Charging Current in Long Lines and High Voltage Cables – Protection Application Considerations

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Abstract—In the analysis of power line protection behavior, the series impedance of the lumped parameter line model is often sufficient because the impact of the shunt capacitance is not significant. However when long transmission overhead lines or underground cables are present in the system, the effects of the charging current caused by the shunt capacitance need to be considered. This current flows onto the protected line or cable from all terminals. Its impacts are present during normal operation and during system transients. Due to the homogeneity of the line impedances, the charging currents can be relatively equal in each phase in the steady state. Thus the negative and zero sequence components will be small – an advantage when applying relays that operate for sequence components. However, the charging current during line energization, internal, and external faults will differ from steady-state values. This paper explores the impact of charging current on the various types of protection employed to protect line and cable circuits. It reviews methods used to mitigate the effects of charging current and provides general guidance on settings.

I. PRINCIPLES OF HIGH VOLTAGE LINE PROTECTION

We begin this paper with a review of the basic operating principles of those relays typically applied for line or cable protection. Distance relays are widely used for line protection. In a Mho type distance element, the operating signal generally takes the form, \( IZ-V \). It is inherently directional owing to polarization by a voltage measurement. The under-reaching distance element (zone 1) is carefully designed to limit transient over-reach. Consequently it can be applied for instantaneous tripping without a communications channel. Practically, the zone 1 distance reach is typically set to 85-90% of the line to account for instrument transformer inaccuracy and relay manufacturing tolerances.

Overreaching distance elements are also applied in conjunction with a communications channel. Transient overreach is inconsequential because relays at all terminals are involved in the trip decision. However the scheme is dependent on the availability of the channel.

The directional overcurrent relay is similar to the distance relay in that it makes a decision on fault direction through the measurement of local loop voltages and currents. The operating signal is the locally measured terminal current in form of phase quantities or sequence components. Directionality is provided either by a polarizing current or voltage. The element produces a positive indication of a fault, however, since it does not have a definite forward reach it must be used in conjunction with a communications channel in order to provide correct operations.

A second category of line protection is the current-only scheme. This category includes phase comparison and current differential relays. In a phase comparison scheme, the operating signal is the local current. Polarities of the local and remote currents are exchanged and compared using a communication channel to determine if the fault is internal. Conceptually, the transmitted signal is a square wave with rising and falling edges that correspond with the positive and negative zero crossings of the local waveform. A timer accounts for phenomena which prevent a perfect coincidence of the local and remote currents [1].
angles are exchanged through the digital communication channel. Summation of local and remote current gives a positive identification of an internal fault. The scheme is more sensitive than phase comparison. However, the security of the scheme can be negatively impacted by CT saturation. As a result, common implementations employ either a percent-differential signal exceeds the pickup threshold which is channel. Summation of local and remote current gives a absolute magnitude of the differential current and to the characteristic shape shown in fig 5. This allows magnitude and angle differences to be treated separately. The characteristic shape is set to provide security for channel synchronization errors and for CT saturation.

II. CHARACTERIZATION OF CHARGING CURRENT

Next we turn to the phenomenon of charging current and try to characterize it in terms of the magnitude of its phase and sequence components.

- Calculation of shunt capacitance of line or cable

In general, two arbitrarily spaced conductors exhibit capacitance with each other due to the potential difference between them.

\[ V = \frac{q}{\pi \varepsilon} \ln \frac{d}{r} \]  

where \( \varepsilon \) is the permittivity of dielectric between the conductors. For overhead transmission lines, the permittivity of air is approximately equal to dielectric constant of a vacuum, \( \varepsilon = \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \). From Eq. (1) and per definition, the capacitance between two conductors in unit length is

\[ C = \frac{q}{V} = \frac{\pi \varepsilon}{\ln \frac{d}{r}} \]  

The Eq. (2) is the general formula to calculate the capacitance. Depending on the structures and geometry of the line or cable, the parameters \( d \) and \( r \) in Eq. 2 would be defined differently. But this general formula tells us that the capacitance of an overhead line is determined by the conductor size, the spacing (between conductors, between conductor and ground), and the total length of the line. For a cable, the permittivity \( \varepsilon \) of the dielectric around the conductors is generally 2–4 times the dielectric constant \( \varepsilon_0 \). In addition, the spacing between each cable conductor and ground is usually much smaller than those of overhead line, so the cable will exhibit much higher capacitance than the overhead line with the same length.

In a typical three phase power system, since there are potential differences between the phase conductors and between each phase conductor and ground, each conductor exhibits self
capacitance between itself and ground, and mutual capacitance with regards to other conductors, as illustrated in Fig. 7.

\[
\begin{bmatrix} C_{AA} & -C_{AB} & -C_{AC} \\ -C_{BA} & C_{BB} & -C_{BC} \\ -C_{CA} & -C_{CB} & C_{CC} \end{bmatrix} = \ln \frac{2\pi e}{r_{eq}d_m^2}
\]

where \(h_m = \sqrt{h_a h_b h_c}\) is the geometric mean height of the line on the tower, and \(D_m = \sqrt{D_{AB} D_{AC} D_{BC}}\) is the geometric mean distance between one phase and the image the other phases.

The positive sequence charging current is calculated as

\[
I_{ch} = j\alpha C_{\text{pos}} V_{ph-\text{ave}} \sqrt{3}
\]

- Impact of line transposition

Transposition of a transmission line is the practice of physically rotating the position of each phase conductor over the length of the line such that each conductor occupies each position for 1/3 of the total line length as shown in figure 8.

\[
\begin{bmatrix} 127.6 - 96.0 j \\ -127.6 - 96.0 j \end{bmatrix}
\]

Figure 8. Transposed Transmission Line

We can calculate the capacitance matrix for a 345 kV, 100 mile line with the line geometry of Fig. 7. We assume a bundle of 2 1590 ACSR conductors (radius=0.219 in) spaced at 18 inches. Spacing between phases is 15 feet and the height the three conductors is 120 feet. We will ignore the sag and also the ground conductors. These simplifications have only a small impact on the result. For this exercise we will use a line constants program to determine the impedance components of the line. The resulting capacitance matrix is

\[
\begin{bmatrix} 17.91 & -5.81 & -5.81 \\ -5.81 & 16.79 & -2.83 \\ -5.81 & -2.83 & 16.79 \end{bmatrix} \text{nF/mi}
\]

Note that Phase B and C self-capacitance are equal and lower than A as suggested by the line geometry. The AB and AC mutual values are also equal and larger than BC.

Assuming a line length of 100 miles and applying Eq. (3) we get the following.

\[
\begin{bmatrix} 178.1 j \\ 127.6 - 96.0 j \end{bmatrix}
\]

The resulting positive-, negative-, and zero-sequence current magnitudes are 165A, 18A, and respectively 4.6A. Note that although the line is un-transposed, the negative and zero sequence currents are quite small in comparison to the phase values.

We can calculate a transposed capacitance matrix based on rotations shown in Fig. 8. On a line which is fully transposed, the resulting self and mutual admittances will be equal and can be calculated as \((C_{AA} + C_{BB} + C_{CC})/3 = 17.16 \text{ nF/mi}\) and \((C_{AB} + C_{BC} + C_{CA})/3 = 4.82 \text{ nF/km}\).
$C_{\text{transposed}} = \begin{bmatrix} 17.16 & -4.82 & -4.82 \\ -4.82 & 17.16 & -4.82 \\ -4.82 & -4.82 & 17.16 \end{bmatrix} \frac{nF}{\text{km}}$

The resulting positive-, negative-, and zero-sequence current magnitudes now becomes 165A, 0A, and 0A respectively. The positive sequence current is unchanged. The zero value of negative- and zero-sequence charging currents is a result of perfectly balanced 3 phase currents that are due to the symmetry of the capacitance matrix (assuming no major physical differences between the 3 line sections) and under the assumption that 3 phase voltages are balanced.

It is important to note that a significant cost will be incurred in the construction of transposition structures. The right-of-way may require more space. In addition, the possibility of electrical faults is often greater at the transposition locations. For these reasons transposed lines are not at all common in many power systems.

- **Line and Cable examples**

The following table presents the shunt capacitance and charging currents of three example circuits: a 345kV cable, a 345kV overhead line (OHL) and a 765kV overhead line. The cable/line data are provided in the appendix of this paper. The capacitance are calculated by using EMTP/ATP JMart Model and ATPDraw5.6 Line Check Tool. The charging current are calculated per nominal voltage of the line. From these examples, the charging current of a 5-mile cable is equivalent to that of a 100-mile overhead line with the same voltage level. The table also shows that charging current is quite significant for long distance EHV lines.

<table>
<thead>
<tr>
<th>Length</th>
<th>Shunt C1 (@60Hz)</th>
<th>Shunt C0 (@60Hz)</th>
<th>Charging current</th>
</tr>
</thead>
<tbody>
<tr>
<td>345kV Cable</td>
<td>5mile</td>
<td>1.9341 uF</td>
<td>1.0468 uF</td>
</tr>
<tr>
<td>345kV OHL</td>
<td>100mile</td>
<td>2.1363 uF</td>
<td>0.9892 uF</td>
</tr>
<tr>
<td>765kV OHL</td>
<td>150mile</td>
<td>2.9604 uF</td>
<td>1.9889 uF</td>
</tr>
</tbody>
</table>

**III. IMPACT OF CHARGING CURRENT ON PROTECTION**

We now can examine the impact of charging current on various line protection relays or elements. The analysis is performed for both steady state and transient conditions. The real time digital simulation (RTDS) is used to aid the analysis and a 150-mile 765kV line was modeled on RTDS as shown in Fig. 9. The 765kV line data are given in the Appendix. The CT ratio for line protection is 3000/5. To evaluate the charging current under the worst scenarios, the shunt reactor breakers were open in a number of simulation cases.
directional overcurrent elements are building blocks of pilot schemes such as Directional Comparison Blocking (DCB) or Permissive Overreaching Transfer Trip (POTT), the pilot scheme may misoperate when energizing the line or cable.

Differential Element

Assume the line is protected by a percentage differential element (87L) that has a pickup setting of 10% (0.1 p.u. or 300A primary). This 87L element also has a slope setting of 25%. The same settings apply to both phase currents and negative sequence current, as shown in Figure 11. Under a single-end feed situation, the magnitudes of the differential and restraint current are equal. Therefore, whether the element will operate or not is solely depends on the magnitude of the differential current and the pickup setting.

The geometry of the overhead line conductors is in general symmetrical. Naturally, the phase charging current is much more prominent than the sequence charging current. In this case, the phase differential current has a magnitude almost twice the pickup setting while the negative sequence current is about half of pickup setting. Therefore, the phase element is not safe if a sensitive pickup setting is applied. The degree of line asymmetry determines the security margin of the negative sequence element.

Differential relays that use the alpha plane will check that the magnitude of the differential current is above the pickup setting and that the complex ratio \( k \) lies in the operate region of the alpha plane, as shown in Fig. 13. If the differential current is lower than the pickup, \( k \) is forced to the (-1, 0), which is the ideal blocking point on alpha plane.

The outcome of mapping the local and remote current phasors to the alpha plane characteristics is similar to that of percentage differential characteristic. With the current from one line end being zero, the complex ratio \( k \) is either infinity or at the origin, which is always within the trip region of the alpha plane characteristic. Assuming the pickup setting is also 0.1 p.u. for phase and negative sequence element, similarly, the phase differential current magnitude surpasses the pickup threshold, which leads to a trip decision. The negative sequence element is secure with the ratio \( k \) being \( 1 \leq 180^\circ \) owing to the low steady-state value of the negative sequence charging current.

![Figure 11. Magnitude of Negative Sequence Current (3I2) and Angle Different Between -3\( \sqrt{2} \) and 3I2 with standing charging current](image)

**Figure 11.** Magnitude of Negative Sequence Current (3I2) and Angle Different Between -3\( \sqrt{2} \) and 3I2 with standing charging current

**B. Transient Operation**

The existence of charging current in conjunction with certain power system transients poses greater threat to line protection elements. Typically, the charging current appears with a higher magnitude during transients than that at steady state. This subsection will cover the behavior of charging current during three different power system transients: line energization, external fault and single pole open.

1. Line Energization

When the CB closes to energize the line, the line capacitance \( (C_L) \) draws inrush charging current in the first few cycles. As illustrated in Figure 14, this phenomenon can be understood as a resonance of the source plus the line reactance \( (L_S + L_L) \) against the line capacitance \( (C_L) \), which is damped by the resistance \( (R_S + R_L) \) in this RLC circuit. The natural frequency of this LC resonance is:

\[
 f_n = \frac{1}{2\pi \sqrt{(L_S + L_L) \cdot C_L}} \tag{10}
 \]

Because the serial line inductive reactance is much smaller than the shunt capacitance reactance, this initial resonance contains an abundance of high frequency components. For the 765kV line in Fig. 9, the frequency components in the inrush
charging current are predominately in the neighborhood of the third harmonic (170Hz). As the harmonic content decays over time, the charging current waveform becomes more sinusoidal at the fundamental frequency.

Figure 14. Line Energization Resonance and Inrush Charging Current

In [3], the oscillation of the distance measurement was observed and the authors claimed such oscillation can cause the distance protection to overreach or to operate slowly. However, throughout our RTDS study with the 765kV system in Fig. 9, there was no distance relay mis-operation for either internal or external faults. It is recognized that different distance relays would have different filters and different algorithms to compute phasors as well as impedance reach. The relays used in our RTDS tests are based on low pass filter and cosine filters, which can effectively remove the high frequency content in the transient. However, it was observed that there is some potential risk during the energization of the line. Figure 15 shows the impedance loci when the line was energized. It can be seen that the apparent impedance moved erratically before eventually settling at the steady state operating point ($65° - 84°$). The trace of apparent impedances appears to swiftly cross both zone 1 and zone 2 mho circles. However, the calculated impedance points all fall outside of both mho circles. It may be possible for zone 1 distance elements to be armed for one processing interval if the CB closing takes place at a different point on wave (POW). But modern distance relays typically have multiple security measures that can prevent mis-operation caused by transients. It is unlikely that distance zone 1 will simply trip by such kind of transients.

Figure 15. Distance Element Response to Power System Transients

The directional element could be adversely affected by charging current during line energization. The Figure 16 shows the angle difference of negative sequence voltage and current, and the magnitude of negative sequence current. For EHV lines, three single-pole breakers are typically applied. When the CB closes, the three poles may not be closed at exactly the same instant. The typical time delay is 0.2~1.5ms among three phases. Due to the combination of unequal pole closing and non-fundamental components in the inrush charging current, the polarizing quantity (3V2) and operating quantity (3I2) developed a series of angle difference values going in and out of the forward region (between the two horizontal green lines) multiple times in the test case. The highest negative sequence magnitude is almost 3 times that at steady state. But it lasted just for a very short moment. Under the worst scenario, the directional overcurrent could assert forward fault momentarily, which means risk of mis-operation for pilot schemes such as DCB or POTT. The coordination delay of such pilot schemes may be able to override such momentary directional overcurrent pickup, but it would be more secure to use a higher pickup setting or slightly longer time delay settings to handle such transients caused by charging current at line energization in this example.

Figure 16. Negative Sequence Directional Element during Line Energization

The negative sequence percentage differential element (87LQ) was proven to be secure in steady state. In the event of line energization, the 87LQ element can be affected by unequal pole closing. In the RTDS case study, the A phase took the
lead to close first. Approximately 0.23 ms later, B phase followed the A phase and closed. The C phase pole conducts after another 0.92 ms delay. The results are plotted in Figure 17. The discrepancy of pole closing time results in negative sequence current. In this study, the pickup of 0.1 p.u. guaranteed safe operation in steady states. But it was not enough to prevent the 87LQ to misoperate unless the pickup setting is doubled or even tripled temporarily for the line energization.

Some protection may be affected by the transients or CT saturation incurred by an external fault. Protective relays must be restrained for a fault adjacent to its protection zone in order for other relays designated to protect that part of the system to interrupt the fault, resulting in smaller system impact.

A B-C phase to phase fault on Bus B was simulated on the sample system. The green trace in Figure 14 represents the apparent impedance seen by the distance relay at Station A. It enters the zone 2 mho circle and oscillates within an area close to the positive sequence line impedance. It is obvious that zone 1 distance element is not in danger. The case study shows that the charging current does not affect the distance element other than causing small oscillation in the measured impedance values.

Because the operating quantity is also the restraint quantity during line energization, the alpha plane based 87LQ element is equally vulnerable to the elevated level of negative sequence current due to unequal pole closing. Figure 18 shows that the alpha plane 87LQ element would also trip for this case. A higher 87LQ pickup setting or temporary increase of pickup setting can help the relay to ride through the line energization, which means compromise on the sensitivity of 87LQ element. However, this may not be a problem if the zero-sequence current based current differential element is used in parallel to provide coverage for high resistive ground fault.

For the same case, the negative sequence current seen by relay at Station A is considerably larger than the charging current. The magnitude of the fault current shown in Figure 19 is almost 30 times that of the charging current, which is understandable for a bus fault. This eliminates the impact of charging current in this case. Going into the fault, the angle difference between $-3\sqrt{2}$ and $3\sqrt{2}$ bounced for a number of processing intervals because of transients. Then, it quickly moves back into the forward region as soon as the magnitude of the operating quantity shoots above the pickup threshold. The forward indication from this relay is correct. The response of the relay at Station B was recorded and analyzed as well, the fault in reverse direction was asserted correctly.

For exactly the same reason, neither percentage differential element nor alpha plane differential element was triggered for this external fault, which also caused mild CT saturation. In case of asymmetrical CT saturation, i.e., only one among all the CT’s saturates heavily, the relay response to external fault looked like that to a single-end feed condition. Proper relay design such as external fault detector can prevent the differential relay to mis-operate due to CT saturation. However, this is not related to charging current.

In Figure 17, the restraint-differential pair travels to the far right side of the percentage differential characteristic following the fault inception and stays well within the restraining region. The ratio of local over remote current
phasor also sits in the vicinity of the ideal blocking point as shown in Figure 19.

![Figure 19](image1.png)

Figure 20. Security of Alpha Plane When Exposed to an External Fault

Some relays are based on phase angle comparison principle to utilize local and remote information with limited channel bandwidth. Figure 21 plots the equivalent angle difference in electrical degrees reflecting the time difference between the local current positive zero-crossing to that of the remote current. Owing to the load current, the angle difference hovers around -150° prior to the fault. In case the line carries very light load, the angle comparison could make a trip decision because both the local and remote currents are mainly composed of charging current. This can cause trouble for the phase angle comparison element if no additional check is available.

When a fault occurs, the angle difference leaves its initial value and jumps to the opposite side of the trip region. The large through fault current pulls the zero crossing of local and remote current further apart, approaching the 180 degree theoretical limit, which prevents the relay from tripping. The conclusion is that charging current does affect the phase comparison relay in the event of external fault.

![Figure 21](image2.png)

Figure 21. Phase Angle Comparison Element Response to Power System Transients

3. Single Pole Open

Single pole tripping of transmission lines is sometimes applied in order to improve system stability. To complete the single pole tripping and reclosing cycle successfully, protective element must remain secure during the pole open time. Undesired operation from a protective relay when exposed to a single pole open (SPO) condition will inadvertently convert a SPT action to a three pole tripping (3PT) event. Once all three poles of the circuit breaker are open, the capacity to transmit power between the equivalent systems at either end of the line is reduced; thereby increasing the potential for system break-up.

The B-C phase to phase distance element was evaluated and shown in Figure 14. The cluster of apparent impedances seen by this element hardly moved from before and after pole open. It can be confidently concluded that the distance element will not trip by charging current under SPO condition.

![Figure 22](image3.png)

Figure 22. Impact of Single Pole Open on the Negative Sequence Directional Element

When one phase is open, the negative sequence current is the result of both the unbalanced load and charging current. In Figure 22, the angle difference between the operating and polarizing quantity leaves the forward region and enters the reverse region as the magnitude of $3I_2$ increases from 0.4 to 2.7 amps. Without charging current, the negative sequence current phasor leads the negated negative sequence voltage phasor by about 166 degrees. The presence of charging current pulls the operating quantity towards the forward region. Nevertheless, as can be seen from Figure 22, this effect does not change the decision from the directional element.

![Figure 23](image4.png)

Figure 23. Phasor Diagram Showing the Relationship between $3V_2$ and $3I_2$ at the local and remote ends during a SPO condition

At the other end of the line, the direction of load flow creates an operating quantity in the forward region. The charging current moves the remote negative sequence current...
closer to the forward direction maximum torque line. The forward looking directional overcurrent element could operate. This justifies the need of inhibiting the sequence directional element during the period of pole open.

Figure 24. Impact of Single Pole Open and Charging Current on the Security of Alpha Plane

On the percentage differential plane, the main source of the negative sequence differential current switches from asymmetrical conductor placement to the absence of charging current contribution from the opened phase. Its magnitude grows approximately 5 times in this particular application. The trajectory of restraint-differential pair gets fairly close to the operating boundary in both transient and steady state (refer to fig 16). Should the slope setting be more sensitive, the charging current may cause the operating point to creep into the tripping zone.

Figure 24 gives the similar results on the alpha plane characteristic. The elevated differential current drives the complex ratio k away from the ideal blocking point, making this element less secure. If the charging current has a higher magnitude compared to the load current, the security of alpha plane element is at risk.

Typically, the phase angle comparison scheme operates on phase quantities. From the per phase point of view, the relationship between the load current and charging current does not change by the SPO condition. There is only a 2 degree shift in angle difference between the local and remote current (see Fig 20).

IV. METHODS OF CHARGING CURRENT COMPENSATION

From the previous simulations and analysis, the major impact of charging current is for differential relays (87L). The directional overcurrent may also be affected under specific conditions. With a focus on 87L relays, this section presents a few solutions to handle the large charging current of long EHV lines or cables.

A. Setting Desensitization

Manual setting desensitization is the practice of accounting for charging current during the development of settings for the application. In the case of line current differential elements (both percent differential and alpha plane), the setting procedure should begin with an assessment of the line charging current for the particular application. The pickup setting must be set at a safe margin above the charging current during line pickup to ensure security. Once the pickup setting is chosen, a calculation should be carried out to determine resistive fault coverage under worst case circuit loading. In the many applications it is likely the case that the differential can be safely desensitized while still providing good resistive fault coverage.

Dynamic desensitization is a process of automatic adjustment of the protection element characteristics. It can take the form of logic implemented in the relay by the manufacturer or user-programmed logic or setting groups. These schemes adjust the sensitivity of the element during specific conditions when the charging current is known to be at a high level.

For instance, one dynamic de-sensitization scheme introduces a ½ cycle delay time into the trip path and doubles the differential pickup setting when any terminal is open. This state remains in effect for 3 cycles after the terminal closes in order to preserve security during energization inrush. This alleviates the need to consider inrush during the setting calculation process. One disadvantage of the approach is that it can create additional dependencies (for example, circuit breaker aux contacts). A second obvious disadvantage is that sensitivity is compromised for a fault that coincides with desensitization condition.

B. Self compensation

There is no formal name for this charging compensation method so we will refer to it as self compensation, because this method uses the differential current to compensate the differential current itself [4]. During normal operation conditions, the 87L relay takes the average differential current measured during the last few cycles as the charging current magnitude and subtracts it from the presently measured differential current. If a disturbance is detected, the updating of the pre-fault differential currents will freeze and resume after the normal operation condition is re-established.

Since the differential current is continuously updated by subtracting the measured charging current, the operating quantity of such 87L scheme is zero or near zero under steady state, no matter how high the charging current is. In the same way, the “false” differential current that may be caused by CT error, communication channel problem, tap load or other reasons will be treated as charging current to be compensated. It is a desirable feature of this method to have zero differential current under normal conditions because this would allow more sensitive 87L settings for high resistive internal faults. Compared with voltage-based charging compensation, this method can avoid voltage signals and line capacitance settings in the 87L scheme. If shunt reactor is installed for the line, such 87L relay will also be immune to the variations of charging current when shunt reactor is put into or taken out of service.
On one hand, this compensation method helps to increase the 87L sensitivity. On the other hand, it may introduce extra differential current under external fault condition. For an external fault, the voltage will be suppressed and the actual charging current will be less than that at pre-fault condition. Since the pre-fault differential current is taken as charging current, the compensation process will result in “false” differential current. The increased restraint currents or external fault detector could help to prevent the 87L operation. But it will be prudent to evaluate the 87L characteristic settings for some EHV lines/cables or tap load applications.

Another concern of this compensation method is during the line or cable energization process, the method cannot provide any charging compensation simply because there is no current prior to energization. From Figure 14, the transient current caused by line capacitance could be quite high during energization so the relay using this method may mis-operate if the 87L were set for sensitivity. A possible solution is to increase the 87L settings temporarily before and during the energization. But it will compromise the line protection during the energization process.

C. Voltage-based compensation

The modern line differential relay usually incorporates voltage measurement for back up protections. When the voltage signal is available, the instantaneous charging current drawn by the line or cable can be calculated in real time by applying equation (2) from Section II. The calculated charging current is then subtracted from the operating quantity such that the 87L relay can have greater sensitivity. The basis of equation (2) is that the transmission line can be modeled as a two port component shown in Figure 25. This representation is called the transmission line T model. A more accurate way of approximating a physical line is to use the PI model, where the line capacitance is split evenly at the two line terminals.

\[
I_{ch} = \frac{C_L}{2} \cdot \frac{dV_S}{dt} + \frac{C_L}{2} \cdot \frac{dV_R}{dt} = C_L \cdot d\left(\frac{V_S + V_R}{2}\right)/dt
\]  

(11)

From equation (11), the charging current is estimated based on the averaged line voltage. This approach works well when the voltage profile of the line is not flat.

In addition to loss of potential (LOP), the location of potential transformer (PT) affects the availability of compensation as well. Assuming that the PT is placed on the bus side of the CB, the charging current compensation needs to be suspended if one phase of the CB is open. This is because the bus voltage does not follow the change in line voltage under SPO conditions. If it is still used to calculate the line charging current, the 87L can be inaccurate in a SPT application.

In order for multiple 87L relays to perform charging current compensation simultaneously, each relay in the scheme needs to know how many remote peers are also contributing. In any two terminal applications, this requirement is satisfied naturally because there must be a communication link between the local and remote relay. A bit in the data packet can be used to indicate if the sending relay is able to compensate.

A three terminal line with a tap point in the middle brings more complexity to the design of a multi-ended charging current compensation scheme. As shown in Figure 26, the communication channel between the 87L Relay X and Relay Z may be temporarily unavailable, which results in a three terminal master-slave operation. Under such situation, these two relays are unable to perform differential calculation and are treated as slaves. Only Relay Y can perform 87L calculations as it has access to all the current information required to derive the differential and restraint quantities. It behaves as the master by commanding the slave relays to trip as soon as it sees a fault.

Since the slave relays cannot communicate with each other, neither can decide the portion of the line capacitance that it needs to compensate for. Consequently, the compensation algorithm has to be inhibited in slave relays. However, the
master relay is capable of handling all of the charging current compensation for the 87L zone, albeit with reduced accuracy.

D. Other compensation methods

From literature [5, 6], the charging current may be handled by unconventional current differential schemes. In [5], the 87L relaying is built upon the calculated currents from a distributed line parameter model and the charging current will be eliminated in the calculated currents.

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\[
-\frac{\partial u}{\partial x} = r_0 i + l_0 \frac{\partial i}{\partial t}
\]

(12)

\[
-\frac{\partial i}{\partial x} = g_0 j + c_0 \frac{\partial u}{\partial t}
\]

(13)

Where \( r_0, l_0, g_0, c_0 \) are series resistance, series inductance, shunt conductance and shunt capacitance in unit length.

From (12) and (13), the positive sequence, negative sequence or zero sequence current components at any point \( k \) on the line can be calculated by

\[
I_{mki} = I_{m\#} c h(\gamma_{m\#} l_{mk}) - \frac{U_{m\#}}{Z_{c\#}} C h(\gamma'_{m\#} l_{mk})
\]

(14)

\[
I_{nk\#} = I_{nk\#} c h(\gamma_{nk\#} l_{nk}) - \frac{U_{nk\#}}{Z_{c\#}} C h(\gamma'_{nk\#} l_{nk})
\]

(15)

where \( c h( ) \) and \( C h( ) \) are hyperbolic functions, \( Z_c \) is the line characteristic impedance, \( \gamma' \) is the propagation constant and \( l_{xy} \) is the distance from point \( x \) to point \( y \) on the line. The \( \# \) in Eq. (14) and (15) are to be replaced by 1, 2 or 0 for positive, negative or zero sequence currents. With sequence components, the three phase currents at point \( k \) can be obtained as well. Using positive sequence currents as example, the differential current and restraint current of the 87L scheme are based on the calculated currents at a specific point \( k \) on the line,

\[
I_{diff\_1} = |I_{mk1} + I_{nk1}|
\]

(16)

\[
I_{restraint\_1} = |I_{mk1} - I_{nk1}|
\]

(17)

Since the 87L operating and restraint quantities are derived from the distributed line model per Eq. (12) ~ (15), the charging current is excluded naturally. As with the conventional voltage-based compensation, this method also needs a voltage signal, but this method can take any point on the line to perform differential and restraint calculation, which can improve the sensitivity of 87L scheme, according to [5]. From the simulation tests in [5], the proposed 87L relay can handle high resistive faults and is secure for external faults. There are also recommendations in [5] on how to select the \( k \) point to optimize the sensitivity and dependability of the 87L relay.

Similarly, there are other 87L schemes that use calculated current per line modeling to eliminate the impact of charging current for UHV lines. Theoretically, such 87L schemes can provide alternative solutions to handle large charging current for UHV lines or cables. But the practical applications and operational experience of such 87L relays not evident at this time.

V. Dynamic Analysis of Voltage Based Compensation Method

This section focuses on the performance of voltage-based compensation under the same system transients as those discussed in Section III. The T model and PI model method introduced in Section IV both belong to the category of approximating the line with lumped parameters.

The accuracy of the lumped model degrades as the line length increases and so does the charging current calculated from such a model. A long line can be better approximated by connecting a number of T sections in series so that each T section represents a shorter distance. A continuation of this process brings out the distributed model where the line is divided into infinite number of T sections. This is also how the classic Telegrapher’s equation describes the current and voltage relationship of a transmission line.

Implementing a distributed model for charging current estimation in most digital relays would be a challenge. The lumped model works well at fundamental frequency. However, oscillations as a result of power system transients cause the line to draw charging current at harmonic frequencies. Depending on the line length, the line shunt capacitance modeled by a single T section might deviate from the lumped value at the harmonic (natural) frequencies of the line. These harmonic frequencies will be significantly larger than the fundamental if the line is relatively short (<100 miles). For lines of longer length (>200 mi) the harmonic frequencies will approach the fundamental.

![Distributed vs Lumped Model](image-url)
Using the 765kV line data from the appendix, the magnitude and angle of the shunt susceptance are plotted in Figure 28. According to the lumped model, the line susceptance has a magnitude proportional to the system frequency and its angle is always at 90 degrees. The distributed model offers an accurate representation until the frequency and its angle is always at 90 degrees. The overall characteristic of line shunt component shifts from being capacitive to being reactive at certain frequencies.

The theoretical analysis can be verified by the simulation results presented below. These three transients have one thing in common, i.e. a temporary harmonic surge in the first a few cycles of the event.

1. Line Energization

![Figure 28. Comparing the lumped and distributed line capacitance model](image)

The lumped model is in fact the differential current seen by the 87L element after the compensation. The lower half of Figure 29 plots the fundamental magnitude of differential current with and without voltage-based compensation.

It is evident that the compensated differential current has a much smaller magnitude in comparison with that of the phase charging current even during the transient when there is a mismatch between the distributed and the lumped model. With charging current compensation enabled, the differential current never exceeds 0.1 amps (0.02 p.u.) throughout the simulated event. Since most digital relays operate on only fundamental quantities, a sensitive pickup setting can be safely applied to the 87L element without concern about inrush charging current.

2. External Fault

When a low impedance path is formed by a fault, the energy stored in line capacitance will be discharged into that phase to ground fault and secondary arcing can be ignored. Assume the A phase voltage drops to zero because of an A phase to ground fault and secondary arcing can be ignored after the breaker interrupts the fault current. Prior to the fault, the B-phase charging current can be expressed as

![Figure 29. Accuracy of charging current calculation during line energization transient](image)

![Figure 30. Charging current compensation at the time of an external fault](image)

There is a small difference between the behavior of the lumped and distributed model at the resonant frequency. However, the fundamental magnitude of the difference current is no higher than the pre-fault standing differential current. And with voltage-based compensation, it is much lower than that of the real charging current. In the steady state of an external fault, the averaged line voltage on the faulted phase is lower than nominal. The amount of charging current absorbed by the faulted phase is consequently lower.

3. Single Pole Open

Assume the A phase voltage drops to zero because of an A phase to ground fault and secondary arcing can be ignored after the breaker interrupts the fault current. Prior to the fault, the B-phase charging current can be expressed as
\[ I_{bc} = j \omega C_{bg} V_{bg} + j \omega C_{ab} V_{ba} + j \omega C_{bc} V_{bc} \]  

(18)

During the pole open interval, \( V_{ba} \) is identical to \( V_{bg} \) considering that the faulty phase is grounded. This effect is visualized in Figure 31.

Figure 31. Shift of charging current phasor due to SPO

\( I_{bc_{SPO}} \) represents the charging current phasor at the time when the breaker A phase is open. It has a slightly smaller magnitude and advanced angle compared with \( I_{bc} \).

![Figure 32. Impact of SPO on line charging current](image)

From Figure 32, it can be observed that the high frequency discharge transient on the faulted phase lasted for about two cycles. The transition of B-phase and C-phase charging currents from their pre-fault values to their respective pole open state values completed within the same time frame. The top oscillography in Figure 32 proves the anticipated magnitude reduction and phase shift. The compensated differential current magnitude plotted in the lower half of Figure 32 dropped to 0.05A once the transient came to an end.

To conclude, the 87L element will not be stressed by any above events as long as the voltage based charging current compensation is active.

VI. APPLICATION GUIDELINES

Section II showed that charging current is mainly a concern for line current differential and phase comparison schemes. Indeed, these are the only types of relay for which manufacturers provide charging current compensation. In addition, sequence directional elements should be checked for line energization and open pole operation. In this section we provide guidelines for determining when to use charging current compensation for current differential applications.

Step 1 in the process is determination of the charging current. Shunt capacitances can be calculated using (6) and (7) or using a line constants program. The difference between the results obtained by the two approaches is typically less than 10%. Charging current is then calculated using (8).

When charging current is significant, sequence directional elements could misoperate during line energization. In this case consider either to de-sensitize the element or to delay operation when the line is energized. Sequence directional elements should be blocked by open pole logic on lines that employ single pole tripping.

The pickup setting of the phase differential element must be set higher than the value of the standing charging current. To ensure security during line energization a margin of 200% could be considered. In relays which employ dynamic desensitization, a lower margin (150%) can be chosen; depending on the particular implementation.

Step 2 checks the coverage provided for resistive faults during line loading. In general the following equation gives the internal ground fault current for a two terminal line [8].

\[ I_{phg} = \frac{3}{2} \left[ V_{phn} - I_{load} \left( Z1S + d \cdot Z1L \right) \right] \]

(19)

Where

\[ Z1R + (1 - d) \cdot ZIL \]

\[ Z1S + ZIL + ZIR \]

\[ C0 = \frac{Z0R + (1 - d) \cdot Z0L}{Z0S + Z0L + Z0R} \]

(20)

Where Z1R, Z0R, Z1S, and Z0S are the positive and zero sequence impedance elements, Z1L and Z0L are the positive and zero sequence line impedances. \( V_{phn} \) is the line to neutral voltage, d is the location of the fault (0-1) and \( R_F \) is the fault resistance.

The fault current should be checked for d=0 and d=1 for the highest fault resistance for which the phase elements need to operate. This value should be greater than the pickup setting chosen in step 1.

For an alpha plane element the ratio \( K \) can be calculated as

\[ K_{ph} = \frac{2 \cdot (1 - C1) + (1 - C0) + 3 \cdot I_{load}}{2 \cdot C1 + C0 - 3 \cdot I_{load}} \]

(21)

Adequate coverage is verified by checking the magnitude and angle of \( K_{ph} \) against the ratio and blocking angle settings of the element.

For a percent differential the restraint signal is

\[ I_{r} = \left| \frac{I_{phg}}{I_{load}} \right| \]

(22)

Adequate coverage is verified by checking that the differential current is greater than the \( I_{r} \) multiplied by the slope setting.

Sequence differential elements applied on lines employing single pole tripping and with significant charging current should either be de-sensitized or be blocked by open pole logic.
If the differential element cannot provide the needed fault coverage then the use of line charging compensation is warranted. Relays which employ voltage-based compensation require that the positive and zero sequence capacitance (or susceptance) of the line be entered as a setting. Consequently, the differential elements can now be set without having to consider charging current. However, since a voltage measurement is required, voltage-based compensation is impacted by loss of potential or fuse-failure events. Some relays have a built-in logic which allows the user to fallback to more secure settings under LOP conditions. Other relays may not have built-in logic but the same functionality may be achievable using programmable logic and setting groups. In either case such schemes improve the availability of the differential protection but require additional effort in settings development. Relays which employ the self-compensation method described in section IV benefit from reduced settings requirements.

When negative sequence and zero sequence elements are applied an alternate strategy is to require the phase elements only to be sensitive for three-phase faults. The fault resistance requirements are lower for this fault type. As a result more margin is available for setting the element. The sequence elements provide excellent resistive fault coverage irrespective of loading. Sequence charging currents are significantly lower, even on un-transposed lines as evidenced in section II. The relaxed sensitivity requirement on the phase element lessens the need for charging current compensation.

Shunt reactors are often applied on long lines for voltage control (figure 32). These reactors will provide a portion of the charging current. This will create an error in compensation provided by voltage-based schemes. One solution to the problem is to calculate the combined susceptance of the parallel inductive and capacitive branches and to use this value when setting the relay. However, there are several problems with this approach. The first problem is that the degree to which the two branches cancel will differ in the transient and steady states. As a consequence capacitive inrush can still occur. The second problem is dealing with reactor switching. To achieve optimal compensation different settings would need to be applied with the reactors in and out of service and this may be impractical because changes need to be made to both local and remote relays.

A better solution is to measure the contribution of the reactors to the zone as shown in figure 33. Bringing the CT at shunt reactor branch into the 87L scheme, the shunt reactor is excluded from the 87L protection zone. Now the voltage based compensation can use full susceptance of the line as its setting once again. Reactor switching and line energization are no longer an issue.

![Figure 33. Direct measurement of shunt reactor contribution](image)

The impact of charging current on line protection elements has been explored through the use of a 765 kV line model.

Differential elements are more adversely impacted than other elements since they derive their operating signal from a summation of currents into the protected circuit and charging current is an unbalanced current entering the 87L zone.

Directional and differential elements that use negative or zero sequence components are at risk during line energization with unequal pole closing or under open pole conditions with low load. These elements should either be set at a safe margin above the phase capacitive current or be supervised by an open-pole indication (assuming no charging current compensation).

The security of distance elements was virtually unaffected during the specified testing. Proper filtering ensures that the impact on the impedance measurement for internal faults is minimal. This was confirmed in our testing.

The paper also has reviewed schemes for line charging current compensation. Several schemes are evaluated practically. Each scheme has particular advantages and disadvantages. The voltage-based compensation scheme has been analyzed during dynamic operation. Given that the requirement for a voltage measurement and additional settings are typically not onerous, the voltage-based compensation scheme provides good performance both in the steady state and during transients.

Application of charging current compensation is not always required. Often the charging current can be accounted for through the appropriate application of settings.

VIII. APPENDIX

**Circuit parameters for Table 1**

### 345kV Cable Parameters
- Conductor radius: 1.079 inch
- Sheath radius: 1.147 inch
- Total radius: 2.5 inch
- Resistivity of conductor: 1.7241e-8 ohm*m
- Resistivity of sheath: 2.14e-7 ohm*m
- Relative permittivity of insulation: 2.4
- Earth resistivity: 100 ohms*m
345kV Line Example:
Number of sub-conductor per bundle: 2
Sub conductor radius: 0.772 inch
Sub conductor spacing: 18.0 inch
Conductor dc resistivity: 0.028275 ohms/mile
Horizontal Distance between two bundles: 15 feet
Height at tower: (120.0, 120.0, 120.0) feet
Sag at Midspan: 28.0 feet
Ground wire radius: 0.21875 inch
Ground wire horizontal distance: 24 feet
Ground wire height at tower: (145.0, 145.0) feet
Ground wire sag at midspan: 16.0 feet
Ground wire dc resistivity: 0.646 ohms/mile

765kV Line Example:
Number of sub-conductor per bundle: 6
Sub conductor radius: 0.503 inch
Sub conductor spacing: 15.0 inch
Conductor dc resistivity: 0.015817 ohms/mile
Horizontal Distance between two bundles: 45 feet
Height at tower: (115.0, 115.0, 115.0) feet
Sag at Midspan: 65.0 feet
Ground wire radius: 0.323 inch
Ground wire horizontal distance: 90 feet
Ground wire height at tower: (155.0, 155.0) feet
Ground wire sag at midspan: 50.0 feet
Ground wire dc resistivity: 0.646 ohms/mile

**Capacitance of a three phase overhead line**

As per the method of images, the potential difference between the A-phase conductor and earth generated by the positive charge on itself and the negative charge carried by its mirrored image is

$$V_{A_{SELF}} = \int_{h_a}^{b_a} \frac{q_a}{2 \pi e} \frac{dx}{x} + \int_{b_a}^{2b_a} \frac{q_a}{2 \pi e} \frac{dx}{x}$$

$$= \frac{q_a}{2 \pi e} \ln \frac{h_a}{r_{eq}} - \frac{q_a}{2 \pi e} \ln \frac{h_a}{2h_a}$$

(23)

Likewise, the potential difference between the A-phase conductor and earth generated by the positive charge on the B-phase conductor and its negative image is

$$V_{AB} = \int_{h_a}^{b_a} \frac{q_a}{2 \pi e} \frac{dx}{x} + \int_{h_a}^{b_a} \frac{q_a}{2 \pi e} \frac{dx}{x}$$

$$= \frac{q_b}{2 \pi e} \ln \frac{h_b}{d_{AB}} - \frac{q_b}{2 \pi e} \ln \frac{h_b}{D_{AB}}$$

(24)

The potential differences between the conductor and earth when taking all three phases into account are

$$V_A = \frac{q_a}{2 \pi e} \ln \frac{2h_A}{r_{eq}} + \frac{q_b}{2 \pi e} \ln \frac{D_{AB}}{d_{AB}} + \frac{q_c}{2 \pi e} \ln \frac{D_{CA}}{d_{CA}}$$

(25)

$$V_B = \frac{q_b}{2 \pi e} \ln \frac{D_{AB}}{d_{AB}} + \frac{q_b}{2 \pi e} \ln \frac{2h_b}{r_{eq}} + \frac{q_c}{2 \pi e} \ln \frac{D_{BC}}{d_{BC}}$$

(26)

$$V_C = \frac{q_c}{2 \pi e} \ln \frac{D_{CA}}{d_{CA}} + \frac{q_b}{2 \pi e} \ln \frac{D_{BC}}{d_{BC}} + \frac{q_c}{2 \pi e} \ln \frac{2h_c}{r_{eq}}$$

(27)

In zero sequence capacitance calculation, assume that
\[ q_a = q_b = q_c = q_0 \]  
\[ 3V_0 = V_a + V_b + V_c \]  
\[ 3V_0 = \frac{q_0}{2\pi} \ln \frac{2h_a \cdot 2h_b \cdot 2h_c}{2} + \frac{q_0}{2\pi} \ln \frac{D_{AB}^2 \cdot D_{BC}^2 \cdot D_{CA}^2}{r_{eq}^3} \]  
\[ = \frac{q_0}{2\pi} \ln \left( \frac{2h_a}{r_{eq}} \right)^3 + \frac{q_0}{2\pi} \ln \frac{D_e^6}{d_{eq}^6} \]  
\[ V_0 = \frac{q_0}{2\pi} \ln \frac{2h_m}{r_{eq} \cdot d_m} \]  
\[ C_0 = \frac{V_0}{q_0} = \frac{2\pi}{\ln \left( \frac{2h_m}{r_{eq} \cdot d_m} \right)} \]  
\[ \text{When calculating the positive sequence capacitance, the relationship turns into} \]  
\[ q_a = \alpha \cdot q_0 = \alpha^2 \cdot q_c \]  
\[ 3V_1 = V_a + \alpha \cdot V_b + \alpha^2 \cdot V_c \]  
\[ 3V_1 = \frac{q_0}{2\pi} \ln \frac{2h_a \cdot 2h_b \cdot 2h_c}{2} + \frac{\alpha \cdot q_a}{2\pi} \ln \frac{D_{AB}^3 \cdot D_{BC}^3 \cdot D_{CA}^3}{r_{eq}^3} + \frac{\alpha^2 \cdot q_a}{2\pi} \ln \frac{D_{AB}^2 \cdot D_{BC}^2 \cdot D_{CA}^2}{d_{eq}^6} \]  
\[ = \frac{q_a}{2\pi} \ln \left( \frac{2h_a}{r_{eq}} \right)^3 + \frac{\alpha + \alpha^2}{2\pi} \cdot q_a \ln \frac{D_e^3}{d_m^3} \]  
\[ = \frac{q_a}{2\pi} \ln \left( \frac{2h_m}{d_m} \right)^3 \]  
\[ \text{Since } D_m \approx 2h_m, \text{ the above equation can be simplified to} \]  
\[ 3V_1 = \frac{q_a}{2\pi} \ln \frac{d_m^3}{r_{eq}^3} \]  
\[ \text{The positive sequence line capacitance can thus be found as} \]  
\[ C_1 = \frac{2\pi \varepsilon}{\ln \frac{d_m}{r_{eq}}} \]  

**IX. References**


**X. Biographies**

Yiyan Xue received his B.Eng. from Zhejiang University in 1993 and M.Sc. from the University of Guelph in 2007. He is currently a Senior Engineer in AEP P&C Standards Group, working on protection standards, relay settings, fault analysis and simulation studies. Before joining AEP, he was an Application Engineer with GE Multilin to provide consulting services on relay settings, scheme design and RTDS studies. Prior to GE, he had 10 years with ABB Inc. working on P&C system design, commissioning of relays and RTU systems. He is a senior member of IEEE and a Professional Engineer registered in Ohio.

Dale Finney received a bachelor of engineering degree from Lakehead University in 1988 and a Master of Engineering degree from the University of Toronto in 2002. He began his career with Ontario Hydro, where he worked as a protection and control engineer. Currently, Dale is employed as a senior power engineer with Schweitzer Engineering Laboratories, Inc. His areas of interest include generator protection, line protection, and substation automation. Dale holds of several patents and has authored more than twenty papers in the area of power system protection. He is a member of the main committee of the IEEE PSRC, a member of the rotating machinery subcommittee, and a registered professional engineer in the province of Ontario.

Bin Le received his BSEE from Shanghai Jiao Tong University in 2006 and an MSEE degree from the University of Texas at Austin in 2008. He has been employed by Schweitzer Engineering Laboratories, Inc. ever since. Mr. Le
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