitive current flowing between the still-energized sound phases and the now disconnected faulted phase. This current causes the deionization time to be prolonged beyond that which would be needed for three-pole tripping, possibly as much as 5 to 8 cycles. Reclosing time must be extended by an appropriate amount to accommodate this.

During the short single-phasing period, positive, negative, and zero sequence currents flow in the line (in one end and out the other) and the inherent scheme or back-up devices must be chosen carefully to avoid misoperation, while at the same time being able to recognize subsequent faults which may then occur involving the "sound" phases. This becomes an awesome task for most relaying schemes, because of the unbalanced load influences, possible line-side location of voltage transformer, all possible combinations of internal and external faults and the necessary blocked character of some relaying functions. The remarkably simple character of segregated-phase-comparison relaying is confounded by ***none*** of this.



a) AG Fault

b) BCG Fault

c) Typical Currents

Figure 5: I_{A2} and I_{A0} for AG & BCG Faults

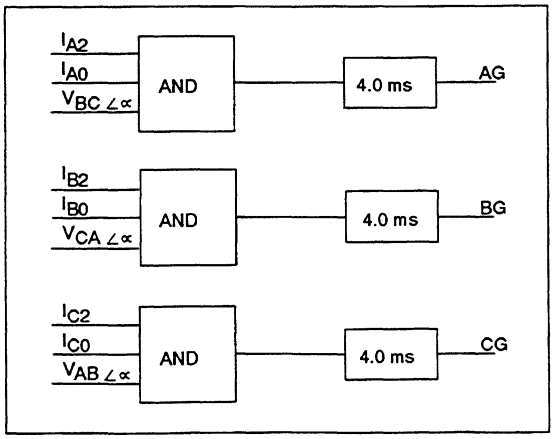


Figure 6: One Form of Phase Selector

Adjacent circuits also experience the short term influence of single-phasing, and the relaying associated with those circuits must either ignore this effect, through the nature of the relaying or its setting, or it must be undesirably time-delayed long enough for successful reclosing or three-pole tripping on the faulted circuit to take place.

For long transmission lines, (for example, greater than 45 miles of 500 kV, see Reference 1) capacitive and inductive coupling to the deenergized phase from the two energized phases may be severe enough to prevent deionization of the fault arc. To mitigate this, four-legged high-voltage reactors may be required to provide a near-parallel resonant supply to the arc, producing a self-quenching effect (see Reference 2)

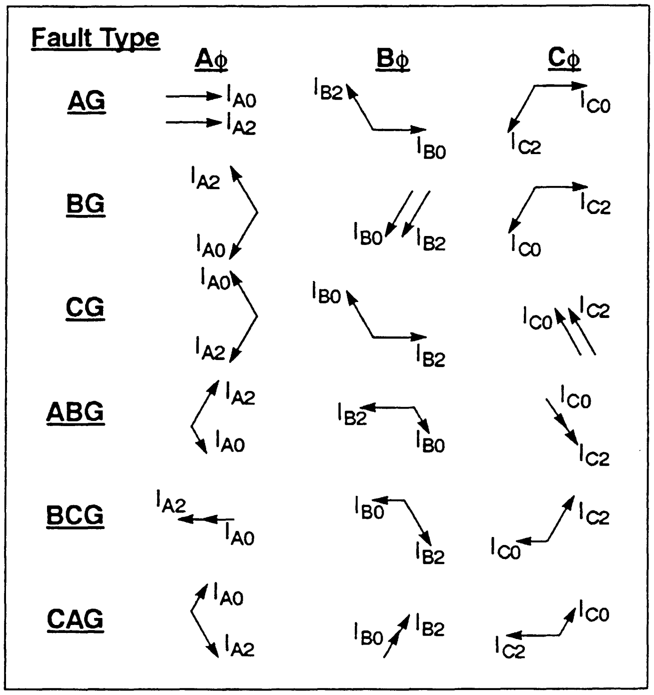


Figure 7: Relationship of Negative and Zero Sequence Components for Ground Faults.

The switching action associated with single-pole tripping produces swinging between machines as the variation of f in Fig.s 3C shows. Blocking of distance units during these swings may be necessary, to avoid undesired response. Where line-side voltage transformers are used, the relaying system must take cognizance of the need to block tripping during swings even though one voltage transformer may be deenergized.

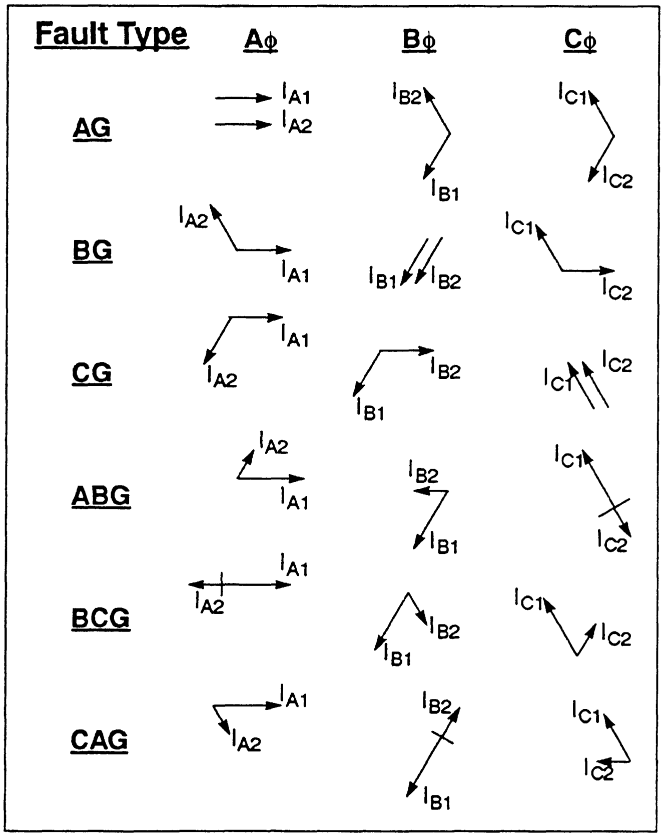


Figure 8: Relationship of Positive and Negative Sequence Components for Ground Faults.

Rotating machinery experiences exaggerated heating effects as a result of the presence of negative sequence current flow. The closer the proximity to the open point, the greater will be this influence. The relaying system must be equipped with provision for limiting the single-phasing period to minimize the exposure of rotating machinery to this hazard.

Trend

The continuing restrictions on right-of-way availability and the resultant tendency toward increased transmission line loading forces re-evaluation of practices that may provide even marginal improvements. In some cases very large benefits in transient stability are possible using the single-pole tripping concept. In other cases, only marginal improvement is possible.

The key thing that makes single-pole tripping a viable factor is the minor increase in relaying space and cost and the minor, if any, increase in circuit breaker costs that are involved in such an application contrasted with what was involved only 20 years ago. Also, the relaying available is highly sophisticated and incorporates the accumulated years of experience, while requiring only additional built-in output relays to provide single-pole tripping.

Conclusion

The relaying and circuit breakers are available for single-pole tripping, allowing with minor cost addition the possibility, in some cases, of substantial improvements in power system stability. The problems are well defined and the solutions, through many years of experience, are clear. The cleanest and least complicated relaying system appears to be some form of segregated-phase-comparison.

References

1. "Suppression of Ground-Fault Arcs on Single-Pole Switched EHV Lines by Shunt Reactors" by E. W. Kimbark, "IEEE Transactions on Power Apparatus and Systems" March 1964.

2. "Single Phase Tripping and Auto Reclosing of Transmission Lines," IEEE Committee Report, "IEEE Transactions on Power Delivery," Vol. 7, No. 1, January 1992.