TRANSMISSION LINE PROTECTION SYSTEM FOR INCREASING POWER SYSTEM REQUIREMENTS

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***Abstract*—This paper describes a protective relay for fast and reliable transmission line protection that combines elements that respond only to transient conditions with elements that respond to transient and steady state conditions. In this paper, we also present an algorithm that prevents Zone 1 distance element overreach in series-compensated line applications and show how to prevent corruption of the distance element polarization during pole-open conditions. We also introduce an efficient frequency estimation logic for single-pole-tripping (SPT) applications with line-side potentials. This logic prevents distance element misoperation during a system frequency excursion when one pole is open. We also discuss an algorithm and logic to prevent singlepole reclosing while the fault is present, avoiding additional power system damage and minimizing system disturbance. Applying these algorithms and logics results in a protective system suitable for increasing power system requirements such as heavy loading, SPT, series line compensation, and shunt line compensation.**

***Keywords*-distance; frequency; high-speed; line; overreach; polarization; protection; secondary-arc; transmission**

I. INTRODUCTION

Right-of-way restrictions and limitations on building new transmission lines necessitate optimization of transmission networks. This optimization imposes challenges on distance relay-based transmission line protection. Network optimization increases transmission line loading and requires fast fault clearing times because of reduced stability margins. In many cases, series compensation, SPT, or the combination of both is necessary to optimize transmission network investment. Series compensation generates subharmonics that can cause distance element overreach. SPT adds complexity to the ability of the distance element to track the power system frequency during single-pole open (SPO) conditions when the line protection uses line-side potentials. Shunt compensation can corrupt the distance element polarization because of the presence of transient voltages during three-pole open conditions when the line protection uses line-side potentials. SPT applications without arc extinction methods can jeopardize power system operation if the fault condition has not disappeared before the reclosing attempt; that is, the breaker closes under fault condition, making the power system prone to instability. Combining elements that respond only to transient conditions with elements that respond to transient and steady state conditions results in dependable, high-speed protection. Dedicated logic for series compensation applications adds security to the distance elements in the presence of subharmonics. Flexible polarizing quantities and frequency tracking algorithms adapt to different breaker and system operating conditions. Secondary arc extinction detection optimizes the single-pole open interval and minimizes power system damage in SPT applications.

II. RELIABLE HIGH-SPEED TRIPPING

A significant reduction in operating time is one trend in recently developed digital transmission line relays. A number of new techniques allow secure sub-cycle tripping of transmission line distance relays. One of the first proposed methods uses variable-length data-window filtering with adaptive zone reach [1]. Developments described in Reference [2] introduced the concept of multiple data-window filters (a total of four) with corresponding fixed reach (the smaller the data-window, the smaller the reach). Line protective relays not only need to pick up fast for incipient faults but also to provide proper and fast fault type selection in SPT applications.

A. High-Speed Distance Element Operating Principles

Based on the principle of multiple data-window filters mentioned above, we developed the concept of the dualfilter scheme. This scheme combines voltage and current data from half-cycle and one-cycle windows (Figure 1) to obtain Zone 1 distance element detection and achieve fast tripping

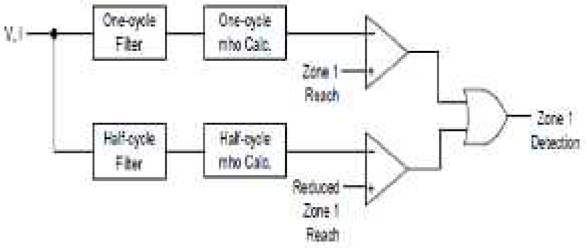

Figure 1. Concept of a Zone 1 Distance Element Using Dual-Filter Scheme

The mho calculation in Figure 1 uses operating (SOP) and polarizing (SPOL) vector quantities defined as follows to implement mho distance element calculations [3]: SOP r • ZL1 • IR– VR (1) SPOL VPOL (2) Where: VR = line voltage of the corresponding impedance loop IR = line current of the corresponding impedance loop ZL1 = positive-sequence line impedance r = per-unit mho element reach VPOL = polarizing voltage VR and IR are the relay voltage and current phasors particular to an impedance loop (six loops are necessary to detect all faults), and VPOL is the polarizing voltage, consisting of the memorized positive-sequence phasor [3]. A mho element with reach r detects the fault when the scalar product between the two vectors is positive (i.e., the angle difference between SOP and SPOL is less than 90 degrees). We can represent this condition mathematically as:

$$r \bullet \left|Z_{L1}\right| \geq m \bullet \left|Z_{L1}\right| = \frac{\mathrm{Real}\left[V_R \bullet V_{POL}^{*}\right]}{\mathrm{Real}\left[\left(1\angle\theta_{L1}\right) \bullet I_R \bullet V_{POL}^{*}\right]} \qquad (4)$$

Where:

$1\angle\theta_{L1}$ = phasor with unity magnitude and an angle equal to the positive-sequence line impedance angle

m = per-unit distance to fault

n this expression, “Real” stands for “real part of” and “*” for “complex conjugate of.” For a forward fault, this expression becomes equivalent to the reach r being greater than a distance m computed in 1∠θL1 = phasor with unity magnitude and an angle equal to the positive-sequence line impedance angle m = per-unit distance to fault As Figure 1 shows, we use two sets of filtering systems to achieve speed in fault detection: one fast (data window of one half-cycle) and one conventional (data window of one-cycle) to compute the line voltage and current phasors. For each loop, we implement two mho-type detectors, each of which uses the fast or the conventional phasors. We achieve the final detection logic simply by “ORing” the outputs from the two mho-type detectors. We apply this principle for Zone 1 detection and for zones (normally 2 and 3) used in communications-assisted schemes (POTT, DCB, etc.). In the case of Zone 1, the half-cycle detector has a reach less than the one-cycle detector reach. For Zones 2 and 3, the reach remains the same. We do not apply the principle in time-delayed stepped distance schemes because high-speed detection.

III. SERIES COMPENSATION OVERREACHING PROBLEMS AND SOLUTION

Series capacitors applied on transmission systems improve system stability and increase power transfer capability. The application of a series capacitor reduces the inductive reactance of the given transmission line, making the line appear electrically shorter. Although series capacitors may improve power system operation, using these capacitors results in a challenging problem for impedance-based line protection. Adding series capacitors on a transmission line causes subharmonic transients to occur following faults or switching of the series capacitor. These subharmonics can cause underreaching Zone 1 distance elements to overreach for external faults. There are other problems associated with subsynchronous resonance in generators. In this paper, we focus on problems associated with distance relays. All series capacitors come equipped with protective elements that reduce or eliminate over-voltages across the capacitor. The protection may be as simple as a spark gap set to flashover at a given voltage or as elaborate as metal-oxide varistors (MOV) using complex energy monitoring schemes. In any case, operation of the series capacitor protection elements can either remove the series capacitor completely or change capacitive reactance in a nonlinear fashion. The simplest series capacitor protection scheme removes the series capacitor when the series capacitor voltage exceeds a set threshold. The use of a spark gap protection scheme can simplify use of underreaching distance relays on seriescompensated lines. Firing of the spark gap for external faults may prevent Zone 1 overreach, so it is then possible to ignore the series capacitor. In most applications, however, the spark gap firing voltage threshold is high enough that the spark gap does not fire for external faults. MOVs present an interesting challenge because this type of protection scheme does not fully remove the series capacitor. In fact, the capacitive reactance can be very nonlinear. We can use an iterative model [16] to approximate the effective reactance of the MOV-protected bank. However, this model does not provide insight about the transient response.

A. Distance Relay Overreaching Problems

The series connection of the capacitor, the transmission line, and the system source create a resonant RLC circuit. The natural frequency of the circuit is a function of the level of compensation and the equivalent power system source. The level of compensation can change according to the switching in and out of series capacitor "segments." The source impedance can change because of switching operations external to the protected line section. Figure 5 illustrates a transmission line with a 50 percent series-compensated system (e.g., the series capacitor reactance equals 50 percent of the positive-sequence line reactance). For the fault location shown, the underreaching distance element at the remote terminal (Station S) should not operate. Intuitively, we would expect that setting the reach to 80 percent of the compensated impedance (ZL1 – jXC) would be an appropriate reach setting. However, the series capacitor and the system inductance generate subharmonic oscillations that can cause severe overreach of the distance element. Figure 6 shows the impedance plane plot for the fault location shown in Figure 5.

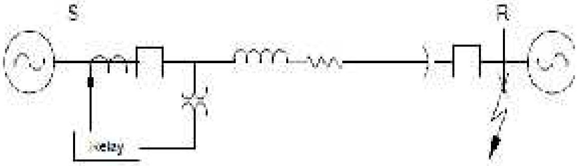

Figure 5. System With Series Capacitors at One End With a Fault at the End of the Line

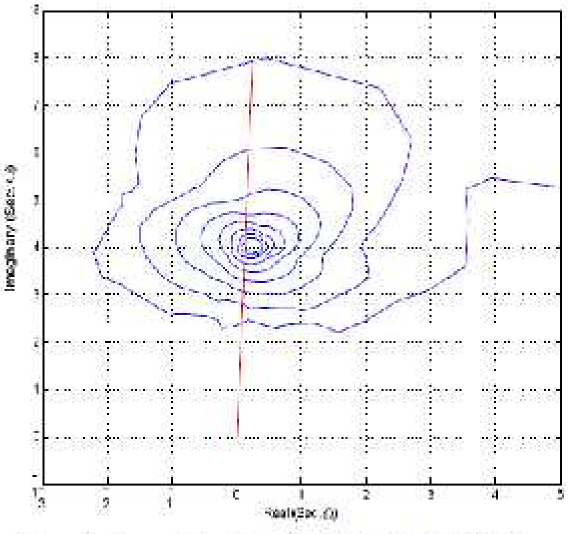

Figure 6. Apparent Impedance for a Fault at the End of the Line

As we can see from the impedance plot, the apparent impedance magnitude decreases to a value as low as 2 ohms secondary. This value is close to half of the compensated line impedance! Note that in Figure 6 the capacitor is modeled with no overvoltage protection. This condition is common for most external faults, because the overvoltage protection is typically sized to accommodate external faults (e.g., the overvoltage protection does not operate for external faults).

IV. DISTANCE ELEMENT POLARIZATION DURING POLE-OPEN CONDITIONS

VPOL is the polarizing voltage for calculating the distance to fault, m, as Equation 4 illustrates. The most popular polarizing quantity for distance protection is positive-sequence voltage with memory [2]. During pole-open conditions in applications with line-side potentials, eventual corruption of the polarizing quantity can occur if the input voltage to the memory circuit is corrupted. Invalid memory polarization may cause distance element misoperation. Shunt reactor switching generates damped oscillations with signals that have frequencies different from the actual system frequency. Let us look at an example of these signals and the logic that prevents the memory polarization from using unhealthy voltages. A. Shunt Reactor Switching Shunt reactors compensate the line charging currents and reduce overvoltages in long transmission lines. Figure 8 shows a 735 kV transmission line with shunt compensation at both ends of the line, 200 MVARs at each line end. The figure also shows line capacitance that generates 546 MVARs of reactive power. After the circuit breakers open at both line ends, the remaining circuit is basically an RLC circuit with a natural frequency of about 51.36 Hz; the circuit has stored energy in the reactor and in the line capacitance. Note that the circuit natural frequency is close to the nominal system frequency of 60 Hz. After the three poles of each line breaker open, the shunt reactors interact with the line capacitance and maintain line voltages for several cycles. The circuit applies these voltages to the potential transformers (PTs) or capacitive voltage transformers (CVTs). These voltages corrupt the distance protection polarization and frequency estimation. Figure 9 shows the A-phase voltage at the relay location after de-energization of the line (in Figure 8). There is no need to feed this distorted voltage to the distance protection polarization and frequency estimation algorithm, as we explain later.

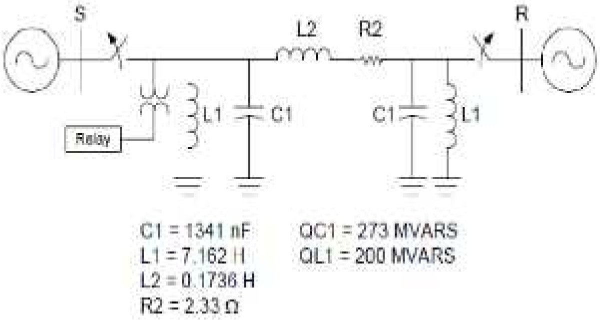

Figure 8. 735 kV Transmission Line With Shunt Compensation at Both Ends of the Line

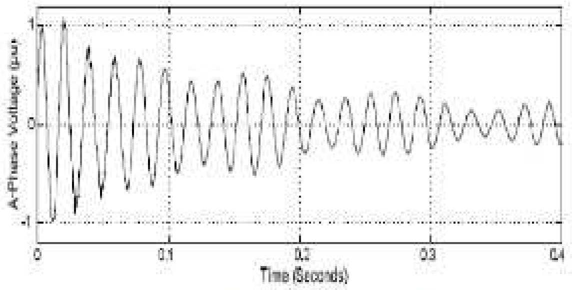

Figure 9. A-Phase Line Voltage After Line De-energization

V. EFFICIENT FREQUENCY ESTIMATION DURING POLE-OPEN CONDITIONS

Figure 11 shows a two-source system with line protection using line-side potentials in an SPT application. This figure also shows Breaker 1 (BK1) and Breaker 2 (BK2) A-phase open, indicating a single-pole open condition for both breakers. The distance element can misoperate during frequency excursions and single-pole open conditions if it does not track the system frequency correctly [2]. To prevent relay misoperations, the distance element needs a reliable frequency estimation algorithm for proper frequency tracking during breaker pole-open conditions. Traditionally, relays that calculate frequency must have circuitry that detects zero-crossings of the voltage signals to determine the signal period. The inverse of the signal period is the frequency. Normally, this circuitry monitors a single-phase voltage; the relay cannot measure frequency if the monitored phase is de-energized during the pole-open condition. Some numerical relays use zero-crossing detection [7] or rate-ofchange of angle algorithms to calculate frequency [8]. Some of these relays use positive-sequence voltage to include voltage information from the three phases [8]. These relays calculate frequency reliably as long as the voltages are present and healthy.

VII. CONCLUSIONS

1. The result of using the dual-filter scheme technique is reliable high-speed transmission line protection compared to conventional one-cycle only filtering schemes.
2. The ratio of the measured voltage, V_{MEAS}, to the calculated voltage, V_{CAL}, in series compensation applications provides information to block Zone 1 distance elements and prevent distance element overreach.
3. The ability to remove the open phase voltage prevents using corrupted signals for distance element polarization and frequency tracking during pole-open conditions or loss-of-potential conditions.
4. Using the composite signal, V_α, allows relays to track system frequency during pole-open conditions. The composite signal combines information from the three phases without additional signal manipulation, as in the case of positive-sequence quantity.
5. Secondary arc extinction detection prevents single-pole reclosing while the fault is present and optimizes the single pole-open interval, avoiding additional power system damage and minimizing system disturbance.

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