A DIRECTIONAL WAVE DETECTOR RELAY WITH ENHANCED APPLICATION CAPABILITIES FOR EHV AND UHV LINES

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Abstract - An ultra-high speed (UHS) directional wave detector relay capable of fulfilling the protection requirements for EHV and UHV transmission lines is described. The benefits of combining directional wave detection with distance relay functions and a sensitive ground overcurrent unit are discussed. Multiple series and parallel functions enhance the security and dependability by mutual support, whereby the inherent strengths of each measurement technique are used to improve the characteristics of others. Solutions for difficult application problems are presented. In addition, economic considerations are noted for increased power transfer and reduced circuit breaker costs.

INTRODUCTION

Line protection having greater speed, selectivity, and sensitivity are constantly required to meet the increasing demands of modern EHV and UHV transmission systems. A step in this direction was taken when the RALDA directional wave detector (DWD) relay was developed and introduced first on the Bonneville Power Administration's 525 kV system. This relay satisfied the ultra high-speed requirements for one cycle total fault clearance and has been in successful service for over 5 years. More than 100 terminals of this type have been delivered. Being a pure pilot scheme, it provided no remote back-up and its maximum sensitivity could be limited for certain system conditions.

The RALZA (RALZB) relay is described which combines the features of the high-speed directional wave detector relay with a distance relay for remote back-up, plus neutral current monitoring for maximum high-resistance ground-fault sensitivity without loss of security. With these features, the relay is able to provide very fast fault clearance for the protected line, remote distance back-up, a relatively fast zone 1 independent of the communication channel, excellent high-resistance fault sensitivity with clearance in 20-40ms even with in-zone surge arrestors. It is also able to cope with weak infeeds and in-zone reactor switching. The relay measures on a per phase basis which provides an enhanced adaption to system parameters compared to a pure negative-, positive-, or zero-sequence directional comparison scheme. A phase selector is provided for single-phase tripping applications or where breaker failure times or the reclosing mode must differ for different fault types. In addition, distance type switch-into-fault protection independent of breaker-closing signals is provided. Inherent in the directional wave detection principle is the ability to protect series compensated lines and to be relatively independent of power swings. This capability has been used to control the distance measurements thus retaining these desirable characteristics.

Problems such as transient saturation of current transformers, transient phenomena of CCVT's, and the detection of broken loaded phase conductors are also solved by the relay. Because the directional wave detector controls the zone 1 and 2 distance measurement, high load transfer capability is provided and there is no need for high-speed blocking for a VT fuse failure.

DESCRIPTION

Directional wave detectors are combined with three distance functions and a neutral current unit to provide complete phase and ground protection for transmission lines. The relay utilizes a single communication channel in each direction. Also included are back-up functions which operate independent of the communication channel. System signals are obtained from conventional current and voltage transformers.

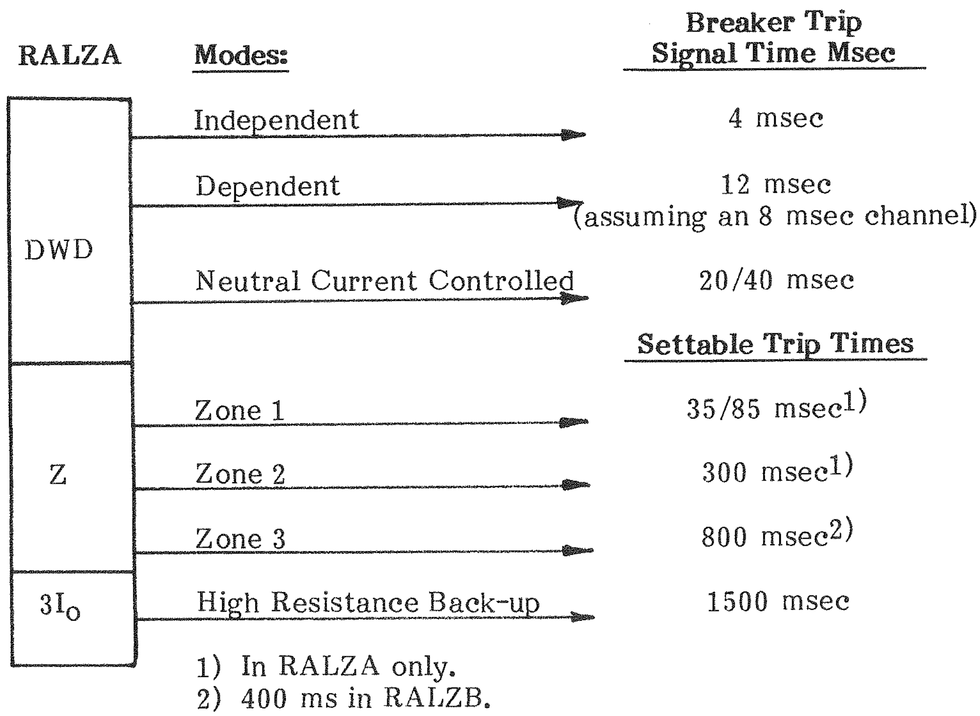


Fig. 1: The relay consists of three basic sections under control of the traveling wave detectors. Typical trip delays are shown.

DWD - Directional Wave Detectors

Directional wave detectors (DWD) ignore steady state load conditions by suppressing those input signals to the DWD by filtering. The DWD's operate only if sudden changes in voltage and current exceed their settings since the filters will pass only the change of current and voltage. The relay utilizes three different directional wave detecting modes (Figure 1). The dependent mode (DM) works in conjunction with the communication channel to provide complete pilot protection for the majority of faults. The directional decision, forward or reverse, is made independently at each line terminal and then compared over the channel to provide a trip signal for internal faults or blocking for external faults.

The neutral current controlled mode (NCM) is the most sensitive and uses criteria of neutral current and a selectable time delay of either 20 or 40 ms, combined with the directional wave detection principle. This mode provides high-resistance ground-fault detection capability without degrading security. The additional delay is acceptable for the low level faults covered by this mode.

The independent mode (IM) can be compared with a high-set instantaneous directional overcurrent relay except that it ignores the load current. It operates independent of the channel to provide fast tripping (1-2 ms) of severe close-in faults.

DWD Operating Principle

The directional wave detectors detect the wave magnitude and the direction from which the traveling waves originate. If the point of origin is external to the protected line section the protection blocks, and if internal, the protection provides a high speed output which is phase selective. Tripping is obtained in via the channel information for the "overreaching" DWD elements.

This principle is illustrated in Fig. 2 in terms of the direction of motion of traveling waves generated by a change in the electrical state of the network (i.e., fault, breaker operation, etc.). At A the direction of motion of the traveling wave will be different for an external fault compared to an internal one.

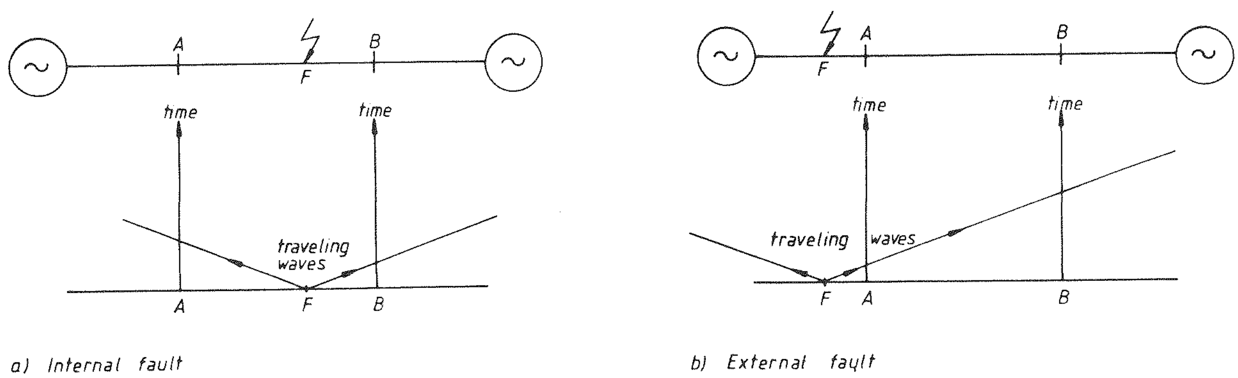


Fig. 2: Propagation of traveling waves.

Steady state currents and voltage are suppressed in active and passive filters and only sudden changes are detected. The direction to the fault is established by determining the relative polarity of the sudden changes in voltage V and current i. For external conditions these have the same polarity and for internal conditions the opposite polarity. The directional decision is made in the first 1-3 ms after fault incidence and all subsequent information is ignored, until DWD resets. For the unlikely event of a subsequent internal fault occurring during this reset time, the zone 1 and 2 distance measuring functions will be enabled by the wave detector start, either forward or reverse. As shown in the overall block diagram, Fig. 3, three DWD elements are used per phase, each with forward and reverse looking elements.

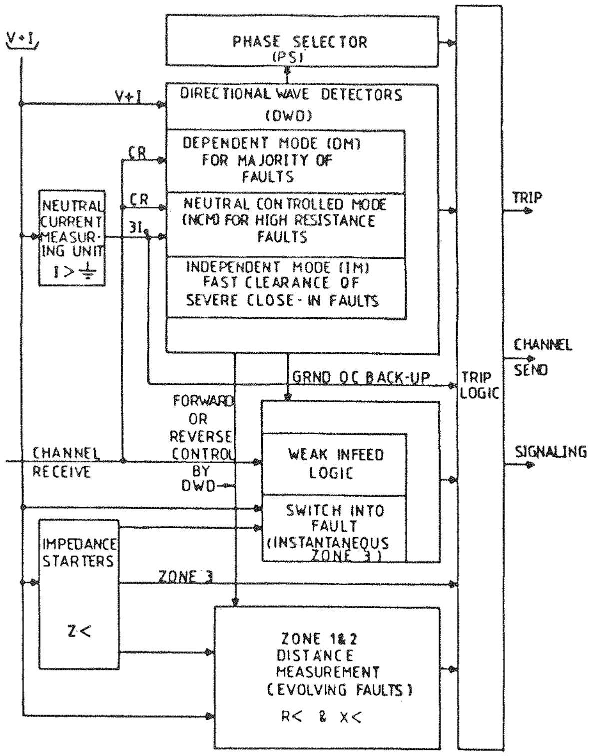


Fig. 3: Overall block diagram of RALZA.

Z - Distance Elements

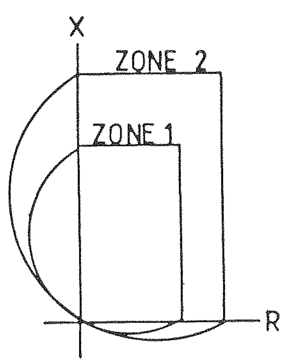
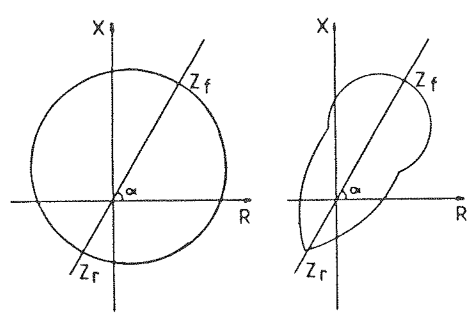


Fig. 4: Zone 1 and 2 distance characteristics



Circular **Modified Lens**

Fig. 5: Zone 3 distance and starting characteristics

By controlling zone 1 and 2 distance measurement with the wave detectors, the inherent and highly desirable DWD features of insensitivity to power swing and VT fuse failure are retained for these measurements. The zone 1 and 3 distance measurements are of the sequential measurement type using dual measuring elements and 3 impedance and 1 neutral current starters. Depending on the fault type as determined by the starters, optimum measuring quantities (e.g., distance measurement is unaffected by the unfaulted phase quantities) are selected by a static signal selector and fed into the measuring element for determination of direction and distance to the fault. Highly selective directional sensing is ensured by unfaulted phase polarization for unbalanced faults and memory for three-phase faults. The memory function utilizes a phase locked loop oscillator which locks-in on the phase of the voltage signal immediately prior to the faults and is unaffected by the fault voltages.

The zone 1 reach in the resistive and reactive axes is set independently. Therefore, the distance protection characteristic can be set to coordinate better with load impedance of heavily loaded lines, yet affords maximum fault-resistance coverage. The source impedance does not change the resistive reach, which makes this coordination easier than with conventional cross-polarized Mho-type relays. After expiration of the set zone 2 time delay, the reach is extended. See Figure 4.

The impedance starters operate independent of the wave detector section and provide three functions:

1. Instantaneous switch-into-fault protection when the line is being energized. This always gives a three-phase trip output.

2. Time delayed non-directional zone 3 back-up distance protection.

3. Starting (determination of fault-type) for the zone 1 and 2 distance measurements.

The impedance starters have two possible characteristics, circular or modified lens, Figure 5. These starters can be set to have the desired forward and reverse reaches. Generally, a modified lens characteristic with minimum reverse reach would be selected for a long, heavily loaded line. Extra high-resistance fault detection capability is not required by these starters since this function is covered by the neutral current controlled mode of the wave detector.

In type RALZB the described zone 1 and 2 distance relay functions are excluded. RALZB relies on zone 3 for impedance back-up and switch-into fault protection.

The switch-into-fault protection is necessary since the directional wave detector with the normal line side VT's may not detect an adequate voltage change because of the presence of maintenance grounds or a line fault. This protection operates if, after the line voltage has been low for a set time, the impedance starters operate. It remains enabled as long as any line voltage is below a set value and is disabled immediately when all line voltages exceed this value. This eliminates the need for breaker-closing signals.

$3I_O$ - Neutral Current Monitor

The current monitor for the neutral current controlled mode can be arranged to provide definite-long-time delayed ground overcurrent back-up thru an optional timer.

Weak-Infeed Logic

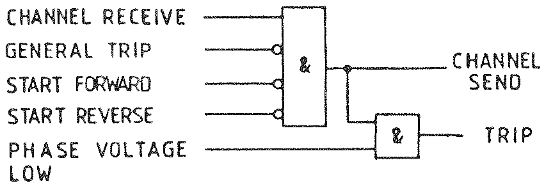


Fig. 6: DWD weak-infeed logic.

In some applications one line terminal may at times have a weak source. Since the operation of each end in a permissive scheme is dependent on receiving a communication signal from the opposite end, the weak-infeed end must be arranged to echo the signal received from the stronger end. The logic available for achieving this is shown in Figure 6. If a communication signal is received from the remote end and there is no local general trip or start of the wave detector in either direction, forward or reverse, the local end retransmits the channel received signal, thus enabling the remote end to trip. If, in addition, one or more phase voltages are low at the weak-infeed end, the relay will initiate a local trip. The necessary signal level coordination between blocking at the weak-infeed end and tripping at the strong-infeed end to prevent misoperation for marginal external fault conditions is built into the relays.

Phase-Selector

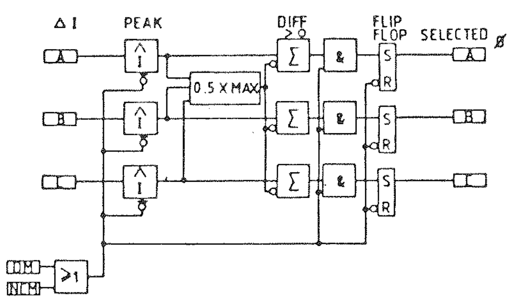


Fig. 7: DWD phase selection logic.

For applications such as single-phase tripping, phase selectors are included with the directional wave detector. The simplified phase selection logic is shown in Figure 7. The maximum of the peak current changes of the three phases is extracted and halved and, in an individual summing amplifier per phase, the difference between this maximum and the individual phase peak change is determined. If this difference is positive and either the DWD dependent mode (DM) or neutral current controlled mode (NCM) has started in the forward direction, the corresponding AND gate is armed and sets its flip-flop to give an output indicating the phase involved.

Further logic ensures a three-phase trip for internal faults involving more than one phase. Therefore, a phase will only give an output to the indication and trip logic if there has been a neutral or dependent mode start and the peak current change signal of that phase is greater than 50% of the maximum peak current change of the three phases. With these phase selectors the use of current changes, rather than current signals exceeding an absolute level, enhances the reliability of the phase selection appreciably.

The relay conceptual design is based on ensuring optimum reliability, both dependability and security, by series and parallel combinations of functional criteria. The use of multiple measurement techniques such as continuous steady state measurement, sudden changes, and sequential measurement also contribute significantly to reliability.

APPLICATION

The relay is applied on EHV and UHV lines. It must be emphasized that its application is not limited to systems requiring ultra high-speed fault clearance although it is well suited for such applications when combined with a communication channel having an appropriate speed. In general, overall operating time will be determined by the channel since the directional wave detector will make its directional decision independently in 1-2ms. Consequently, by suitable choice of the channel, overall operating time can be controlled by the user to suit system needs.

Besides speed, other reasons for applying this relay are:

- Different measurement principle required for redundancy.
- High-resistance faults.
- High load transfer.
- Power swing insensitivity.
- Series compensated line.
- CT or CCVT transient response problems.
- Zero sequence mutual coupling.
- Single-phase tripping and reclosing.
- Phase selection for breaker failure, reclosing or fault locators.
- Broken loaded-conductor detection.

High-Speed Advantages ($\frac{1}{4}$c vs 1$\frac{1}{4}$c relay)

- Stability improvements in network may permit higher power transfer.
- Reduced stress on major equipment.
- Faster reclosure more likely to succeed.
- Permits e.g., 3 cycle breakers at cost savings.
- May avoid need for 1 cycle breakers.
- Reduced fault damage.
- Higher speed and consistency could permit shorter breaker failure back-up clearing times.

Sensitivity to High-Resistance Faults

In many areas high-resistance ground-faults can occur due to broken conductors falling onto rocky ground, trees under the line, bush fires, or where there are no ground wires and high tower footing resistances represent a high resistance fault for all single-phase to tower faults. The described relay provides sensitive (as low as 10% of rated current) pilot protection for these faults and an operating time of the order of 20-40 ms.

Such an operating time ensures that there is no loss of security during in-zone surge arrestor discharge of power-follow current after a lightning surge. A definite-long-time delayed function (alarming or tripping) for these high-resistance faults has been added for redundancy.

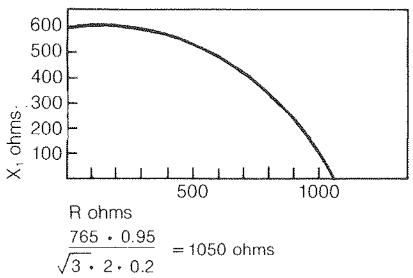


Fig. 7: Very sensitive ground fault protection is afforded by the neutral-ground-current controlled mode, here shown at 765 kV.

Effects of Shunt Reactor Switching

Independently switched shunt reactors should preferably be excluded from the protected zone by locating current transformers in the reactor circuits. Where switched shunt reactors cannot be excluded from the zone, provision has been made to block the sensitive neutral controlled mode output and desensitize or block the dependent mode output of the directional wave detector, as desired, for a preselected time, typically 500 ms. This action is initated from the reactor switching controls. The independent mode output is never blocked nor desensitized since its settings are chosen such that it cannot respond to changes resulting from reactor switching in-rush current. This function is therefore always available for rapid clearance of severe close-in faults. Directional wave starting is not blocked, enabling zone 1 and zone 2 functions and provide the line with direct zone 1 local tripping and stepped distance protection during the reactor switching period.

Sensitivity with Heavy Loading

Applying relays on modern transmission systems is often made more difficult because heavy load flow situations must be considered. Conventional relays often require less sensitive settings as a result of heavy loading. The DWD relay overcomes this difficulty by responding only to sudden current and voltage changes. The distance measuring functions in the relay have characteristics which should be set insensitive to maximum load flow since high-resistance faults are covered by the neutral current controlled mode. Hence the complete relay retains its high sensitivity, even for heavy load flow conditions.

Power Swing Insensitivity

Power swings do not cause the DWD to respond because the associated changes occur sufficiently slow for suppression by the filters. Since the zone 1 and 2 distance functions are controlled by the DWD they also are unaffected by power swings and, unlike conventional distance relays, do not require power swing blocking. The zone 3 impedance starters are not controlled by the directional wave detectors and therefore their tripping output must be blocked by power swing detection relays if the swing can enter their characteristic and remain there for 800 ms (the set trip delay). If a fault is introduced during the swing, the distance relay could operate if the swing impedance is within the set characteristic. If this is a concern, blocking should be provided for the distance portion only. The DWD portion only would, in that case, protect during the swing.

Series Compensated Lines

Applying the relay on series compensated lines poses no problem since the DWD responds only to the changes in the voltage and current and, unlike conventional distance relays, is not affected by bus voltage reversals. Figure 9 shows how the change in voltage, ΔV_A retains its sign even though the bus voltage has reversed due to the capacitors. Thus, the directional wave detectors provide high-speed protection for internal faults.

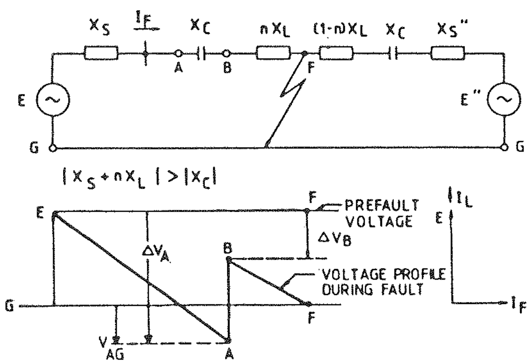


Fig. 9: Effect of series capacitors. Bus voltage reversal but no reversal in voltage change.

For evolving faults the zone 1 and 2 distance functions will provide backup protection. For unbalanced faults, the zone 1 and 2 directional measurements are unaffected because of unfaulted phase polarization. This, in effect, means that they obtain their directional polarizing quantity from the voltage behind the source impedance which does not suffer reversal. For balanced three-phase faults, the zone 1 backup function is delayed to allow capacitor gap firing to take place so it makes its directional decision based on memory or after the bus voltage reversal has been removed. Zones 2 and 3 provide overreaching remote backup like other types of distance relays on series compensated lines for such faults.

Instrument Transformer Response

Near modern large power plants the system primary time constants tend to increase. Also, fault levels are rising steadily and this combination can lead to rapid transient saturation of current transformers. Remanent magnetism left by previous faults can aggravate the problem. Since some distance relays cannot measure correctly with the distorted secondary currents, appreciable delays in operation could occur with consequent adverse effect on system stability. The directional wave relay makes its directional decision in 1-2 ms, before transient saturation can occur, and is unaffected by the distorted waves. The zone 1 distance measurement, which backs the DWD, requires that the current transformers reproduce the primary waves faithfully for only 50 ms, to provide an accurate measurement. This is not a requirement for faults within the set zone 1 reach, which means that the relay will operate even with CT's saturating on internal faults.

At EHV and UHV levels distance relays often require extra high capacitances for the coupling capacitor voltage transformers (CCVT's) to ensure correct distance and directional measurement for faults which result in low voltage at the relaying point. For such faults, the low frequency transient of CCVT's can have several times greater amplitude than the signal to be measured, resulting in a signal/noise ratio less than unity. The directional wave relay measures change in voltage and for these conditions the change is many times greater than the low frequency transient amplitude. This implies that the signal/noise ratio is always much greater than unity so correct measurement is ensured, even in the presence of CCVT transients (Figure 10).

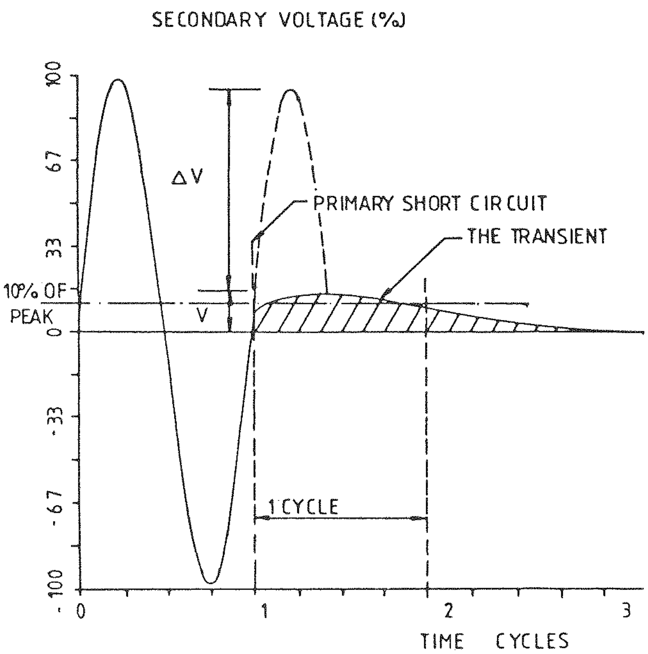


Fig. 10: Influence from CCVT transient errors minimized by measuring voltage change.

Effects of Mutual Coupling

Zero sequence mutual coupling between parallel lines normally gives difficulty of reach with ground distance relays. The directional wave detector, which provides the primary protection function, is unaffected by this coupling. Only the distance measurement, which is secondary in function, requires settings which take mutual coupling into account. Only the ground distance zone 1 reach is therefore reduced to inhibit any overreach due to mutual coupling. The phase distance reach setting is unaffected.

Phase Selection Capability

The special phase selectors discriminate between single-phase-ground and other faults to make the relay particularly suitable for single-phase tripping and reclosing applications or for situations where different breaker failure times are desired for single-phase and multi-phase faults. It can also be used where different reclosing policies are applied for single-phase and multi-phase faults or where phase selection is required for fault locators.

Broken Loaded-Conductor Detection

One of the most difficult faults to detect on a line is a series fault or broken phase conductor even if this also results in an actual shunt fault since the latter can usually be detected only from one end. Because it measures the changes in voltage and current, the DWD can often detect the series interruption of one phase of a loaded line at both ends, whether or not it results in a shunt fault. The change in current is equal to the lost load current and, provided the changes in voltage at each end of the line (which depend on load magnitude and source impedances) exceed the setting, the relay will detect the condition and could conceivably clear the line before the broken phase creates fault current.

Other Effects

High-speed VT fuse failure detection is required by distance relays to prevent misoperation from the resulting voltage loss. The DWD, requiring simultaneous sudden changes in both voltage and current for its operation, does not misoperate from this cause. The zone 1 and 2 distance functions are controlled by the directional wave detectors (in either direction) thus they are also unaffected. Slow VT fuse failure detection is required to block the zone 3 impedance relays and to give an alarm so that the fuses can be replaced before any system fault occurs. Miniature circuit breakers can be used instead of VT fuses to eliminate the need for fuse failure detection. Blocking of the zone 3 impedance relays is then accomplished by an auxiliary contact in the miniature circuit breaker.

In a conventional permissive overreaching pilot scheme, overreaching distance relays covering an unfaulted line require blocking during sudden power reversals to prevent them from misoperating. Such blocking is built into the DWD since the directional wave detector will have blocked at one end. Subsequent internal faults occurring on the previously unfaulted line during the blocking of the directional wave detector are covered by the zone 1 and 2 functions.

The directional wave detector relay responds correctly to transients so line transients due to switching or faults are no problem. For internal faults they tend to increase the required operating signal change and for external faults they can only cause the relay to block temporarily if they exceed the relay setting.

Setting and Testing

It is of fundamental importance to appreciate that the setting and testing of the relay, including the directional wave detector modes, is based entirely on 60 Hz quantities in spite of the fact that the relay responds to sudden changes. It is not necessary to have knowledge of the system transient behavior to apply, set, or test these relays. Allowance for these phenomena is built into the design. For setting the directional wave detectors the only departure from normal system studies is that the rms values of the changes instead of the actual rms current and voltage values must be determined. Determination of the settings and testing of the distance functions follow standard practice.

Adjustment of the relay to the required settings is simple since it merely involves the setting of precision calibrated potentiometers or thumb-wheel switches located on the front panels. No special tools are required for making these adjustments. No charcteristic is created by timers requiring calibration. Therefore the commissioning and maintenance procedures are simplified.

Built-in functional test facilities are provided for simulating the various fault types and checking of the logic behavior of both the directional wave and distance functions. Calibration is performed during secondary injection testing which is facilitated by a built-in test switch. The RALZA relay is shown in Figure 11. RALZB is shown in Figure 12.

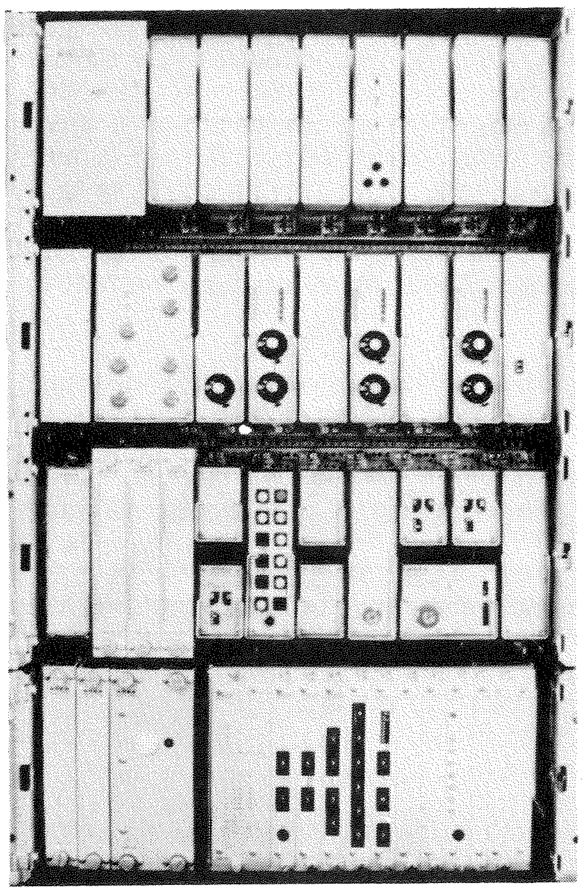


Fig. 11: Type RALZA Relay.

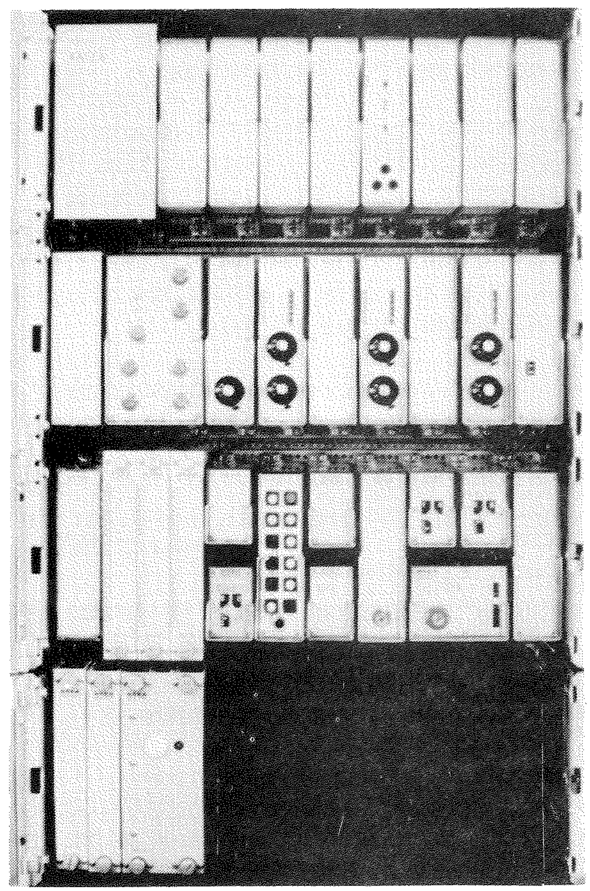


Fig. 12: Type RALZB Relay.

TABLE I: ADVANTAGES AND DISADVANTAGES OF PURE TRAVELING WAVE RELAY PROTECTION

Advantages	Disadvantages
o Unaffected by current transformer saturation and capacitative voltage transformer transients.	o Protects only a well-defined zone of a line, and nothing outside that zone.
o Ultrahigh speed of fault detection, typical 1-3 millisec.	o Cannot trip for an internal fault that follows an external fault within the DWD reset time.
o Compatable with any type of relay communication channel.	o High resistive sensitivity results in possible operation for an arrester discharge, series-capacitor switching, or lightning strokes near to protected line.
o Can operate independently of communication channel for close-in faults in less than a ¼ cycle.	o May not clear long-line, strong-source faults when closing into a faulted line, due to limited voltage drop.
o Suitable for any line length.	
o Suitable for series-compensated lines.	
o Suitable for single-phase tripping schemes.	
o Unaffected by fuse failure or sudden loss of ac supply.	

TABLE II: SOLUTIONS TO TRAVELING-WAVE LIMITATIONS

- o Faults occurring after an external fault: Add a Zone 1 distance-protection package.
- o Faults outside zone: Add a Zone 2 distance-protection package.
- o Unwanted side effects of high resistive sensitivity: Add a neutral-current-controlled directional package.
- o Long-line strong-source problem: Add a switch-into-fault detector based on impedance measurements.

USER EXPERIENCE

User experience with ASEA traveling-wave relays has been very good. For example, on four Nebraska Public Power District's 345 kV lines, oscillographs have recorded the consistent ultrahigh-speed (UHS) capability of the RALDA system.

The independent mode has produced 1.5-cycle total clearing time with two-cycle breakers for close-in faults. Typical operating times obtained at Minnkota, another RALDA user, are 4 millisec for independent-mode and 8 millisec for dependent-mode operations.

In general, the best performance is obtained when "permissive" communications systems are used. "Blocking" systems have the weakness of favoring tripping upon loss of communication (i.e., an external fault may lead to tripping), whereas the "permissive" or "unblocking" systems favor security, i.e., no pilot tripping is allowed, upon loss of communication. With RALZA having the zone 1 impedance element, an overlap is obtained to allow the majority of faults to be cleared in 35 (or 85) ms even if communication is lost, using the permissive or unblocking communication methods. The RALZA system therefore provides added reliability compared to "pilot only" systems.

CONCLUSIONS

To overcome the problems cuased by the one-shot nature of a pure traveling-wave relay, impedance elements have been added to the system to provide protection against internal faults occuring after the DWD determines that the inital fault was external, and also to provide remote backup facilities to other relay systems that could fail to clear the fault. The neutral current controlled mode has been introduced to provide a highly sensitive DWD channel dependent mode that enables surge arrester discharge within protected zone.

The described relay employs proven multiple measurement techniques and functions to ensure the largest possible fault coverage at speeds commensurate with the power system requirements. Optimum sensitivity and reliability, immunity from system and transducer error phenomena, phase selectivity, and modest demands on the communication channel are features achieved by the unique combination of measuring techniques. Multiple functions are integrated in the relay to provide superior performance by mutal support whereby the inherent strenghts of each measurement technique are used to improve the characteristics of others.

Wide setting ranges and flexibility of characteristics enable the relay to be used to protect any EHV or UHV line which may be short or long, series compensated, heavily loaded, or equipped with in-zone switched shunt reactors.

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