Time-domain application of superimposed quantities in the phase comparison transmission line protection scheme

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Abstract: Here, the use of incremental currents in time-domain phase comparison (PC) line protection schemes is evaluated. The incremental currents have been applied in modern high-speed protection relays, showing to be suitable for protection functions based on time-domain analysis. To carry out the proposed studies, the alternative transients programme was used to simulate a wide variety of fault scenarios in a 500 kV/60 Hz test power system, considering different fault features (distance, resistance, and inception angle), source-to-line impedance ratio values, and system loading conditions. In each case, the tripping times of the time-domain PC protection when implemented using traditional phase currents, sequence currents, traditional incremental currents, and incremental replica currents are compared. The obtained results show the use of incremental currents improves the PC protection reliability, speeding up the protection operation times.

1 Introduction

The growing demand for electric energy in modern power grids has requested the transmission lines to transmit bulk power with good continuity of service [1]. As a result, stability margins of transmission networks are reducing year after year, what has been a concern to the electric power utilities. Therefore, utilities have invested in technologies capable of promoting fast and reliable protection schemes, such as electromechanical and electrostatic protection schemes. Such a protection compares the polarity of currents at the terminals of the power system shown in Fig. 1. In order to do so, the alternative transients programme (ATP) is used to simulate faults on a 500 kV/60 Hz transmission line 200 km long, considering different system loading conditions, fault parameters, and source impedance-to-line ratio (SIR) values. The obtained results reveal that the use of superimposed quantities makes the time-domain PC line protection faster and as sensitive as the traditional sequence elements, but providing phase selectivity.

2 Time-domain PC protection

2.1 PC protection principles

Aiming to better understand the PC protection principles, consider the power system shown in Fig. 1a. The time-domain PC function performs the analysis of the modulated values $S_L$ and $S_S$ of the instantaneous currents signals $i_L$ and $i_S$ at the local and remote line ends, respectively. The signal modulation is performed according to the polarity of the monitored signals, so that for positive values, the modulated signal receives a positive unit value and, for negative signal samples, the modulated signal receives a zero value. Thus, the comparison between the modulated signals is performed by an AND gate, being its output $I_{AND}$ analysed for posterior detection of internal faults on the protected line [3, 8].

The AND gate output asserts only when the instantaneous values of both signals are positive. This approach is called half-wave PC scheme because it only analyses the positive half cycles of the monitored current signals. In Fig. 1c, the modulated signals $S_L$ and $S_S$ are presented for internal and external fault cases. For external faults or under normal operating conditions, the currents are practically out of phase, so that, by associating $i_L$ and $i_S$, the AND gate output does not assert or asserts for short time intervals depending on the time shift caused by the line capacitive effect (see Fig. 1d). On the other hand, for internal faults, $i_L$ and $i_S$ are practically in phase and, thus, the AND gate output lasts about half a cycle.

According to [3, 8], when the AND gate output remains in high level for more than one-quarter of a cycle, an internal fault condition may be indicated (see Fig. 1e). In this work, counters are used to estimate the pulse length, which are activated whenever $I_{AND} = 1$ and reset when $I_{AND} = 0$. For the sake of illustration, the outputs of these counters will be referred to from now on as $n(t)$.
2.2 Full-wave PC scheme

The PC scheme presented in [3] does not consider the negative half cycle of the current signal, which may cause delays in the order of half cycle in the PC protection tripping time depending on the fault inception angle. In this work, in order to overcome this delay, both positive and negative half cycles of the monitored current signals are analysed, which is usually called full cycle PC protection scheme [8]. To do so, currents measured at both line terminals and their polarity-inverted versions, i.e. multiplied by (−1), are simultaneously considered as input signals of the time-domain PC function. In Fig. 2, a case of an internal fault with inception angle of −180°, which results in negative current values in the first disturbance moments is depicted. In this case, both \(i_R\) and \(i_L\) have negative signals in the first half cycle of the fault period, which is a condition that does not result in a positive AND gate output in the half-wave PC scheme, as shown in Fig. 2c at left.

For the analysis of the complete signal, \(i_{L,neg} = i_L\) and \(i_{R,neg} = -i_R\) were defined, which are equivalent to the currents with inverted-polarity of the measured signals at the local and remote terminals, respectively. By analysing these signals, both currents have positive values soon after the fault inception, as shown in Fig. 2a at right. By combining the analysis of \(i_R\) and \(i_L\), and \(i_{L,neg}\) and \(i_{R,neg}\), at least one of these pairs of currents results in large pulses, so that \(\psi(t)\) assumes values greater than the operating threshold, regardless of the fault inception angle. However, it should be noted that the use of the polarity-inverted currents does not change the basic principle of PC protection. In fact, when a fault occurs within a given line, the polarity-inverted currents also tend to stay in phase and, otherwise in external fault cases, in out of phase. Therefore, the evaluation of \(i_{L,neg}\) and \(i_{R,neg}\) in addition to the analysis of \(i_R\) and \(i_L\) guarantees a faster protection operation, without loss of reliability. In this context, it is noted that by using the half-wave PC protection scheme to analyse \(i_R\) and \(i_L\), and \(i_{L,neg}\) and \(i_{R,neg}\), simultaneously, the full-wave PC protection scheme is obtained, which is the PC protection version evaluated in the present paper.

3 Time-domain incremental quantities

3.1 Principles

The results presented in [9] show that the use of incremental quantities as input signals in phasor-based PC function is advantageous. In fact, as will be presented next, it is ideally expected that the incremental currents are not influenced by the loading conditions, maintaining good performance even in situations of weak sources [10]. The same advantage is verified in time-domain approaches, as demonstrated in this paper.

To explain the principles of the incremental quantities, the simplified power system illustrated in Fig. 3a has been considered, where a transmission line with \(Z_{LT}\) impedance connects two Thévenin-equivalent circuits with \(Z_L\) and \(Z_R\) impedances at the terminals \(L\) and \(R\), respectively. It is assumed that a fault occurs at a distance \(d\) (in pu) from bus \(L\). This circuit is typically referred to as a faulted network, and can be represented as the sum of two other circuits: the pre-fault network (shown in Fig. 3b) and the pure-fault network (shown in Fig. 3c).

The pure-fault network represents only the system variations due to the short circuit, so that it is also known as incremental circuit. In this way, incremental voltages and currents represent only the increments observed in the voltages and currents within the fault period, and they are ideally not affected by the system loading conditions [10]. In this context, it should be noted that, for slower functions, the incremental components may present errors because of the loading variation during the fault period \(\Delta t\). However, in the first instants after the fault inception, these load flow variations are negligible due to the rotating machines inertia, reducing the inaccuracies in high-speed time-domain incremental quantity-based protection elements [1].

In the frequency domain, from the analysis of the circuits illustrated in Fig. 3, it is concluded that incremental quantities can be calculated using [10, 11]

\[
\Delta i_x = \hat{i}_x - \hat{i}_x^{pre},
\]

where \(\Delta i_x\) is the measured phasor-based incremental current at a given terminal \(x\).

On the other hand, for time-domain applications, (1) is adapted to use only instantaneous values of the monitored signals, being rewritten as [1]

\[
\Delta i(x) = i_x(t) - i_x(t - p \cdot N \cdot \Delta t),
\]

where \(p\) is an arbitrary number of cycles, \(N\) the number of samples per cycle, and \(\Delta t\) the sampling period.

The use of time-domain incremental elements improves the PC function performance in high-loaded systems and in cases of weak sources (high SIR values). As a result, its performance becomes similar to that one observed when negative-sequence elements are
applied [10], but maintaining the phase selectivity. It should be noted that the incremental quantities are valid only during \( p \) cycles. Therefore, in this work, \( p = 2 \) was used in (2), which is enough to sensitise the evaluated function.

### 3.2 Incremental replica current

From the literature, it is known that, depending on the fault inception angle, there may be a greater or smaller content of the DC offset in the measured current signals [12]. In this way, it is noticed that in cases of relevant DC offset, the problem of the initial negative values of current signals can be aggravated. Although the use of the full-wave PC protection scheme greatly minimises this problem, it is not able to eliminate the exponential decaying DC offset effect.

In [1], the use of a current immune to the decaying DC offset is proposed for time-domain application, which is called incremental replica current [1]. The incremental replica current, here represented by \( \Delta i^2 \), is calculated using

\[
\Delta i_2(t) = D_m \cdot \Delta i(t) + D_R \cdot \frac{d}{dt} \Delta i(t),
\]

where

\[
D_m = \frac{R_{TL,1}}{Z_{TL,1}} \quad \text{and} \quad D_R = \frac{L_{TL,1}}{Z_{TL,1}}.
\]

with \( Z_{TL,1}, R_{TL,1}, \) and \( L_{TL,1} \) being the positive-sequence impedance, resistance, and inductance of the monitored TL, respectively.

The replica current \( \Delta i_2 \) consists of a combination of the incremental current component and its derivative, which can be numerically calculated without the need for great computational effort, as reported in [8]. It is important to note that the calculation of \( \Delta i_2 \) resembles the application of the digital mimic filter reported in [13]. Therefore, as shown in Fig. 4, the exponential decaying DC offset is attenuated, but maintaining an unity gain, which may reduce its influence on the time-domain PC protection function.

### 4 Simulations and performance evaluation

To better evaluate the PC protection performance under different fault scenarios, a parametric sensitivity analysis is performed by means of fault simulations in the system illustrated in Fig. 5. The simulated power system consists in a 500 kV/60 Hz transmission line that connects two Thevenin equivalent circuits, which in turn represent the power systems connected to buses \( L \) and \( R \).

The analysed system was implemented in the ATP software considering the perfectly transposed line model with distributed parameters constant in frequency. In this paper, to evaluate the PC protection function itself, currents transformers and capacitor voltage transformers were intentionally modelled as ideal instrument transformers. An ATP time-step equal to 1 \( \mu \)s was used and a sample rate of 256 samples per cycle \( (N = 256) \) was simulated. Thereby, third-order Butterworth anti-aliasing filters with a cut-off frequency at 180 Hz were implemented. Also, currents with the capacitive effect compensation were taken into account, such as suggested in [14].

To perform the proposed parametric analysis of the time-domain PC function, a database was built with ATP files for simulation of a wide variety of fault scenarios. In each case, the cross-variation of parameters such as fault type, system loading, SIR at the remote line terminal, fault location, fault inception angle, and fault resistance were considered, resulting in 13,500 different fault scenarios. A fixed value of SIR \( = 0.1 \) (SIR at the local terminal) and the voltages of the terminals \( L \) and \( R \) equal to 1 \( \angle \delta \) pu and 1 \( \angle \delta \) pu were taken into account, respectively, being \( \delta \) the load angle of the evaluated system. In Table 1, the simulation parameters are listed.

In order to evaluate the PC function in terms of performance, for each simulated case, the protection operating time was analysed considering elements based on traditional phase currents, sequence currents, phase incremental currents, and incremental replica currents. In each simulation, when the phase currents are used, the operating time of the fastest element among phases \( A, B, \) and \( C \)}
The use of the traditional incremental quantities $\Delta i_{ABC}$ and the incremental replica currents $\Delta i_{ABC}$ as inputs of the PC function improves the protection speed compared with the cases in which traditional phase currents $i_{ABC}$ and sequence currents $i_0i_2$ are used, as shown in Figs. 7 and 8, respectively. It can be seen that most points in both figures take place in the region at bottom right, indicating that the incremental elements resulted in tripping times smaller than those obtained from phase and sequence current elements. Although few cases resulted in points at the region at top left indicating that the incremental elements were slower than the other evaluated traditional phase and sequence elements, the tripping times were smaller than a power cycle, which is still advantageous for utilities. Even so, it is worth emphasising that the scatter plots illustrate only cases in which the protection elements operated, removing those ones in which the PC function was not sensitised as previously depicted in Fig. 6.

Aiming to have a better global notion of the operating times of the evaluated time-domain PC function, Fig. 9 shows boxplots which illustrate the tripping times of the PC protection function when using phase current, sequence currents, incremental phase currents, and incremental replica currents, considering only cases in which all elements were sensitised. The boxplot allows the representation of a set of data in visual format by means of five indexes: the maximum value, represented by the upper tail; the upper quartile, represented by the upper limit of the box; the median, represented by the intermediate line; the lower quartile, represented by the lower limit of the box; and the minimum value, represented by lower tail. The upper quartile, median, and lower quartile represent the maximum error found in 75%, 50%, and 25% of the cases analysed, respectively.

It is noticed that the maximum operating time was smaller when $i_0i_2$, $\Delta i_{ABC}$, and $\Delta i_{ABC}$ have been used. Also, the boxplot obtained by using $\Delta i_{ABC}$ has shown to be flatter and closer to the minimum value when compared with the other evaluated elements. It indicates that the variation of operating times among the simulated cases was smaller for $\Delta i_{ABC}$ with a slight performance improvement when $\Delta i_{ABC}$ is applied.

5 Conclusions

In this work, the performance of a transmission line protection function based on the full-wave PC using incremental currents was analysed. A total of 13,500 different fault cases were simulated using the ATP software, in which the fault distance, fault resistance, system loading, SIR, and fault inception angle were varied.

It was observed that the use of the incremental currents is advantageous, since it results in overall faster PC function operations, without loss of reliability. In addition, the use of incremental currents also makes the PC protection robust to outfeed cases, since the effects of the system loading are eliminated, similarly to the negative-sequence elements. However, by using incremental quantities, a phase-segregated scheme may be used, what is not possible when negative-sequence elements are

![Accumulative frequency diagram](image)

**Fig. 6** Accumulative frequency diagram

![Comparative scatterplot between the incremental replica current use and the phase and sequence currents use](image)

**Fig. 7** Comparative scatterplot between the traditional phase incremental current use and the phase and sequence currents use

![Comparative scatterplot between the incremental replica current use and the phase and sequence currents use](image)

**Fig. 8** Comparative scatterplot between the incremental replica current use and the phase and sequence currents use
applied. Furthermore, it was concluded that the effects of the DC offset do not significantly affect the full-wave PC function performance.

In most simulated cases, the faster operation times were obtained by using the incremental components (traditional and replica). Also, cases in which the PC function did not operate when using phase currents were properly detected when incremental currents were taken into account, even in severe loading scenarios and in cases of high SIR values. Finally, the PC performance when incremental phase current and incremental replica current were applied was very similar, except by slight improvements in the protection operation times when the incremental replica current was analysed.

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Fig. 9 Boxplot relating the tripping times of PC function