Loss of ac Voltage Considerations For Line Protection

A report prepared for the Line Protection Subcommittee
Of the IEEE Power Engineering Society, Power System Relaying Committee

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1.0 Introduction

Protection of power system elements such as transmission lines, generators, etc., often requires accurate measurement of three-phase voltage to provide reliable fault detection and breaker operations to minimize power system disruptions. Incorrectly measuring one or more of the three-phase voltages by a protective relay may result in erroneous trips (breaker operations) and/or clearing more of the power system than desired. A common failure that causes incorrect voltage measurement is when one or more fuses protecting the three-phase voltage transformer (vt) secondary circuit blow. Protective relays connected to that secondary circuit would measure zero voltage if the secondary phases are isolated (only phase-to-ground load connections) or some non-zero coupled value if there are phase-to-phase connections in the secondary circuit. Conditions, other than blown fuses, may also occur where one or more phase voltages are unintentionally removed from the protective relay. Operating in this state of abnormal secondary voltage is referred to as "loss-of-voltage" or LOV in this report. Industry documentation may refer to LOV as loss-of-potential (LOP), or fuse failure. LOV alarming and prompt voltage restoration is the best practice. Some control of voltage dependent measuring units or relay system logic is generally required during the LOV state.

This report reviews typical LOV protection schemes as applied to line protection and points out potential application problems based on the system, control choices made, scheme or potential circuit redundancy, etc. Also, considerations for future logic implementations to improve system reliability during the LOV state are discussed. This report can be used as a resource for the protection engineer to understand LOV application and select the most appropriate LOV control option that produces the least detrimental effect to the power system. LOV applications discussed in this report apply specifically to line protection applications and may not be applicable to other apparatus protection.

2.0 LOV Effects on Protection Measuring Units

2.1 Impedance and Distance Units

Distance relays having self-polarized offset characteristics encompassing the zero impedance point of the R/X diagram, sound phase polarization or voltage memory polarization may misoperate if one or more voltage inputs are removed.

Distance relays are designed to respond to current, voltage, and the phase angle between the current and voltage. These quantities are used to compute the impedance seen by the relay. Distance relays compare the quantities (ZI – V) and V_P, where V_P is a polarizing voltage. There are many choices for the polarizing quantity.

When the polarizing voltage selected is the same as V, then the relay is said to be "self polarized". Thus, the quantity ($ZI_{BC} – V_{BC}$) would be compared to V_{BC} for a self-polarized distance element looking at phase BC quantities. This type of mho characteristic has no expansion characteristic and is shown in Figure 1.

The apparent impedance measured by the self-polarized mho is computed with the following formula (for the BC element, similar equations apply to the AB and CA elements).

$$Z_{BC} = V_{BC}/I_{BC}$$

From this equation you can see that the impedance measured by the element is directly proportional to the voltage, V_{BC}. Under normal conditions the voltage V_{BC} is 1.73 times larger in magnitude than the phase voltages V_B or V_C and 30° ahead of V_B as shown in Figure 2. If one of those potentials is lost the magnitude of Z_{BC} and its phase angle will change. Assuming system phase voltages are balanced and the C-phase voltage fuse blows, the C-phase voltage input to the relay will be zero ($V_C = 0$). Now, the numerator of our equation will be 1.73 times smaller in magnitude and shifted -30° in phase.

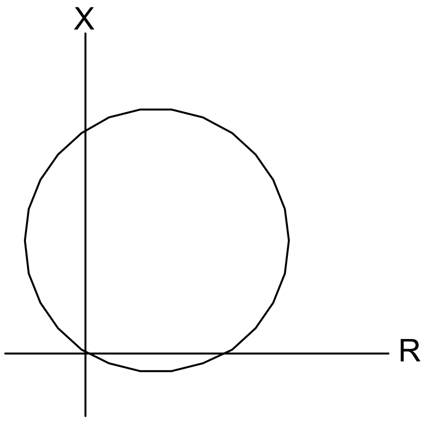


Figure 1. Self-polarized Mho Characteristics

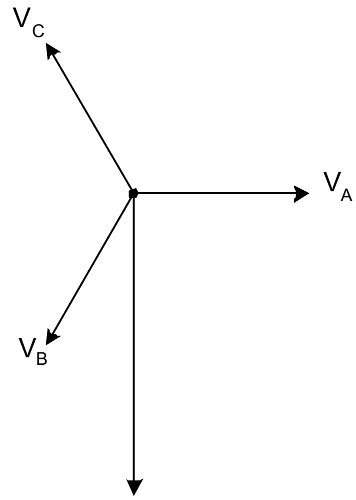


Figure 2. $V_{BC} = V_B - V_C$

The Figure 3 shows the mho characteristic plotted on the R-X diagram. Two points on the circle are shown, the impedance at the maximum torque angle (MTA) and the impedance at MTA - 30°.

Figure 4 shows two points that correspond to the apparent impedance measured by the BC distance element for the following two conditions.

Point **A:** $Z_{BC} = 13.4e^{j75°}$ calculated from $V_B = 67e^{-j120°}$, $V_C = 67e^{j120°}$, $I_B = 5.0e^{j165°}$, and $I_C = 5.0e^{j45°}$.

Point **B:** $Z_{BC} = 7.7e^{j45°}$ calculated from $V_B = 67e^{-j120°}$, V_C = zero, $I_B = 5.0e^{j165°}$, and $I_C = 5.0e^{j45°}$.

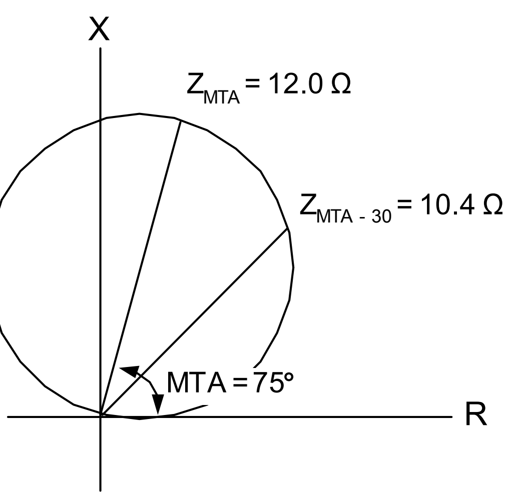


Figure 3. Boundary Impedance at MTA and MTA- 30^0

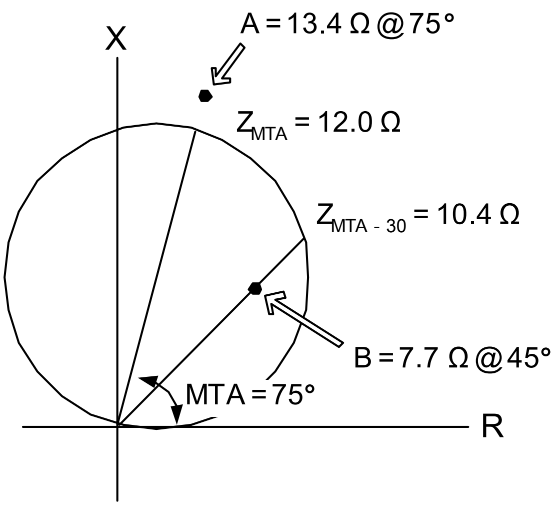


Figure 4. Effect of Impedance Measurement During LOV State

From this R-X plot it can be seen that the impedance measured by the BC distance element has moved from outside the characteristic to inside upon losing the C-phase voltage.

Similar analysis will show that sound phase polarization may also misoperate for LOV conditions. Memory polarization is applied where there is a loss of the polarizing voltage due to a close-in fault. The relay remembers the prefault voltage and uses it to polarize for a period of time sufficient for the distance unit to operate. Under an LOV condition the memory voltage will be lost and operation will occur similar to the case described above.

It is therefore reasonable to conclude that all impedance-measuring units may be adversely affected by LOV conditions and will require some form of supervision to prevent their operation. This is covered in more detail in clause 7.4.1

2.2 Directional Units

A directional unit determines the direction of current flow in an ac circuit. It is used to supervise a fault-sensing unit, such as an overcurrent relay, and allows tripping only in the desired direction. It may do this by comparing the angular relationship between the current in the protected circuit and an independent voltage source. The current (I_{OP}) of a protected circuit can vary significantly for various fault types. Therefore in order to establish directionality, an independent voltage (V_{POL}) may be used as a reference or polarizing quantity. This reference voltage should be available during system fault conditions for proper operation.

There are a number of directional units that are generally available. Traditional units are referred to as 30°, 60°, and 0° units. The 30° unit is used for phase fault directional sensing and the 60° and 0° units are used for ground fault directional sensing. For the 30° unit, maximum operating torque occurs when the current (Iop) flow from polarity to non-polarity of the current coil leads the voltage (V_{POL}) drop from polarity to non-polarity of the voltage coil by 30°. The 60° and 0° units are defined similarly. For all units, the minimum current pickup value occurs at the maximum torque line. Also, as this current lags or leads the maximum torque line position, more current is required (for the same V_{POL} quantity) in order to achieve the same torque value. A number of variations exist with microprocessor relays, but they all depend on accurately measuring current and voltage.

To help understand the effect that a loss of voltage condition will have on a phase directional unit, consider an A-phase 30° directional unit using a 90° - 60° connection as shown in Figure 5. In this example $I_{OP} = I_A$ and $V_{POL} = V_{BC}$. They are 90° apart and I_A is at maximum torque where it lags its unit power factor direction by 60°. As can be determined from the figure, if one or both of the phase B and Phase C voltages are lost, the maximum torque line will be shifted or become undefined accordingly. When this occurs, the directional unit will not provide proper directional supervision and may contribute to a misoperation.

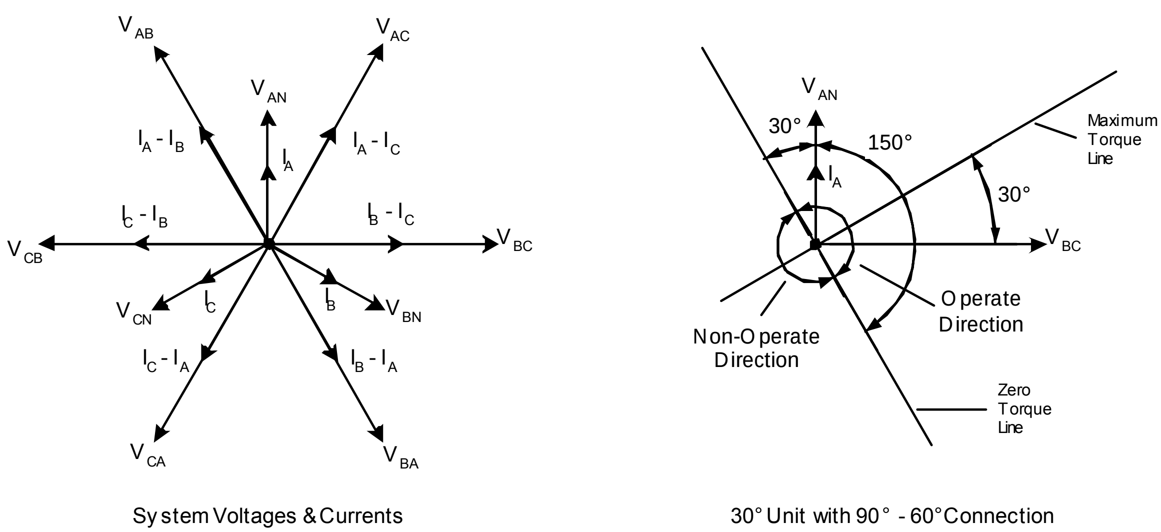


Figure 5. Phase Directional Unit Operating Characteristics

Ground fault directional units may use zero sequence voltage or negative sequence voltage as a polarizing quantity. To aid in understanding the effect that a loss of voltage condition will have on a ground directional unit, consider a 60° directional unit using 3Io and 3Vo sequence quantities for an A-phase to ground fault as shown in Figure 6. In this example $I_{OP} = 3I_0$ and $V_{POL} = -3V_0$. In this application, if one or two phase voltages are lost, an improper zero sequence voltage will result and the unit will be prone to misoperation if subjected to an unbalance or ground fault condition. If all three-phase voltages are lost, a polarizing voltage will not be created during a ground fault condition. In this case, the directional unit will not provide proper directional supervision and may contribute to a misoperation.

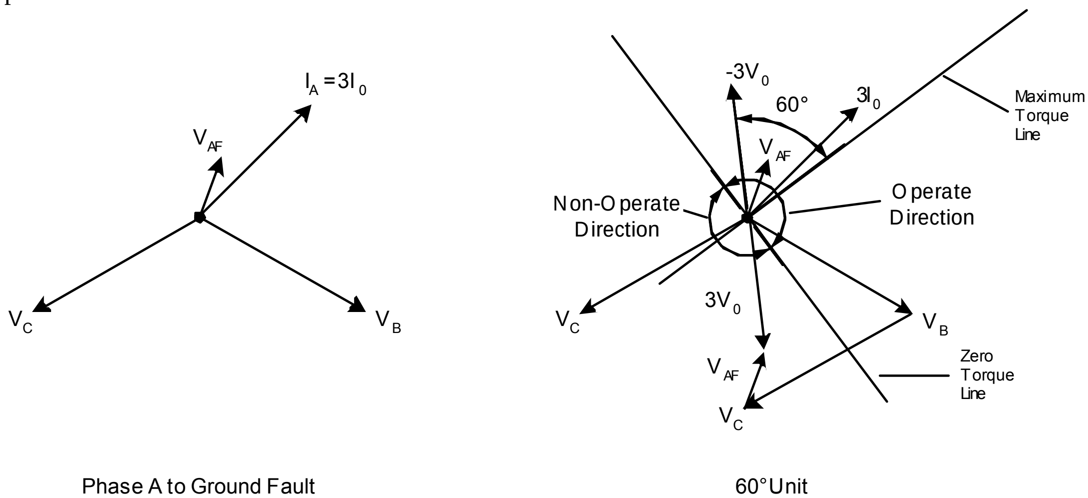


Figure 6. Ground Directional Unit Operating Characteristics

2.3 Other Measuring Units

2.3.1 Undervoltage

Undervoltage applications may be adversely affected by an LOV condition. Attempts should be made to differentiate between system undervoltage conditions to which the application is intended to respond and the complete loss of voltage as with a blown vt secondary fuse.

For example, undervoltage load shedding (UVLS) schemes are intended to protect against total system collapse. They should only operate when the local voltage is depressed and not operate when the voltage is completely zero. The UVLS scheme should distinguish between zero voltage (station dead) and depressed voltage (system stressed). Additionally, UVLS schemes should operate only when all three phase voltages are depressed. Therefore, the loss of one, two, or even three fuses should not result in false operation of a UVLS installation.

2.3.2 Frequency

Generally, frequency is measured from one phase. A loss of voltage on that phase could result in incorrect operation. Most modern frequency relays, however, have a low voltage trip block function. Furthermore, when the phase quantity used for frequency measurement is unavailable or present in insufficient magnitude an alternate quantity may be used for the frequency calculation.

2.3.3 Reclosing

Automatic reclosing usually requires synchronization or comparison of voltage on each side of the open line circuit breaker. These comparisons are often accomplished by comparing the voltage from one phase vt on each side of the open breaker. If an LOV condition exists on either vt reclosing may operate incorrectly and prevent automatic system restoration, cause a line outage, or possibly cause circuit breaker damage. Some possible scenarios are:

- Hot bus - dead line check: If the LOV occurs on the line side vt that is energized, the breaker will attempt to reclose without synchronizing when there is a voltage present on each side of the circuit breaker. The breaker will be stressed based on the voltage across the open breaker contacts at the time of closing.
- Hot line - dead bus check: If the LOV occurs on the bus side vt that is energized, the breaker will attempt to reclose without synchronizing when there is a voltage present on each side of the circuit breaker. The breaker will be stressed based on the voltage across the open breaker contacts at the time of closing.

- Sync-check: If the LOV occurs on either side of the open breaker, closing will not occur.

3.0 Technology

3.1 Electromechanical

Electromechanical relays other than the voltage unbalance relay (60) do not have the capability to internally detect an LOV condition. A typical solution to prevent misoperation due to LOV is to supervise tripping with a separate instantaneous overcurrent relay used as a fault detector. This fault detector has to be set below the minimum fault current to allow the relay to operate for all faults in the zone of protection. The effectiveness of this solution is limited if the minimum fault current is less than or close to the expected load current. Potential indicating lights are typically used with all technologies to alert field personnel of an LOV condition. Potential lights for all three phases are preferred as two phase-to-phase lights can give misleading indications.

3.2 Solid State

Some solid-state relay systems have an overcurrent fault detector available that is set above maximum load current to be used to supervise tripping and prevent misoperation during LOV conditions. Like the Electromechanical relays, minimum fault current and load current can limit the effectiveness of this scheme. Not all Solid State relays have the internal fault detector. An external overcurrent fault detector is needed to supervise tripping to prevent a misoperation for an LOV condition for those relays without an internal fault detector.

3.3 Microprocessor

Microprocessor relays have the processing capability to monitor voltage and current to detect an LOV condition, alarm and adaptively modify the operation of protection logic elements to minimize the impact on protection reliability. This technology also affords the opportunity to look beyond existing practices and selectively apply LOV based upon the application. Both LOV logic and adaptive modifications to the logic during LOV conditions are discussed in a later section.

4.0 ac Voltage Circuit Configurations

4.1 Voltage Transformers

Relays use measured voltages and currents to derive impedance, power flow, fault information, etc. The secondary voltage is typically the nominal three-phase voltage derived from the secondary circuit of vts connected in a four-wire grounded wye, a three-wire broken delta, or a three-wire open delta arrangement. The vts may or may not have dual protection-rated secondary circuits. Traditionally, the use of the phase-to-phase secondary circuit voltage is used for metering, recloser power, or auxiliary functions.

The open-delta connection allows the measurement of positive and negative sequence voltages but cannot measure zero sequence voltage. This limitation needs to be considered when applying LOV logic. The broken delta connection is used to measure zero sequence voltage for ground fault protection.

4.2 Primary Fusing

Each phase may be fused on the high-voltage power system side of the vt. An open-circuit in any phase’s primary will create LOV to the relaying system. Only the provision of two vts could prevent a total LOV occurrence. This solution is not a common practice today due to additional costs of the extra vt and the reliability issues with fuse application, or the existing station design may be of a vintage without this capability.

4.3 Single Secondary

Where the vt contains a single secondary winding the upstream secondary fuse creates a single point of failure of the voltage signal shared by all devices receiving this signal. Correct application and coordination of the downstream fused distribution for individual devices will minimize, but not completely eliminate, the probability of this type of failure. Because of the usual outdoor location of the upstream secondary fuse, selection of the fuse type is important in its ability to withstand the environment without deterioration, which would eventually result in failure. Even in the case of dual directional relays, the two relays may share a single primary or secondary winding or common fuse.

In this case both relays may simultaneously lose correct operation of their primary directional and impedance functions leaving the line unprotected.

4.4 Dual Secondaries

Ideally the vt selected for the application of dual directional relays or relay systems will have two identical protection-rated secondary windings, each independently fused. An example is shown in Figure 7 (a). This type of design, with proper downstream fusing, will further reduce the possibility of failure to the primary fuse circuit. This redundancy will limit the impact to the protection system of any short-circuit or open-circuit in the secondary ac circuit. Also, with modern relaying it is possible for dual relays to share their state and for each to make a better-informed choice of action based on the status of the other.

4.5 Molded Case Circuit Breakers (MCCB)

Gang operated MCCBs will interrupt all three-phase voltages for a fault in a secondary voltage circuit. Under heavy load conditions interruption by MCCBs may be interpreted by the relay to be a close-in three-phase fault. MCCB auxiliary contacts can be used as inputs to the relays to prevent a relay misoperation of this type, but they need to operate very fast to insure correct blocking operation. The advantage of individual phase fuses over MCCB's is that generally only one fuse will blow for a single-phase fault on the secondary circuit.

5.0 Application Considerations

Each application where voltage is required for protection should be considered unique, and appropriate decisions about the application must be made. At a minimum the following should be considered:

- What are the consequences of no LOV protection?
- What is the probability of an incorrect operation as a result?
- How will the system be affected?
- What is the potential size and cost of any outage if LOV protection is not applied?
- What are the consequences if LOV logic is implemented and incorrectly prevents tripping of one or more circuit breakers?
- Is there backup tripping available?
- Can equipment be damaged?
- What are the limitations of the LOV protection (e.g. will it operate fast enough to prevent a misoperation) and how does that impact other protection functions?
- How is the system affected and what is the potential size and cost of the outage for an incorrect block of tripping?

The utility industry contains a wide range of applications using electromechanical, solid-state, and microprocessor based relay systems, each of which providing different degrees of LOV protection. Therefore, each application will not have the same solution.

Modern microprocessor protection LOV logic will generally be different for different fault types. The logic that uses negative or zero sequence components to reliably distinguish between a single or two-phase fault and one or two blown fuses will be different from logic that must use positive sequence or phase quantities to distinguish between a three-phase fault and the loss of the three phase voltages. It is generally assumed that an unbalanced fault is much more likely to occur than a balanced three-phase fault and that an unbalanced LOV condition is much more likely to occur than a balanced (three-phase) LOV condition. Therefore, the protection engineer may consider applying unbalanced and balanced LOV separately. However, other problems may arise such as an application that uses an LOV block and delays tripping for a three-phase fault. The application might provide secure operation during LOV for unbalanced faults but allow an incorrect trip during the three-phase LOV.

5.1 Balanced and Unbalanced LOV

The following data show the relative percent of fault types that occur on transmission lines. This supports the idea to apply separate logic to distinguish between one or two phase LOV conditions and unbalanced faults and between three phase LOV and three-phase faults.

Table 1. Percent Variation of Fault Types on Transmission Lines

Reference	Percent Fault Type			
	Balanced	Unbalanced		
	3Φ	ΦΦ	ΦΦG	ΦG
Westinghouse T & D Reference Book	5	15	10	70
TVA Data (1973-1978)	6	3	17	74
TVA Data (1979-1981)	5	10	13	72
Average	**5**	**95**		

The majority of LOV conditions occurs on one phase and is the result of a blown fuse or perhaps an occasional open knife switch or a loose connection in the vt circuit. A small number of two-phase LOV conditions occur for such reasons as a failure of a component between two phases. Other LOV conditions are assumed to be three-phase and occur as a result of the voltage circuit being accidentally opened, failure of the vt or slow bus transfer schemes. Another form of three-phase LOV occurs when MCCBs are used to protect the control circuit instead of fuses. They are, however, usually provided with a contact that can be used for trip blocking. Another major contributor to three-phase LOV problems is the loss of the vt primary voltage source due to system switching operations resulting from fault clearing or system reconfiguration operations.

The Working Group was unable to find quantifiable utility data that would categorize loss of voltage occurrences into number of phases lost or the type of faults. A survey based on individual experience indicated that more than 80% of LOV occurrences are unbalanced. Accepted utility experience also indicated that 95% of all faults are unbalanced, thus producing zero and negative sequence quantities.

5.2 Application Analysis

Assuming that 80% of LOV conditions are unbalanced and that 95% of system faults are unbalanced, LOV logic that utilizes sequence components to distinguish between LOV and fault types is highly recommended. The proper utilization of sequence quantities has proven to be a reliable method for determining these unbalanced LOV conditions. Since only about 5% of the system faults are three-phase faults and that system conditions may be interpreted falsely as three-phase LOV conditions, three-phase LOV protection should be cautiously considered. The utilization of phase or positive sequence quantities to determine three-phase LOV conditions is necessary, but it responds to balanced system operating conditions producing low or no voltages. This is less reliable than the use of negative and zero sequence quantities to distinguish between unbalanced LOV conditions and unbalanced faults. Given the advantage of using sequence quantities and the low probabilities of three-phase LOV and faults, the application of balanced and unbalanced LOV protection should be considered separately.

5.3 Vt Location

In addition to reclosing as discussed in Section 2.3.3, the location of the vt may impact protection functions. Relays connected to line-side vts must be evaluated differently from those connected to bus-side vts. An LOV condition on a line-side vt would affect the operation of the connected relay systems operating the line breaker, whereas an LOV condition on a bus vt would affect the operation of all the connected line relays and associated circuit breakers connected to that bus. Blocking all tripping of line breakers connected to a common bus vt may be an unacceptable risk for an LOV condition.

6.0 Application Reliability

The response to an LOV in a transmission line application will vary depending on several factors that include: the number, type, and technology of systems protecting the line; the design of the secondary voltage circuit; and the available options provided by each relay system.

6.1 Protection

Ideally the line protection would include at least two relay systems measuring the system voltage from two separately fused voltage circuits. In reality there may only be one system and one voltage circuit. Therefore, for simplicity, the following definitions are provided to reduce the complexity of analysis.

6.2 Single Fused Circuit

A single fused circuit includes single or redundant protection systems supplied from a common fused voltage circuit. Failure of the single fuse can impact multiple systems, thus is the least reliable system.

6.3 Dual Fused Circuits

A dual fused circuit includes single or redundant protection systems supplied from a separately fused voltage circuit as shown in Figure 7. Failure of a single fuse would not necessarily impact multiple systems, thus is a more reliable system.

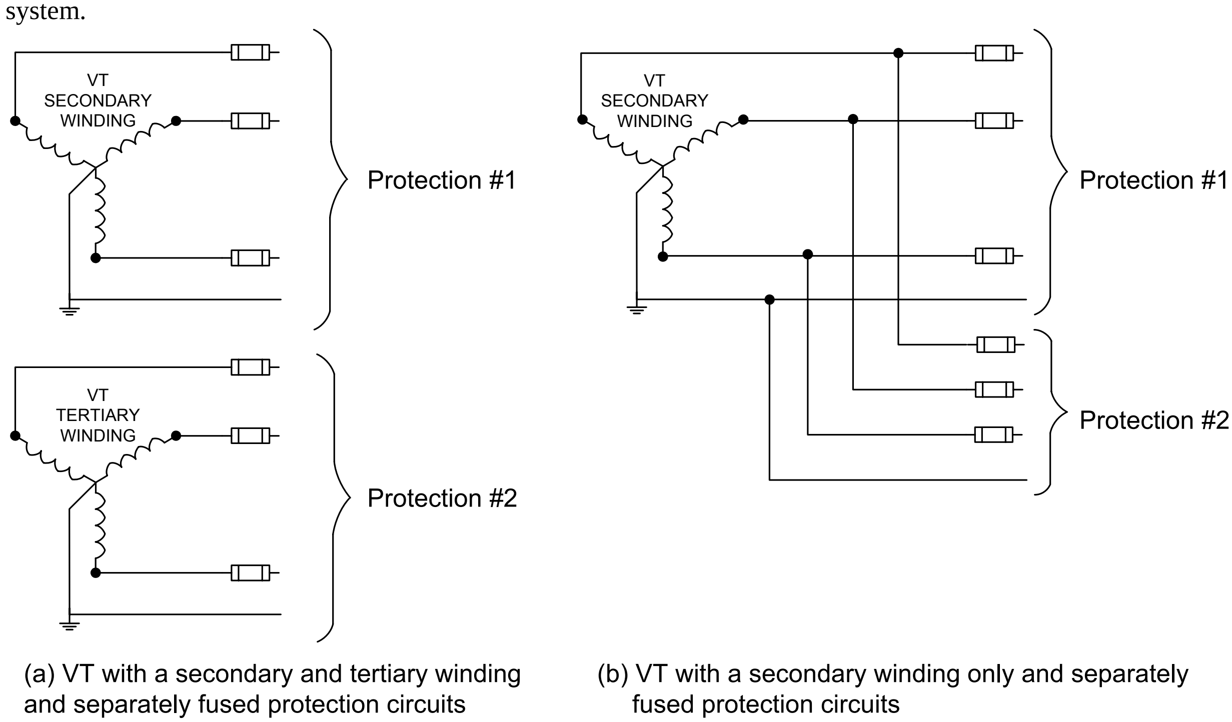


Figure 7. Dual Vt Secondary Fused Circuits

6.4 LOV Control Options

Available LOV control options depend on the relay system technology and specific options offered by the relay manufacturer. Different options can be combined, such as alarming and distance element blocking, to achieve the desired results. All options have benefits and drawbacks. A utility may choose not to use any option and the relay technology may not allow any option. The following summarizes LOV options.

6.4.1 Alarm Only

For this option, the relay alarms but no other action is taken. All relay measuring units operate per their design. Although this option is better than doing nothing, it will not prevent a false trip for an LOV.

6.4.2 Disable Distance Elements

For this option, all impedance-measuring units are disabled. This option may prevent a false trip but may not allow local fault clearing during an LOV condition.

6.43 Block All Tripping (Impedance and Overcurrent)

For this option all tripping is blocked. This option will not allow local fault clearing during an LOV condition.

6.4.4 Disable Voltage Polarized Directional Overcurrent Elements

For this option, voltage polarized directional elements that supervise an overcurrent element are disabled. The largest advantage is that the relay is not prevented from operating for a fault due to the loss of directionality control during an LOV condition. Several possibilities exist for this option.

- Enable Directional Instantaneous Elements

  Directional instantaneous overcurrent units are allowed to operate non-directional. All other overcurrent functions are disabled. In some cases, this function may be set non-directional, in which case the relay operation is unaffected during an LOV condition.
- Enable Directional Time Overcurrent Element

  Directional time-overcurrent units are allowed to operate non-directional. All other overcurrent functions are disabled. In some cases, this function may be set non-directional, in which case the relay operation is unaffected during an LOV condition.
- Enable Directional Pilot Ground Element

  The pilot forward directional overcurrent ground unit is allowed to operate non-directional. All other overcurrent functions are disabled.

6.4.5 Enable Non-Directional Phase Overcurrent Element

Phase overcurrent units might not be used in a typical step-distance application. This option uses a combination of a special non-directional phase overcurrent element and an LOV condition to enable a time delayed action. This scheme is typically used to provide phase fault protection while the distance elements are disabled during an LOV condition. The LOV phase overcurrent element should be set below the minimum expected fault level and should be set above expected load levels. The overcurrent element trip is time-delayed to provide coordination with remote terminal tripping. The largest advantage of this scheme is that it will provide fault clearing for a phase fault during an LOV condition. This option may not be settable where low fault current magnitudes are too close to load current levels. More discussion on this situation occurs in clause 7.1.2

6.4.6 Enable Current Polarized Directional Elements

For this option, zero sequence (residual) current units are polarized by an external source, such as a grounding transformer. The LOV indication is used to enable current polarization of normally voltage polarized zero sequence (residual) elements. The advantage is similar to disabling a voltage-polarized unit described above.

6.5 System Operation

Protection schemes are highly variable among utilities due to company protection practices, reclosing practices, system configuration, equipment usage, etc. Therefore, the implementation of an LOV scheme should be carefully considered. The protection engineer may develop a methodology to determine the best LOV control option for a specific application but should be cautious of employing only a particular scheme for all applications. Many factors will influence the final decision, such as the importance placed on high-speed fault clearing, tolerance to outages, etc. For example, the following factors are good reasons for not blocking the distance (21) functions or for modifying the directionality of the directional ground (67) functions:

- The possibility of the loss of two voltage windings
- The overriding need to trip dependably rather than securely
- The primary scheme is significantly faster than the backup scheme
- Stability concerns such that delayed clearing of faults is not tolerable

Appendix A provides a method of analysis and presents two key concepts: Some of the LOV control options are more desirable for certain fault scenarios; and the use of dual fused vt circuits for primary and secondary line protection lessens the chance of undesirable tripping.

7.0 Loss of ac Voltage Logic

7.1 Typical Schemes Applied to Modern Microprocessor Relays

The LOV logic in the relay is designed to detect voltage failure and automatically adjust the configuration of protection elements whose reliability would otherwise be compromised. A time-delayed alarm output is normally provided. There are three main aspects to consider regarding the failure of the vt supply: loss of one or two phase voltages, loss of all three phase voltages under load conditions and the absence of three phase voltages upon line energization. Following are simple logic diagrams that address these aspects of LOV protection as well as some additional considerations.

7.1.1 Loss of One or Two Phase Voltages

The LOV function within the relay operates on detection of zero sequence (residual) voltage without zero sequence current or detection of negative sequence voltage without negative sequence current. Simple detection logic is shown in Figure 8. Scheme (a) uses zero sequence quantities and scheme (b) uses negative sequence quantities. Either method detects the loss of one or two phase voltages. The currents will be very nearly balanced for normal load conditions and there will be no negative or zero sequence current. Stability of the LOV function is assured during system fault conditions by the presence of zero sequence and/or negative sequence voltages and currents. Also, LOV operation may be blocked when any phase current exceeds a set value, which is typically set above the maximum load current. Using negative sequence voltage without negative sequence current is not recommended for applications where a strong zero sequence ground source (delta-wye grounded transformer) is nearby and can affect the operation. This application is discussed in reference 10.

The threshold settings for zero and negative sequence current must be set above maximum expected unbalance current, and more sensitive than the current seen by the relay for remote faults under weak source conditions. Likewise, the zero and negative sequence voltage thresholds must be set above maximum system unbalance voltage, and below the voltage created by the complete loss of one phase voltage ($3V_0 = 3V_2 = V_{l\text{-}n}$), the complete loss of two phase voltages ($3V_0 = 3V_2 = V_{l\text{-}n}$), and the more remote possibility where one phase is coupled to another phase by a phase-to-phase secondary short that only causes one secondary phase fuse to open ($3V_0 = 3V_2 = 1.732 * V_{l\text{-}n}$). Note that these voltage thresholds are a function of the nominal secondary line-to-neutral voltage applied to the relay.

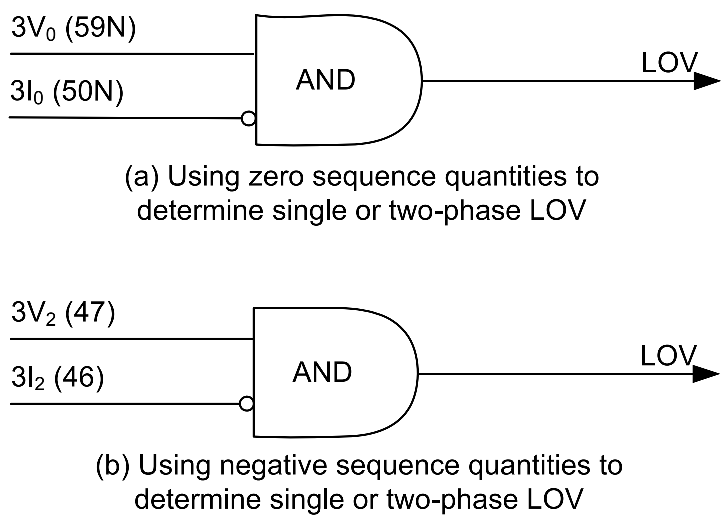
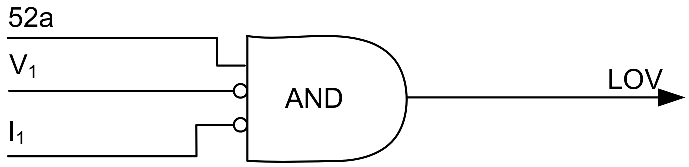


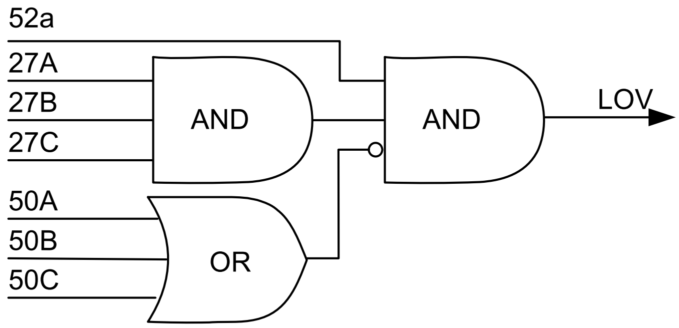
Figure 8. Basic LOV Logic to Detect LOV on One or Two Phases

7.1.2 Loss of All Three Phase Voltages Under Load Conditions

Under the loss of all three-phase voltages to the relay, there will be little or no zero or negative sequence quantities present to operate the LOV function described above. However, under such circumstances a collapse of the three phase voltages will occur. If this condition is detected without a corresponding increase in line current, which would be indicative of a system fault, then an LOV condition is assumed. Figure 9 shows two simplified schemes of detecting loss of all three phase voltages. Scheme (a) uses positive sequence quantities and scheme (b) uses phase quantities to detect a three-phase LOV condition. An overcurrent setting above maximum load and below minimum fault current is necessary for the positive sequence current, I_1, and the phase currents, 50A, 50B, and 50C. In cases where minimum fault current can be below maximum load, change detector logic as described in Section 7.1.4 may be utilized. The positive sequence voltage setting, V_1, and phase undervoltage settings, 27A, 27B, and 27C, must be set based on the nominal secondary line-to-neutral voltage applied to the relay. It should be noted that this logic would assert LOV for applications where line side potentials are used and the breaker is open. Therefore, the logic uses the breaker's 52a auxiliary contact, which indicates a closed breaker, to allow operation. There are other variations of the logic to prevent LOV assertion when line potential is removed by opening the line breaker.



(a) Using positive sequence quantities to determine three-phase LOV with closed breaker supervision



(b) Using phase quantities to determine three-phase LOV with closed breaker supervision

Figure 9. Basic LOV Logic to Detect LOV on Three Phases

7.1.3 Absence of Three Phase Voltages upon Line Energization

If a vt was inadvertently left isolated prior to line energization, incorrect operation of distance and other voltage dependent elements could result. Previously described logic detects a three-phase vt failure by the absence of all phase voltages with no corresponding change in current. Upon line energization there will, however, be a change in current as a result of load or line charging current and LOV cannot be detected. An alternative method of detecting three-phase vt failure is, therefore, required on line energization.

The absence of measured voltage on all three phases on line energization can be as a result of two conditions. The first is a three-phase PT failure and the second is a close-in three-phase fault. The first condition would require blocking of the distance and other voltage dependent functions and the second would require tripping. To differentiate between these two conditions an overcurrent level detector is used to prevent an LOV block from being issued if its current pickup is exceeded. This element should be set in excess of any non-fault based currents on line energization (load, line charging current, transformer inrush current if applicable) but below the level of current produced by a close-in three-phase fault. If the line is now closed where a three-phase vt failure is present, the overcurrent detector will not operate and an LOV block will be applied. Closing into a three-phase fault will result in operation of the overcurrent detector and prevent an LOV block being applied.

For those cases where line energization current may exceed minimum fault current, the accurate discrimination between a close into fault or close into an LOV condition cannot be made. Close into fault tripping must always be ensured for this condition and the LOV logic that blocks operation should be disabled for a very short period after breaker closing.

7.1.4 Change Detectors

Adequate LOV blocking requires the detection of LOV and inhibiting the operation of an impedance unit, for example, before the impedance unit can operate. There may, however, be a race between the voltage and current units detecting LOV and the operation of the impedance unit subjected to the LOV condition. Therefore, the impedance unit may need to be delayed. This is usually undesirable. Change detectors are often used to complement or replace the actual phase and sequence voltage and current measuring units to improve the speed of detecting an LOV condition. The changes in voltages and currents are detected by measuring the difference between the present instantaneous current or voltage sample and the sample collected one cycle before. For normal system operation the change will be zero or very small. For abrupt changes associated with faults the change may be detected with the first sample after the fault. Change detectors can operate in just a few milliseconds or less depending on the sampling rate. A discussion of change detectors is found in reference 10. For LOV conditions only changes in voltage are expected. For fault condition changes in both voltage and current are expected. Figure 10 illustrates how change detectors, ΔV_0 and ΔI_0, are used to enhance the logic of Figure 8(a). Change detectors alone can detect LOV conditions, but it is suggested that they are complemented with their corresponding undervoltage and overcurrent units.

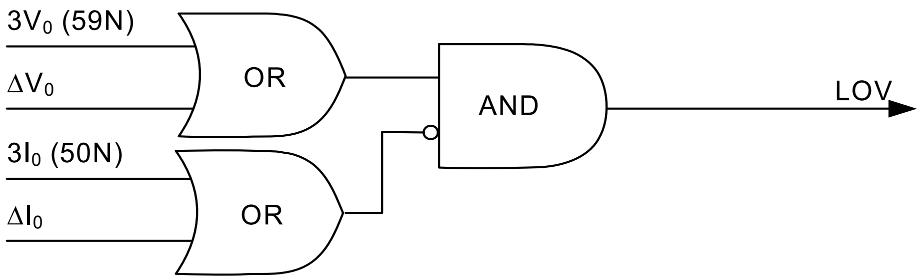


Figure 10. Using Change Detectors to Minimize Assertion Time

7.1.5 Latching LOV Logic

When the LOV condition is positively identified it is generally desirable to latch the LOV logic so that subsequent faults (changes in current) do not cause the logic to reset and allow an incorrect operation. Latching of LOV logic is commonly done 30 to 60 cycles after the initial LOV assertion. A typical latching scheme is shown in Figure 11. The latching logic is either automatically reset by the correction of the LOV condition (a sustained condition of no phase undervoltage) or manually through control input. The resetting voltage threshold must be less than the nominal secondary voltage applied to the relay, but greater than the undervoltage caused by one or two blown secondary fuses, including one fuse blown with two coupled phase voltages. The latter condition cannot be accomplished with individual phase voltages alone because all phases will have normal secondary voltage magnitude. With greater than 90% of nominal phase voltage magnitude on all three phases and less than 10% zero-sequence voltage ($V_0/V_{l\text{-}n\ nominal}$) is a good indication of voltage restoration and, therefore, may be used to reset the LOV logic. Alternatively, having greater than 70% of nominal positive sequence voltage may also be used for the resetting logic. One fuse blown with two coupled phases creates a positive sequence voltage, V_1, of 57.7% of nominal V_1 with balanced secondary voltage, and one fuse blown without phase coupling creates a positive sequence voltage, V_1, of 66.7% of nominal V_1. For added assurance, it is also prudent to make sure the ratio of zero-sequence to positive-sequence nominal voltage (V_0/V_1-nom) is less than 10%.

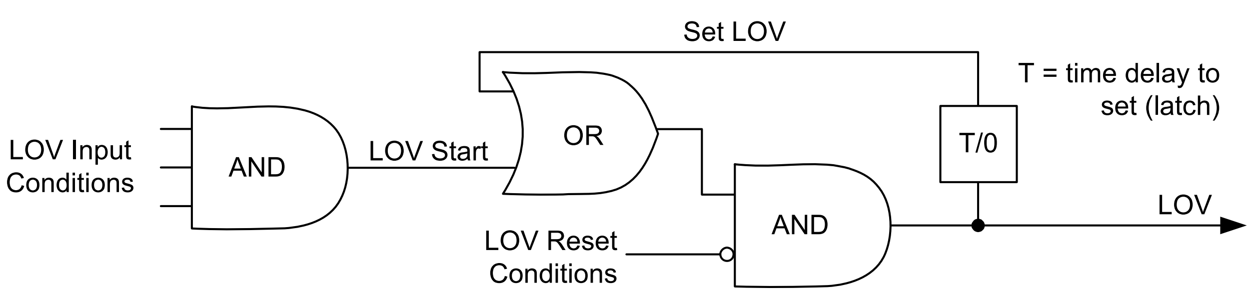


Figure 11. Typical LOV Latching Logic

7.1.6 Open Delta Connections

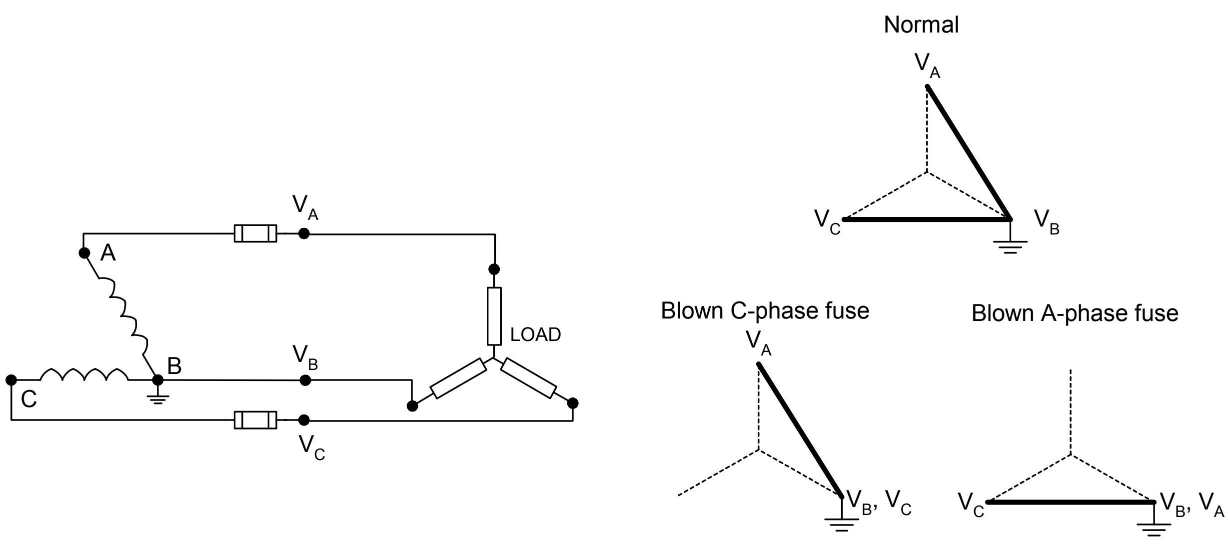
In open-delta applications it is possible to detect an LOV condition using the changes in positive- and negative-sequence voltages, while checking for simultaneous changes in the respective currents. The positive and negative sequence voltages may be calculated from V_{AB} and V_{BC} as:

$$V_1 = \frac{1}{3}\left(V_{AB} - a^2 \cdot V_{BC}\right),\ a = 1\angle 120°$$

$$V_2 = \frac{1}{3}\left(V_{AB} - a \cdot V_{BC}\right)$$

Typically the secondary connections have fuses in the A-phase and C-phase leads, while B-phase is grounded. When both V_{AB} and V_{BC} are normal, assuming 115V nominal, V_1 is 66.4V secondary, and V_2 is zero. If either fuse blows, both V_1 and V_2 become 38.3V secondary. This is 58% of the normal positive sequence voltage. If this is detected with no corresponding change in current, an LOV condition can be declared.

Should this occur, while the magnitude of the remaining phase-phase voltages will be correct, the phase angle of V_{CA} will be shifted by 60 degrees, either clockwise or counterclockwise depending on which fuse is blown. For example, if the A-phase fuse blows, V_{AB} goes to zero, V_{BC} is still correct at $115\angle{-90°}$, while V_{CA} is $115\angle{+90°}$ (where the normal angle of V_{CA} is +150 degrees). Similarly, if the C-phase fuse blows, V_{BC} goes to zero, V_{AB} is still correct at $115\angle{+30°}$, while V_{CA} is $115\angle{+210°}$ (where the normal angle of V_{CA} is +150 degrees). Therefore, any protective elements that are polarized by phase-phase voltage can obviously not be depended on to measure properly and should be disabled.



(a) Open Delta Fused Circuit

(b) Circuit Voltages After Fuse Failure

Figure 12. Open Delta Connection

7.1.7 Broken Delta Connections

For broken-delta vt arrangements, the secondary connections have all three phase windings in series, with the two leads at the ends connected to the polarizing coils of directional ground relays. Some utilities fuse one lead, while some install a slug. The voltage is normally zero for balance three-phase voltage. During an unbalanced system fault, zero sequence voltage will develop across the polarizing coils of the connected relays. If the fuse were blown, no zero sequence voltage would be applied to the polarizing coils of the connected relays. The result could be failure to trip for a line fault. There does not appear to be any method of monitoring this condition, except for periodic field checks of the condition of the wiring from the vts to the relays, which should include a “phantom” ground test. Another condition that can occur is the shorting or partial shorting of a secondary winding. This results in a standing false polarizing voltage to the relays and can lead to a misoperation or non-operation.

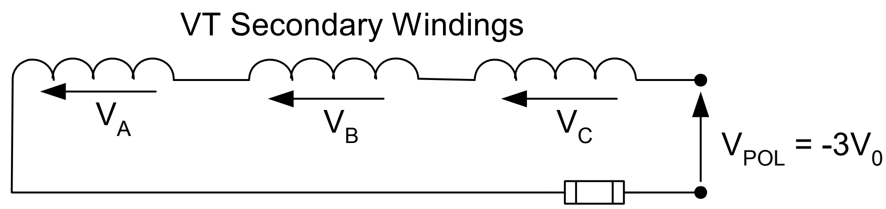


Figure 13. Broken Delta Connection

7.2 Application of LOV Logic

LOV logic should only be enabled during a live line condition as indicated by the relay logic or breaker position to prevent operation under dead system conditions, i.e. where no voltage will be present. The relay should respond as follows on occurrence of any LOV condition:

- LOV alarm indication
- When blocking the distance protection or other measuring elements it is important that LOV logic can assert faster than the measuring elements can operate.
- When disabling the directional control of selected overcurrent elements the current pick-up setting of these elements must be reviewed and possibly reset to prevent tripping under normal operating conditions.

7.3 Reclose Supervision LOV Logic

As described in Section 2.3.3, synchrocheck and voltage condition supervision of line breaker automatic reclosing relies on valid voltage measurements to correctly close the breaker and reconnect power system elements. Loss of voltage conditions caused by primary or secondary blown fuses, bad connections, or improper wiring polarity can lead to inadvertent breaker closing, prevention of breaker closing, or closing the breaker with an undesirable voltage across the breaker. In the simplest form, synchro-check and voltage-check relays are connected to single-phase line and bus potentials as shown in Figure 14.

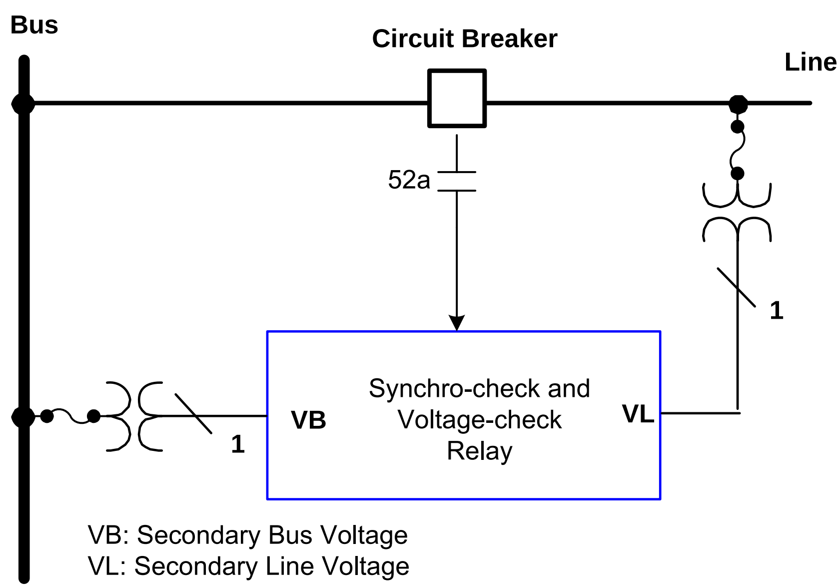


Figure 14. Synchro-check and Voltage Check Relay Connections

7.3.1 Synchro-check Relay LOV Alarm Logic

Synchro-check supervision requires that proper and adequate voltage are measured on both sides of the breaker to assure that the synchro-check relay can measure the voltage angle between line and bus side voltages. Furthermore, the voltage angle of the secondary voltage measured by the relay must accurately reflect the voltage angle between the primary bus and line potentials. An incorrect phase connection or incorrect polarity connection can cause the synchro-check relay to permit breaker closing when the primary voltage angle is excessive, causing considerable shock to the system.

Likewise, voltage-check relay Hot Bus/Dead Line, Hot Line/Dead Bus, and Dead Bus/Dead Line voltage condition logic requires that the secondary voltages measured by the relay accurately reflect the actual primary voltage on each side of the open line breaker. Incorrect detection of dead bus or line voltage could permit the breaker to close when both sides of the breaker are energized but out of phase, permitting the breaker to close at an excessive phase angle or even when the two systems are out of synchronism.

In general, the line breaker is closed under normal operation. When the breaker is closed, the primary voltages on each side of the breaker are in phase and have the same magnitude. Secondary voltage measurements and simple logic checks can be made while the breaker is closed to assure the integrity of the voltage applied for synchro-check and voltage-check logic. For example, with the breaker closed and the line energized, the synchro-check relay's output element, device 25, should be asserted because the primary voltages on each side of the breaker are in phase with each other. Therefore, simple logic can be applied as shown in Figure 15 to alarm if the breaker is closed and the 25 element is not asserted.

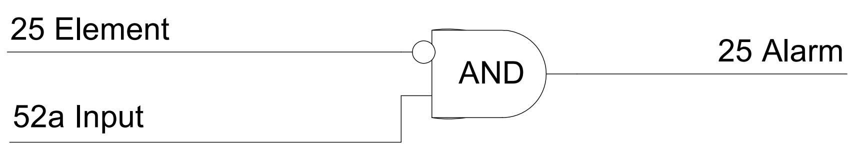


Figure 15. 25 Alarm Logic

A short pickup and dropout time delay can be added to the alarm output to prevent spurious alarms during power system faults and breaker open-close transitions.

7.3.2 Voltage-check Relay LOV Alarm Logic

The logic above may also verify that the voltage magnitudes are adequate for voltage-check relay logic operation. However, if necessary, separate voltage magnitude logic can be programmed to alarm if either bus or line voltage appears dead when the breaker is closed. This logic is shown in Figure 16.

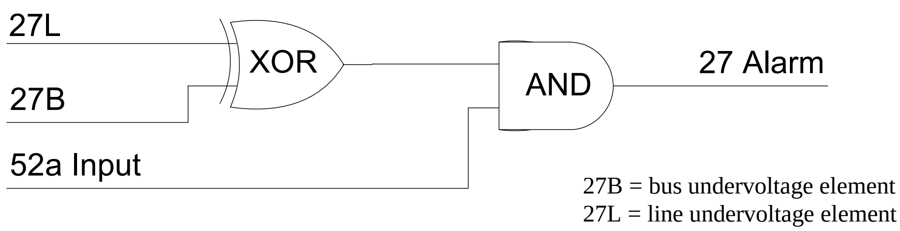


Figure 16. 27 Alarm Logic

A short pickup and dropout time delay can be added to the alarm output to prevent spurious alarms during power system faults and breaker open-close transitions.

7.3.3 Sync-check Relay LOV Reclose Block Logic

When three-phase line voltage is available, residual line voltage can be used to block sync-check reclosing. Reasons to use the scheme might include avoiding reclosing into a multiphase fault. Consider a terminal using B-phase for the sync-check voltage. An A-C phase line fault occurs and the remote terminal clears only phases A and C with independent pole tripping. The breaker failure scheme does not operate. This leaves B-phase energized. All three-phases clear at the local terminal. Since the B-phase line voltage stays hot from the remote terminal, the local terminal will sync-check reclose into a multiphase fault. For short sync-check time delays faster than the pole discordance timer, the result could be unwanted high-speed reclosing.

If this scheme is in-service, and voltage is lost from one or two line vts, a residual voltage will be measured and sync-check reclosing will be defeated until condition resolution.

A modification of this scheme uses two line vts and a single-phase voltage relay connected phase-to-phase. The sync-check reclose is blocked unless both phases are hot, thus effectively accomplishing the same purpose. For an LOV condition of either vt, sync-check reclosing is blocked.

7.3.4 Three-Phase Voltage LOV Alarm Logic

Where the synchro-check or voltage-check logic is performed in relays that incorporate all three phase voltages from the line and/or bus potentials, another check can be made to make sure that all three voltages are available on one or both sides of the breaker before reclosing the breaker. Relay connections with all three bus and line potentials are shown in Figure 17.

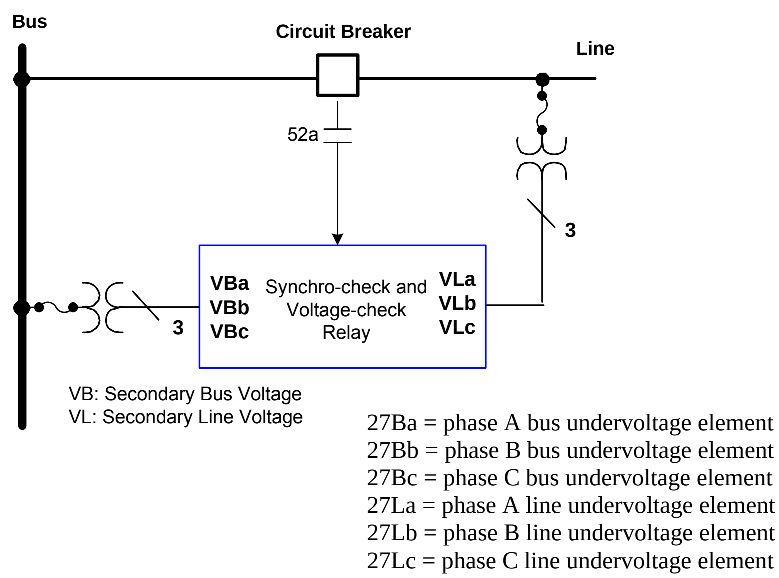


Figure 17. Synchro-check and Voltage Check Relay Connections

With all three phase voltages connected to the relay, logic as shown in Figure 18 can be applied to alarm if all three phase voltages are not present on each side of the breaker while the breaker is closed.

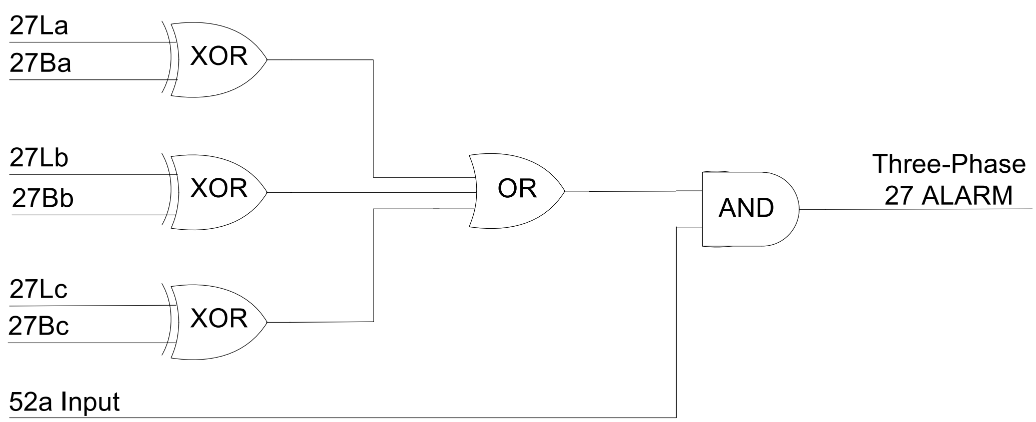


Figure 18. Three-phase 27 Alarm Logic

A short pickup and dropout time delay can be added to the alarm output to prevent spurious alarms during power system faults and breaker open-close transitions.

7.4 Schemes provided by Solid State and Electromechanical Relays

7.4.1 Basic overcurrent supervision of impedance units.

For electromechanical and solid-state relays, the calculation of sequence quantities cannot be practically implemented. So in most cases, LOV logic is provided by the use of a supervising overcurrent relay or fault detector, which could be implemented in the solid-state relay with a level detector. This method also applies to electromechanical relays requiring LOV supervision. The overcurrent relay contacts are in series with the distance relay contacts, so that the distance relay cannot trip unless the overcurrent relay is picked up. If an LOV condition occurs, the distance relay may operate but will not be allowed to trip if the overcurrent relay is not picked up. The overcurrent relay pickup must be set above maximum expected load but below minimum expected fault current. This method is usually applicable to ring, breaker-and-a-half, and double breaker/double bus stations where line-side potential is used. A disadvantage to this scheme is that the overcurrent element must pick up before tripping for line faults can be initiated, introducing an additional failure mode for line protection.

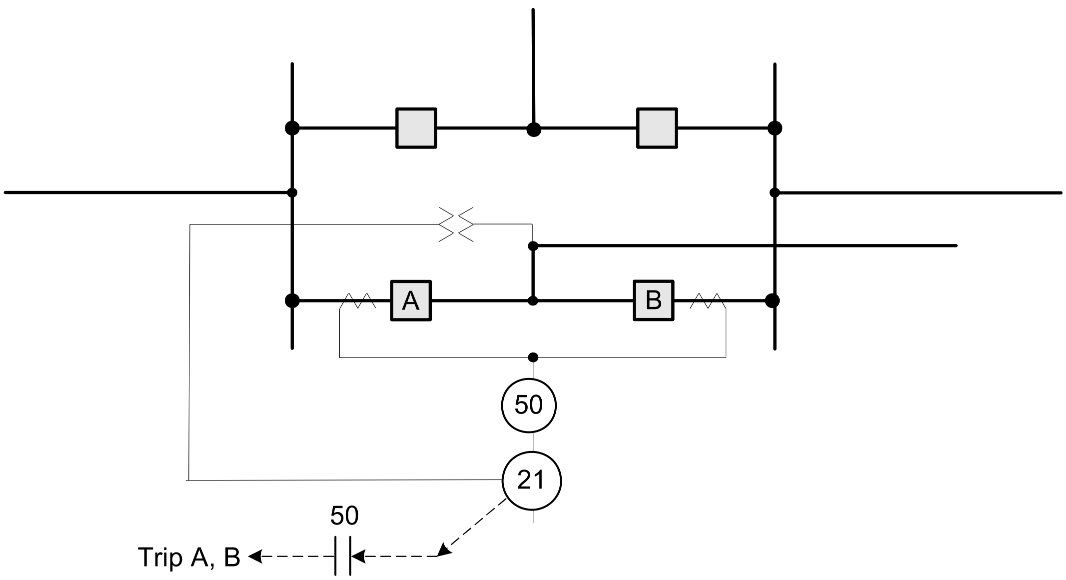


Figure 19. Supervision of Distance Relay (21) by overcurrent Unit (50)

7.4.2 Enhanced Method

An enhancement to this scheme is illustrated in the following figure. A 0.5-ohm resistor is connected between each vt and the paralleling point. If a fault should occur in one of the vts or sources, the voltage at the paralleling point will not drop below one-half normal due to the voltage dividing effect on the two resistors. Protective relays are provided to detect such a fault and to open the proper switch, which removes the faulted vt. The overcurrent relays are connected to operate for faults external to the panel. The proper switch is then selected by one of the power directional relays. The respective bus differential relays will also trip the switch connected to the faulted bus.

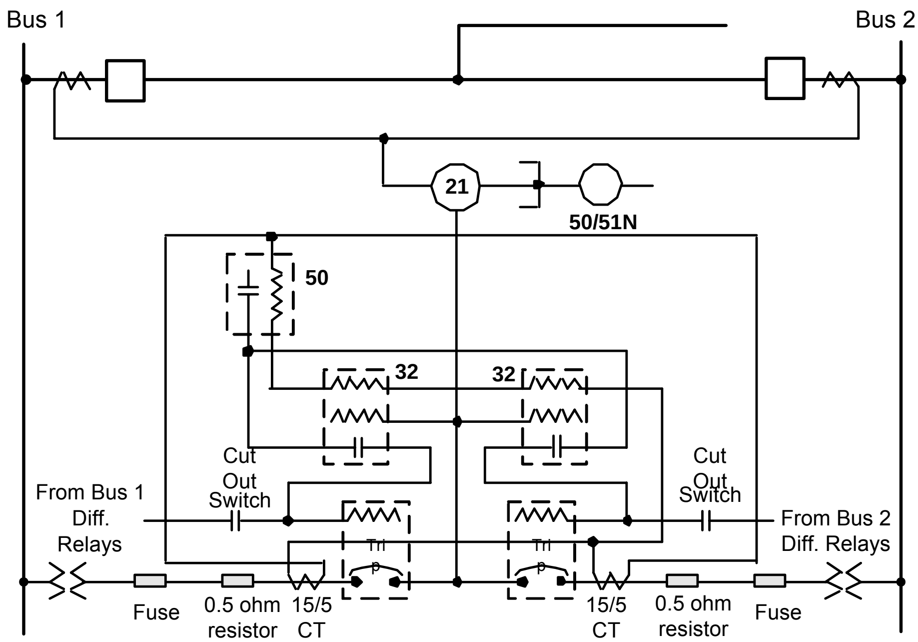


Figure 20. Enhanced Method

7.4.3 Manual Trip Cutout

A means of providing LOV logic manually is a simple trip-cutout switch. This switch disables tripping for the line distance relays while the relaying potential source is swapped from one bus section to another. Directional ground overcurrent relays for the lines can be left in-service, since they do not use potential for restraint (only for polarizing). This method is only applicable to station configurations that have multiple bus ties that are not all open simultaneously and only is useful for planned switching that deenergizes bus vts, not for LOV due to bus clearing from faults.

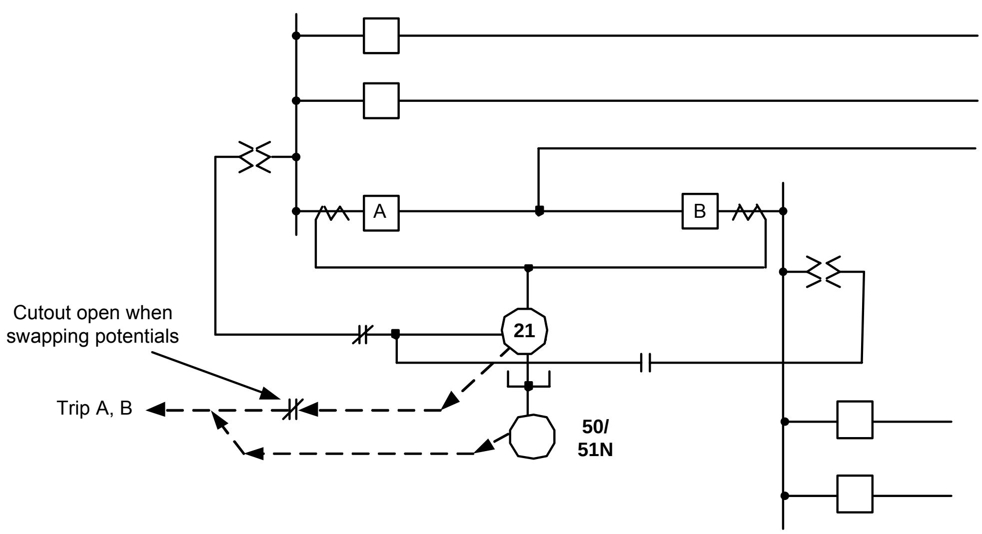


Figure 21. Manual Trip Cutout

7.4.4 Bus Voltage Transformers

In stations where one or more lines are terminated in double breaker bays, but where line-side potential is not installed in favor of bus potential, the situation becomes complicated. For bus faults, the potential source for multiple lines can be lost. In these situations, some utilities have applied contacts from the bus differential auxiliary relay to supervise tripping of the distance elements.

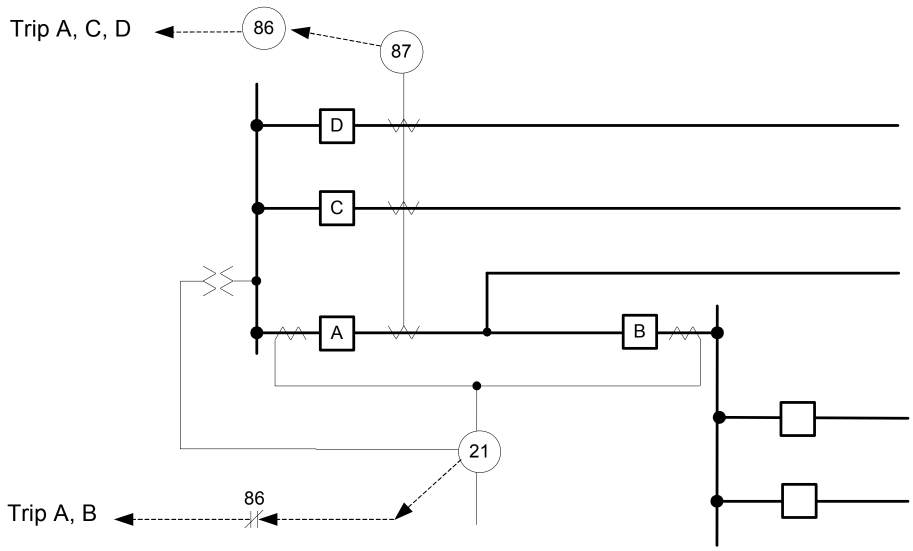


Figure 22. Bus Differential Supervision of Distance Relays

8.0 Operational Configurations That Cause LOV

8.1 Transmission Switchyards

The following conditions apply to conventional switchyards with multiple high-voltage lines tied to one or more buses, which can serve zero to several transformer banks.

8.1.1 Deenergizing the bus to which the vts are connected

The substation high voltage bus may be deenergized for a number of reasons. Some of these are:

- Bus outage for maintenance (manual switching) (Figure 23)
- Bus fault with subsequent clearing by protective relays, either local or remote (Figure 23)
- Stuck line breaker, failing to trip on a line fault, resulting in breaker failure relays operating to clear the fault and the local bus (Figure 23)
- Tripping of a line or transformer connected to a ring bus that is already open at one spot, resulting in separating other lines or transformers from their only remaining source of power. (Figure 24)
- On ring buses, if vts are installed on the line side of a line isolating switch. If the line is out of service for line maintenance and the switch is open, but the ring breakers are closed to avoid splitting the ring, the line's distance relays cannot protect the stub bus between the breakers. (Figure 25)
- On breaker-and-a-half configurations, if vts are located only on the buses and not the rungs or lines, a bus fault, or the switching out of a bus, will eliminate the vts connected to it, leaving some of the protection schemes without a voltage source even though the protected elements remain in service. (Figure 26)

8.1.2 Separating the protection scheme from its vts

Some system operations may separate the line protective scheme from its voltage source causing an incorrect voltage to be presented to the scheme. This can be the result of:

- Vts connected to another bus section, i.e., a bus section breaker lies between the cts for the protected element (line) and the vts. Should the bus section breaker be opened, whether for a fault on the bus, intentional operation or human error, the voltage presented to the protection scheme may no longer be operationally related to the protected element (line). (Figure 23)
- Line vts inadvertently remain isolated after maintenance and the line is reenergized. (Figure 27)
- Depending on how vt secondary circuits are wired, when adding new devices it may be necessary to lift wires. This can result in a momentary LOV to the pre-existing devices.

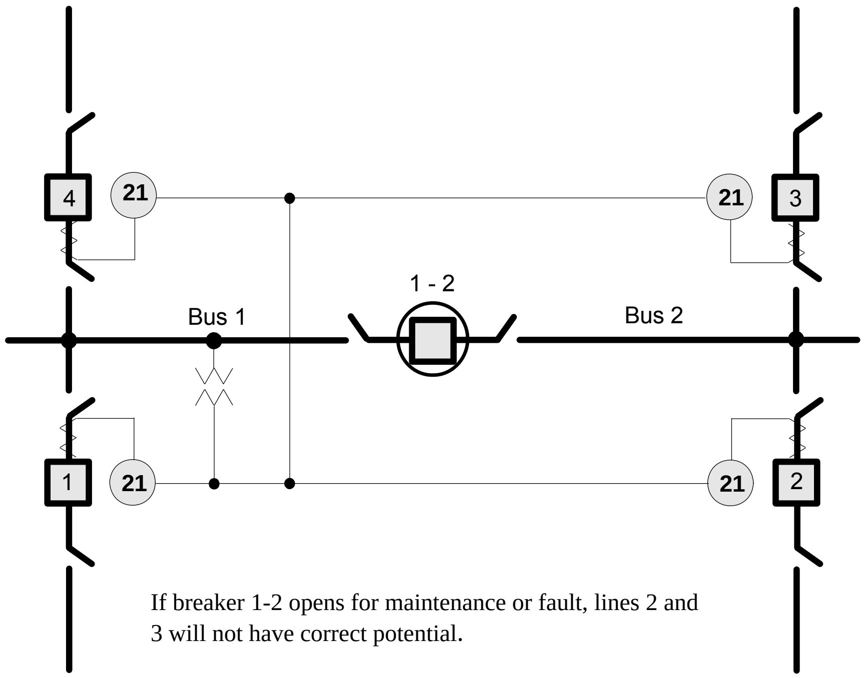


Figure 23. One Voltage Transformer in Substation

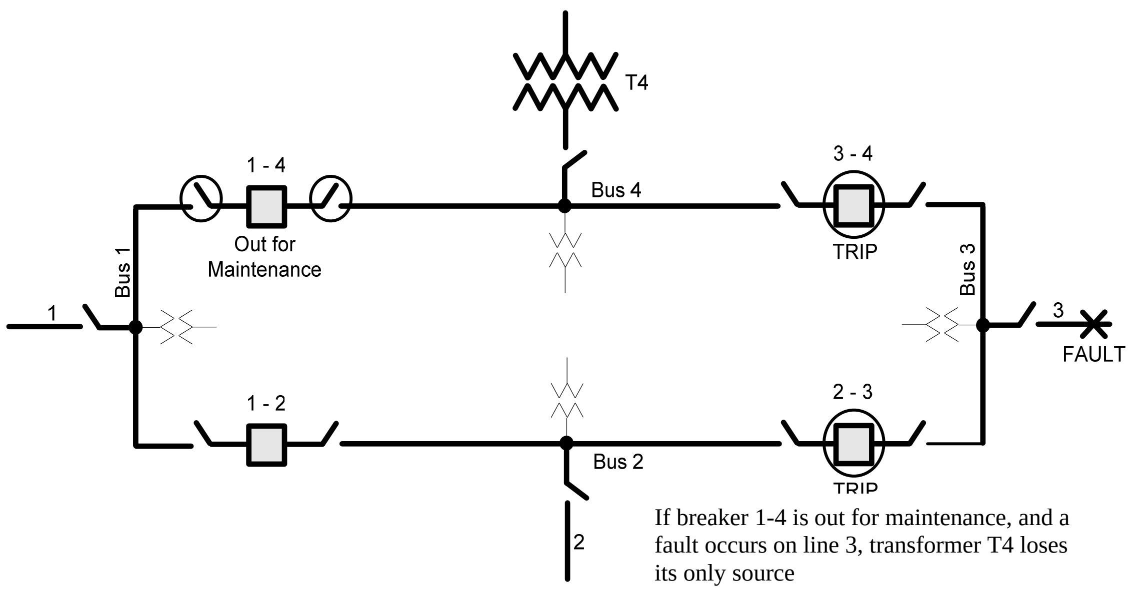
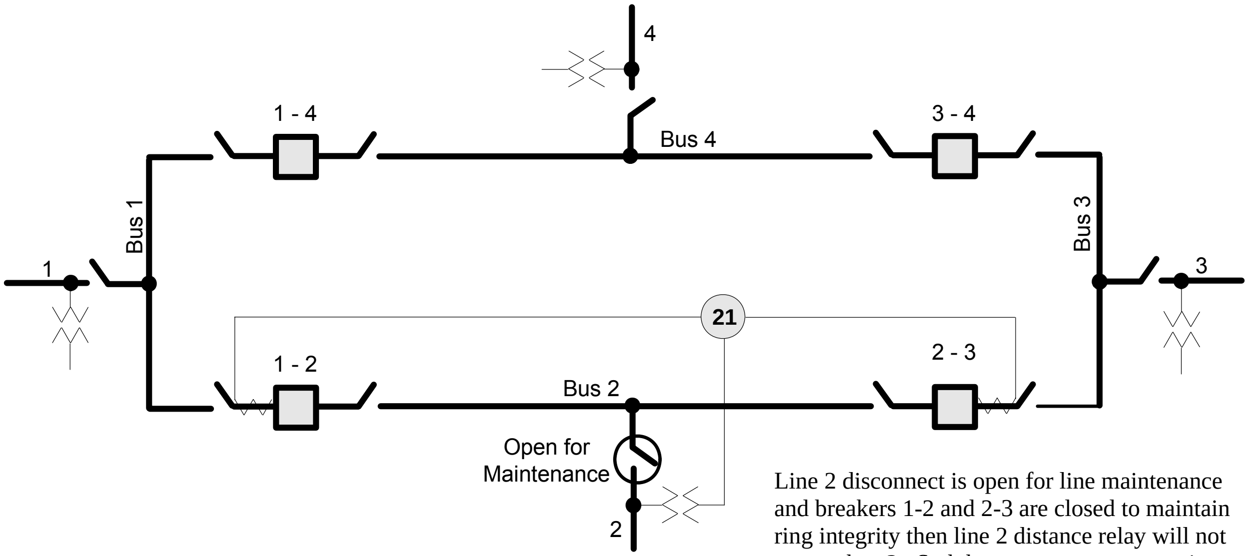
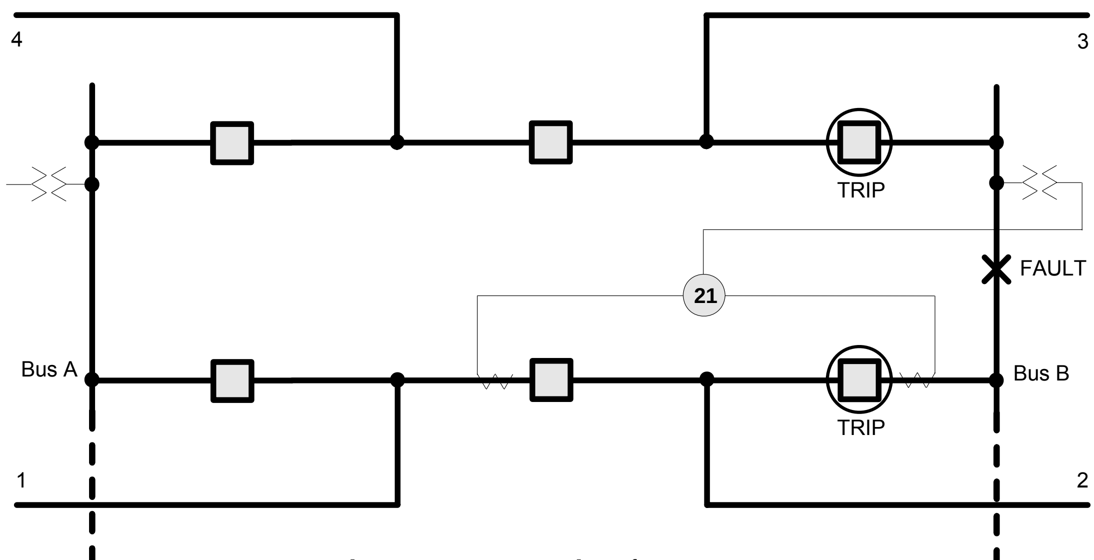


Figure 24. Loss of Source



Line 2 disconnect is open for line maintenance and breakers 1-2 and 2-3 are closed to maintain ring integrity then line 2 distance relay will not protect bus 2. Stub bus overcurrent protection is required.

Figure 25. Voltage Transformer on Line-side of Disconnect Switches



Fault on Bus B removes voltage from Lines 2 and 3 while they still remain in service.

Figure 26. Bus Connected Voltage Transformers

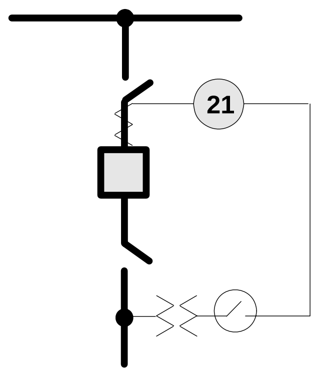


Figure 27. Line Energization Without Voltage

8.2 Secondary Vt Circuit Connections

Vt secondary circuit single and three-phase loads are generally connected phase to neutral (ground) as illustrated in Figure 28 where $Z_{\phi g}$ is the total relay phase input impedance. In the event that a load is connected phase-to-phase, $Z_{\phi\phi}$, whether intended or not, there may be significant error introduced in the measured zero and negative sequence voltages. $Z_{\phi\phi}$ may be an indicating light or some other intended connection or it may be a short circuit or some other accidental phase-to-phase connection.

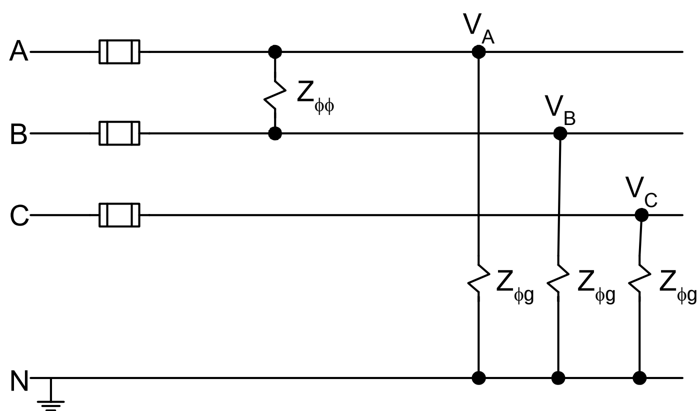


Figure 28. Vt Secondary Connections

Assume there is an accidental short circuit between phases A and B and $Z_{\phi\phi}$ is equal to zero. Fuse A blows to clear the permanent phase-to-phase fault. In this case there should be no problem detecting an LOV condition based on the zero sequence quantity comparison method of Figure 8(a). However, if the logic was measuring just the loss of phase voltage the LOV condition could not be detected.

If $Z_{\phi\phi}$ is a permanent load, as an indicating light, there is a possibility that LOV logic based on sequence quantities may not work if the fuse on phase-A or B blows. Consider a blown phase-A fuse. In this case the voltage, V_A, will be determined as follows:

$$V_A = \left(\frac{Z_{\phi g}}{Z_{\phi\phi} + Z_{\phi g}} \right) V_B$$

The resulting value of V_A during this condition will determine the operation of the logic.

A momentary (temporary) phase-to-phase short that does not blow a fuse will cause V_A and V_B to be equal during the temporary fault period. This will generate momentary zero and negative sequence voltages that may be sufficient to cause LOV to set.

8.3 Bus Potential Transfer

It is not uncommon to transfer sources of polarizing voltage, either manually or automatically, from one bus to another. Breaker-and-one-half bus arrangements, for example, are sometimes designed with vts on each bus instead of on the line side of each line breaker pair. A planned or unplanned outage on one bus requires that all of the relay polarizing voltage connections be switched to the healthy bus. The transfer scheme, manual or automatic, is typically designed with a break-before-make switching sequence to prevent temporarily tying the secondaries of the two bus vts during the switching. This will cause a momentary loss of polarizing voltage to the line relays, which may cause line distance relays to operate upon loss of voltage.

The line distance relays supplied from the bus vts may incorporate LOV protection or overcurrent supervision to prevent inadvertent operation of the line relay distance elements during the bus potential transfer. One scheme used to supplement LOV or current supervision protection on microprocessor based relays during manual bus potential transfer is called Trip Suspicion Logic. This logic simply delays the operation of the relay trip output by a few cycles to ride through the momentary loss of voltage on the relay. This logic is asserted for a fixed time period, typically several seconds, just prior to initiating the manual transfer, by momentarily initiating an input (PTXFR) on the relay. This input could be from a separate pushbutton switch, or from a leading contact on the potential transfer switch. In either case, the actual voltage transition must occur within the time that the logic is active in the relay. A logic diagram of a typical Trip Suspicion Logic is shown in the figure below, which provides a three cycle trip delay for 5 seconds after the PTXFR input is asserted on the relay.

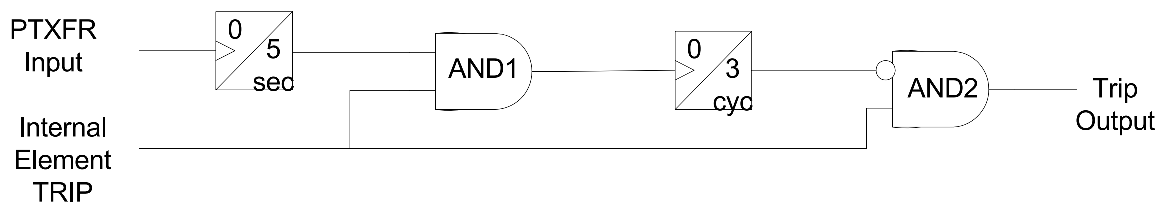


Figure 29. Trip Suspicion Logic

9.0 Future Considerations for LOV Applications

Reliable operation during an LOV state is far short of what it could possibly be given the capabilities of the microprocessor relay and advancing automation in the substation. Currently we are provided choices . . . block tripping, force directional units forward, etc., as discussed in Section 6. These choices are made based on the application to minimize unwanted outages that may occur when a system fault occurs during the LOV state. The challenge put forth here is that reliability during LOV can be improved with the development and testing of new adaptive schemes within the microprocessor relay and new substation automation functions. Following are a few examples.

9.1 Using an LOV Memory Voltage to Compute Polarization Voltages

Adaptive techniques can be developed that will provide reliable fault detection and clearing during a single-phase LOV condition, at least for faults on the non-LOV phases. Single phase LOV [as opposed to multiphase LOV] is most likely to occur and can still provide sufficient information [the other two phase voltages and line currents] to act on. Two-phase LOV conditions provide information on only one phase voltage and line currents and reliable automated action by the line relay becomes more difficult. That is not to say that it cannot be done. It just requires study. Three-phase LOV is rare and provides no voltage information. Therefore, automated response by the relay may be limited to that already discussed.

The fundamental requisites for this approach are that the LOV state occurs only on one phase and that phase can be identified, and an accurate faulted phase selection not affected by an LOV state can be provided. These capabilities are available on most microprocessor relays applied today. During a single-phase LOV state the voltage on the lost phase can be calculated with reasonable accuracy using zero or negative sequence voltage calculations with the understanding that with a perfectly balanced three-phase system V_0 and V_2 are equal to zero. Therefore, the lost phase voltage can be accurately calculated, and in the event of a single phase-to-ground fault, can be used to compute polarization voltages for both impedance and directional units.

9.1.1 Impedance Units

Reliable operation of the impedance unit may be expected during the loss of a single phase voltage as long as the fault is not on the LOV phase. The non-faulted phases are generally used to develop polarizing quantities. Also, the impedance unit requires an accurate measurement of fault voltage to operate reliability.

9.1.2 Directional Units

Reliable operation of the directional unit may be expected regardless of the faulted phase. Sufficiently accurate zero and negative sequence polarizing voltages can be computed for a fault occurring on a non-LOV phase. A fault that occurs on the LOV phase will appear as a ground fault at the vt and in the forward direction.

9.2 Using Substation Automation Functions to Improve System Reliability During LOV Conditions

9.2.1 Automatic Potential Transfer

Advances in substation automation technology have allowed an increase in automated decisions at the substation. One possible application that transfers the relay's voltage source to a backup voltage source might be used to complement the adaptive method discussed in Section 9.1, which is limited to single-phase LOV conditions only. The fundamental requisites for this approach are that the LOV phases can be identified accurately, and a second vt source is available as the backup voltage source to the relay. For a single-phase LOV condition the adaptive method as described in Section 9.1 would be handled by the relay. Should a multi-phase LOV condition occur then a voltage source (potential) transfer would be automatically executed switching the relay to the alternate voltage source and taking necessary precautions to prevent relay misoperation during the transfer process.

9.2.2 IEC 61850 Implementation

The application of IEC 61850 envisages sharing analog and digital data on the Ethernet (process) bus. Modern relays have a great deal of flexibility in developing logic based on system conditions. Relay designs that share data can be programmed to detect loss of voltage from one particular source and substitute the appropriate available alternate voltage in the relay logic. For example, if loss of voltage is detected on Phase C, and the relay has access to the Phase C voltage from another source that is substantially identical to the voltage at the failed source, then a substitution for the failed Phase C voltage can be performed by the relay logic.

10.0 Conclusions and Recommendations

The utility industry lacks documentation on the occurrence of LOV conditions and the number of phases involved. However, individual experience of Working Group members indicated most faults and LOV conditions are unbalanced. Thus, the frequency of occurrence of single or two-phase LOV conditions far exceeds a three-phase LOV condition. The implementation of LOV logic for a single and two-phase fault response should be considered separately from the LOV logic for a three-phase fault response. Also, three-phase LOV conditions are more likely caused by system operations.

Different applications dictate the use of particular schemes and no single scheme or method can be universally applied. Section 6 and Appendix A provide methods to guide LOV application.

The utility industry should document LOV experience such as phases affected, causes, remedies, and outage effects. Direct improvements in protection, maintenance, and operation could be realized. Protection and substation automation developers should look for more ways to improve protection reliability during LOV conditions.

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Appendix A: LOV Option Analysis Example

The following presents a typical methodology that might be employed to determine the best control option when line protection detects an LOV condition. The results obtained here are only applicable for the application studied and should not be uniformly applied at all line protection applications.

Consider the system of Figure A1. These lines are protected by one system relay providing pilot protection and step distance backup. The pilot system is POTT (permissive overreaching transfer trip) utilizing both overreaching phase and ground impedance and directional ground overcurrent to key the permissive signal to the remote terminal. Relay C1 is operating in a LOV state. There are several setting choices as defined above depending on the redundancy of protection and the connection to the vt. Table A1 evaluates the possible line outages (operations of local and remote relays) resulting from a phase-to-ground fault for the application of a single system relay or two systems on a single fused secondary voltage circuit. Table A2 evaluates the line outages for the application of two systems on separately fused circuits. It is assumed that two relays are applied with the same LOV setting and LOV occurs only on one of the secondary voltage circuits. The evaluation score is the average outaged lines for each LOV application group. A lower score indicates fewer potential outages.

Analysis of Table A1 shows that disabling the impedance units from tripping and having the zero sequence (residual) current units, in particular the forward pilot ground overcurrent unit, supervised by a reliable external zero sequence current polarizing source will result in no additional outages as a result of LOV. This polarizing quantity is derived from a delta-wye transformer or other grounding transformer and may not be readily available as an input to the relay. The next best approach, if backup coordination exists, is to disable the impedance units from tripping and force the time overcurrent backup to forward (Set32 – 51). However, if backup coordination does not exist, the next best approach is to disable the impedance units from tripping and force the pilot ground overcurrent function to forward (Set32 – 67NP). This will force tripping of the line on which the LOV occurs for internal and some reverse external faults but will prevent remote backup tripping on adjacent buses for internal faults.

Analysis of Table A2 shows similar results as Table A1 except that the scores are lower since the scheme without an LOV condition is assumed to operate correctly.

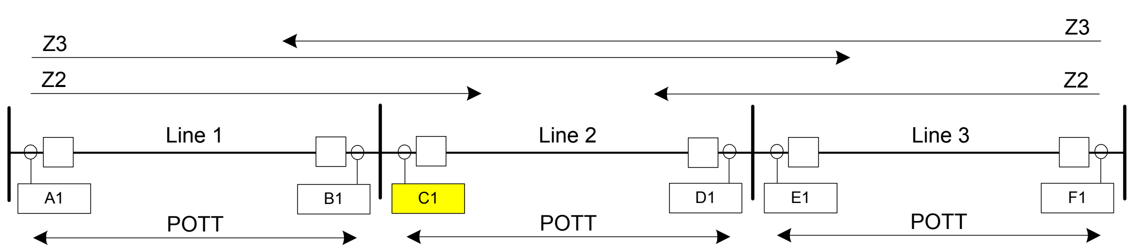

Figure A1. Example System for LOV Analysis

Table A1 Single Fused Circuit - Single Relay or Two Relays With a Common Fused Potential Circuit				
LOV Application	**Faulted Line**	**Protection Operations**	**No. of Outaged Lines**	**Score**
Alarm Only	2	If Relay C1 correctly sees a forward fault, then relays C1 and D1 POTT trip correctly.	1	1.5+
	2	If Relay C1 incorrectly sees a reverse fault, then relay C1 does not trip, relay D1 trips on zone-2 and relay A1 trips on zone-2, zone-3 or 51 backup if available. It is also possible that relays at A1 may not see the fault and the fault is not cleared by protection.	2+	
	1	Relays A1 and B1 POTT trip. If Relay C1 correctly sees a reverse fault, then Line 2 does not trip.	1	
	1	Relays A1 and B1 trip. If Relay C1 incorrectly sees a forward fault, then relays C1 and D1 pilot trip.	2	
Disable 21 and 50/51 (Block all tripping)	2	Relay C1 blocks tripping. Relay D1 trips on zone-2 and relay A1 trips on zone-2, zone-3 or 51 backup if available. It is also possible that relays at A1 may not see the fault and the fault is not cleared by protection.	2+	1.5+
	1	Relay C1 blocks tripping. Relays A1 and B1 correctly pilot trip.	1	
Disable 21 Set 32 – 67NP	2	Relay C1 keys on forward overcurrent pilot ground. Relays C1 and D1 POTT trip.	1	1.5
	1	Relays A1 and B1 POTT trip. Relay C1 keys on forward overcurrent pilot ground. Relays C1 and D1 POTT trip.	2	
Disable 21 Set 32 - 51	2	No POTT tripping. Relay D1 trips zone-1 or zone-2. Relay C1 trips time delayed on 51. Relays A1 may trip on zone-2 or zone-3 depending on time coordination with 51 at C1	2+~	1.5+
	1	Relays A1 and B1 POTT trip.	1	
Disable 21 Set 32 – 50	2	No pilot tripping. Relay D1 trips zone-1 or zone-2. Assuming high fault current, relay C1 trips instantly on 50.	1	1.5+
	2	No pilot tripping. Relay D1 trips zone-1 or zone-2. Assuming insufficient fault current, relay C1 does not trip. Relay A1 trips on zone-2, zone-3 or 51 backup if available. It is also possible relays at A1 may not see the fault and the fault is not cleared by protection.	2+	
	1	Relays A1 and B1 pilot trip. Assuming high fault current, relay C1 trips instantly on 50. A small time delay might prevent this.	2	
	1	Relays A1 and B1 pilot trip. Assuming insufficient reverse fault current, relay C1 correctly does not trip.	1	
Disable 21 I0 Polarize 32	2	Relay C1 forward directional unit operations may be affected be mutual coupling. Correct operations can be expected on lines where mutual coupling does not affect polarizing current direction.	1*	1 *
	1	Relays A1 and B1 pilot trip. Relay C1 reverse directional unit operations may be affected be mutual coupling. Correct operations can be expected on lines where mutual coupling does not affect polarizing current direction.	1*	
Score = (Outaged Lines) / (Number of Scenarios). Score = 1 is normal. + Indicates that all remote terminals (A1) of lines connected to the bus between B1 and C1 will trip increasing the number of outaged lines. The Score will increase 0.5 times the number of connected lines. * Correct polarization may be affected by mutual coupling. ~Assumes that backup coordination does not exist. If coordination is adequate, there would be 1 outaged line.				

Table A2. Dual Fused Circuit - Relay systems C1-A/D1-A and C1-B/D1-B, LOV on C1-A and C1-B operates correctly -				
LOV Application	**Faulted Line**	**Protection Operations**	**No. of Outaged Lines**	**Score**
Alarm Only	2	If Relay C1-A correctly sees a forward fault, then relays C1-A and D1-A pilot trip correctly.	1	1.25
	2	If Relay C1-A incorrectly sees a reverse fault, then relay C1-A does not trip. System B trips POTT.	1	
	1	Relays A1 and B1 pilot trip. If Relay C1-A correctly sees a reverse fault then Line 2 does not trip.	1	
	1	Relays A1 and B1 trip. If Relay C1 incorrectly sees a forward fault then relays C1-A and D1-A trip.	2	
Disable 21 and 50/51 (Block all tripping)	2	Relay C1-A blocks tripping. System B trips correctly.	1	1
	1	Relay C1-A blocks tripping. Relays A1 and B1 correctly pilot trip.	1	
Disable 21 Set 32 – 67NP	2	Relay C1-A keys on forward overcurrent pilot ground. Relays C1-A and D1-A pilot trip. System B correctly trips.	1	1.5
	1	Relays A1 and B1 pilot trip. Relay C1-A keys on forward overcurrent pilot ground. Relays C1-A and D1-A pilot trip.	2	
Disable 21 Set 32 - 51	2	No pilot tripping of System A. System B trips correctly	1	1
	1	Relays A1 and B1 pilot trip.	1	
Disable 21 Set 32 - 50	2	No pilot tripping of system A. Assuming high fault current relay C1-A trips instantly on 50. System B trips correctly	1	1.5
	1	Relays A1 and B1 pilot trip. Assuming high fault current relay C1-A trips instantly on 50.	2	
Disable 21 I0 Polarize 32	2	Relay C1-A forward directional unit operations may be affected by mutual coupling. Correct operations can be expected on lines where mutual coupling does not affect polarizing current direction.	1*	1*
	1	Relays A1 and B1 pilot trip. Relay C1-A reverse directional unit operations may be affected by mutual coupling. Correct operations can be expected on lines where mutual coupling does not affect polarizing current direction.	1*	
LOV occurs only on one vt circuit. Score = (Outaged Lines) / (Number of Scenarios). Score = 1 is normal. + Indicates that all remote terminals (A1) of lines connected to the bus between B1 and C1 will trip increasing the number of outaged lines. The Score will increase 0.5 times the number of connected lines. * Correct polarization may be affected by mutual coupling.				