Impedance-based pilot protection for ultra-high-voltage/extra-high-voltage transmission lines

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Abstract: Current differential protection is one of the major protections for extra-high-voltage/ultra-high-voltage transmission lines, but its performance is severely weakened by the prominent capacitive charging current along transmission lines. Travelling waves take the charging current into account inherently, hence travelling wave-based protection is not impacted by the charging current. Based on the principle of travelling waves, this study proposes the concept of integrated surge impedance (ISI), which is defined as the ratio of the difference of voltage quantities at two ends of a line to the sum of current quantities at two terminals of the same line. The ISI, closely related to travelling wave differential current, can discriminate between internal and external faults clearly. The ISI-based criterion is composed of power frequency quantities in order to ensure the robustness of the protection. The action zone is designed on an impedance plane. EMTP simulation verifies the correctness of the proposed pilot protection.

1 Introduction

Extra-high-voltage/ultra-high-voltage (EHV/UHV) transmission lines are increasingly built to transfer a large amount of power across a long distance in many countries, which brings a high demand for fast, sensitive, selective and reliable line protection. Line protection can isolate the faulted line, secure the rest healthy lines and improve power system transient stability.

For years, current differential protection has been demonstrated an effective and successful protection method for transmission lines [1], but the prominent capacitive charging current along the EHV/UHV transmission lines severely degrades its performance [2]. To solve this problem, many methods of compensating capacitive charging current have been presented. These methods are classified into three categories: frequency-domain based compensation methods, time-domain based compensation methods and travelling wave differential protection. Time-domain or frequency-domain based compensation methods usually utilise a lumped parameter model to calculate capacitive charging current [2, 3] and subtract it from the differential current, whereas travelling wave differential protection constitutes the protection criterion by fault travelling waves which essentially take capacitive charging current into account [4, 5].

The theoretical basis of travelling wave differential protection is based on two facts. The first fact is that there always exist voltage and current waves moving along the transmission line both in transient and steady states [6]. The second fact is that travelling waves can transmit from one end to another end if the transmission line is complete. At present, all travelling wave differential protection methods derive travelling wave differential current as operation quantity and the criterion is not flexible enough.

In [7], the initial voltage travelling wave divided by the initial current travelling wave forms the so-called composite surge impedance. Suonan et al. [8] defined the ratio of the sum of the voltage fault components at two ends to the sum of the current fault components at two ends as integrated impedance. Bolandi et al. [9] used differential impedance to build a differential protection criterion. Following the idea of the above three references, this study proposes the concept of integrated surge impedance (ISI). The ISI is defined as the difference of voltage quantities at two ends of a line divided by the sum of currents at two ends of the same line. By analysing the propagation rule of travelling waves, the ISIs under internal or external faults are deduced, which has an obvious difference. Finally, a new travelling wave pilot protection is constituted by a power frequency component of the ISI. The criterion setting is made of an impedance plane and the non-active zone is a circle whose centre denotes the surge impedance of the protected line.

2 Fundamental principle

2.1 Travelling waves on transmission line

The voltage and current on a transmission line are formulated by the transmission line equation

\[
\begin{align*}
\frac{\partial v}{\partial x} &= R_0 i + L_0 \frac{\partial i}{\partial t}, \\
\frac{\partial i}{\partial x} &= G_0 i + C_0 \frac{\partial u}{\partial t}.
\end{align*}
\]

(1)

where \(R_0\), \(L_0\), \(G_0\) and \(C_0\) mean the resistance, inductance, conductance and capacitance, respectively, per unit length of the line; \(u\) and \(i\) are the voltage and current at the location with a distance of \(x\) from the fault point. As for lossless line (without regard to \(G_0\) and \(R_0\)), the general solution of the above equation is

\[
\begin{align*}
u(t) &= u(t - \frac{x}{v}) + i_0(t - \frac{x}{v}), \\
i(t) &= i(t - \frac{x}{v}) + i_0(t - \frac{x}{v}).
\end{align*}
\]

(2)

where \(u(t-x/v)\) and \(i_0(t-x/v)\) denote the forward and backward travelling waves; \(Z\) and \(v\) are the surge impedance and the velocity of travelling waves, respectively. Therefore, the voltage or current at any point of the line is composed of forward and backward travelling waves. The forward and backward travelling waves satisfy

\[
\begin{align*}
\frac{u(t-i_0)}{i_0} &= Z, \\
i(t+i_0b_0) &= -Z.
\end{align*}
\]

(3)

According to (2), the travelling waves can be calculated by voltage and current at any point.
\[
\begin{align*}
\begin{cases}
u_0 &= u + Z_i, \\
u_b &= u - Z_i.
\end{cases}
\end{align*}
\]

Due to the coupling between phases in a three-phase transmission system, the three-phase quantities are usually decoupled into three independent modal quantities by
\[
y_m = S^\dagger y_p
\]
where \(y_m\) and \(y_p\) are the modal and phase quantities, respectively; \(S\) is the Karenbauer phase-mode transformation matrix as shown
\[
S = \begin{bmatrix}
1 & 1 & 1 \\
1 & -2 & 1 \\
1 & 1 & -2
\end{bmatrix}.
\]

### 2.2 Definition of the ISI

Figs. 1 and 2 show a transmission system network with an internal fault and an external fault, respectively. \(F\) indicates the fault point; \(u_F\) is the voltage at \(F\), \(i_F\) is the current across the fault branch; \(i_{FM}\) and \(i_{FN}\) are the currents at \(F\) towards two terminals. \(u_M\) and \(i_M\) are the voltage and current measured at bus \(M\), whereas \(u_N\) and \(i_N\) are the voltage and current measured at bus \(N\). In particular, the reference direction of the current is marked on figures. \(Z_M\) and \(Z_N\), which are the ISIs at terminal \(M\) and \(N\), are defined as
\[
\begin{align*}
Z_M(t) &= \Delta u_{MB}(t)/\Delta \delta_{MN}(t), \\
Z_N(t) &= \Delta u_{NB}(t)/\Delta \delta_{NM}(t),
\end{align*}
\]
where \(\delta\) is the time of a travelling wave propagating in the whole line \(MN\).

Since the voltage and current at either end can be regarded as the sum of forward and backward travelling waves, (8) can be expressed as follows:
\[
\begin{align*}
\Delta u_{MB}(t) &= u_{MB}(t) + u_{MF}(t) - u_{NB}(t - \tau) - u_{MF}(t - \tau), \\
\Delta u_{NB}(t) &= u_{NB}(t) + u_{NF}(t) + u_{MF}(t - \tau) - u_{MF}(t - \tau), \\
\Delta \delta_{MN}(t) &= u_{MF}(t) + u_{MF}(t) - u_{MF}(t - \tau) - u_{MF}(t - \tau), \\
\Delta \delta_{NM}(t) &= u_{MF}(t) - u_{MF}(t) + u_{MF}(t - \tau) - u_{MF}(t - \tau),
\end{align*}
\]
where \(u_{NB}\) and \(u_{MF}\) are the backward and forward travelling waves at terminal \(M\), whereas \(u_{NB}\) and \(u_{MF}\) are the backward and forward travelling waves at bus \(N\); so do current travelling waves.

### 2.3 ISI for no fault or an external fault

For a complete lossless line, a travelling wave takes time \(\tau\) to propagate from one terminal to the opposite terminal losslessly. Therefore, we can derive the following relation:
\[
\begin{align*}
\delta_{MB}(t) &= \delta_{MF}(t) - \delta_{MF}(t - \tau), \\
\delta_{NB}(t) &= \delta_{MF}(t) - \delta_{MF}(t - \tau), \\
\delta_{MN}(t) &= \delta_{MF}(t) - \delta_{MF}(t - \tau).
\end{align*}
\]
When no fault or an external fault occurs, the line \(MN\) is complete as shown in Fig. 2, taking the ISI at bus \(M\) for example, we deduce the ISI:
\[
Z_M(t) = \frac{u_{MB}(t) - u_{MB}(t - \tau)}{u_{MF}(t) + \delta_{MF}(t - \tau)} = Z.
\]

As a result, the ISI is equal to the surge impedance of the transmission line theoretically, when no fault or an external fault occurs and the whole line is complete.

### 2.4 ISI for an internal fault

For an internal fault, the line \(MN\) is not complete as shown in Fig. 1. The backward travelling wave \(u_{MB}\) at bus \(M\) can be represented by the forward travelling wave at fault \(F\) towards \(M\) with a delay \(\tau_F\) (which is the time of a travelling wave propagating the line section \(MF\)). The forward travelling wave \(u_{NF}\) at bus \(N\) can be represented by the backward travelling wave at fault \(F\) towards \(N\) with a delay \(\tau_F\).

Taking the ISI at bus \(M\) as an example too, the difference of voltages and the sum of currents are calculated as follows:
\[
\begin{align*}
\Delta u_{MB}(t) &= [u_M(t - \tau_F) + Z_i \delta_{MN}(t - \tau_F)] + \delta_{MF}(t) - [u_M(t - \tau_F) - Z_i \delta_{MN}(t - \tau_F)] + \delta_{MF}(t), \\
\Delta u_{NF}(t) &= [u_N(t - \tau_F) - Z_i \delta_{MN}(t - \tau_F)] + \delta_{MF}(t).
\end{align*}
\]
Finally, we get the ISI at bus \(M\)
\[
Z_M = \frac{u_{MB}(t) - u_{MB}(t - \tau) - Z_i \delta_{MN}(t - \tau)}{u_{MF}(t) + \delta_{MF}(t - \tau) + \delta_{MF}(t - \tau)} = Z(1 - \frac{2\delta_{MF}(t - \tau)}{u_{MF}(t) + \delta_{MF}(t - \tau)}).
\]
The ISI is far away from the point where the surge impedance \(Z\) stands on an impedance plane when an internal fault occurs. The result can be applied to distinguish an internal fault from an external fault.

### 2.5 Protection principle based on the ISI

From the above analysis, a pilot protection criterion can be obtained by constituting the ISI with communication. In the cases of no fault or an external fault, the ISI reflects only the surge impedance, whereas, in the case of an internal fault, the ISI reflects the surge impedance plus a superposition, which results in the ISI far away from the surge impedance.

It should be noted that (11) and (13) are satisfied in the time domain, which means any time and frequency bands of fault information can be applied to constitute the pilot protection criterion. Therefore, in order to ensure the robustness of the pilot protection performance, we constitute the criterion using the power frequency quantities as below
\[
|Z_{ISI} - Z| < K_{\text{ref}} Z_c.
\]
where \( Z_{ISI} \) is calculated in the power frequency domain as follows (also take \( Z_{ISI} \) at bus M for example)

\[
Z_M = \frac{U_M - U_N e^{-j\Omega \tau}}{I_M + I_N e^{-j\Omega \tau}},
\]

(15)

where \( \Omega \) is the angular frequency. The impedance setting \( K_{rel} \) is a reliability factor, which can be set as 0.6–0.8 to ensure the reliability of the proposed pilot protection based on simulation results. The non-active zone on an impedance plane of the pilot protection is a circle whose centre denotes the surge impedance \( Z \) and the radium is \( K_{rel} Z_c \).

### 3 Simulation and verification

The proposed pilot protection has been verified by the EMTP simulation. Fig. 3 shows a 50-Hz and 750-kV transmission system with a frequency-dependent distributed parameter line model. The configuration and parameters of the transmission line are displayed in Fig. 4 and Table 1.

**Table 1** Conductor parameters

| Parameter          | Value                      |
|--------------------|----------------------------|
| Conductor inter/outer radius | 0.55/1.55 cm             |
| direct current (DC) resistance | 0.0585 Ω/km             |
| ground wire inter/outer radius | 0.3/0.8 cm             |
| DC resistance     | 0.304 Ω/km                |
| ground resistivity | 100 Ω m                   |

where \( Z_{ISI} \) is calculated in the power frequency domain as follows (also take \( Z_{ISI} \) at bus M for example)

\[
Z_M = \frac{U_M - U_N e^{-j\Omega \tau}}{I_M + I_N e^{-j\Omega \tau}},
\]

(15)

where \( \Omega \) is the angular frequency. The impedance setting \( K_{rel} \) is a reliability factor, which can be set as 0.6–0.8 to ensure the reliability of the proposed pilot protection based on simulation results. The non-active zone on an impedance plane of the pilot protection is a circle whose centre denotes the surge impedance \( Z \) and the radium is \( K_{rel} Z_c \).

### 3 Simulation and verification

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In Fig. 3, K1 is near bus M at the start of the line, K2 and K3 are located at the middle and end of the line MN, and K4, out of the line MN, is located at the negative direction of bus N. Various fault conditions are simulated at these four points. The sampling frequency is 5 kHz and the length of the data window is 20 ms. The simulated duration is 0.1 s and the fault instant is 0.03 s. \( K_{rel} \) is selected as 0.8.

A Fourier filter algorithm is used to estimate the power frequency phasors. Fig. 5 shows the calculated α-mode ISI at bus M when an A-phase-to-ground fault occurs at K1 without transition resistance. Before the fault happens, the ISI stays in the non-active zone (yellow circle area according to criterion (14)). After the fault occurs, the ISI runs out the yellow area quickly and runs into the active zone (white area), which means an internal fault occurs.

Fig. 6 shows the calculated α-mode ISI at terminal M when an A-phase-to-ground fault occurs at K4 without transition resistance. Before and after the fault happens, the ISI always stays in the non-active zone, which means the protection criterion does not act on an external fault.

Table 2 shows the simulation results under various fault conditions. For internal faults, the critical time of the ISI across operation boundary are recorded (which means operation speed), whereas, for external faults, the maximal distances between the ISI and the surge impedance are recorded. It can be derived from Table 2 that the proposed pilot protection operates quickly when internal faults occur, whereas it has enough margins not to act for external faults reliably.

### 4 Conclusion

This study proposes the concept of ISI, which has an inherent relationship with a travelling wave differential current. By means of the travelling waves, the ISI under internal or external faults is deduced. The ISI can effectively discriminate between internal faults and external faults, which can be used to constitute a transmission pilot protection criterion. This study utilises power frequency quantities to calculate the ISI and presents a circle criterion. EMTP simulation verifies that the criterion can differentiate internal and external faults correctly.

There are still works to be done in the next stage of research. The setting of the ISI-based protection criterion is based on the
impedance plane. This study only gives a simple and rough circle setting. After analysing comprehensively the characteristics of the ISI affected by various errors, a setting which has an arbitrary boundary with better performance should be given on the impedance plane in the future.

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6 References

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Table 2 Simulation results

| Fault point | Fault type | Critical time of ZM/ms | Critical time of ZN/ms |
|-------------|------------|------------------------|------------------------|
| K1          | AG         | 5.03                   | 0.80                   |
|             | BC         | 8.03                   | 5.00                   |
| K2          | BCG        | 8.32                   | 6.92                   |
|             | BG         | 12.9                   | 13.9                   |
| K3          | ABC        | 3.20                   | 0.63                   |
|             | CA         | 4.40                   | 2.23                   |
| K4          | AG         | 46                     | 101                    |
|             | AB         | 61                     | 93                     |

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