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SINGLE PHASE TRIPPING AND AUTO RECLOSING OF TRANSMISSION LINES
IEEE COMMITTEE REPORT

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Key words: Single Phase Trip, single phase relay, auto-reclose, secondary arc current, recovery voltage, four reactor scheme.

ABSTRACT

This paper has been prepared to aid in the effective and uniform application of single-phase tripping and auto-reclosing of transmission lines. The benefits of application, relaying techniques, performance, and statistics will be discussed. The paper covers areas such as system stability, single-phase tripping and auto-reclosing, methods of secondary arc extinction, and related system requirements.

Descriptions of the various devices, definitions of terms, and references to other technical publications have been included to make the paper useful not only to relay engineers, but also to other technical people who are responsible for the installation and operation of such systems.

INTRODUCTION

The benefits of single-phase tripping and auto-reclosing are:

A. Improvements in transient state stability

B. Improvements in system reliability and availability, especially where remote generating stations are connected to load centers with one or two transmission lines

C. Reduction of switching overvoltages

D. Reduction of shaft torsional oscillation of large thermal units

Single-phase relaying application takes advantage of the fact that most faults on HV transmission lines are phase-to-ground faults. Some representative statistics are shown on Table I.[9]

TABLE I.
Relative Number of Different Types of Faults on HV Transmission Lines

Fault Types	Percent
Single Phase-to-Ground Faults	70
Phase-to-Phase Faults	15
Double Phase-to-Ground Faults	10
Three Phase Faults	5
Total	100

On EHV/UHV lines the conductor spacing is increased, therefore, the percentage of multi-phase faults decreases. Some representative statistics for the relative number of different type of faults on a 525 kV Transmission Lines are shown on Table II.[9]

TABLE II.

Relative Number of Different Types of Faults on 500 kV Transmission Lines

Fault Types	Percent
Single Phase-to-Ground Faults	93
Phase-to-Phase Faults	4
Double Phase-to-Ground Faults	2
Three Phase Faults	1
Total	100

DEFINITIONS

For the purposes of this paper, the following definitions apply.

Single-phase tripping: The opening of the faulted phase during a single-phase to ground fault.

Single-phase auto-reclosing: The reclosing of the faulted phase following a single-phase trip.

Primary arc current: The current in the phase to ground arcing fault prior to single-phase tripping.

Secondary arc current (Is): The current which flows in the arc after single-phase tripping is completed. (Is) is the sum of two currents derived from the electrostatic (Isc) and electromagnetic (Ism) coupling from the two energized phases and adjacent lines after the primary arc current is cleared via the line circuit breakers. The secondary arc if persistent, may prevent successful reclosing.

Recovery Voltage (Vr): The voltage which appears across the secondary arc path as soon as the arc is extinguished.

Cross Country Fault: The occurrence of simultaneous faults on the same or different phases on double circuit lines.

Neutral Reactor: A reactor used in combination with the three line-connected shunt reactors to create a high impedance against the flow of the secondary arc current.

SYSTEM REQUIREMENTS

A. Transient Stability Criteria

Conventional studies of transient stability are based on the subject system being able to withstand a three-phase bus fault at critical locations.

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Although three-phase bus faults are a convenient way to test the transient stability of a system, experiences and statistical data indicate that double or triple contingency faults are more common than three-phase faults.

One double contingency event more common than a three-phase fault is a fault on one line and a simultaneous trip of another line due to relay misoperation.

For example, Figure 1 shows a system with three parallel lines where a single phase-to-ground fault is applied on Line 1 and cleared in 3 cycles. Assume a simultaneous false trip of Line 2.

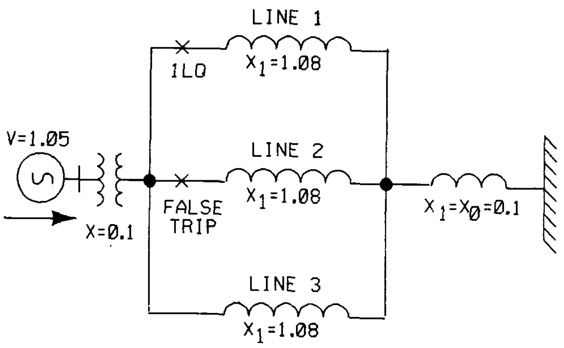


Figure 1. Single Machine-Infinite Bus Three Line Model System.

Figure 2. shows the results of the transient stability studies with three-phase and single-phase trip. The machines go unstable for a three-phase trip of line 1 (curve C), but remain stable for a single-phase trip (curves A and B). Reclose time is not critical. Note, that the units settle faster for the 90 cycle reclose than the 30 cycle reclose.

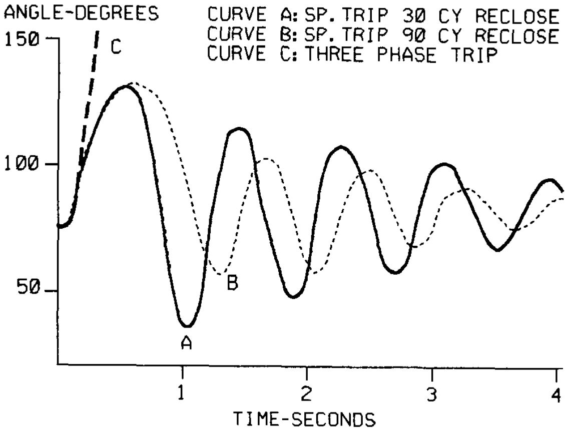


Figure 2. Rotor Angle Curves-Three Cycle Fault on Line 1 with False Three-Phase Trip on Line 2

Ideally, *transient stability studies* should include the statistical data of past system performance during multiple contingency events as well as three-phase bus faults. When realistic probabilities, statistical data, and cost of disturbance data are used, single-phase tripping will be cost effective in many cases.

B. Design Requirements

Some of the obvious design requirements are:

1) A relay system which is capable of selecting and tripping only the faulted phase for single-phase-to-ground faults.

2) The circuit breakers must have independent pole operating capability to execute a single-phase trip properly.

3) The transmission line tower footing resistances must be within the range of the relay single-phase selector logic.

Other design requirements of the transmission line are less obvious namely, the effect of the electrostatic and electromagnetic coupling between the still energized phase conductors and parallel line(s). This phenomenon:

4) *Tends to sustain a secondary arc current* (I_s) in the primary arc path and lengthens the time of de-ionization which in turn can prevent a successful auto-reclose.

5) Causes recovery voltage (Vr) to appear across the secondary arc path as soon as the arc is broken. The magnitude of V_r and/or its rate of rise can initiate a re-strike, which can prevent a successful auto-reclose.

C. Calculation of the Secondary Arc Current

The secondary arc current (I_s) on a single, symmetrical, fully transposed transmission line is basically the phasor sum of two currents maintained by electrostatic (I_{sc}) and electromagnetic (I_{sm}) coupling from the two energized phases.

$$I_s = I_{sc} + I_{sm} \qquad [1]$$

1) Calculation of the Secondary Arc Current via Electrostatic Coupling

The calculation of the secondary arc current via electrostatic coupling on a single, symmetrical, fully transposed transmission line was developed by Kimbark, Peterson, Dravid, et. al. [1,2,3]. For untransposed line analysis refer to [11, 12, 13]. Figure 3a. represents a single, symmetrical, fully transposed transmission line with phase A in an open condition with a capacitance C_Δ between each pair of phases and a capacitance C_G from each phase-to-ground. The phase A-Gnd fault is represented by SW_F.

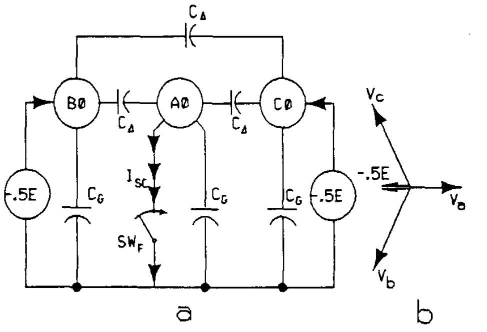


Figure 3. Electrostatic Coupling Diagram of a Single, Symmetrical, Fully Transposed Transmission Line.

The phasor of the effective voltage is shown on Figure 3b. The Thevenin equivalent circuit derived from Figure 3. is shown on Figure 4a. It is achieved by folding phase C to phase B.

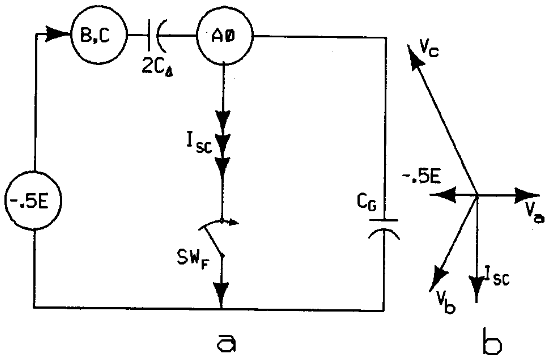


Figure 4. Electrostatic Coupling Thevenin Equivalent Diagram of a Single, Symmetrical, Fully Transposed Transmission Line.

The magnitude of the secondary arc current due to electrostatic coupling is in direct proportion to the line voltage and the line length. From inspection of Figure 4a with SW_F closed:

$$I_{sc} = -.5E \times \frac{1}{1/-j\omega 2C_\Delta} = E\, j\omega C_\Delta \qquad [2]$$

A typical secondary arc value for 500-kV lines is 20 A per 100 miles. The phase relationship between the effective phase voltages and I_{sc} is shown on Figure 4b.

2) Calculation of the Secondary Arc Current via Electromagnetic Coupling

When the transmission line is equipped with shunt reactors, there is a component of secondary arc current induced by the electromagnetic coupling from the unfaulted phases.

The simplified diagram depicting secondary arc current (I_{sm}) due to electromagnetic coupling to the open-phase A is shown on Figure 5.

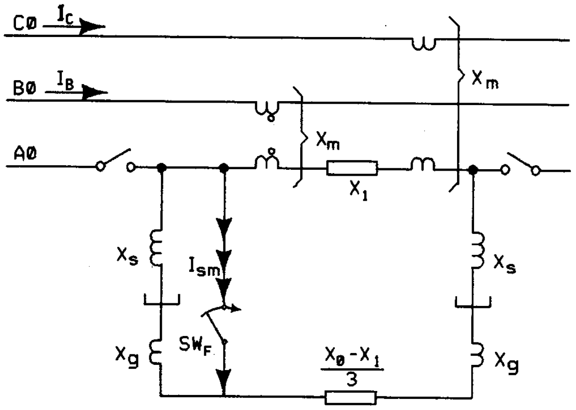


Figure 5. Electromagnetic Coupling Diagram of a Single, Symmetrical, Fully Transposed Transmission Line.

Accurate calculation of I_{sm} requires Electro Magnetic Transient Program (EMTP) studies due to the fact that mutual induction is the sum of many dynamic variables involving the line currents flowing in the sound phases, adjacent line loading, the method of secondary arc extinction, etc.

A simplified calculation of I_{sm} for a single, symmetrical, fully transposed line using a four-reactor scheme is shown in Appendix-B.

3) Calculation of the Recovery Voltage

The magnitude of the recovery voltage (V_r) is directly proportional to the line voltage and the relative values of C_Δ and C_G. Consequently, V_r does not vary with line length.

From inspection of Figure 4a. the recovery voltage on phase A with SW_F open:

$$V_r = -.5E \times \frac{1/-j\omega C_G}{(1/-j\omega 2C_\Delta)+(1/-j\omega C_G)} \qquad [3]$$

$$V_r = -E \times \frac{C_\Delta}{2C_\Delta+C_G} \qquad [4]$$

Typical V_r values are 10-25% of the line voltage without shunt reactors.

The oscillograph of a typical recovery voltage and the secondary arc current on a line without shunt compensation is shown on Figure 6.

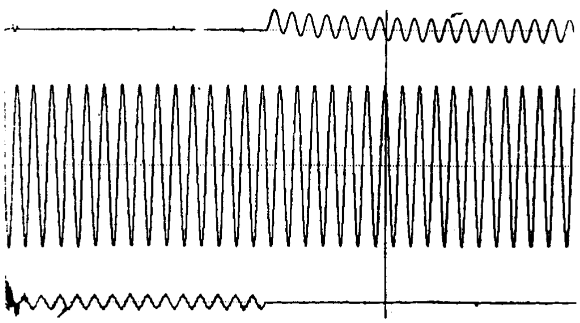


Figure 6. Recovery Voltage (top trace) and secondary arc current (bottom trace) from the 500 kV Malin-Round Mountain staged fault test.

If solidly grounded reactors are applied to the line for shunt compensation, they reduce the effective capacitance of C_G without affecting C_Δ, thus leading to higher values of recovery voltage. For shunt compensated lines where C_G represents less than one-half of the total line charging MVAR, the shunt reactors may overcompensate C_G. In these cases, the effective phase-to-ground impedance is inductive and the recovery voltage may exceed normal line to neutral voltage, limited by saturation of the shunt reactors.

The oscillograph of a typical recovery voltage and secondary arc current on a line with shunt compensation is shown on Figure 7. The voltage wave low frequency envelope is attributed to the beat frequency of the 60 Hz source to the off tuned circuit created by the open phase capacitance and the shunt compensating reactors.

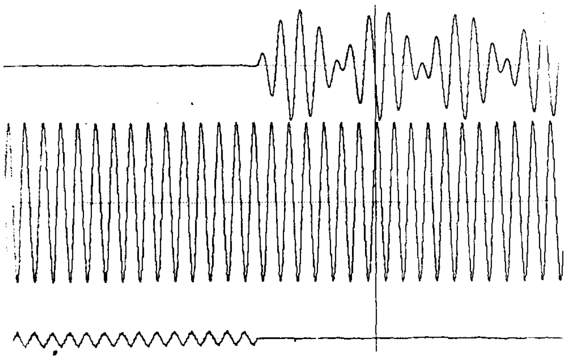


Figure 7. Recovery voltage (top trace) and secondary arc current (bottom trace) from the 500 kv Malin-Round Mountain staged fault test.

D. Methods of secondary arc extinction

The magnitude of the secondary arc current and the recovery voltage are the most important factors which determines whether or not the secondary arc will be self-extinguishing.

Briefly, the high current, high energy primary arc heats and ionizes the arc path until the faulted phase is tripped. Afterwards, the heated, ionized arc path can support the smaller secondary arc current induced by the electrostatic and electromagnetic coupling. All methods of secondary arc extinction are directed toward reducing the magnitude of the secondary arc current, which in turn will reduce the extinction time of the arc. Table III. indicates the following probable performance based on line voltage for lines without supplemental arc extinction measures.

TABLE III.

Line lengths for single-phase auto-reclosure without supplemental arc extinction devices. e.g. shunt reactors

	Line Length (Mi)	
Line to Line Voltage (kV)	Successful Range	Doubtful Range
765	0- 50	50 - 80
500	0- 60	60 - 100
345	0-140	140 - 260
230	0-300	300 - 500

If the line is longer than that given in the above table and single-phase tripping and auto-reclosing is to be applied, then additional measures must be taken to reduce the secondary arc as outlined below:

1) Transmission Lines with Four-Reactor Bank

Most long EHV lines require three, single-phase reactors to provide shunt reactor compensation for voltage control. A four-reactor bank is created by adding a fourth reactor in the neutral of the three single-phase reactors. The fourth reactor is used to reduce the secondary arc currents. The reactance value of the neutral reactor needed to neutralize the secondary arc current can be calculated by using the formulas given below.

Figure 8. represents a symmetrical transmission line with four reactors. The phase A to ground fault is represented by SW_F.

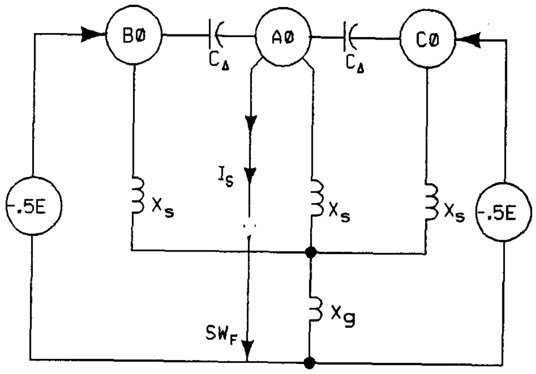


Figure 8. Transmission Line with Permanently Connected Four-Reactor Bank

The Thevenin equivalent circuit derived from Figure 8. is shown on Figure 9a. It is achieved by folding phase C to phase B.

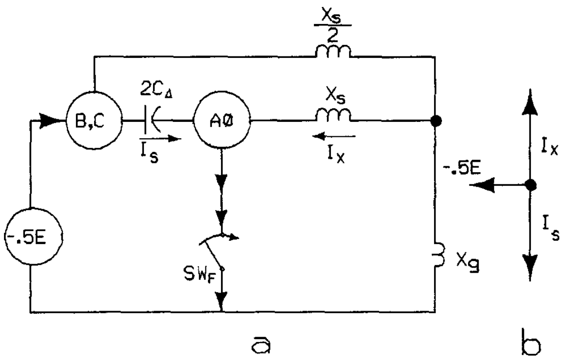


Figure 9. Permanently Connected Four-Reactor Bank Thevenin Equivalent One Line Diagram

From inspection of Figure 9a. with SW_F closed, if the magnitude of the current through the shunt reactor I_x is equal,and opposite to the magnitude of the secondary arc I_s, then the effective current through SW_F is zero.

The phasor diagram for the current I_s and I_x is shown on Figure 9b.

The voltage Eg necessary at the fourth reactor to provide I_x equal to I_s is calculated.

$$Eg = -I_x \cdot X_s \qquad -I_x = I_s \tag{5}$$

Xs:the reactance value of the phase shunt reactor.

The current through the reactors (Xs/2) of the unfaulted phases is

$$I_T = \frac{.5E-Eg}{X_s/2} = \frac{E-2Eg}{X_s} \tag{6}$$

The current through the neutral reactor is

$$I_g = I_T - I_x \qquad [7]$$

The reactance value of the neutral reactor is

$$X_g = \frac{E_g}{I_g} \qquad [8]$$

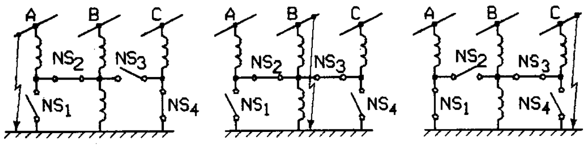
2) Modified Selective Switched Four-Reactor Scheme.

This scheme is recommended on untransposed lines where the four-reactor banks are not effective to extinguish the secondary arc.

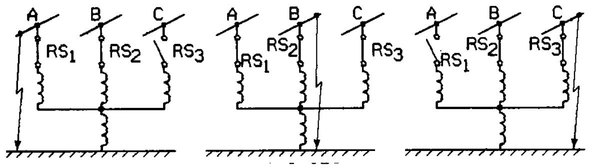
On long untransposed 765kV EHV lines built in a horizontal configuration, the ratio of outer-to-middle phase capacitance (C_{A-B} or C_{B-C}) to outer-to-outer phase capacitance (C_{A-C}) varies from 3.5 to 3.9. For these lines, one four-reactor bank and one modified four-reactor bank may be specified [10, 11].

The four-reactor bank at one end of the line is designed to compensate the inter-phase capacitances by a value equal to C_{A-C}. The modified four-reactor bank at the other end of the line is switched to compensate the unbalanced capacitance (C_{A-B}-C_{A-C} or C_{B-C}-C_{A-C}). The actual reactor value selected allows for the electromagnetic component of the secondary arc current [10, 11].

Figure 10a. shows a modified four-reactor bank with a neutral switching design.



a. Neutral Switch Scheme



b. Reactor Switch Sheme

Figure 10. Modified Four-Reactor Bank with Neutral Switches (NS) and High Side Reactor Switches (RS) and Their Positions for Different Phase-to-Ground Faults.

All switches are normally closed but a specific pair of neutral switches operate when a particular faulted phase is identified open.

Figure 10b. shows a modified four-reactor bank with different high side reactor switch positions. This design can provide the necessary compensation for faults on various phases. The modified four-reactor bank for untransposed 765-kV lines was studied for a wide range of line lengths and reactor arrangements. The results show that the secondary arc current can be reduced to 25 A rms for 765kV lines up to 350km having practical levels of shunt reactive compensation [12].

3) High Speed Grounding Switch Scheme

This scheme involves the application of a high speed grounding switch in each phase at each end of the line. The ground switch is closed onto the faulted phase after the circuit breaker pole on that phase opens and vice versa for reclosing. In principle, the ground switch removes all voltage from the open phase on the line and, therefore, removes the driving voltage behind the secondary arc. [8, 9]

4) Hybrid Single-Phase Scheme

The scheme trips the faulted phase first. The two unfaulted phases are tripped with time delay 50-60 cycles later. The trip cycle is followed by a fast three-phase auto-reclose (within 10-15 cycles). The hybrid scheme has a dual purpose:

> Keeping the two unfaulted phases closed for 50-60 cycles after the fault is cleared, which significantly reduces the system power swing.
>
> The three-phase trip and fast auto-reclose eliminates the secondary fault current without additional hardware requirement.

E. Summary of secondary arc extinction methods

1) Permanently connected four-reactor bank:

Advantages	Disadvantages
Proven design	High cost, neutral end of phase reactors must have higher insulation, possible operational problems due to lack of flexibility in placement and lack of switching ability. May not work on closely coupled parallel lines.

2) Selectively switched four-reactor bank:

Advantages	Disadvantages
More flexibility than method 1).	Higher cost than method 1) plus complexity of high speed switches and controls.

3) High speed ground switch scheme:

Advantages	Disadvantages
Lower cost, does not require neutral reactors.	More complex protection and control scheme.

4) Hybrid single phase trip scheme:

Advantages	Disadvantages
No additional hardware is required to eliminate the secondary arc.	Cannot be used where single phase is required to maintain synchronism between the system and a remote generating plant. The torsional duty due to the multiple switching events must be evaluated when the scheme is used close-in to a thermal generating plant.[6]

Other Schemes

Two other schemes have been proposed in the references but have never been seriously considered. They are the series capacitor scheme [3] and the line sectionalizer scheme.

5) Series capacitor scheme:

Advantages	Disadvantages
Flexibility of reactor placement.	Complexity of design, unproven in practice.

6) Line sectionalizing scheme:

Advantages	Disadvantages
May negate need for shunt reactor.	Sectionalizer must be located in middle of line.

SINGLE-PHASE RELAYING

A. General Requirements

The installation of a single-phase relay scheme can be justified only if there is assurance that a large percentage of the phase-to-ground faults will in fact clear with single-phase trip that is followed by a fast auto-reclose.

1) Three-Phase Trip Logic

In general, the single-phase relay scheme should have the following logic that initiate three-phase trip and blocks auto-reclose:

Out-of-Step blocking logic; prevents the scheme from tripping during swing conditions.

Close-into-fault detection logic; detects a fault when the circuit breaker is being closed.

Multi-phase fault detection logic; detects multi-phase faults.

Evolving fault detection logic; detects fault on one phase, evolving into another phase during the dead time of the auto-reclose.

Directional ground overcurrent relay; provides a time delayed backup for high resistance faults.

Time delayed backup relaying.

2) Single-Phase Trip Logic

In general, the single-phase trip scheme should have the demonstrated capability to detect phase-to-ground faults on the entire length of the transmission line under the following conditions:

Heavy line loading. Heavy loading can be one of the justification to install single-phase relaying.

Tower footing resistance. Successful single-phase operation requires that a large percentage of the towers have the tower footing resistance within the range of the phase selector logic.

Series compensation.

Parallel line(s). Mutual coupling of adjacent line(s) increases the apparent resistance.

Three terminal line.

3) Verification by Testing

Model line tests by digital or analog simulations provides a check of the performance. It is necessary that extensive factory tests are run on the complete relay system and its components to judge performance over a wide range of test conditions, such as maximum and minimum source impedance, shunt reactor compensation included or excluded, and series compensation included or bypassed. Non-linear elements such as MOV's shunting series capacitors provide recent complexity additions. Staged fault testing provides a check of the complete installation and is an excellent way of obtaining proof of the performance.

B. Single-Phase Relaying Techniques

Any of the commonly applied relaying schemes can be selected in accordance with the user's philosophy with the understanding that each scheme may have drawbacks as well as advantages.

1) Distance Relays

The most common type of line protection, the distance relay, is based on the measurement of the fundamental frequency positive sequence impedance of the line. The impedance measurement has many advantages over other concepts and a few disadvantages. The distance relay measuring elements perform four different tasks:

Fault zone detection
Directional discrimination
Load discrimination
Phase selection

Trip decisions are generally carried out through logic circuits combining information from several measuring elements.

One important benefit is that the fault detection, the directional phase selection, and the trip decisions are made at the local line terminal. The relay "reach" is relatively well defined for all fault types, and system source impedance conditions do not affect the relay settings except when series capacitor compensation exists.

The ground distance relay resistive reach is restricted by the maximum line loading. The resistive reach is also influenced by the method of polarization and the system source to line impedance ratio. Modern ground distance relays have circular or other composite characteristics which enable improved resistive reach for phase-to-ground faults. These characteristics permit better discrimination between maximum load and fault impedance. System requirements, such as "Out of Step" swing conditions may reduce permissible resistive reach even further. It is therefore, necessary to add a negative or zero sequence directional current relay that will detect high resistance faults. With conventional directional overcurrent relays it is not possible to obtain phase selectivity. High resistance faults must be tripped three-phase.

Phase distance functions can operate for some phase-to-ground faults. These conditions occur when the system zero sequence impedance is small relative to the system positive sequence impedance (both viewed at the point of fault). Provisions must be made to block the phase distance functions from a false trip for a close-in phase-to-ground fault. One method utilizes a restraining signal that is proportional to the zero sequence current to supervise the phase functions. This method may not be satisfactory for remote faults if the zero sequence current is very small. This type of supervision may also block the phase functions from initiating a three-phase trip during close-in, phase-to-phase-to-ground faults.

2) Directional Comparison Relays

Directional comparison relaying is usually a hybrid scheme. The most common types use mho type directional distance relays to detect three-phase and/or phase-to-phase faults. A combination of positive, negative and zero sequence measuring techniques are used to detect phase-to-phase or phase-to-ground faults. Negative or zero sequence measurement is used provide a better sensitivity for phase-to-ground faults with high fault resistance. High resistance ground faults can be detected through separate directional comparison relay logic based on zero sequence current. The communications channel can often be shared with the pilot distance relay. It is also common to supplement this scheme with a sensitive directional ground overcurrent relay with long time delay (1-2 sec.) for back up tripping upon loss of communication.

Various methods are available to eliminate or minimize the effect of the operation of the ground functions associated with the unfaulted phases during a phase-to-ground fault. One method uses the negative and zero sequence current components to form a phase selector to minimize the area of coverage of the function associated with the unfaulted phases. Another solution is to allow the ground overreaching functions to take priority over the phase overreaching functions to prevent them from initiating a three-phase trip.

The phase selection logic that is based on the measurement of symmetrical components suffer from being dependent on source and line impedances, mutual coupling and their sensitivities.

3) Wave Comparison Relays

In addition to being fast (1/4 cycle), one of the advantages of traveling wave comparison relays is that they act on the changes in phase voltage and current, eliminating the pre-fault quantities. The simplicity of the change analysis, as compared to a more complex analysis of, for example, symmetrical components can also result in improved sensitivity by virtue of the fact that all symmetrical components are available in the phase quantities. The ability to operate on the change and not the absolute quantity of voltage and current enhances the reliability by an improvement in the signal-to-noise ratio as obtained from the instrument transformers.

This eliminates problems with CVT transients and CT saturation. Since the traveling wave relay uses the fault generated transient, the relay cannot provide a measurement after the transient subsides. The system, therefore, requires back up, usually from a more conventional distance relay.

Lightning arrester discharge, as well as switched reactors require desensitizing or delay of operation. The system is also affected by long-line/strong source limitations. Inherent phase selection is a strong feature, as well as being unaffected by fuse failure conditions, or sudden loss of A-C supply.

4) Phase Comparison and Current Differential Relays

Phase comparison or current differential relays require only line current as an input signal. One advantage of this type of protection is that it is inherently immune to tripping on a power swing or inadvertent loss of potential. The disadvantages are the critical dependency on properly functioning communications and the lack of any remote backup capability for external faults.

There are three principal types of systems:

Mixed Excitation Phase Comparison Relays: Mixed excitation phase comparison relays use a phase sequence component filter to combine three-phase currents into a single-phase signal which is compared with a similarly combined signal from the remote end terminal(s). Mixed excitation systems are not well suited for single-phase relaying since the sequence filter arrangement does not inherently identify the faulted phase. To provide single-phase relaying additional phase selection logic must be added.

If the phase selectors are current only type, the operation of the scheme depends upon having reliable sources of negative and zero sequence current at both end terminals. Mixed excitation phase comparison has possible problems when applied on series compensated lines. On such lines the sequence filters may develop a zero output for certain combinations of capacitor gap bypassing, leading to "blind spots" in the protection.

Segregated Phase Comparison Relays: Segregated phase comparison relays use three systems, one for each phase. Segregated phase comparison systems are inherently phase selective and can operate correctly for faults on another phase during the dead time of the auto-reclose. They are also immune to the problems of evolving faults on parallel lines. Weak in-feed and some out-feed conditions for internal faults can be detected with segregated phase comparison, using the offset keying technique. A fourth sub system may be added in the neutral circuit to provide three-phase tripping for high impedance ground faults.

Current Differential Relays. Current differential relays are either phase segregated or use filters and/or summation current transformers to derive an operating and restraint quantity that is the vector function of the three-phase current. Phase segregated type current differential relays are inherently capable for single-phase trip. The current values are transmitted to the remote end via metallic or optical channels, carrier or microwave radio. In one method, the operating quantity is the vector addition of the single-phase current phase and amplitude, while the restraint quantity is the arithmetic sum of the currents phase and amplitude from each end end terminal.

Current differential systems are available that use time tagged sampling of data, which therefore, make the system usable for long, multi-terminal lines.

C. Operation During the Open Pole Period Following a Single-Phase Trip

Due to the capacitive and inductive coupling, the voltage associated with an open phase can vary significantly, and may even be reversed. Therefore, when one phase has been opened, care must be taken to assure that no misoperations occur during and immediately following the (.5 to 1.5 sec.) open-phase period. This is often done via sensitively set overcurrent functions which are set to drop out during the open phase. Overcurrent supervision is also used to avoid any problems that might occur because of load flow.

Positive sequence voltage that is referenced to the associated phase will not reverse when a phase is open. It is used sometimes to provide a stable polarizing signal. The "sound" phase voltages are also often used to derive polarizing signals.

D. Double Circuit Lines

In regions where large blocks of power are being transferred over double circuit EHV transmission lines, the occurrence of a "cross country" fault, could initiate serious system stability problems, if the fault is followed by a three-phase trip of both lines. For example, consider the double circuit EHV transmission lines shown in Figure 11.

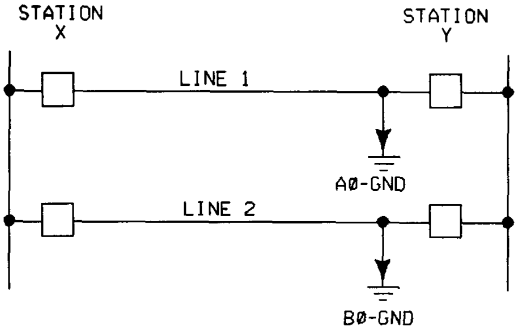


Figure 11. Double Circuit EHV Transmission Lines With "Cross Country " Type of Fault on Different Phases.

At station X, the cross country fault will appear as an A-B-Gnd fault in both lines with an attendant operation of the A-B phase functions and possibly the A and B ground functions. Thus, at station X, this condition will be recognized as a multi-phase fault.

At station Y, the fault will appear as an A-Gnd fault in line 1 and as a B-Gnd fault in line 2. Thus, at station Y, correct identification of the fault type will be made.

Segregated current phase comparison or the segregated current differential schemes are inherently phase selective. Other single-phase tripping schemes on each of the lines will initiate three-phase tripping at station X and single-phase tripping at station Y if precautions are not taken.

The problem is not insurmountable, and techniques are available to provide correct tripping of the faulted phases only. One method utilizes ground distance functions that are designed not to operate for double-line-to-ground faults, multiple communications channels, and appropriate scheme logic to recognize the fault type, and so initiate correct tripping.

E. Back Up Relaying and Redundancy Considerations

The commonly used backup involves using a second primary relay system and dual trip coils. In addition, two local breaker failure systems may be used. Single-phase reclose failure should also be considered (i.e., three-phase trip should result if the opened breaker pole in the faulted phase will not reclose). This can be taken care of by a breaker pole disagreement logic.

F. Breaker Failure

Breaker Failure protection (BF) with single-phase trip is more complex than three-phase trip.

The majority of the BF schemes use the dropout of the fault current detector logic to sense that the breaker poles have opened. In a three-phase trip scheme, it is only necessary to detect that all of the fault current detectors have dropped out.

In a single-phase trip scheme, only the breaker pole associated with the faulted phase will trip while the two remaining phases stay closed. The load current in the unfaulted phases may be above the pickup of the BF current logic. Therefore, in single-phase trip schemes, a segregated phase type BF scheme should be used.

The effect on the performance of the BF needs to be considered when a single-phase-to-ground fault evolves into other phase(s). If the BF logic uses a single timer, the overall time delay will have to be based on clearing of the evolving fault. This overall time may be excessive relative to the overall time required to clear a multi-phase fault. A possible solution for this case is to use two timers, the first timer set for single-phase-to-ground faults only, with a long enough time delay to override an evolving fault, the second timer can be set with a shorter time delay to meet system stability requirements for multi-phase faults. An alternative is to use separate timers for each phase.

OPERATIONAL REQUIREMENTS

A. Evaluation of Current Unbalance During Open Phase Conditions

When one phase of a transmission line is opened, load current still flows through the other two phases. The unbalance generate negative and zero sequence currents and voltages. Their effect should be carefully analyzed. The negative and zero sequence impedances of the power system help to reduce the amount of load current flowing through the healthy phases. The negative sequence current is usually larger than the zero sequence current flowing through the opened phase transmission line because of higher zero sequence line impedance. However, weaker negative and stronger zero sequence sources may produce higher zero sequence current.

Large generators close to the transmission line may have high negative sequence current flowing. Similarly, strong zero sequence sources will carry large amounts of zero sequence current (e.g., delta tertiary of an auto-transformer). Also, in adjacent transmission lines, negative and zero sequence directional relays, having enough polarizing signal, may try to operate the directional overcurrent relay or the pole disagreement logic unless they are properly coordinated. A sample calculation is shown in Appendix-A.

B. Reclosing

The reclosing relay required for single-phase trip is normally different than that used for three-phase trip. It is usually preferable to have different dead time settings for single-phase-to-ground faults versus multi-phase faults. It is also desirable to be able to select whether reclosing should occur after multi-phase fault or three-phase tripping operations. On some conventional reclose schemes a mode selector switch is provided.

More advanced reclose schemes use adaptive reclosing where the line relay logic is interlocked with the recloser to delay, block or override reclose. A single-phase reclose attempt should always lead to a three-phase trip if the fault persists. A logic circuit or a "prepare three-phase trip" signal is required from the reclosing relay.

Sequential (or evolving faults) during the first phase open period should normally lead to three-phase tripping. Ring bus or breaker and half applications require special consideration regarding reclosing. It may be simpler to always trip one breaker three-phase and the other single-phase.

Synchro-check reclosing is often combined with the single-phase and three-phase reclosing relay for three-phase trip operations.

APPENDIX-A

Approximate Calculation of Current Unbalance

Calculation of the current unbalance is difficult because an open phase action involves many dynamic variables which change with respect to time from the fault inception to the phase opening. However, with some judicious assumptions the engineer can estimate the maximum negative and zero sequence current unbalance.

During single phase tripping, the reactance values of the system change with respect to time depending whether:

1) The moment of the fault is taken as the criterion.
2) The moment just after the fault is the criterion.
3) Some time after the fault has taken place.

In case 1) the reactance is the subtransient reactance X''_d

In case 2) the reactance is the transient reactance X'_d

In case 3) the reactance is the synchronous reactance X_d

o by definition $X''_d \leq X'_d \leq X_d$ [9]

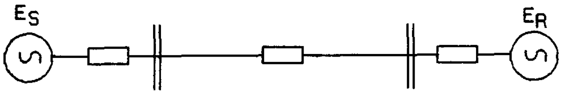
Therefore, for the "worst case" type of calculation the X"d values should be selected on the assumption that if there is no problem with negative and zero sequence current magnitudes with the X"d reactance then the X'd and Xd values will always provide less negative and zero sequence current flow.

The positive, negative and zero sequence subtransient reactance values for the sources and the line are readily available from system impedance data.

For example: A simplified two machine diagram is shown on Figure 12.

The base quantities 1 per unit (pu) on a 100 MVA base are:

$E_S = E_R = 525kV = 1 \text{ (pu)}$ [10]



X1 0.0041	X1 0.0038	X1 0.0025
Xo 0.0062	Xo 0.0108	Xo 0.0038

$Z_1(pu) = 0.0041 + 0.0038 + 0.0025 = 0.0104 \text{ (pu)}$

Figure 12. Two Machine Diagram

For the "worst case" condition assume that the positive sequence MVA is equal to the maximum steady state power flow P_S.

Assume:

$$P_S = 1000 \text{ MVA} \qquad [11]$$

1000 MVA is 10 per unit on a 100MVA Base.

by definition $P_S = \dfrac{E^2(pu) \times \sin\delta}{X_1(pu)}$ [12]

Therefore $10 = \dfrac{E^2 \times \sin\delta}{0.0104}$ [13]

for E = 1 (pu) $\sin\delta = 0.104$ [14]

The sequence network interconnection for phase A open is shown on Figure 13.

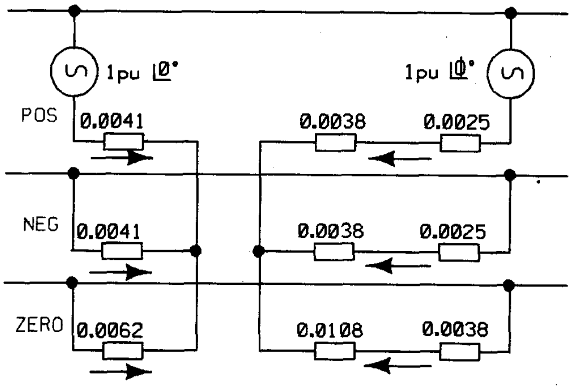


Figure 13. Two Machine Diagram with One Phase Open

Assume that the power angle δ does not change between the two sources when one phase is opened. The system symmetrical component configuration is positive sequence plus a parallel configuration of negative and zero sequence network, which with one phase open will reduce the power transfer to:

$$P_S = \frac{E^2 \times \sin \delta}{X(pu)} \qquad [15]$$

$$\text{where } X(pu) = .0104 + \frac{1}{\frac{1}{.0104} + \frac{1}{.0208}} \qquad [16]$$

$$X(pu) = 0.0104 + 0.0069 = 0.0173 \text{ (pu)} \qquad [17]$$

From inspection of Figure 13. the per unit magnitude of the positive sequence current during open phase is the same as the MVA pu.

$$I_1 = \frac{E^2 \times \sin \delta}{X(pu)} \qquad [18]$$

From which

$$I_1 = \frac{1 \times 0.104}{0.0173} = 6.0 \text{ (pu)} \qquad [19]$$

% distribution of negative sequence current

$$-I_2 = \frac{0.0069}{0.0104} \times 100 = 66\% \qquad [20]$$

or

$$I_2 = -.66 \times 6.0 = -4.0 \text{ (pu)} \qquad [21]$$

% distribution of zero sequence current

$$-I_0 = \frac{0.0069}{0.0208} \times 100 = 34\% \qquad [22]$$

or

$$I_0 = -.34 \times 6.0 = -2.0 \text{ (pu)} \qquad [23]$$

100MVA at 525KV = 110 A [24]

Under the "worst case" criteria, during one phase open:

Maximum positive sequence amps: $I_1 = 660$ A [25]

Maximum negative sequence amps: $I_2 = -440$ A [26]

Maximum zero sequence amps : $I_0 = -220$ A [27]

It is advisable to study the effect of 440 A negative sequence and 660 A ($3I_0$) ground current flow on the power equipment and the relaying during open phase condition.

APPENDIX-B

Approximate Calculation of Secondary Arc Current via Electromagnetic Coupling

Reference the example presented in Appendix-A. The MVA power transfer during open phase are:

$$I_1 = 6.0(pu) \quad I_2 = -4.0(pu) \quad I_0 = -2.0(pu) \qquad [28]$$

from which

$$I_B = a^2 I_1 + a I_2 + I_0 = -3.0 - j8.66(pu) \qquad [29]$$

$$I_C = a I_1 + a^2 I_2 + I_0 = -3.0 + j8.66(pu) \qquad [30]$$

The relationship between I_B and I_C and the driving current Idr is shown on Figure 14.

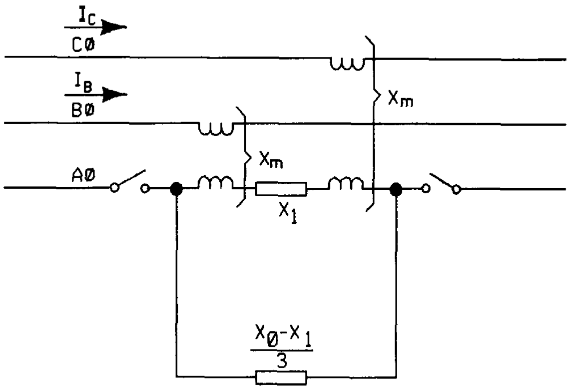


Figure 14. Driving Current One-Line Diagram.

From which the driving current:

$$I_{dr} = I_B + I_C = 2 \times (-3.0) = -6.0 \text{ (pu)} \qquad [31]$$

Note that the driving current I_{dr} is the same as $3I_0$.

$$Idr = 3I_0 \qquad [32]$$

The driving voltage Vdr induced in phase A via electromagnetic coupling Xm and driving current $3I_0$.

$$Vdr = 3I_0 \times X_m \qquad [33]$$

The Carson equations define Xm for symmetrical three-phase circuits.

$$Xm = 1/3(X_0 - X_1) = 1/3(.0108 - .0038) = 0.0023 \qquad [34]$$

from which

$$Vdr = -6.0 \times 0.0023 = -0.0140 \text{ (pu)} \qquad [35]$$

The magnitude of the secondary arc current depends on the driving voltage Vdr and the location of the fault.

1) If, for example, the open phase A is shorted at each end we have the maximum Ism. (As shown on Figure 14.).

$$Ism = \frac{Vdr}{1/3(X_1 + X_2 + X_0)_{line}} \qquad [36]$$

$$Ism = \frac{.0140}{1/3(.0076 + .0108)} = 2.28 \text{ (pu)} \qquad [37]$$

$$Ism = 251 \text{ A} \qquad [38]$$

2) If the fault is in the midpoint of the line, the circulating Ism currents cancel as shown on Figure 15.

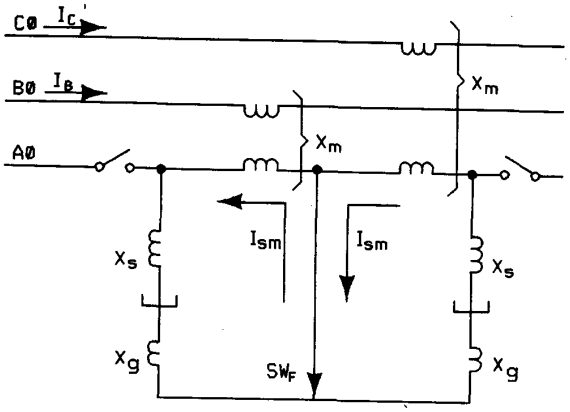


Figure 15. Midpoint Fault One-Line Diagram.

3) If the fault is at one end of the open phase with a 4 reactor scheme at the other end.

$$Ism = \frac{Vdr}{1/3(X_1+X_2+X_0)+Xs+Xg} \qquad [39]$$

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