New Fault-Location Algorithm for Series-Compensated Double-Circuit Transmission Line

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ABSTRACT This paper proposes a new fault location algorithm to accurately locate the faults of series-compensated double-circuit transmission line and improve the stability of power system operation, which is not affected by fault types. The proposed algorithm is based on asynchronous voltage and current at both ends of the line, the pre-fault voltage and current are used to synchronize time. The six-sequence component transformation is introduced, and with the help of the phase-sequence selection rule, the proposed algorithm eliminates the non-linear impedance of metal oxide varistor (MOV). Simultaneously, to confirm the robustness of the algorithm, different fault types, different fault initial angles and different fault resistances are taken into account in the system simulation. Not only that, the influence of series capacitors (SCs) installation positions, line parameter errors, different sampling rates and measurement errors are also tested. In general, the proposed fault-location algorithm has excellent performance. PSCAD/EMTDC and MATLAB are used in simulation studies, the results show that the maximum estimated error of fault-location does not exceed 1.8631%.

INDEX TERMS Keyword series-compensated double-circuit transmission line, fault-location, six-sequence component transformation, metal oxide varistor (MOV), series capacitors (SCs).

I. INTRODUCTION
Continuous and reliable power supply is the goal of power system operation. However, faults in the power system are unavoidable. Transmission lines are the most fault-prone part of the power system [1]. Fault-location is very important to the economic operation of the power system and the quality of power supply. The form of the fault is a short circuit between conductors or to ground. The fault locator is used to accurately locate the fault of the transmission line, it can reduce the maintenance time, thereby improving the availability of the system.

To determine the faulted location of transmission lines, several fault-location algorithms are proposed [2]–[12]. These algorithms can be divided into two categories. In the first category, single-terminal voltage and current are used in fault-location algorithm [2]–[6]. In these algorithms, it may be difficult to accurately determine the locations of the faults, since these algorithms are usually valid under approximate assumptions, in the absence of data from the other terminal, existing algorithms generally have accuracy problems. For another category algorithm, two-terminal voltage and current are employed [7]–[12]. In the latter category, phasor measurement units (PMUs) are adopted to measure voltage and current [7]–[11], asynchronous voltage and current are used in [9], [12].

SCs are widely used in long-distance transmission line to improve power transmission capabilities [13]. It also increases the margin of transient stability, optimizes the load distribution of parallel transmission line, and reduces system losses.

The protector of SC device is usually integrated together to provide overcurrent protection, as shown in Figure 1. SC consists of series capacitor branch, MOV protection branch, gap protection branch and protection controller [14]. Line faults are accompanied by tremendous currents, the protection controller will trigger MOV-protection or gap-protection through current-threshold, then the current will decrease. If current is lower than conduction threshold of series capacitor, the series capacitor reconducts. Generally, MOV provides first...
protection and gap provides secondary protection because of the conduction threshold of MOV is lower than gap. When line fault happens, internal series capacitor, MOV and gap alternately conduct in each fundamen-tal frequency cycle [14]. The on-off time of each branch of each fundamental frequency period depends on the fault current. It means that the behavior of the impedances of SCs device at fault phases are highly non-linear, which is in contrast to the linear impedances of conventional lines. Therefore, developing fault location algorithm specially for series-compensated line is indispensable.

In recent years, fault-location of series-compensated line has become a research focus [15]–[24]. Several fault-location algorithms of single-circuit series-compensated transmission line were proposed [15]–[21], and the fault-location of double-circuit series-compensated line was studied in [22]–[24]. In [15], [17], the impedance of the MOV is estimated through the impedance characteristic curve, and then the fault distance is estimated. In [16], transmission line between the fault point and the installation point of the SCs is regarded as RLC series circuit, and the fault-location algorithm is obtained. SCs device with MOV protection and gap protection are applied in [18], [21], MOVs are bypassed by gap protection in the later stage of faults, then the influence of MOVs on fault-location is eliminated. The symmetrical component method is employed in [19], an impedance-based algorithm for single-circuit transmission line is proposed, the impedances of MOVs are eliminated. Since the double-circuit transmission line is more complicated in structure than the single- circuit transmission line, the traditional symmetrical component method cannot directly decouple the double-circuit transmission line, and the algorithm of [19] is not suitable for symmetrical faults. In [20], assuming that voltages at two bus are equal, a single-phase fault location method is proposed. In [22], the six-sequence component method is employed to calculate the fault distance. In [23], the zero-sequence equivalent network of double-circuit transmission line is established to estimate the fault distance. A specific phase-to-mode transformation is introduced in [24], and a pi-model of transmission line is established to obtain the fault distance.

This paper presents a new fault location algorithm for series-compensated double-circuit transmission line, which is not affected by fault types. Asynchronous voltage and current at both terminals of the lines are used to estimate the fault distance. The pre-fault voltage and current at both terminals are used for time synchronization, and the six-sequence component method is introduced to convert the voltage and current into the mode domain, the proposed fault-location algorithm eliminates nonlinear impedances generated by MOVs, and it is suitable for all fault types including fault between different circuits.

The rest of this paper is organized as follows. The second section explains the basic principles of series-compensated double-circuit line and derives the fault-location algorithm. In the third section, the results of PSCAD and MATLAB are given to verify the proposed algorithm performance. The fourth part summarizes this paper.

The notations adopted in this paper are summarized first.

- \( M, N \) Two terminals of the series-compensated transmission line.
- \( L, R \) Two terminals of the SCs device.
- \( i \) Six-component index, \( i = 1, 2, 3, 4, 5, 6 \) respectively.
- \( Z_c, \gamma \) line characteristic impedance and line propagation constant, respectively.
- \( l \) length of series-compensated transmission line.
- \( I_c \) SCs device away from \( M \)-terminal distance.
- \( x \) Fault point away from \( M \)-terminal distance.
- \( R_f \) fault transition resistance.
- \( I_{M-pre}, U_{M-pre} \) pre-fault current and voltage at the \( M \)-terminal, respectively.
- \( I_{N-pre}, U_{N-pre} \) pre-fault current and voltage at the \( N \)-terminal, respectively.
- \( I_{L-pre}, I_{R-pre} \) pre-fault current at the point \( L \) and point \( R \), respectively.
- \( Z_{ci}, \gamma_i \) \( i \)-th sequence characteristic impedance and line propagation constant, respectively.
- \( I_{Ms}, U_{Ms} \) sequence current and sequence voltage at the \( M \)-terminal, respectively.
- \( I_{Ns}, U_{Ns} \) sequence current and sequence voltage at the \( N \)-terminal, respectively.
- \( I_{Msi}, I_{Nsi} \) \( i \)-th sequence current and sequence voltage at the \( M \)-terminal, respectively.
- \( U_{Msi} \) voltage at the \( N \)-terminal, respectively.
- \( I_{Mfs}, I_{Nfs} \) sequence current of both sides of the fault point, respectively.
- \( I_{f}, U_{f} \) sequence current and sequence voltage at the fault point, respectively.
- \( I_{SC1s}, I_{SC2s} \) sequence current of both sides of the SCs device, respectively.
- \( I_{SC1si}, I_{SC2si} \) \( i \)-th sequence current of left side of SCs device.
- \( I_{DSCsi} \) \( i \)-th sequence current of right side of SCs device.
- \( \Delta V_{SCsi} \) \( i \)-th sequence voltage-drop of SCs device.
- \( [Z_{SC}] \) impedance matrix of SCs device.
- \( [Z_{SCi}] \) sequence impedance matrix of SCs device.
where the indexes 2 and 0 represent the positive, negative and zero sequence current direction as the original current, the indexes 1, circuit and the differential-component circuit, respectively, and the current of the transmission network can be written as network of the distributed parameter model. The voltage of \([25]\), the transformation matrix \([Q]\) is carried out with reference to \([25]\). Based on the conclusion obtained by the symmetrical component method. The deviation then, the mutual impedances between the phases are eliminated to eliminate the mutual impedances between circuits \([8]\). And the common-component and the differential-component are used to decouple the mutual impedances between circuits \([8]\).

In the six-sequence component method, firstly, the common-component and the differential-component are used to eliminate the mutual impedances between circuits \([8]\). And then, the mutual impedances between the phases are eliminated by the symmetrical component method. The deviation is carried out with reference to \([25]\). Based on the conclusion of \([25]\), the transformation matrix \([Q]\) is used to decouple the voltage and current, resulting in the following six-sequence network of the distributed parameter model. The voltage and current of the transmission network can be written as six-sequence components, and the formula is as follows:

\[
[Q] = \frac{1}{3} \begin{bmatrix}
a & a^2 & 1 & a & a^2 \\
1 & a^2 & a & 1 & a^2 \\
1 & 1 & 1 & 1 & 1 \\
a & a^2 & -1 & -a & -a^2 \\
a^2 & a & -1 & -a^2 & -a \\
1 & 1 & -1 & 1 & 1 \\
1 & 1 & 1 & -1 & -1 \\
\end{bmatrix}
\]  

\[
[I_S] = [Q][I] 
\]  

\[
[U_S] = [Q][U] 
\]

where \(a = e^{j120}\).

\[
[I_S] = \begin{bmatrix} I_{T1} & I_{T2} & I_{T0} & I_{F1} & I_{F2} & I_{F0} \end{bmatrix}^T 
\]

\[
[U_S] = \begin{bmatrix} U_{T1} & U_{T2} & U_{T0} & U_{F1} & U_{F2} & U_{F0} \end{bmatrix}^T 
\]

In the six-sequence component method, firstly, the common-component and the differential-component are used to eliminate the mutual impedances between circuits \([8]\). And then, the mutual impedances between the phases are eliminated by the symmetrical component method. The deviation is carried out with reference to \([25]\). Based on the conclusion of \([25]\), the transformation matrix \([Q]\) is used to decouple the voltage and current, resulting in the following six-sequence network of the distributed parameter model. The voltage and current of the transmission network can be written as six-sequence components, and the formula is as follows:

\[
[I_S] = \begin{bmatrix} I_{T1} & I_{T2} & I_{T0} & I_{F1} & I_{F2} & I_{F0} \end{bmatrix}^T 
\]

\[
[U_S] = \begin{bmatrix} U_{T1} & U_{T2} & U_{T0} & U_{F1} & U_{F2} & U_{F0} \end{bmatrix}^T 
\]

\[
[I_R] = e^{j\delta} \cdot \left( -\frac{1}{Z_c} \sinh(\gamma l_{c})U_{N-pre} + \cosh(\gamma l_{c})I_{N-pre} \right) 
\]

\[
[I_{R-pre}] \text{ refers to the pre-fault corrected current at point } R, \quad U_{N-pre} \text{ and } I_{N-pre} \text{ refer to the voltage and current of the pre-fault bus } N, \text{ respectively.} 
\]
Obviously, since SC devices are pure capacitors at this time, the currents at both terminals of the SC device are equal.

$$I_{L-pre} = -I_{R-pre}$$  \(9\)

The synchronization angle $\delta$ can be derived from the Eq (10):

$$\delta = \arccos(Re \cdot \frac{-K_1}{K_2})$$  \(10\)

where $Re(\cdot)$ represents the real part, $K_1$ and $K_2$ are as follows:

$K_1 = \cosh(\gamma l_1)I_{M-pre}Z_c - \sinh(\gamma l_1)U_{M-pre}$  \(11\)

$K_2 = -\cosh(\gamma (l - l_c))I_{N-pre}Z_c + \sinh(\gamma (l - l_c))U_{N-pre}$  \(12\)

It should be noted that, to simplify the process of derivation, the voltage and current at the $M$-terminal and $N$-terminal are synchronized in the derivation below.

**B. FAULT LOCATION METHOD**

1) **SUBROUTINE I: FAULT ON THE LEFT SIDE OF THE SERIES COMPENSATOR**

The equivalent six-sequence circuit with the fault on the left side of SCs device is shown in Figure 4. Now, the fault distance $x$ can be obtained by the $i_6$ sequence measurements and parameters of the transmission line [27]. The fault distance $x$ satisfies the Eq (13), $\Delta V_{SCi}$ is $i_6$ sequence voltage dropped across SCs from Node $N$ to Node $M$.

$$x = \tanh^{-1}\left(\frac{-B_i + \Delta V_{SCi}}{A_i}\right) / \gamma_i$$  \(13\)

where

$$A_i = Z_{si} \cosh(\gamma l_c)I_{Msi} - \sinh(\gamma l_c)U_{Msi} + Z_{ci}I_{SC1si}$$  \(14\)

$$B_i = \cosh(\gamma l_c)U_{Msi} - Z_{ci} \sinh(\gamma l_c)I_{Msi} - U_{SC2si}$$  \(15\)

In above (14) and (15), $U_{SC2si}$ can be obtained by (16), $I_{SC1si}$ and $I_{SC2si}$ are sequence current at both sides of the SCs, and they are equal, can be derive from bus $N$.

$$U_{SC2si} = \cosh(\gamma(l - l_c))U_{Nsi} - Z_{ci} \sinh(\gamma(l - l_c))I_{Nsi}$$  \(16\)

$$I_{SC1si} = I_{SC2si} = \frac{-1}{Z_{ci}} \sinh(\gamma(l - l_c))U_{Nsi}$$

$$+ \cosh(\gamma(l - l_c))I_{Nsi}$$  \(17\)

In (13), there are $\Delta V_{SCi}$ and $x$ two unknown variables, so determine $\Delta V_{SCi}$ is main problem of fault-location. However, MOV is a nonlinear impedance component, the estimation of $\Delta V_{SCi}$ is not straightforward. In order to overcome this limitation, the fault-location equation (13) is rearranged as:

$$A_i \tanh(\gamma_i x) + B_i + \Delta V_{SCi} = 0$$  \(18\)

From the circuit shown in Figure 4, the sequence voltage drop of the SCs device satisfies (19). In (19), $Z_{SCi}$ is obtained by the (20).

$$[\Delta V_{SCi}] = [Z_{SCi}] [I_{SC2si}]$$  \(19\)

$$[Z_{SCi}] = [Q^{-1}] [Z_{SCi}] [\Omega]$$  \(20\)

where

$$[\Delta V_{SCi}] = [\Delta V_{SC1i}, \Delta V_{SC2i}, \Delta V_{SC3i}, \Delta V_{SC4i}, \Delta V_{SC5i}, \Delta V_{SC6i}]^T$$  \(21\)

$$[I_{SC2si}] = [I_{SC2si1}, I_{SC2si2}, I_{SC2si3}, I_{SC2si4}, I_{SC2si5}, I_{SC2si6}]^T$$  \(22\)

In phase domain, the impedance matrix of the SC&MOV device is as follows:

$$[Z_{SC}] = \begin{bmatrix} Z_{a1} & Z_{b1} & Z_{c1} \\ Z_{a2} & Z_{b2} & Z_{c2} \end{bmatrix}$$  \(23\)

$Z_{a1}, Z_{b1}, Z_{c1}, Z_{a2}, Z_{b2}$ and $Z_{c2}$ refer to impedances of SC&MOV device in each line. $[Z_{SCi}]$ can be obtained through (20), which is shown in the Appendix.

Bring $[Z_{SCi}]$ into (19), and then sum all sequence components of $[\Delta V_{SCi}]$, and (24) is derived, where only $Z_{a1}$ still exists.

$$\sum_i^6 V_{SCi} = Z_{a1} (\sum_i^6 I_{SC2si})$$  \(24\)

Assuming that the impedance of the SC in healthy line and faulted line is $Z_{Cap}$ and $Z_M$, respectively. $Z_{Cap}$ is a constant capacitance, $Z_M$ is indefinite impedance. To eliminate the impedance $Z_M$, $Z_{a1}$ cannot be equal to $Z_M$ in (24). In another word, phase $a1$ cannot be a fault phase, and the phase-sequence $(a1, b1, c1, a2, b2, c2)$ of the three-phase system is artificially selected [27], the proper phase-sequence is necessary. The process shown in Figure 6, for example, assuming the fault type is $a1a2 - g$, after selecting the phase sequence according to (25), the fault type is converted to $b1b2-g$.

$$(a1, a2) \rightarrow (b1, b2) \rightarrow (c1, c2) \rightarrow (a1, a2) \rightarrow \ldots$$  \(25\)

Similarly, summing all the sequence components in (18), the fault locating function $f(x)$ is obtained, which is shown in (26).

$$f(x) = \sum_i^6 A_i \tanh(\gamma_i x) + \sum_i^6 B_i + Z_{a1} (\sum_i^6 I_{SC2si})$$  \(26\)
The derivation process is similar to subroutine I, and the fault distance estimation equation is given in (27).

\[
  f(x) = \sum_{i=1}^{6} C_i \tanh(\gamma_i(l-x)) + \sum_{i=1}^{6} D_i + Z_{ci}(\sum_{i=1}^{6} I_{SC1si}) \tag{27}
\]

\[
  C_i = Z_{ci} \cosh(\gamma_i(l-l_i))I_{Nsi} - \sinh(\gamma_i(l-l_i))U_{Nsi} + Z_{ci}I_{SC2i} \tag{28}
\]

\[
  D_i = \cosh(\gamma_i(l-l_i))U_{Nsi} - Z_{ci} \sinh(\gamma_i(l-l_i))I_{Nsi} - U_{SC1si} \tag{29}
\]

\[
  U_{SC1si} = \cosh(\gamma_i l_i)U_{Msi} - Z_{ci} \sinh(\gamma_i l_i)I_{Msi} \tag{30}
\]

\[
  I_{SC1si} = I_{SC2si} = \frac{1}{Z_{ci}} \sinh(\gamma_i l_i)U_{Msi} + \cosh(\gamma_i l_i)I_{Msi} \tag{31}
\]

\[
  \Delta V_{SCsi} \text{ is sequence voltage dropped across SCs device from Node } M \text{ to Node } N.
\]

Due to the possibility of pseudo roots when solving \( f(x) \), in order to solve the problem of pseudo roots. Bringing (29) or (27) into (32), the possible value of \( x \) can be obtained. Obviously, the solution of \( f(x) \) is a complex number, and only the solution that satisfies its real part and imaginary part equal to 0 is meaningful. In other words, \( x \) satisfies (33) is the true estimated fault distance, and \( \epsilon(x = 25) \) is an empirical value, and the value of \( \epsilon \) is derived from subsequent experiments.

\[
  \text{Re} \cdot f(x) = 0 \tag{32}
\]

\[
  |\text{Im} \cdot f(x)| \leq \epsilon \tag{33}
\]

According to the algorithm proposed in the above sections, subroutine I and subroutine II are applicable to the fault location on the left and right sides of the SCs device, respectively. Therefore, it is crucial to determine the fault section. Obviously, the reasonable solution \( x \) of subroutine I and subroutine II satisfy the boundary conditions \([0, l_c]\) and \([l_c, l]\), respectively. First input the data into subroutine I to calculate the fault distance \( x \), if \( x \) meets the boundary conditions \([0, l_c]\), it can be determined that the fault is located on the left side of the SCs device; on the contrary, the fault is located on the right side of the SCs device, and then input data to subroutine II, and the fault distance \( x \) is calculated by (27), and \( x \) must meet the boundary condition \([l_c, l]\).

**C. CALCULATION PROCESS**

The flowchart of the proposed fault location method is shown in Figure 7. According to the proposed algorithm in the previous article, the fault-location process is as follows:

Step 1: Recording and sampling the voltage and current at both ends. Eq (10) is used for time synchronization at both ends;

Step 2: Using (6) to determine the fault phases, if phase \( a_1 \) is fault phase, reselect the phase sequence by progress shown in Figure 6;

Step 3: Using (2) and (3) to decouple the data obtained by step 1;

Step 4: Input data obtained by step 3 into subroutine I to obtain the fault distance \( x \), if \( x \) meets the boundary condition of subroutine I \([0, l_c]\), skip to step 6;

Step 5: Input data obtained by step 3 into subroutine II to obtain the fault distance \( x \). If \( x \) meets the boundary condition of subroutine II \([l_c, l]\), skip to step 6.

Step 6: Bring the \( x \) obtained by step 4 or step 5 into (33) to eliminate the possibility of pseudo-roots. If \( x \) is less than the threshold \( \epsilon \), output \( x \) as the fault distance.

**III. ALGORITHM PERFORMANCE ANALYSIS**

**A. TEST SYSTEM**

This section presents the evaluation of the proposed fault location method. PSCAD/EMTDC is used to simulate series-compensated double-circuit line under different fault conditions. MATLAB will read the simulation results and estimates the location of each fault. Figure 2 shows a 315 kV, 300 km, 50 Hz double-circuit transmission line compensated at the degree of 40% (\( C = 29.11 \mu F \)) is simulated, the SCs device
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FIGURE 7. Flowchart of fault-location algorithm.

is installed 150 km away from the terminal-M [28]. The voltage sources parameters and transmission line parameters are shown in Table.1 and Table.2, respectively. Regardless of the influence of meters and transformers, current and voltage transformers are considered as ideal equipment. Since the proposed algorithm only uses the series capacitances in the SCs device, the type and model of SCs device has no influence on the algorithm. However, the model of MOV is similar to [16], [19], [22], [24]. The correlation error is adopted as follows:

\[
\text{Error} = \frac{|\text{estimated length} - \text{actual length}|}{\text{line branch length}} \tag{34}
\]

B. SYNCHRONIZE EFFORTS

The phase distribution curve of different SCs device installation positions is shown in Figure 8. \(\theta\) represents the voltage phase distribution curve of the voltage recorded on the remote terminal (bus N). \(\delta\) is the phase error distribution curve, \(\theta_c\) is the phase distribution curve after corrected, and \(\theta_i\) is the phase distribution curve of the ideal synchronization voltage. It can be clearly seen that the curves \(\theta_c\) and \(\theta_i\) are always very close, indicating that the synchronization effect is excellent.

C. RESULTS OF TEST CASES

Table.3 shows the effect of the proposed fault location algorithm. In Table 1, tests are carried out for different fault resistances, different fault angles and different fault types.

**TABLE 1. Voltage source data.**

| Quantity                  | Source M      | Source N      |
|---------------------------|---------------|---------------|
| Erms (KV)                 | 315 \angle 0^\circ | 300 \angle 10^\circ |
| Pos. Seq. Impedance (\(\Omega\)) | 1.125 + j15.773 | 1.042 + j14.110 |
| Zero. Seq. Impedance (\(\Omega\)) | 6.421 + j39.562 | 5.447 + j35.54 |

**TABLE 2. Transmission line data.**

| Parameter | Self | Mutl-Pha. | Mutl-Cir. |
|-----------|------|-----------|-----------|
| R (\(\Omega/km\)) | 0.0880 | 0.0611 | 0.0611 |
| L (mH/km) | 0.0019 | 0.0009 | 0.0008 |
| C (nF/km) | 1.0106e^{-8} | -1.5554e^{-9} | -7.0293e^{-10} |

**TABLE 3. Results of simulation cases.**

| Area  | Type | \(x(km)\) | \(R(\Omega)\) | Angle(\(^\circ\)) | Sub- I | Sub-II | Error(%) |
|-------|------|-----------|-------------|-----------------|--------|--------|----------|
| Left  | b1-g | 31        | 10          | 135             | 31.65  | -5744  | 0.0155   |
|       | s2-g | 85        | 10          | 45              | 84.59  | -7355  | 0.1359   |
|       | cla2-g | 69      | 100         | 90              | 68.58  | 7920   | 0.1396   |
|       | s2e2-g | 61      | 100         | 45              | 61.19  | -3205  | 0.0659   |
|       | nbl1 | 113      | 0.1         | 90              | 114.6  | -316   | 0.5424   |
|       | cla2 | 117      | 100         | 45              | 117.7  | 8443   | 0.2463   |
|       | bh2c-2-g | 62 | 0.1 | 90 | 62.62 | -4092 | 0.0050 |
|       | abh2b2-g | 146 | 100 | 45 | 146.3 | 1186 | 0.1254 |
| Right | ai-g  | 172      | 0.1         | 90              | -7045  | 171.25 | 0.2515   |
|       | b1-g  | 235      | 100         | 45              | -5440  | 234.10 | 0.2999   |
|       | ai1-c-g | 159 | 100 | 45 | 1279 | 159.23 | 0.0779 |
|       | s2b2-g | 214 | 10 | 135 | 5369 | 215.42 | 0.4746 |
|       | a1a2  | 164      | 100         | 45              | -7144  | 166.32 | 0.7726   |
|       | b1c2  | 278      | 10          | 45              | 8649   | 278.86 | 0.2877   |
|       | b1c1b2-g | 179 | 100 | 90 | 9454 | 179.69 | 0.2316 |
|       | c1b2c2-g | 261 | 0.1 | 90 | 2142 | 261.79 | 0.2648 |

**FIGURE 8. Synchronize efforts of different SCs location.**
In the cases of faults locate in the left side of the SCs device, all results of subroutine I satisfy the interval \([0, l_c]\), and all results of subroutine II does not satisfy the interval \([l_c, l]\), so these faults are determined in left side of SCs device. In the fault cases of the right side of the SCs device, the results of subroutine I are not in the interval \([0, l_c]\), and all results of subroutine II in the interval \([l_c, l]\), so these faults are determined in right side of SCs device.

At the same time, in Figure 10, \(|\text{Im}(f(x))|\) corresponds to different fault types and locations are less than the threshold \(\varepsilon (\varepsilon = 25)\), indicating that there is no possibility of pseudo roots.

### D. INFLUENCE OF SCs INSTALLATION POSITION

The influence of the different SCs device installation locations is shown in Figure 9. Five different \(l_c\) values (50, 100, 150, 200 and 250 km) are adopted, the other fault conditions are the same as Table 3. In Figure 9, the maximum value of the mean error is 0.2753%, the maximum value of the max error is 0.7952%. Moreover, the fluctuation of error is very small, so the accuracy can be accepted in different SCs installation positions.

### E. COMPARED TO PREVIOUS ALGORITHMS

In order to prove the superiority in the proposed algorithm in this paper, it was compared with the previous algorithms in [16] and [19]. The results are shown in Table 4. The fault conditions are the same as in Table 3. It is worth noting that the algorithm in [19] is only applicable to single-circuit transmission line. Therefore, assume that the mutual inductance between the circuits is zero. Since the algorithm in [19] only focuses on asymmetric faults, Table 4 only lists the location results of asymmetric faults.

In Table 4, the maximum error of the proposed algorithm in this paper is 0.7726%, the maximum error of the proposed algorithm in [16] is 2.1281%, and the maximum error of the proposed algorithm in [19] is 16.38%. It can be explained as follows: in [16], RLC circuit is used to replace the transmission line from the SCs device to the fault point, which will inevitably produce additional errors; in [19], the mutual inductance of different transmission line circuits is ignored, the results of Table 4 indicate that the mutual inductance between circuits is essential to locate fault, so the algorithm in [19] cannot be applied to double-circuit series compensation transmission line. The results in Table 4 show that the algorithm proposed in this paper is more accurate. Not only that, the algorithm proposed in this paper has a unified fault location formula for all fault types, while the algorithm of [19] has different fault location formulas for single-phase faults and two-phase faults. The algorithm of [19] requires additional fault diagnosis before fault location.

### F. EFFECT OF ERROR IN TRANSMISSION LINE PARAMETERS

In the actual transmission line, the line parameters cannot be completely accurate. Therefore, to verify the performance of the proposed fault location algorithm under different line parameter errors is necessary.

In Figure 11, 1%, 2% and 3% parameter errors are considered, the other fault conditions are the same as Table 3. The mean error and max error are shown in Figure 10, when 3% parameter error is adopted, the mean error and the max error reach the maximums, which are 1.0965% and 1.7874%, respectively. As expected, the fault location accuracy is affected by transmission line parameter errors, however, from a practical perspective, the accuracy under parameter error is still acceptable.

### G. INFLUENCE OF MEASUREMENT ERRORS AND DIFFERENT SAMPLING RATES

In order to test the influence of the measurement errors, according to the IEEE standard [30], 3% measurement error is considered. The mean error and max error for different fault types are shown in Figure 12. The fault conditions are the same as Tables 3. Tables 3 and Figure 12 shows that the max error increased from 0.7726% to 1.8631%. It can be seen that the fault location accuracy is affected by measurement error. However, the accuracy is still acceptable in practice.

### TABLE 4. Results of different algorithm.

| Fault types | Actual fault distance(km) | Proposed algorithm (%) | Algorithm in [16] (%) | Algorithm in [19] (%) |
|-------------|---------------------------|------------------------|-----------------------|-----------------------|
| b1-g        | 0.1033                    | 0.0155                 | 1.8881                | 14.16                 |
| a2-g        | 0.2833                    | 0.1359                 | 1.1945                | 12.23                 |
| a1-g        | 0.5733                    | 0.2515                 | 0.3204                | 6.481                 |
| b1-g        | 0.7833                    | 0.2999                 | 1.1945                | 7.234                 |
| a1a2-g      | 0.2300                    | 0.1396                 | 2.1281                | 14.56                 |
| a2c2-g      | 0.2033                    | 0.0639                 | 1.2641                | 12.92                 |
| a1c1-g      | 0.5300                    | 0.0779                 | 0.4801                | 10.08                 |
| a2b2-g      | 0.7133                    | 0.4746                 | 1.1816                | 14.10                 |
| a1b1        | 0.3767                    | 0.5424                 | 0.6089                | 11.37                 |
| a1a2        | 0.3900                    | 0.2463                 | 0.5809                | 7.091                 |
| a2a2        | 0.5467                    | 0.7726                 | 0.4916                | 10.20                 |
| b1c2        | 0.9267                    | 0.2877                 | 2.1104                | 16.38                 |
| b1b2c2-g    | 0.2067                    | 0.005                  | 1.1464                | -                     |
| a1b1b2-g    | 0.4867                    | 0.1254                 | 0.3736                | -                     |
| b1c1b2-g    | 0.5967                    | 0.2316                 | 0.73561               | -                     |
| c1b2c2-g    | 0.8700                    | 0.2648                 | 1.5041                | -                     |
In addition, the results of new algorithm using different sampling rates (2.5, 5 and 10 kHz) are shown in Figure 13, it’s easy to see changing the sampling rates has little effect on accuracy. As a result, it can be concluded that the proposed algorithm suitable for different sampling rates.

IV. CONCLUSION
This paper presents a fault location algorithm for series-compensated double-circuit transmission line. The proposed algorithm is based on asynchronous voltage and current at both ends of the line, the pre-fault voltage and current...
is used to synchronize time. The six-sequence component transformation is introduced, and with the help of the phase sequence selection rule, the nonlinear impedances of MOVs are eliminated. Simultaneously, to confirm the robustness of the algorithm, different fault types, different fault initial angles and different fault resistances are taken into account in the system simulation. Not only that, the influence of SCs installation positions, line parameter errors, different sampling rates and measurement errors are also tested. In general, the proposed fault location algorithm has excellent fault location performance.

**APPENDIX**

From Eq (20), $[Z_{SC}]$ is shown at the top of the page given as follows:

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