A novel non-unit protection scheme for HVDC transmission lines based on multi-resolution morphology gradient

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Abstract
This paper presents a novel non-unit protection scheme for the protection of LCC-HVDC transmission lines. The fault-generated travelling waves at the faulty line ends are filtered by a filter-reactor unit. The filtered current waveforms are then processed by a multi-resolution morphological gradient and are used by a fast non-unit protection scheme for LCC-HVDC transmission lines. The proposed method does not require communication links between transmission line ends and uses only current signals with a low sampling rate of 10 kHz. In addition, the proposed scheme is computationally efficient, making it suitable for practical applications. The performance of the proposed protection scheme is validated by comprehensive simulation studies as well as field data on a bipolar LCC-HVDC system. Both simulation and field data test results verify the accurate performance of the proposed method for different internal fault conditions, including high fault resistances up to 1000 Ω.

Furthermore, the proposed scheme is robust against external DC and AC faults, change of sampling frequency and data window length, non-ideal faults, change of power flow, change of DC filter parameters and smoothing reactor, change of operation mode, and measurement noise.

INTRODUCTION
With significant advances in power systems, High-Voltage Direct Current (HVDC) transmission systems are being widely used [1]. Compared to high-voltage alternative current transmission systems, HVDC transmission systems have distinct advantages such as higher transmission capacity in longer distances, fast and flexible power control, and the ability to interconnect asynchronous networks. These unique advantages make the use of HVDC transmission systems more attractive in modern power systems [2, 3]. Protection of HVDC lines is of high importance as these lines, in general, transfer bulk power over long distances.

The existing protection systems for HVDC transmission lines are based on travelling wave protection and voltage derivatives protection and back-up protection including under-voltage protection and current differential protection [4]. Travelling-wave-based protection systems have limitations such as difficulties in receiving and identifying the wavefront and high sensitivity to fault resistance and noise [5]. Protection methods based on voltage derivatives use the rate of voltage variations (\(\frac{\partial v}{\partial t}\)) to detect faults and, thus, are sensitive to fault resistance [6]. In addition, under-voltage protection has low reliability in distinguishing internal from external faults [7]. Therefore, more studies are needed to devise more reliable and accurate protection system. In [8], a high-speed protection based on mode-0 and mode-1 of travelling waves is proposed, which has lower sensitivity against internal faults with high fault resistance. A travelling wave protection scheme using Teager Energy Operator (TEO) is proposed in [9]. A travelling wave protection method is proposed in [10], which makes use of the step response of a transmission line with consideration for its frequency-dependent characteristics. However, this method has high computational burden than conventional travelling wave protection methods. da Silva et al. [11] present a travelling wave protection scheme using Wavelet Transform (WT), which can be computationally expensive. Methods in [8–11] have used both voltage and current signals for the protection scheme and, thus, require additional measurement elements. Furthermore, methods presented in [10] and [11] are unit protection and require
communication links between the two sides of the transmission line. This can limit practical implementations of such methods, and also, the reliability of such protection methods is strongly dependent on the reliability of the communication links.

Current differential protection schemes are used as the backup protection in HVDC transmission lines due to the time delays in the order of several hundreds of milliseconds [6, 7]. This time delay is due to the transmission line capacitive effect arising from long transmission lines. To compensate for the delay time in the current differential protection, recently, protection schemes have been proposed that calculate the transmission line capacitive effect in the transient period and use the current differential protection as the primary protection scheme. In [12], a current differential protection scheme consisting of two units, the current difference unit and a block unit, is proposed. In [13], a current differential protection scheme based on the distributed parameters model is presented. In [14], a protection algorithm that takes into account the transmission line capacitive effect, using the π model of the transmission line, and voltage at the rectifier and inverter side is proposed. In [15] and [16], current differential protection algorithms are proposed to compensate for the transmission line capacitive effect using the distributed parameter model and the frequency-dependent parameters of the transmission line, respectively. All of the proposed methods in [12–16] are unit protection schemes. Algorithms based on boundary protection (e.g., [17–19]) use the high-frequency signals. However, they may not be able to protect the entire length of transmission lines when a high-impedance fault occurs close to the inverter station. In [20], a non-unit transient protection scheme based on the difference of high-frequency morphological entropy of voltage signal is presented. In [21], a synchrosqueezing WT-based non-unit transient boundary protection algorithm is proposed, which requires relatively intensive computations. The proposed protection schemes in [22] and [23] are based on the transient energy difference and the transient power difference between the rectifier and inverter sides, which are sensitive to high fault resistance. The protection schemes in [24] and [25] are based on the transient measured impedance between two sides of the transmission line, whose accuracy depends on the data window length. In [26], a pilot protection scheme based on the Pearson correlation coefficient of current derivatives is proposed. A protection scheme based on the transient energy ratio in the specific frequency band on both sides of the transmission line is proposed in [27]. All proposed methods in [22–27] are unit protection and use both current and voltage signals except for [26].

This paper presents a non-unit protection scheme based on boundary characteristics of transmission lines using the energy of the current Multi-resolution Morphological Gradient (MMG). The main advantage of the proposed protection scheme is its computationally efficient and straightforward process, which enables its straightforward implementation for practical applications. Due to the existence of the filter-reactor unit, high-frequency components can hardly reach the relay when external faults occur, while under internal faults, these components can easily reach the relay. Therefore, this feature can be used to distinguish internal faults from external ones. In order to detect sudden changes in the current transient signal, an MMG is introduced to limit steady-state components and enhance transient components. The MMG requires only summation, subtraction, and maximum and minimum operations without any multiplication and division. Therefore, the proposed scheme is a high-speed one and requires low computations compared with the WT-, S-Transform (ST)-, and Fourier Transform (FT)-based algorithms.

The structure of this paper is organised as follows. The fault current studies on the bipolar LCC-HVDC system are described in Section 2. The Mathematical Morphology (MM) is explained in Section 3. The proposed protection scheme and simulation results are presented in Sections 4 and 5, respectively. In Sections 6 and 7, the sensitivity of the proposed protection scheme is assessed and comparison with the other protection methods is presented, respectively. Finally, the conclusion is given in Section 8.

## 2 Fault Current Studies

The structure of a bipolar LCC-HVDC transmission system is shown in Figure 1. \(I_P\) and \(I_N\) are the currents from the positive and negative pole at the rectifier side, respectively. \(F_x\) is an internal fault at \(x\) km from the rectifier terminal. \(F_R\) and \(F_I\) faults are pole-to-ground external faults at the rectifier and inverter sides, respectively. \(F_A\) and \(F_B\) faults are one of the three-phase faults types [i.e. single-phase-to-ground (A-G), double-phase (AB), double-phase-to-ground (AB-G), three-phase (ABC), or three-phase-to-ground (ABC-G)] at the rectifier and inverter sides, respectively.

Based on the superposition theorem, when a fault occurs in the HVDC system shown in Figure 1, for the fault analysis, the equivalent network of the HVDC system can be divided into two equivalent networks as pre-fault and post-fault networks (superimposed equivalent network) [28]. The fault superimposed networks for three faults, i.e. \(F_x\), \(F_R\), and \(F_I\) are shown in Figure 2.

### 2.1 Internal fault \(F_x\)

According to Figure 2(a), when an internal fault occurs at a distance of \(x\) km from the relay location, the first travelling wave of the fault voltage and current that arrives to the rectifier terminal is given by

\[
V_R = V_{R1} e^{\beta_N x} + V_{R2} e^{-\beta_N x} \Rightarrow
\]

\[
K_v = \frac{V_{R1}}{V_{R2}} e^{\beta_N x} \Rightarrow V_{R1} = K_v V_{R2} e^{-\beta_N x} \Rightarrow
\]

\[
V_R = K_v V_{R2} e^{-\beta_N x} + V_{R2} e^{-\beta_N x}
\]

(1)
FIGURE 1 The structure of the bipolar LCC-HVDC transmission system

\[ VR^2 = Z_C \div (Z_C + 2R_f)(-V_n) \]  

\[ \beta = \sqrt{Z Y} \approx 1.3 \times 10^{-8} \]  

where \( Z_C, R_f, V_n \), and \( K_r \) are the characteristic impedance of the transmission line, the fault resistance, the pre-fault normal operating DC voltage, and the reflection coefficient at the rectifier side, respectively. Also, \( x \) is the distance of the fault to the relay location, and \( \beta \) is the propagation coefficient of the transmission line given by

In addition, for the sake of simplicity, the fault impedance is assumed to be zero; hence, \( V_{R2} = -V_n \). Thus, (1) can be written as follows:

\[ V_R = V_{R2} e^{-\beta x} (K_r + 1) \Rightarrow \]

\[ K_r = \left( \frac{Z_f \| (Z_R + Z_{SR})}{Z_f \| (Z_R + Z_{SR}) + Z_C} \right) \Rightarrow \]

\[ V_R = V_{R2} e^{-\beta x} \left( \frac{2Z_f}{Z_R + Z_{SR} + Z_C + Z_f Z_C} \right) \]  

\[ I_R = \left( \frac{1}{Z_C} \right) \left( V_{R1} e^{\beta x} - V_{R2} e^{-\beta x} \right) \Rightarrow \]

\[ I_R = \left( \frac{1}{Z_C} \right) \left( K_r V_{R2} e^{-\beta x} - V_{R2} e^{-\beta x} \right) \Rightarrow \]

\[ I_R = \left( \frac{V_{R2} e^{-\beta x}}{Z_C} \right) (K_r - 1) \Rightarrow \]

\[ I_R = \left( \frac{V_{R2} e^{-\beta x}}{Z_C} \right) \left( K_r Z_C + Z_R + Z_{SR} + Z_f \right) \]  

where \( Z_R, Z_{SR}, \) and \( Z_f \) are the equivalent impedance at the rectifier side, smoothing reactor impedance, and DC filter impedance, respectively.

2.2 | External fault at the rectifier side

Two types of fault, including FA and FR, can occur at the rectifier side. Due to the presence of the converter transformer, the travelling waves corresponding to the FA fault are more attenuated compared to the travelling waves of the FR fault. This results in a higher rate of change of voltage and current for the FR fault. Therefore, the FR fault is considered as the worst-case one. According to Figure 2(b), under the FR

FIGURE 2 Fault superimposed networks. (a) Superimposed network for Fx. (b) Superimposed network for FR. (c) Superimposed network for FI
fault, the first fault-originated travelling waves of the voltage and current reaching to the rectifier terminal are expressed by

\[ V_R = (-V_a) \ A_r \Rightarrow A_r = \frac{Z_f||Z_c}{Z_f||Z_c + Z_{SR}} \]  
\[ I_R = \frac{1}{Z_c} (-V_a) \ A_r \Rightarrow I_R = \frac{Z_f}{Z_{SR}(Z_f + Z_c) + Z_f Z_c} \]  

where \( A_r \) is the refractive coefficient at the rectifier side.

2.3 | External fault at the inverter side

Two types of fault, including FI and FB, can occur at the inverter side. Similarly, due to the presence of the converter transformer, the worst case of the external fault is considered at the inverter side, i.e. FI. According to Figure 2(c), under the FI fault, the first travelling waves of the fault voltage and current arriving to the rectifier terminal are given by

\[ V_R = (-V_a) \ e^{-\beta l} (K_e + 1) \ A_j \Rightarrow A_j = \frac{Z_f||Z_c}{Z_f||Z_c + Z_{SR}} \]  
\[ I_R = \frac{1}{Z_c} (-V_a) \ e^{-\beta l} (K_e - 1) \ A_j \Rightarrow I_R = \frac{-2 Z_f}{Z_f||Z_{SR} + Z_R|| + Z_c} \]  

where \( A_j \) is the refractive coefficient at the inverter side.

Based on Equations (5), (7), and (9), Figure 3 depicts the amplitude–frequency characteristic curves for three faults FR, FR, and FI. It can be observed that, the high-frequency components are attenuated in the case of external faults, while these components remain almost constant under internal faults. The reason for this is that the propagated travelling waves first pass through the filter–reactor unit and then reach the relay; thereby, the filter–reactor unit attenuates the high-frequency components. In the case of internal faults, propagated travelling waves from the fault point directly reach the relay location, so its high-frequency components remain almost constant. Due to the difference in high-frequency components, it is possible to design a criterion for distinguishing between internal and external faults. In this work, MMG is used to extract high-frequency components.

3 | MATHEMATICAL MORPHOLOGY

MM considers the form, shape, and size of a signal waveform in the time domain. Compared to the FT and WT that are based on integral transforms, which use multiplication and division operators, the arithmetical calculations involved in the MM include only subtraction, addition, and minimum and maximum operations without any multiplication and division. This makes it computationally straightforward for time-sensitive applications. An important mathematical morphological function involved in the processing of single-dimensional signals is the extraction of the structure of a set of samples. In other words, the extraction of this structure is done by the interaction between the neighbouring instances of each other through the structure element based on the two basic operators of dilation and erosion [30]. In what follows, different operators of MM are introduced.

3.1 | Morphological gradient

Assuming a signal denoted by \( f \) and a Structuring Element (SE) denoted by \( g \), the operators of dilation and erosion, respectively, are given by [30]

\[ f \oplus g = \max_s \{ f(\lambda + s) + g(\lambda) | (\lambda + s) \in \mathfrak{D}_f, s \in \mathfrak{D}_g \} \]  
\[ f \ominus g = \min_s \{ f(\lambda + s) - g(\lambda) | (\lambda + s) \in \mathfrak{D}_f, s \in \mathfrak{D}_g \} \]  

where \( \mathfrak{D}_f \) and \( \mathfrak{D}_g \) are definition domains of \( f \) and \( g \), respectively, and the length of \( g \) needs to be considerably shorter than that of \( f \). If the set of flat structural elements is taken into account, it means that \( g(\lambda) \equiv 0, \forall \lambda \in D_g \), then the relationships (10) and (11) can be simplified as follows:

\[ f \oplus g = \max_s \{ f(\lambda + s) | (\lambda + s) \in \mathfrak{D}_f, s \in \mathfrak{D}_g \} \]  
\[ f \ominus g = \min_s \{ f(\lambda + s) | (\lambda + s) \in \mathfrak{D}_f, s \in \mathfrak{D}_g \} \]  

The operation of the two dilation and erosion operators is illustrated in Figure 4. The difference between the dilated and eroded outputs of a signal, based on a predetermined SE,
defined as Morphological Gradient (MG) [30] given by

$$\rho = [f \oplus g] - [f \ominus g]$$  \hspace{1cm} (14)

The opening of a one-dimensional signal $f(n)$ by $g(n)$ is denoted by $(f \ast g)(n)$ and determined as the dilation of the eroded signal

$$(f \ast g)(n) = ([f \ominus g] \oplus g)(n).$$  \hspace{1cm} (15)

The closing of $f(n)$ by $g(n)$ is denoted by $(f \circ g)(n)$ and determined as the erosion of the dilated signal

$$(f \circ g)(n) = ([f \oplus g] \ominus g)(n).$$  \hspace{1cm} (16)

The sharp edges of the signal are smoothed by using the opening operator. On the other hand, the narrow valleys and gaps of the signal are filled by using the closing operator.

### 3.2 Multi-resolution morphological gradient

The MM gradient is a tool that affects the transient components in a signal. By increasing the level of signal decomposition using this tool, the high-frequency components of the signal are magnified, and the low-frequency components are attenuated. For instance, the output of the first level of the mathematical MG compared to the second level one contains high-frequency components with lower amplitude and low-frequency components with higher amplitude. Thus, in order to recognise abrupt variations in transient signals, an MMG is presented such that steady-state components are reduced and transient components are enhanced [31]. The gradient calculation operations are implemented in several levels and are based on the following stages.

1. Extraction of ascending and descending edges based on two sets of structure elements $g^+$ and $g^-$ defined as follows:

$$g^+(s) = \{0, 0, \ldots, 0\}, \hspace{0.5cm} 1 - l_a \leq s \leq 0$$  \hspace{1cm} (17)

$$g^-(s) = \{0, 0, \ldots, 0\}, \hspace{0.5cm} 0 \leq s \leq l_a - 1$$  \hspace{1cm} (18)

where $l_a = 2^{a-1} l_g$; $a$ and $l_g$ represent the level of MMG to be decomposed and the initial length of $g$ at level 1, respectively.

2. Calculation of $\rho^a$, which denotes the gradient at $a$ level given by

$$\rho^a = \rho_{g^+}^a + \rho_{g^-}^a$$  \hspace{1cm} (19)

where $\rho_{g^+}^a$ and $\rho_{g^-}^a$ are defined as follows, respectively:

$$\rho_{g^+}^a = [\rho^{a-1} \oplus g^+] - [\rho^{a-1} \ominus g^+]$$  \hspace{1cm} (20)

$$\rho_{g^-}^a = [\rho^{a-1} \oplus g^-] - [\rho^{a-1} \ominus g^-].$$  \hspace{1cm} (21)

### 4 PROPOSED PROTECTION SCHEME

The flowchart of the proposed scheme for protection HVDC transmission lines is shown in Figure 5. The process of implementing the proposed scheme is expressed in the following steps.

**Step 1:** Sampling is done on the positive and negative pole current signals at the relay location on the rectifier side of the HVDC transmission line with the sampling rate of 10 kHz.
Step 2: For a bipolar HVDC system, there is an electromagnetic coupling between positive and negative poles. The pole-to-mode transform in (22) can be used to decouple positive and negative pole components into line-mode and zero-mode components [32]

\[
\begin{bmatrix}
    i_p \\
    i_n
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
    1 & 1 \\
    1 & -1
\end{bmatrix} \begin{bmatrix}
    i_p \\
    i_n
\end{bmatrix} \tag{22}
\]

where subscript \( p \) denotes the positive pole, and subscript \( n \) indicates the negative pole. Also, subscript \( l \) represents line mode, as well as subscript 0 represents zero mode.

Step 3: The data window with a length of 3 ms from the measured current by the relay is recorded.

Step 4: In order to reduce the noise effect, the \( k \)-Opening–Closing–Closing–Opening (\( k \)-OCCO) filter has been used [33]. Another type of morphological operators is known by introducing two Opening–Closing (OC) and Closing–Opening (CO) filters. The OC and CO operators are given by

\[
OC[f(n)] = (f \circ g \bullet g)(n) \tag{23}
\]

\[
CO[f(n)] = (f \bullet g \circ g)(n). \tag{24}
\]

Due to the dilation and erosion properties of the opening and closing operators, the signal obtained from the CO and OC filters undergoes changes in the signal amplitude. The output signal from the CO filter is expanded, while the output signal from the OC filter is contracted. Thus, the average value of the obtained outputs from the CO and OC filters is used to perform the signal denoising as

\[
y(n) = \frac{1}{2} \left\{ OC[f(n)] + CO[f(n)] \right\}. \tag{25}\]

In (25), \( f(n) \) is the noise-contaminated signal and \( y(n) \) is the denoised signal. The OCCO filters, each with a specified and incremental scale, are arranged sequentially such that the output of each filter is used as an input of the next filter. The signal is processed \( k \) times by the OCCO filter. \( k \) is selected such that the denoising is done more effectively. In this study, \( k \) is set to be 2, according to Figure 6.

Step 5: When the signal samples are passed through the \( k \)-OCCO filter, these samples are smoothed. Hence, in order to better discriminate between the signal of the internal fault and the signal of the external fault, the output signal of the \( k \)-OCCO filter is passed through the following filter [34]:

\[
\nabla I(k) = \sum_{j=0}^{2} I(k-j) - \sum_{j=5}^{5} I(k-j) \tag{26}\n\]

where the \( j \)th current value sampled prior to the present moment is expressed by \( I(k-j) \). The calculated current gradient is denoted by \( \nabla I(k) \).

Figure 7 demonstrates the results of applying the current gradient to the output of the \( k \)-OCCO filter. (a) Line-mode current. (b) Output of the \( k \)-OCCO filter. (c) Output of the \( \nabla I \) where the \( j \)th current value sampled prior to the present moment is expressed by \( I(k-j) \). The calculated current gradient is denoted by \( \nabla I(k) \).

Step 6: MMG with three levels is applied to the data window, and the third level of decomposition is extracted, and then, the output energy of MMG is calculated.
The flowchart of the data pre-processing stage

\[ E = \sum_{j=1}^{N} (\rho_3 (j))^2 \]  

(27)

where \( \rho_3 \), \( E \), and \( N \) are third levels of MMG, energy of \( \rho_3 \), and the number of samples in the data window, i.e. \( N = 30 \), respectively. When there is no fault in the system, the calculated energy is zero. The instant that the first fault-originated samples enter the data window, the calculated energy value is greater than zero, and this instant is considered as the moment of fault occurrence. When 20 post-fault samples enter into the sampling window, the average of these samples is considered as the Performance Index (PI) to discriminate faults occurring inside or outside the protected line.

\[ \text{PI} = \frac{1}{M} \sum_{j=1}^{M} E (j) \]  

(28)

where \( M = 20 \).

Step 7: At this stage, the calculated PI is compared with the Protection Threshold (PT). If the PI value is greater than the PT value, the disturbance is recognised as an internal fault. As a result, the relay sends the tripping signal to the DC breaker. Otherwise, the data window will be moved to the first step again.

Step 8: To identify the faulted pole, the sum of components of the zero mode of current is used. By utilizing the energy of the MMG output from the line mode, the instant of the fault is detected, and from the moment of the fault occurrence up to 20 samples after the fault, the components of zero-mode are summed. Then, the Faulted Pole Detection (FPD) is done based on the following logic:

\[ \text{FPD} = \sum_{j=1}^{M} \delta_0 (j) \Rightarrow \]

Here, PDT is the Pole Detection Threshold.

### 4.1 Determination of the thresholds

To determine the PT value, the lowest value of the PI for the worst case of an internal fault from the point of view of generating the least transient states (i.e. Positive-pole-to-Ground (PG) or Negative-pole-to-Ground (NG) faults at the end of the transmission line with the highest fault resistance), and the highest value of the PI for the most severe case of an external fault from the point of view of generating the most transient states (i.e. FI fault with zero fault resistance) are considered. In order to create more security margin and increase the reliability of the proposed protection scheme with respect to unavoidable measurement errors and other potential sources of signal distortion, the PT value has been determined with an appropriate margin of the average value of the minimum PI for internal faults and the maximum PI for external faults.

\[ \text{PT} = K_{\text{SMC}} \times \frac{\text{Minimum(PI)}_{\text{Internal Faults}} + \text{Maximum(PI)}_{\text{External Faults}}}{2} \]

\[ \text{Minimum(PI)}_{\text{Internal Faults}} = 2.8 \]

\[ \text{Maximum(PI)}_{\text{External Faults}} = 0.53 \]

\[ \text{PT} \cong 1.2 \times \frac{2.8 + 0.53}{2} \cong 2 \]  

(30)

\( K_{\text{SMC}} \) is Security Margin Coefficient (SMC) and has been set to 1.2. Therefore, the PT value has been selected equal to 2.

The maximum absolute value of the FPD for Positive-to-Negative-pole (PN) faults is close to zero, and the minimum absolute value of FPD for the pole-to-ground faults at the end of the line with maximum fault resistance is greater than 1. Hence, the PDT is determined considering a minimum margin of about 100% from the PN faults. Based on extensive simulation results, PDT has been selected equal to 1.

### 5 PERFORMANCE EVALUATION

#### 5.1 Test system

In this work, the CIGRE benchmark system [35] (shown in Figure 1) is studied and is simulated in the PSCAD/EMTDC simulation environment. For HVDC transmission lines, the frequency-dependent transmission line model is considered. Also, since the sampling frequency of most practical protection...
5.2 | Internal faults

In order to assess the performance of the proposed scheme, internal faults, including PG and PN at the end of the transmission line at 999 km with a fault resistance of 500 Ω, is simulated on the test system, and the simulation results are shown in Figures 9 and 10, respectively. Figure 9(a) depicts the line-mode and zero-mode measured current at the rectifier side. As shown in Figure 9(b), before the disturbance in the HVDC system, the energy of the MMG output in each data window is zero, and the proposed scheme does not detect any fault. As shown in this figure, since the PI exceeds the PT value, the proposed scheme detects an internal fault. Figure 9(c) shows the FPD, which exceeds the PDT and the positive pole is detected as the faulted pole. In Figure 10, since the FPD is almost zero and PI exceeds the PT value, the fault is identified as a PN internal fault.

5.3 | External DC faults

Both external faults of FR and FI with zero fault resistance are simulated, and the simulation results are reported in Figures 11 and 12. According to Figure 11(b), since the PI does not exceed the PT value, the proposed scheme identifies this fault as an external fault. Additionally, since the fault has occurred behind the installed relay on the rectifier side, the sum of line mode and zero mode are negative in this state, which means that the fault has occurred behind the relay, as can be seen in Figure 11(c). Also, considering Figure 12(b), similarly, since PI does not exceed the PT value, the proposed scheme does not send a trip signal. Moreover, as seen in Figure 12(c), since the fault is on the positive pole, FPD exceeds PDT.

5.4 | External AC faults

An ABC-G three-phase-to-ground external fault on the rectifier side and an AB-G two-phase-to-ground external fault on
the inverter side are simulated with zero fault resistance. As can be seen from Figure 13(b), the PI does not exceed the PT value, indicating an external fault. Also, since the fault has occurred on the rectifier side and is behind the relay, the line mode is negative, as can be seen from Figure 13(a). Furthermore, from Figure 14(b), since PI does not exceed the PT value, the proposed scheme does not send the trip signal.

6 | SENSITIVITY ANALYSIS

6.1 | Effect of fault resistance and fault location

To evaluate the performance of the proposed protection scheme against fault resistance and location, various internal faults, including PG and PN faults at different locations, and with different fault resistance values (0, 250, 500, 750, and 1000 Ω) are simulated. Simulation results are presented in Table 1. For external faults at the rectifier and inverter sides and AC faults, the simulation results are reported in Table 2.

According to the presented results, the proposed scheme is not sensitive to the fault resistance value and the fault location, and it is capable to detect high-resistance faults up to 1000 Ω, close-
TABLE 1  (Continued)

| Fault type | Fault location (km) | $R_f$ (Ω) | PI (p.u.) | FPD | Protection result |
|------------|---------------------|-----------|----------|-----|------------------|
|            | 750                 | 68.682    | 0        |     | Internal fault   |
|            | 1000                | 40.518    | 0        |     | Internal fault   |
| 500        | 0                   | 2233.021  | 0        |     | Internal fault   |
|            | 250                 | 315.373   | 0        |     | Internal fault   |
|            | 500                 | 119.451   | 0        |     | Internal fault   |
|            | 750                 | 119.451   | 0        |     | Internal fault   |
|            | 1000                | 38.121    | 0        |     | Internal fault   |
| 800        | 0                   | 2091.523  | 0        |     | Internal fault   |
|            | 250                 | 281.106   | 0        |     | Internal fault   |
|            | 500                 | 105.419   | 0        |     | Internal fault   |
|            | 750                 | 54.716    | 0        |     | Internal fault   |
|            | 1000                | 33.403    | 0        |     | Internal fault   |
| 999        | 0                   | 1998.189  | 0        |     | Internal fault   |
|            | 250                 | 129.164   | 0        |     | Internal fault   |
|            | 500                 | 41.320    | 0        |     | Internal fault   |
|            | 750                 | 19.912    | 0        |     | Internal fault   |
|            | 1000                | 11.633    | 0        |     | Internal fault   |

FIGURE 15  Effect of noise (during an FI external fault with $R_f = 0$ Ω by adding 30-dB noise). (a) Current modes. (b) PI. (c) FPD

in faults, and far-end faults. Furthermore, the method is capable of distinguishing internal faults from external faults.

6.2  Effect of noise

In order to investigate the effect of noise on the performance of the proposed scheme, an NG external fault, FI, and an NG internal fault at 999 km with 0-Ω fault resistance are considered. Then, an additive Gaussian noise with zero mean and variance corresponding to 30-dB signal-to-noise ratio is added to the measured signals and, then, used as an input for the proposed protection scheme. The simulation results are shown in Figures 15 and 16. It can be seen from Figure 15(b) that the PI is lower than the PT value, and an external fault is detected.

As shown in Figure 16(b), the PI exceeds the PT value, and the proposed scheme detects an internal fault. Also, from Figures 15(c) and 16(c), the FDP exceeds the -PDT value, and the faults have been identified as the NG faults. As a result, the proposed scheme correctly distinguishes internal faults from external faults when the input signal is also contaminated with measurement noise.

TABLE 2  Performance of the proposed protection scheme in case of external faults

| Fault location | Fault type | $R_f$ (Ω) | PI (p.u.) | FPD | Protection result |
|----------------|------------|-----------|----------|-----|------------------|
| FR            | PG         | 0         | 0.275    | -1  | External fault   |
| FI            | PG         | 0         | 0.529    | 1   | External fault   |
| FA            | A-G        | 0         | 0.062    | 0   | External fault   |
|               | B-G        | 0         | 0.077    | 0   | External fault   |
|               | C-G        | 0         | 0.077    | 0   | External fault   |
|               | AB-G       | 0         | 0.056    | 0   | External fault   |
|               | BC-G       | 0         | 0.170    | 0   | External fault   |
|               | AC-G       | 0         | 0.188    | 0   | External fault   |
|               | AB         | 0         | 0.050    | 0   | External fault   |
|               | BC         | 0         | 0.148    | 0   | External fault   |
|               | AC         | 0         | 0.170    | 0   | External fault   |
|               | ABC-G      | 0         | 0.218    | 0   | External fault   |
| FB            | A-G        | 0         | 0.046    | 0   | External fault   |
|               | B-G        | 0         | 0.182    | 0   | External fault   |
|               | C-G        | 0         | 0.044    | 0   | External fault   |
|               | AB-G       | 0         | 0.304    | 0   | External fault   |
|               | BC-G       | 0         | 0.233    | 0   | External fault   |
|               | AC-G       | 0         | 0.014    | 0   | External fault   |
|               | AB         | 0         | 0.266    | 0   | External fault   |
|               | BC         | 0         | 0.173    | 0   | External fault   |
|               | AC         | 0         | 0.038    | 0   | External fault   |
|               | ABC-G      | 0         | 0.382    | 0   | External fault   |

FIGURE 16  Effect of noise (during an NG internal fault at 999 km with $R_f = 0$ Ω by adding 30-dB noise). (a) Current modes. (b) PI. (c) FPD
6.3 Effect of sampling frequency and data window

In order to investigate the effect of sampling frequency on the performance of the proposed scheme, a PN fault at the location of 500 km with a fault impedance of 1000 Ω and an FI external fault are simulated, considering sampling frequencies of 7.5, 10, 15, and 20 kHz. The results of the simulation are shown in Figures 17 and 18. As shown in Figure 17(b), the PI under all four sampling frequencies exceeds the PT value, and the proposed scheme detects an internal fault. Moreover, as seen in Figure 17(c), the PN fault has been identified correctly. Figure 18(b) shows that the PI in all four sampling frequencies does not exceed the PT value indicating an external fault. Furthermore, in order to investigate the effect of data window length, a PG fault at the location of 999 km with the fault impedance of 500 Ω and an FI external fault are studied. Different data window lengths of 1.5, 3, 5, and 7 ms are considered. The output of the proposed scheme for these four data windows is shown in Figures 19 and 20, respectively. Considering Figure 19(b) and (c), the PI in all data windows exceeds the PT value; thus, an internal PG fault is detected. It can be seen from Figure 20(b) that, in none of the data windows, the PI does not exceed the PT value and has a small value; therefore, an external fault has been identified. Moreover, as seen in Figure 20(c), the PG fault is detected correctly. It is observed that the proposed scheme is not sensitive to the sampling frequency and the length of data window.

6.4 Effect of DC filter parameters and the smoothing reactor

In practice, parameters of DC filters and the smoothing reactors may vary with temperature and aging. Thus, the sensitivity
| Parameters of DC filter | %CH | Rectifier side | Inverter side | Protection result |
|------------------------|-----|----------------|---------------|-------------------|
|                        |     | PI (p.u.) | FPD | PI (p.u.) | FPD |
| C1                     | 30  | 30.25 | –1  | 25.32 | –1  | Internal fault |
|                        | 10  | 27.13 | –1  | 25.48 | –1  | Internal fault |
|                        | –10 | 23.45 | –1  | 25.54 | –1  | Internal fault |
|                        | –30 | 17.88 | –1  | 25.00 | –1  | Internal fault |
| L1                     | 30  | 25.21 | –1  | 25.49 | –1  | Internal fault |
|                        | 10  | 25.38 | –1  | 25.50 | –1  | Internal fault |
|                        | –10 | 25.65 | –1  | 25.55 | –1  | Internal fault |
|                        | –30 | 25.61 | –1  | 25.49 | –1  | Internal fault |
| C2                     | 30  | 22.50 | –1  | 23.85 | –1  | Internal fault |
|                        | 10  | 24.22 | –1  | 25.36 | –1  | Internal fault |
|                        | –10 | 26.42 | –1  | 25.57 | –1  | Internal fault |
|                        | –30 | 28.00 | –1  | 25.53 | –1  | Internal fault |
| L2                     | 30  | 22.54 | –1  | 23.39 | –1  | Internal fault |
|                        | 10  | 24.00 | –1  | 25.17 | –1  | Internal fault |
|                        | –10 | 26.25 | –1  | 25.59 | –1  | Internal fault |
|                        | –30 | 27.00 | –1  | 25.15 | –1  | Internal fault |
| C3                     | 30  | 25.88 | –1  | 25.20 | –1  | Internal fault |
|                        | 10  | 25.77 | –1  | 25.46 | –1  | Internal fault |
|                        | –10 | 25.16 | –1  | 25.57 | –1  | Internal fault |
|                        | –30 | 24.20 | –1  | 25.47 | –1  | Internal fault |
| L3                     | 30  | 26.28 | –1  | 25.15 | –1  | Internal fault |
|                        | 10  | 25.86 | –1  | 25.44 | –1  | Internal fault |
|                        | –10 | 25.15 | –1  | 2.603 | –1  | Internal fault |
|                        | –30 | 24.54 | –1  | 25.60 | –1  | Internal fault |

Also, in order to investigate the effect of the smoothing reactor changes on the proposed protection scheme, an NG internal fault at 500 km with a fault resistance of 500 Ω and external faults, FR and FI, are simulated. The initial value for the smoothing reactor is 300 mH. Then, the performance of the proposed scheme is assessed by changing the reactor inductance in the range of ±10% or ±30%. The simulation results in Table 4 show that for internal faults, the effect of the reactor inductance on the PI is not significant. For external faults, increasing the reactor inductance results in decrease of the PI. In the worst case, 30% reduction in the reactor size increases the PI to 1.103, which is still lower than the PT value.

6.5 Effect of operation modes

To evaluate the sensitivity of the protection scheme to the system operation mode, an internal NG fault at 999 km with 0-Ω fault resistance and an NG external fault, FI, are simulated. The simulation results under various asymmetric operation modes are summarised in Table 5. As demonstrated in this table, although the pre-fault current of the HVDC system...
### Performance of the proposed protection scheme under different smoothing reactor sizes

| Fault location | Fault type | %CH | PI (p.u.) | FPD | Protection result |
|----------------|------------|-----|----------|-----|-------------------|
| 500 km ($R_f = 500 \Omega$) | NG | 30 | 26.515 | –1 | Internal fault |
| | 10 | 26.649 | –1 | Internal fault |
| | 0 | 26.733 | –1 | Internal fault |
| | –10 | 26.822 | –1 | Internal fault |
| | –30 | 27.062 | –1 | Internal fault |
| FR | PG | 30 | 0.171 | –1 | External fault |
| | 10 | 0.231 | –1 | External fault |
| | 0 | 0.275 | –1 | External fault |
| | –10 | 0.333 | –1 | External fault |
| | –30 | 0.535 | –1 | External fault |
| FI | NG | 30 | 0.307 | –1 | External fault |
| | 10 | 0.433 | –1 | External fault |
| | 0 | 0.521 | –1 | External fault |
| | –10 | 0.665 | –1 | External fault |
| | –30 | 1.103 | –1 | External fault |

is 0.5 p.u., the PI value is still significantly larger than the PT value; consequently, the fault is determined as an internal fault. Moreover, in the case of the external fault, as PI is significantly lower than the PT value, the fault is determined as an external fault. From the results of the simulation in Table 5, it can be observed that the operation modes do not have any effect on the proposed protection scheme, and in this condition, there is no need to modify threshold values.

### Effect of change of power flow

To examine the sensitivity of the proposed scheme with respect to changes in the power flow in transmission lines, the power set point is changed at $t = 1.5$ s, and the simulation results for changing power set point from 1 p.u. to 0.5 p.u. and 1 p.u. to 1.5 p.u. are shown in Figures 21 and 22, respectively. It can be seen that the proposed protection scheme is not sensitive to changes in the power flow.

### Effect of non-ideal faults

The non-ideal faults with resistive–inductive characteristics are also studied to evaluate the performance of the proposed protection scheme. Multiple faults at different locations with different values of fault impedance are simulated, and the simulation results are reported in Table 6. It can be seen that the proposed protection scheme can correctly distinguish non-ideal faults in various fault locations and with various fault impedance values.

### Effect of different transmission line lengths

In order to investigate the effect of line length on the performance of the proposed scheme, an NG fault at the locations 250, 375, 500, 625, and 750 km with the fault impedance of 250 $\Omega$ and an FI external fault with the fault impedance of 0 $\Omega$ are simulated, considering line lengths of 500, 750, 1000, 1250, and 1500 km. The simulation results are given in Table 7. As shown, the proposed scheme under internal and external faults with different transmission line lengths has a satisfactory performance.

### Field data test results

To further evaluate the accuracy of the proposed method, field data measurements from the Lingzhou-Shaoxing ±800 kV, 5-kA UHVDC system with the line length of 1720 km is extracted from [9]. The current waveforms of the positive and negative poles for four field data cases are depicted in Figure 23. The output of the proposed scheme is reported in Table 8. The proposed protection scheme is able to distinguish internal faults from external ones.

### Performance evaluation for a multi-terminal HVDC grid

To evaluate the performance of the proposed method for a case of multi-terminal HVDC networks, a four-terminal HVDC grid test system (shown in Figure 24) that connects two offshore wind farms (OWFs) to two main AC grids according to [36]. In the middle of the Over-Head Line 13 (OHL13), a PG fault is applied, i.e. F13. As can be seen from Table 9, only OHL13 detects the F13 fault.

### COMPARISON WITH THE OTHER PROTECTION METHODS

The main protection for LCC-HVDC transmission lines can be classified into four groups.

### Methods based on travelling waves

These methods usually use both voltage and current signals. Therefore, the accuracy of these methods is generally high due to the use of both current and voltage signals for the fault detection. However, these methods are sensitive to fault resistance and noise [5] and may have difficulties in detecting faults in long lines and high impedance faults due to the dampening of traveling wave.
TABLE 5  Simulations results under asymmetrical operation modes

| Operation mode | Fault location | PI (p.u.) | FPD | Protection result |
|----------------|----------------|-----------|-----|-------------------|
| $U_1 = 1.0 \text{ p.u.} \quad I_1 = 1.0 \text{ p.u.}$ | 999 km | 426.038 | –1 | Internal fault |
| FI | 0.511 | –1 | External fault |
| $U_1 = 1.0 \text{ p.u.} \quad I_1 = 0.9 \text{ p.u.}$ | 999 km | 442.344 | –1 | Internal fault |
| FI | 0.533 | –1 | External fault |
| $U_1 = 1.0 \text{ p.u.} \quad I_1 = 0.8 \text{ p.u.}$ | 999 km | 457.540 | –1 | Internal fault |
| FI | 0.552 | –1 | External fault |
| $U_1 = 1.0 \text{ p.u.} \quad I_1 = 0.7 \text{ p.u.}$ | 999 km | 471.255 | –1 | Internal fault |
| FI | 0.579 | –1 | External fault |
| $U_1 = 1.0 \text{ p.u.} \quad I_1 = 0.6 \text{ p.u.}$ | 999 km | 482.186 | –1 | Internal fault |
| FI | 0.577 | –1 | External fault |
| $U_1 = 1.0 \text{ p.u.} \quad I_1 = 0.5 \text{ p.u.}$ | 999 km | 491.376 | –1 | Internal fault |
| FI | 0.561 | –1 | External fault |
| $U_1 = 0.9 \text{ p.u.} \quad I_1 = 1.0 \text{ p.u.}$ | 999 km | 427.661 | –1 | Internal fault |
| FI | 0.508 | –1 | External fault |
| $U_1 = 0.8 \text{ p.u.} \quad I_1 = 1.0 \text{ p.u.}$ | 999 km | 427.232 | –1 | Internal fault |
| FI | 0.527 | –1 | External fault |
| $U_1 = 0.7 \text{ p.u.} \quad I_1 = 1.0 \text{ p.u.}$ | 999 km | 428.030 | –1 | Internal fault |
| FI | 0.489 | –1 | External fault |
| $U_1 = 0.6 \text{ p.u.} \quad I_1 = 1.0 \text{ p.u.}$ | 999 km | 430.681 | –1 | Internal fault |
| FI | 0.510 | –1 | External fault |

TABLE 6  Performance of the proposed protection scheme in case of non-ideal faults

| Fault type | Fault location | $R_f(\Omega)$ | $I_f$(mH) | PI (p.u.) | FPD | Protection result |
|------------|----------------|--------------|-----------|-----------|-----|-------------------|
| PG 100 km | 500, 20 | 30.381 | 1 | Internal fault |
| 500, 50 | 25.634 | 1 | Internal fault |
| 500, 100 | 20.413 | 1 | Internal fault |
| 900 km | 500, 20 | 22.408 | 1 | Internal fault |
| 500, 50 | 18.995 | 1 | Internal fault |
| 500, 100 | 7.962 | 1 | Internal fault |
| PN 900 km | 500, 20 | 102.162 | 0 | Internal fault |
| 500, 50 | 78.579 | 0 | Internal fault |
| 500, 100 | 34.901 | 0 | Internal fault |
| PG FI | 0, 20 | 0.424 | 1 | External fault |
| FR | 0, 20 | 0.229 | –1 | External fault |

7.2  Methods based on boundary characteristics

These methods usually use WT or FT to extract high-frequency components, which, in general, require intensive computations. In addition, these methods might not be able to protect the entire length of transmission lines due to attenuation of high-frequency components for faults close to the inverter station with high fault resistance values. Also, in [20], the energy ratio...
### TABLE 7 Performance of the proposed protection scheme against different transmission line lengths

| Fault type | Fault location (km) | line length (km) | PI (p.u.) | FPD | Protection result |
|------------|---------------------|-----------------|-----------|-----|------------------|
| NG, $R_f = 250 \, \Omega$ | 250 | 500 | 63.465 | −1 | Internal fault |
| | 375 | 750 | 64.167 | −1 | Internal fault |
| | 500 | 1000 | 65.226 | −1 | Internal fault |
| | 625 | 1250 | 43.028 | −1 | Internal fault |
| | 750 | 1500 | 54.915 | −1 | Internal fault |
| PG, $R_f = 0 \, \Omega$ | FI | 500 | 0.571 | 1 | External fault |
| | FI | 750 | 0.795 | 1 | External fault |
| | FI | 1000 | 0.529 | 1 | External fault |
| | FI | 1250 | 0.523 | 1 | External fault |
| | FI | 1500 | 0.567 | 1 | External fault |

### TABLE 8 Performance of the proposed protection scheme for four field data cases

| Applied Fault | Fault type | Operation mode | $V_n$ (kV) | $I_n$ (kA) | PI (p.u.) | FPD | Protection result |
|---------------|------------|----------------|------------|------------|-----------|-----|------------------|
| FD_Case 1 PG | PG internal fault close to the rectifier | 800 | 0.5 | 52.300 | 1 | PG | Internal fault |
| FD_Case 2 PG | PG internal fault close to the inverter | 800 | 0.5 | 113.206 | 1 | PG | Internal fault |
| FD_Case 3 NG | NG internal fault close to the inverter | 800 | 0.5 | 84.328 | −1 | NG | Internal fault |
| FD_Case 4 | External AC fault | 400 | 0.5 | 0.633 | 0 | | External fault |

### FIGURE 23 Current waveforms of four field data cases of the UHVDC system. (a) Current waveform of the positive pole. (b) Current waveform of the negative pole

### FIGURE 24 Four-terminal HVDC grid

of the third level of the MMG of the voltage signal to the energy of the first level is used to discriminate the internal and external faults. Our proposed scheme uses third level of MMG energy to distinguish internal and external faults, which provide higher reliability compared to the energy ratio of the third to the first levels. Furthermore, in this work, zero mode is used to detect the faulty pole, which has been shown to be very effective.

#### 7.3 Methods based on current differential

Due to having long transmission line in HVDC systems, the capacitance effect of transmission lines is significant in the fault transient period; hence, these methods have a delay time of about several hundreds of milliseconds. Therefore, the

### TABLE 9 Performance of the proposed protection scheme during a PG fault at F13 at 250 km with $R_f = 0 \, \Omega$ and $R_f = 100 \, \Omega$

| Fault location | $R_f$ (\Omega) | lines | PI (p.u.) | FPD | Protection result |
|----------------|---------------|-------|-----------|-----|------------------|
| F13-PG | 0 Cable 12 | 1 | −1 | External fault |
| 250 | Cable 13 | 28.875 | 1 | Internal fault |
| km | Cable 14 | 1.080 | −1 | External fault |
| | 100 Cable 12 | 1.204 | −1 | External fault |
| | Cable 13 | 13.591 | 1 | Internal fault |
| | Cable 14 | 1.24 | −1 | External fault |
capacitance effect must be considered, which increases the computational burden of these methods. The protection scheme proposed in this work can send the trip signal in less than 3 ms. Moreover, these methods are unit protection, while the proposed protection scheme is non-unit protection.

### 7.4 Methods based on transient signals

These methods are unit protection and usually have high computational burden than the proposed scheme, as well as use both current and voltage signals. Besides, only studies [24] and [27] can detect faults with fault resistance values up to 1000 Ω. These methods are unit protections and use both voltage and current signals, while the proposed scheme is a non-unit protection and uses only the current signal.

Compared to the existing methods, the proposed scheme provides the following advantages.

In terms of the dependability of the protection system, the proposed protection scheme provides the ability to discriminate internal faults from external ones and to detect faulted pole for various internal fault conditions, fault location, fault resistances, external DC and AC faults, change of sampling frequency and data window length, non-ideal faults, change of power flow, change of DC filter parameters and smoothing reactor, change of operation mode, and measurement noise.

With regard to the security aspects, the proposed protection scheme is robust against external faults such as faults at the rectifier side and faults at the inverter side.

Regarding the speed, the protection can trip for internal faults in less than 3 ms.
Concerning the selectivity, the protection scheme protects the entire length of the line without any dead zone and does not mal-operate for external faults.

Finally, the protection scheme is able to correctly operate under high fault resistance up to 1000 Ω.

In summary, in Table 10, each group has been compared in terms of the sampling frequency, maximum detectable fault resistance, data window length, investigate the effect of noise, operation time, computational tool, sensitivity to operation mode, the used signal, and need for data exchange with the proposed protection scheme.

8 | CONCLUSION

This paper proposes a novel non-unit protection scheme using the MMG of DC current to protect transmission lines in bipolar LCC-HVDC systems. The proposed scheme is based on the effect of the filter–reactor unit on attenuating high-frequency current travelling waves propagated from the fault location to the ends of transmission lines. The energy of the MMG of the current travelling waves is used to discriminate internal and external faults, and the sum of zero-mode current during 20 samples after the fault is used to detect the faulty pole. The performance of the proposed scheme is evaluated by extensive simulation studies considering different internal fault conditions, DC and AC external faults, change of sampling frequency and data window length, non-ideal faults, change of power flow, size change of DC filter parameters and smoothing reactor, change of operation mode, noise, and field data. Both simulation data and field data test results show that the proposed protection scheme is able to detect faults accurately in less than 3 ms for various internal fault conditions and faults with the fault resistance values of up to 1000 Ω. The evaluation confirms the reliability, stability, sensitivity, and the speed of the proposed scheme in the protection of LCC-HVDC transmission lines.

Advantages of the proposed protection scheme are as follows:

- The method uses local current measurements;
- Does not require a communication link and GPS;
- Uses a relatively low sampling rate of 10 kHz;
- Is able to detect high fault resistance up to 1000 Ω;
- Low computational burden thanks to MMG;
- Very fast operation time;
- Is not sensitive to operation modes;
- Protect the entire length of the line.

Since the required signals are all available by the existing measurement platforms, the proposed protection scheme can be straightforwardly implemented in existing hardware platforms without additional requirements.

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APPENDIX A

The nominal values of the test system, the structure of the transmission line towers, and the filter–reactor unit are explained in Table A.1, Figure A.1, and Figure B.1, respectively.

| Parameter (Unit) | Rectifier side | Inverter side |
|------------------|----------------|---------------|
| Power (MW)       | 2000           | 2000          |
| dc voltage (kV)  | ±500           | ±500          |
| Line-to-line ac voltage (kV) | 345 | 230 |
| Frequency (Hz)   | 50             | 50            |
| SCR              | 2.5            | 2.5           |
| Equivalent impedance (Ω) | 2.53 ±84 | 2.05 ±75 |
| DC filter        | Triple tuned   | Triple tuned  |
| Smoothing reactor (mH) | 300  | 300 |
| Line length (km) | 1000           | 1000          |

**Figure A.1** Tower structure of the transmission lines

**Figure B.1** The structure and parameters of the filter–reactor unit