Fault Location Algorithm for Non-Homogeneous Transmission Lines Considering Line Asymmetry

Yu Liu, Member, IEEE, Binglin Wang, Student Member, IEEE, Xiaodong Zheng, Senior Member, IEEE, Dayou Lu, Student Member, IEEE, Minfan Fu, Senior Member, IEEE, and Nengling Tai, Member, IEEE

Abstract—This article presents a novel phasor domain approach to determine the location of faults in non-homogeneous transmission lines. Best implementation requires synchronized voltage and current phasor measurements at all terminals of the transmission line. The overall non-homogeneous transmission line model with fault is established by systematically combining the generalized compact models of all homogeneous line sections. The location of the fault is introduced as an additional state of the overall model. The derivation procedure of the model is without further assumptions, resulting in full consideration of three phase line asymmetry as well as distributed parameters of non-homogeneous transmission lines. Afterwards, the location of the fault is identified using the state estimation algorithm. Extensive numerical experiments in a two-terminal and a multi-terminal non-homogeneous transmission line demonstrate that the method has higher accuracy than existing fault location methods, independent of fault types, locations and impedances.

Index Terms—Fault Location, Non-homogeneous Transmission Lines, Generalized Compact Model, Line Asymmetry, Multi-terminal Lines.

I. INTRODUCTION

A TTACTING FAULT location on transmission lines benefits operators and utility crews by minimizing labor, repairing costs and power outage time [1]–[3]. In recent years, a number of two-terminal and multi-terminal non-homogeneous (also known as compound, mixed, or hybrid) transmission lines have emerged in the modern power systems, where the overhead transmission lines are combined with underground cables, to connect off-shore wind farms to the existing grids, mitigate right-of-way related issues, etc. Nevertheless, accurate fault location in non-homogeneous transmission lines is challenging due to the topology complexity, and has been studied by a limited number of literatures. Existing fault location techniques can be mainly categorized into two groups: fundamental frequency phasor based methods and traveling wave based methods. Besides the two main groups of methods, artificial intelligence based methods are also studied in recent years [19], [30]. These methods usually require a large number of high-quality training data as well as heavy training burden and therefore have not been widely adopted in practice. Next, the two main groups of methods are reviewed for classic transmission lines with commentary on specific challenges for non-homogeneous transmission lines.

Fundamental frequency phasor based methods utilize voltage and current phasors of fundamental frequency to calculate the location of the fault. The main idea of these methods is to first find the analytical relationship between the fault location and available phasor measurements, and then solve the fault location. These methods can be further categorized into single-ended and multi-ended methods. Single-ended methods calculate the location of the fault using local measurements only and do not require communication channels. However, to mitigate the influence of the fault impedance, single-ended methods usually employ certain assumptions on the fault current, source impedance and fault impedance [4]–[5]. Multi-ended methods utilize phasors at all terminals of the transmission line to locate faults. Reliable communication channels among terminals of the line are typically required. Compared to single-ended methods, these methods can eliminate the influence of fault impedance without aforementioned assumptions. In addition, due to the redundancy of available measurements, these methods can be further classified into methods with different data sets (voltage and current measurements, voltage and local current measurements, current and local voltage measurements, voltage measurements only) or different data time stamp (GPS synchronized measurements, GPS non-synchronized measurements) [6]–[8]. When applied to non-homogeneous transmission lines, instead of considering one transmission line model, the models of all homogeneous sections with different parameters should be connected together, including the fault location information. Existing literatures [9]–[13] usually adopt multi-terminal measurements and distributed...
parameter models of transmission lines. Fault indices are usually calculated to determine the faulted homogeneous section in the non-homogeneous line. These methods can be similarly classified into methods with different data sets or different time stamp that can be applied to two-terminal, three-terminal or multi-terminal non-homogeneous transmission lines. Specifically, when constructing the three phase distributed parameter model of non-homogeneous lines, most existing literatures adopt constant transformations (eg. sequence component transformation, Clarke’s transformation, Karrenbauer’s transformation) to decouple the three phase networks into three mode networks, and solve the fault location inside a specific mode network [13]. The decoupling procedure is based on the assumption that the all homogeneous transmission line sections are geometrically symmetrical. Therefore, the fault location errors could be potentially generated when dealing with geometrically asymmetrical non-homogeneous transmission lines.

**Traveling wave based methods** utilize traveling waves generated by abrupt changes inside the transmission line system (eg. fault, breaker operation) to find the location of the fault. The main idea of these methods is to first capture the arrival time of wavefronts at terminals of the transmission line, and then calculate the location of the fault from their time differences as well as the wave velocity. **Single-ended methods** calculate the location of the fault using subsequent arrival time of wavefronts at the local terminal of the line [14], [15]. **Multi-ended methods** utilize the arrival time of the first wavefronts at all terminals of the line and calculate the fault location using their time differences [15]–[17]. In addition, to accurately capture the arrival time of wavefronts, digital signal processing techniques including Wavelet Transformation [17] have also been considered. The main challenges of traveling wave based methods include: first, the intensity of traveling wave is greatly dependent on the fault initiation time, compromising the detection reliability of traveling waves; second, very high sampling rates are required to ensure location accuracy [18]. When applied to non-homogeneous transmission lines, complex reflections from the joint-nodes between homogeneous line sections as well as different traveling wave velocities in different homogeneous line sections should be carefully considered [19]. Existing literatures express measured first arrival time at terminals as functions of traveling time of each section as well as the fault time to indicate the faulted section and to calculate the exact location of the fault [20]–[22]. Similar as phasor based methods, most of these methods are also based on mode networks using constant transformations, which may influence the fault location accuracy when applied to geometrically asymmetrical non-homogenous transmission lines.

In this paper, a novel fundamental frequency phasor based method is proposed to locate faults in non-homogeneous transmission lines. Best implementation requires GPS synchronized measurements at all terminals of the line. Instead of using constant transformation matrices to decouple the phase networks into mode networks, this paper proposes a systematic methodology to formulate the model of the overall non-homogeneous transmission line with fault (by utilizing the proposed generalized compact model of each homogeneous line section).

The location of the fault is afterwards obtained by solving the model using state estimation. The proposed fault location method ensures the fault location accuracy by fully considering line asymmetry of non-homogeneous transmission lines. The contribution of the paper is summarized as follows:

- A systematic methodology is proposed to accurately construct the model of the overall non-homogeneous transmission line with fault;
- The proposed method fully considers distributed parameters and line asymmetry of non-homogeneous transmission lines, without any assumptions of tower structures;
- The proposed method can be applied to different two-terminal or multi-terminal geometrically asymmetrical non-homogeneous transmission lines.

The remainder of the paper is arranged as follows. Part II explains the challenges of existing modeling approach and the necessity of a new modeling method. Part III shows the proposed modeling methodology of the overall non-homogeneous transmission line. Part IV describes the procedure of solving the location of the fault using state estimation. Part V demonstrates the numerical results of the proposed method on a two-terminal and a multi-terminal non-homogeneous transmission line. Part VI further discusses the performance of the method. Part VII draws a conclusion.

**II. NECESSITY OF A NEW MODELING METHOD**

The three phase distributed parameter model of the non-homogeneous transmission line can be obtained by combining the models of all homogeneous transmission line sections. Note that the transmission line parameters are the same inside each homogeneous transmission line section but are generally different for different homogeneous sections.

**A. Challenges of Modeling One Homogeneous Line Section**

In fact, for one homogeneous line section, modeling and fault location approaches of transmission lines considering line asymmetry were also studied in literatures. The main idea is to utilize matrix representations to consider the physical laws of the homogeneous section. However, many methods in literatures did not fully consider shunt capacitance of the transmission line, such as neglecting the shunt capacitive current [23], [24], [26], [27], using lumped models of shunt capacitance and neglecting mutual capacitance [25], using lumped models of shunt capacitance and assuming certain tower structures [28], etc. To fully consider the three phase distributed parameters, a homogeneous transmission line section can be modeled through a group of matrix differential equations in phasor domain. The following equation holds,

\[
\begin{align*}
\frac{d^2 \hat{V}(y)}{dy^2} &= (R_1 + j\omega L_1) (G_1 + j\omega C_1) \hat{V}(y) \\
\frac{d\hat{V}(y)}{dy} &= (R_1 + j\omega L_1) \hat{I}(y) \\
\text{Boundary:} \quad \hat{V}(0) &= \hat{V}_R, \hat{V}(l) = \hat{V}_S, \hat{I}(0) = \hat{I}_S, \hat{I}(l) = \hat{I}_S
\end{align*}
\]

where \(\hat{V}(y)\) and \(\hat{I}(y)\) are voltage and current phasor vectors at location \(y\); \(\hat{V}_S, \hat{I}_S, \hat{V}_R\) and \(\hat{I}_R\) are voltage and current
Matrices are not constants and are typically calculated using methods decoupled using constant transformations. Elements are the same. Otherwise, equation (1) cannot be fully solved and expressed in (2), one line of one mode. For mode corresponds to the physical laws of the equivalent transmission of decoupled scalar equations, where each group of equations adopted to decompose the matrix equation into three groups. The first group of methods are further classified into two groups, as shown in Fig. 1, Step 1.

Specifically, the aforementioned phase-mode transformations are usually adopted to decompose the matrix equation into three groups of decoupled scalar equations, where each group of equations corresponds to the physical laws of the equivalent transmission line of one mode. For mode \( j \), the relationship among terminal current and voltage phasors can be solved and expressed in (2),

\[
\begin{bmatrix}
\tilde{V}_{Sj} \\
\tilde{I}_{Sj}
\end{bmatrix} =
\begin{bmatrix}
\cosh (\gamma_j I) & Z_j \sinh (\gamma_j I) \\
\sinh (\gamma_j I) / Z_j & \cosh (\gamma_j I)
\end{bmatrix}
\begin{bmatrix}
\tilde{V}_{Rj} \\
\tilde{I}_{Rj}
\end{bmatrix}
\]

where \( \tilde{I}_{Sj}, \tilde{V}_{Sj}, \tilde{I}_{Rj} \) and \( \tilde{V}_{Rj} \) are current and voltage phasors at both terminals of the line for mode \( j \); \( Z_j = \sqrt{(r_j + j\omega l_j)/(g_j + j\omega c_j)} \), \( \gamma_j = \sqrt{(r_j + j\omega l_j)(g_j + j\omega c_j)} \), and \( r_j, l_j, g_j \) and \( c_j \) are series resistance, series inductance, shunt conductance and shunt capacitance per unit length for mode \( j \).

Specifically, the aforementioned phase-mode transformations are further classified into two groups, as shown in Fig. 1, Step 1. The first group of methods adopts constant transformations such as sequence component transformation (also known as symmetrical component transformation), Clarke’s transformation, Karrenbauer’s transformation, etc. However, these methods assume that the homogeneous transmission line section is geometrically symmetrical, i.e., for parameter matrices \( R_1, L_1, G_1 \) and \( C_1 \), the diagonal elements are the same and the off-diagonal elements are the same. Otherwise, equation (1) cannot be fully decoupled using constant transformations. The second group of methods adopts varying transformations, where transformation matrices are not constants and are typically calculated using eigenvalue decomposition [29]. The transformation matrices are usually different for transmission lines with different parameters. These methods have no specific assumptions for the parameters of the homogeneous transmission line section.

### B. Challenges of Modeling the Overall Non-homogeneous Line and the Necessity of a New Modeling Method

From part II.A, one may conclude when modeling one homogeneous line section, the methods in group 2 (without geometrical symmetry assumption) are more accurate than those in group 1 (with geometrical symmetry assumption). Nevertheless, when establishing the overall non-homogeneous transmission line model, most existing literatures utilize methods in group 1. For example, literatures [9] and [10] utilize positive sequence network in two-terminal non-homogeneous lines; literatures [11], [12] and [13] utilize positive sequence network in multi-terminal non-homogeneous lines. This is due to the fact that in this case the phase-mode transformation matrices are the same for different homogeneous sections of transmission lines. Therefore, with methods in group 1, the overall non-homogeneous transmission line can be simply modeled using three decoupled mode networks (see Mode 1, 2, 0 in Fig. 1). On the contrary, when applying methods in group 2, the phase-mode transformation matrices are different for different homogeneous sections. In this case, different mode networks are generated for different line sections (see Mode 1', 2', 0', 1", 2", 0", etc. in Fig. 1). As a result, the overall non-homogeneous transmission line cannot be modeled using three decoupled mode networks. The modeling of the overall circuit is extremely complex. The above limitations are summarized in Fig. 1, Step 2.

To overcome above limitations, a new modeling method of one homogeneous transmission line section is proposed in part III. Instead of decoupling the three phase homogeneous line section into several modes, the proposed method fully considers line asymmetry by directly utilizing three phase matrix notation, and provides a generalized compact model of the homogeneous section without any assumptions of line parameters. Afterwards, the overall non-homogeneous transmission line can be modeled by simply connecting each section together. This idea is summarized in Fig. 2.

### III. PROPOSED MODELING METHODOLOGY

#### A. Proposed Model of One Homogeneous Line Section

The generalized compact model of a homogeneous line section is derived by directly solving equation (1) without any phase-mode transformations. Note that the modeling procedure is applicable to polyphase lines with \( n \) conductors. Define

\[
\begin{align*}
\tilde{U}(y) &= d\tilde{V}(y)/dy \\
\tilde{d}(y) &= (R_1 + j\omega L_1)(G_1 + j\omega C_1)\tilde{V}(y)
\end{align*}
\]

In a compact form,

\[
d\tilde{W}(y)/dy = BW(y)
\]
where \( \tilde{W}(y) = [\tilde{V}(y)], B = [I_{n \times n}] \), and \( I_{n \times n} \) is the identity matrix with the dimension of \( n \).

The general solution of (4) is,

\[
\tilde{W}(y) = e^{yB}C
\]

where \( C \) is a constant complex vector, and the matrix function \( e^{yB} \) is defined as \( \sum_{m=0}^{\infty} \frac{(yB)^m}{m!} \).

Next, use the boundary conditions in (1) to find \( C \),

\[
\begin{aligned}
&\left\{ \tilde{V}(0) = [C^{1B}C]_{1:n}, \tilde{V}(l) = [C^{1B}C]_{1:n} = \tilde{V}_S \\
&\tilde{I}(0) = [B e^{0B}C]_{1:n} = A \tilde{I}_R, \tilde{I}(l) = [B e^{1B}C]_{1:n} = A \tilde{I}_S
\end{aligned}
\]

where the notation \( [a:b] \) means row \( a \) to row \( b \) of vector \( [a] \), and \( A = R_1 + j\omega L_1 \).

Define \( e^{IB} = [M_{11}, M_{12}, M_{21}, M_{22}] \), where \( M_{ij} \) \( (i, j = 1, 2) \) are sub-matrices of \( e^{IB} \) with the dimension of \( n \times n \). From the first row in (6), one can express the constant vector \( C \) as functions of \( \tilde{V}_R \) and \( \tilde{V}_S \),

\[
C = \left[ \tilde{V}_R (M_{12})^{-1} \left( \tilde{V}_S - M_{11} \tilde{V}_R \right) \right]^T
\]

By substituting (7) into the second row in (6), we have,

\[
\begin{aligned}
&(M_{12})^{-1} \left( \tilde{V}_S - M_{11} \tilde{V}_R \right) = A \tilde{I}_R \\
&M_{21} \tilde{V}_R + M_{22} (M_{12})^{-1} \left( \tilde{V}_S - M_{11} \tilde{V}_R \right) = A \tilde{I}_S
\end{aligned}
\]

Represent \( \tilde{V}_S \) and \( \tilde{I}_S \) as functions of \( \tilde{V}_R \) and \( \tilde{I}_R \),

\[
\begin{bmatrix}
\tilde{V}_S \\
\tilde{I}_S
\end{bmatrix} =
\begin{bmatrix}
I_{n \times n} & 0 \\
0 & A
\end{bmatrix}^{-1} e^{1B} \begin{bmatrix} I_{n \times n} & 0 \\ 0 & A \end{bmatrix} \begin{bmatrix}
\tilde{V}_R \\
\tilde{I}_R
\end{bmatrix}
\]

Remark 1: equation (9) is the generalized compact model of one homogeneous line section. Compared to methods in group 1, the model is without the assumption of geometrical symmetry. Compared to methods in group 2, the model does not require complex mode networks and therefore the modeling of the non-homogeneous line can be easily achieved.

In fact, when modeling one homogeneous section, both the proposed modeling method and existing methods in group 2 fully consider line asymmetry and do not have any assumptions in solving equation (1). In other words, for one homogeneous section with the number of conductors \( n = 3 \), the proposed model should be mathematically equivalent to methods in group 2. This equivalence is proved in Appendix A to validate the correctness of equation (9).

B. Proposed Modeling Methodology of the Overall Non-homogeneous Line

With the generalized compact homogeneous section model described in equation (9), the overall non-homogeneous transmission line can be modeled by connecting all homogeneous sections together. This procedure generates the overall line model, which is a set of complex algebraic equations describing all the physical laws that the transmission line should obey. It has the following format,

\[
\begin{aligned}
&z_{\text{actual}} = f(x) \\
&0 = g(x)
\end{aligned}
\]

where \( z_{\text{actual}} \) is the actual phasor measurements of the system (typically including terminal voltage and current vectors), \( x \) is the state vector of the system. Note that the second equation corresponds to internal constraints that describe the relationship among elements of the state vector.

Specifically, the overall line model could be slightly different for different applications. For the non-homogeneous transmission line without fault, the overall line model can be obtained using the following systematic methodology:

Step 1: Write the generalized compact model of each homogeneous section;
Step 2: Add the Kirchhoff’s Current Laws (KCLs) at nodes connecting adjacent homogeneous sections;
Step 3: Consider the same voltages at nodes connecting adjacent homogeneous sections.

For the non-homogeneous transmission line with fault, the overall line model can be constructed using the following systematic methodology:

Step 1: Establish the non-homogeneous line model without fault at the left side of the fault location;
Step 2: Establish the non-homogeneous line model without fault at the right side of the fault location;
Step 3: Add the model of the fault.

This paper focuses on fault location application which utilizes the model of the non-homogeneous transmission line with fault. The proposed systematic modeling methodology can be applied to any non-homogeneous transmission line (two-terminal, multi-terminal, polyphase, mutually coupled, etc.). Next, the models of a two-terminal line with fault and a three-terminal line with fault are presented as examples.

The first example is a two-terminal two-section line, as shown Fig. 3. Here a fault in Section I is provided as an example (the model differs with faults in different sections). The variables are defined as follows: \( l_j \) is the distance between the fault and the left side of Section I; \( l_1 \) and \( l_2 \) are the length of
Fig. 3. Model of an example two-terminal line with fault.

Table I: $T_{\text{fault}}$ and $n_{\text{fault}}$ for Different Fault Types

<table>
<thead>
<tr>
<th>Fault Type</th>
<th>$T_{\text{fault}}$</th>
<th>$n_{\text{fault}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-N</td>
<td>[0 1 0; 0 0 1]</td>
<td>2</td>
</tr>
<tr>
<td>B-N</td>
<td>[1 0 0; 0 0 1]</td>
<td>2</td>
</tr>
<tr>
<td>C-N</td>
<td>[1 0 0; 0 1 0]</td>
<td>2</td>
</tr>
<tr>
<td>A-B</td>
<td>[1 0 0; 0 0 1]</td>
<td>2</td>
</tr>
<tr>
<td>B-C</td>
<td>[0 1 1; 1 0 0]</td>
<td>2</td>
</tr>
<tr>
<td>C-A</td>
<td>[1 0 1; 0 1 0]</td>
<td>2</td>
</tr>
<tr>
<td>AB-N</td>
<td>[0 0 1]</td>
<td>1</td>
</tr>
<tr>
<td>BC-N</td>
<td>[1 0 0]</td>
<td>1</td>
</tr>
<tr>
<td>CA-N</td>
<td>[0 1 0]</td>
<td>1</td>
</tr>
<tr>
<td>3 phase</td>
<td>[1 1 1]</td>
<td>1</td>
</tr>
</tbody>
</table>

Remark 2: It can be observed that with this proposed modeling methodology, the overall line model with fault is clearly demonstrated with straightforward analytical expressions. In

The model with syntax in (10) is, unnumbered equation shown at the bottom of this page, where $T_{\text{fault}}$ and $n_{\text{fault}}$ are defined in Table I. Detail physical meaning of the model in the first example is shown in Table II.

The second example is a three-terminal four-section line with a fault in Section II, as shown in Fig. 4. The variables are defined as follows: $l_f$ is the distance between the fault and the left side of Section II; $l_1$, $l_2$, $l_3$ and $l_4$ are the length of Sections I, II, III and IV; $\tilde{V}_1$, $\tilde{I}_1$, $\tilde{I}_2$, $\tilde{V}_2$, $\tilde{I}_3$ and $\tilde{V}_3$ are three phase current and voltage phasor vectors at terminals of the line; $\tilde{V}_{T2}$, $\tilde{I}_{T4}$ and $\tilde{I}_{T3}$ are three phase voltage phasor vectors, Section I and II current phasor vectors at the bus between Section I and II; $\tilde{V}_f$, $\tilde{I}_f1$ and $\tilde{I}_f2$ are three phase voltage phasor vector, left side and right side current phasor vectors at the location of the fault.

Section I and II; $\tilde{I}_1$, $\tilde{V}_1$, $\tilde{I}_2$ and $\tilde{V}_2$ are three phase current and voltage phasor vectors at both terminals of the line; $\tilde{V}_T$, $\tilde{I}_{T1}$ and $\tilde{I}_{T2}$ are three phase voltage phasor vector, Section I and II current phasor vectors at the bus between Section I and II; $\tilde{V}_f$, $\tilde{I}_f1$ and $\tilde{I}_f2$ are three phase voltage phasor vector, left side and right side current phasor vectors at the location of the fault.

The model with syntax in (10) is, unnumbered equation shown at the bottom of the next page, where $T_{\text{fault}}$ and $n_{\text{fault}}$ are defined in Table I. Detail physical meaning of the model in the second example is shown in Table III.

$z_{\text{actual}} = \begin{bmatrix} \tilde{V}_1 & \tilde{I}_1 & \tilde{V}_2 & \tilde{I}_2 \end{bmatrix}^T$,  
$x = \begin{bmatrix} \tilde{V}_f & \tilde{I}_{f1} & \tilde{I}_{f2} & \tilde{V}_T & \tilde{I}_{T1} & \tilde{I}_{T2} & l_f \end{bmatrix}^T$,  
$f(x) = \begin{bmatrix} I_{3\times3} & 0_{3\times3} & Z_1 \end{bmatrix}^{-1} e^{l_f B_1} \begin{bmatrix} I_{3\times3} & 0_{3\times3} & Z_1 \end{bmatrix}^{-1} \begin{bmatrix} I_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & Z_1 \end{bmatrix}$,  
g(x) = \begin{bmatrix} I_{3\times3} & 0_{3\times3} & Z_1 \end{bmatrix}^{-1} e^{(l_f - l_f)B_1} \begin{bmatrix} I_{3\times3} & 0_{3\times3} & Z_1 \end{bmatrix}^{-1} \begin{bmatrix} I_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & Z_1 \end{bmatrix} x$.

Table II: Physical Meaning of the Model in the First Example

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Row Index</th>
<th>Physical Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f(x)$</td>
<td>1 to 6</td>
<td>Generalized compact model, left segment of section I</td>
</tr>
<tr>
<td></td>
<td>7 to 12</td>
<td>Generalized compact model, section 2</td>
</tr>
<tr>
<td>$g(x)$</td>
<td>1 to 6</td>
<td>Generalized compact model, right segment of section I</td>
</tr>
<tr>
<td></td>
<td>7 to 9</td>
<td>KCL at the node between section 1 and 2</td>
</tr>
<tr>
<td></td>
<td>10 to (10 + n_{\text{fault}})</td>
<td>KCL at the location of the fault</td>
</tr>
</tbody>
</table>

Fig. 4. Model of an example three-terminal line with fault.
addition, the above models consider the location of the fault as an additional state of the system. The fault location can be obtained by mathematically solving the states of the line model with fault.

IV. STATE ESTIMATION BASED FAULT LOCATION SCHEME

The state estimation algorithm is adopted to solve the state vectors (including the location of the fault) in (10). Here the unconstrained weighted least square method is presented as an example, where the constraints are treated as virtual measurements (with zero measurement values but with much smaller measurement error standard deviations compared to the actual measurements). Therefore, equation (10) can be rewritten as:

\[ z = h(x) \]

The best estimation of the state vector can be obtained by solving the following optimization problem:

\[ \min J = (h(x) - z)^T W (h(x) - z) \]  

where \( W = \text{diag}\{\ldots, 1/\sigma_i^2, \ldots\} \), and \( \sigma_i (i = 1, 2, \ldots) \) are the error standard deviations of the \( i \)th measurement.

The best estimated state vector \( \hat{x} \) is given with the following Newton’s iterative method until convergence:

\[ x^{n+1} = x^n - (H^T W H)^{-1} H^T W (h(x^n) - z) \]

where \( H = \partial h(x)/\partial x |_{x=x^n} \). The fault location is included as one element in \( \hat{x} \).

Above fault location procedure is based on a predefined faulted homogeneous section. To determine the faulted homogeneous section, the proposed method builds \( N \) different overall non-homogeneous line models (\( N \) is the total number of homogeneous sections), where each model corresponds to the overall line model with fault in one section. The procedure of solving of all above models will only result in one correct fault location results (the one with the correct assumption of the faulted section), while other solutions are unrealistic, such as divergence of the algorithm or impractical fault locations (fault location less than zero or larger than the whole length of the section). Details of unrealistic solutions can be found in section VI.D of the paper.

The flow chart of the fault location procedure is demonstrated in Fig. 5.

V. SIMULATION RESULTS

The proposed algorithm is validated via a two-terminal non-homogeneous transmission line in part V.A and a three-terminal non-homogeneous transmission line in part V.B. On the above two systems, extensive number of events with different fault
Fig. 5. Flowchart of the fault location procedure.

Fig. 6. Example test system 1: two-terminal non-homogeneous transmission line.

time, types, locations and impedances have been simulated using frequency-dependent circuit model in PSCAD/EMTDC. The instantaneous measurement data are stored in COMTRADE files for experimentation with 80 samples per cycle according to IEC61850-9-2LE standard. The phasors of corresponding measurements are then calculated according to IEEE C37.118 synchrophasor standard.

A. Example Test System 1: Two-terminal Non-homogeneous Transmission Line

The two-terminal transmission line of interest is line A1-A2, as shown in Fig. 6. The rest of the network is not shown. The transmission line system is with the system nominal frequency of 50 Hz and the line to line rated voltage of 500 kV. The line of interest consists of 2 homogeneous line sections (Section I, an overhead line A1-T; Section II, an underground cable A2-T), with the length of 200 km and 100 km, respectively. Both the transmission line and the cable are geometrically asymmetrical. Three phase voltage and current measurements are installed at both terminals of the line.

To determine the homogeneous section that the fault locates in, the proposed method establishes two different models, where each model corresponds to the fault inside each section. The fault location algorithms with two different models are running simultaneously and one of the fault location algorithms will converge to impractical values (fault location less than zero or larger than the whole length of the section) or simply diverge. Next, the performance of proposed method is compared to the existing two-terminal non-homogeneous line fault location method using sequence component transformation matrix [10] (as described in part II), via the following test cases. Here faults in Section I are selected as examples. The results are similar for faults in Section II. For faults between phases, the maximum fault impedances are selected to be 10 ohm to cover extreme cases.

Test Case 1. Single Phase to Neutral Faults in Section I: A 0.01 ohm phase A to neutral fault occurs at 130 km from side A1 and at time 0.3 seconds for 5 cycles. The fault location results, including the existing method and the proposed method, are shown in Fig. 7(a). The final fault location is calculated by taking the average of the calculated fault location results during the last cycle. One can observe that the proposed method (129.9802 km) has higher accuracy compared to the existing method (128.9860 km).

To further validate the effectiveness of the proposed method, phase A to neutral faults at different fault locations (every 10 km, through the line) with different fault impedances (0.01 ohm, 1 ohm, 5 ohm, and 10 ohm) are tested. The results are depicted in Fig. 7(b). One can observe that the proposed method presents higher accuracy compared to the existing method. The maximum absolute fault location errors are 0.0284 km for the proposed method and 1.2178 km for the existing method.

Test Case 2. Phase to Phase Faults in Section I: Phase B to C faults at different fault locations (every 10 km, through the line) with different fault impedances (0.01 ohm, 1 ohm, 5 ohm, and 10 ohm) are tested. The results are depicted in Fig. 7(c). One can observe that the proposed method is more accurate than the existing method. The maximum absolute fault location errors are 0.0082 km for the proposed method and 4.1899 km for the existing method.

Test Case 3. Phase to Phase to Neutral Faults in Section I: Phase BC to neutral faults at different fault locations (every 10 km, through the line) with different fault impedances (0.01 ohm, 1 ohm, 5 ohm, and 10 ohm) are tested. The results are depicted in Fig. 7(d). One can observe that the proposed method is more accurate than the existing method. The maximum absolute fault location errors are 0.0181 km for the proposed method and 2.4301 km for the existing method.

Test Case 4. Three Phase Faults in Section I: Phase ABC faults at different fault locations (every 10 km, through the line) with different fault impedances (0.01 ohm, 1 ohm, 5 ohm, and 10 ohm) are tested. The results of three phase to neutral faults are similar and are therefore not provided. The results are depicted in Fig. 7(e). One can observe that the proposed method is more accurate than the existing method. The maximum absolute fault location errors are 0.0018 km for the proposed method and 0.6512 km for the existing method.

Test Case 5. High Impedance Faults in Section I: High impedance phase A to neutral faults at different fault locations (every 10 km, through the line) with different fault impedances
Fig. 7. Fault location results comparison, two-terminal transmission line, faults in Section I. (a) 0.01 ohm A-N fault, 130 km from side A1. (b) 0.01 ohm, 1 ohm, 5 ohm and 10 ohm phase A-N faults, variable fault location. (c) 0.01 ohm, 1 ohm, 5 ohm and 10 ohm phase B-C faults, variable fault location. (d) 0.01 ohm, 1 ohm, 5 ohm and 10 ohm phase BC-N faults, variable fault location. (e) 0.01 ohm, 1 ohm, 5 ohm and 10 ohm phase ABC faults, variable fault location. (f) 100 ohm, 200 ohm, 300 ohm and 500 ohm phase A-N faults, variable fault location.

Fig. 8. Example test system 2: three-terminal non-homogeneous transmission line.

B. Example Test System 2: Three-Terminal Non-homogeneous Transmission Line

The three-terminal transmission line of interest is line A1-A2-A3, as shown in Fig. 8. The rest of the network is not shown. The transmission line system is with the system nominal frequency of 50 Hz and the line to line rated voltage of 500 kV. The line of interest consists of 4 homogeneous sections (Section I, an underground cable A1-T2; Sections II, III and IV, overhead lines T2-T1, A2-T1 and A3-T1, with different tower structures), with the length of 80 km, 120 km, 160 km and 180 km, respectively. All homogeneous line sections are geometrically asymmetrical. Three phase voltage and current measurements are installed at all three terminals of the line.

Similarly as part V.A, the proposed method establishes four different models to find the faulted section, where each model corresponds to the fault inside each section. The fault location algorithms with four different models are running simultaneously and three of the fault location algorithms will converge to impractical values (fault location less than zero or larger than the whole length of the section) or simply diverge. Next, the performance of proposed method is compared to the existing three-terminal non-homogeneous line fault location method using sequence component transformation matrix [13] (as described in part II), via the following test cases. Here faults in Section II are selected as examples. The results are similar for faults in Section I, III and IV. For faults between phases, the maximum fault impedances are selected to be 10 ohm to cover extreme cases.

Test Case 6. Single Phase to Neutral Faults in Section II: A 0.01 ohm phase A to neutral fault occurs at 40 km from side T2 and at time 0.3 seconds for 5 cycles. The fault location results,
Fig. 9. Fault location results comparison, three-terminal transmission line, faults in Section II. (a) 0.01 ohm A-N fault, 40 km from side T2. (b) 0.01 ohm, 1 ohm, 5 ohm and 10 ohm phase A-N faults, variable fault location. (c) 0.01 ohm, 1 ohm, 5 ohm and 10 ohm phase B-C faults, variable fault location. (d) 0.01 ohm, 1 ohm, 5 ohm and 10 ohm phase BC-N faults, variable fault location. (e) 0.01 ohm, 1 ohm, 5 ohm and 10 ohm phase ABC faults, variable fault location. (f) 100 ohm, 200 ohm, 300 ohm and 500 ohm phase A-N faults, variable fault location.

including the existing method and the proposed method, are shown in Fig. 9(a). The final fault location is calculated by taking the average of the calculated fault location results during the last cycle. One can observe that the proposed method (39.9918 km) has higher accuracy compared to the existing method (41.0917 km).

To further validate the effectiveness of the proposed method, phase A to neutral faults at different fault locations (every 5 km, through the line) with different fault impedances (0.01 ohm, 1 ohm, 5 ohm and 10 ohm) are tested. The results are depicted in Fig. 9(b). We can observe that the proposed method presents higher accuracy compared to the existing method. The maximum absolute fault location errors are 0.0143 km for the proposed method and 1.3409 km for the existing method.

Test Case 7. Phase to Phase Faults in Section II: Phase B to C faults at different fault locations at different fault locations (every 5 km, through the line) with different fault impedances (0.01 ohm, 1 ohm, 5 ohm, and 10 ohm) are tested. The results are depicted in Fig. 9(c). One can observe that the proposed method is more accurate than the existing method. The maximum absolute fault location errors are 0.0065 km for the proposed method and 1.4997 km for the existing method.

Test Case 8. Phase to Phase to Neutral Faults in Section II: Phase BC to neutral faults at different fault locations at different fault locations (every 5 km, through the line) with different fault impedances (0.01 ohm, 1 ohm, 5 ohm, and 10 ohm) are tested. The results are depicted in Fig. 9(d). One can observe that the proposed method is more accurate than the existing method. The maximum absolute fault location errors are 0.0024 km for the proposed method and 0.6989 km for the existing method.

Test Case 9: Three Phase Faults in Section II: Phase ABC faults at different fault locations at different fault locations (every 5 km, through the line) with different fault impedances (0.01 ohm, 1 ohm, 5 ohm, and 10 ohm) are tested. The results are depicted in Fig. 9(e). One can observe that the proposed method is more accurate than the existing method. The maximum absolute fault location errors are 0.0075 km for the proposed method and 1.0677 km for the existing method.

Test Case 10. High Impedance Faults in Section II: High impedance phase A to neutral faults at different fault locations (every 5 km, through the line) with different fault impedances (100 ohm, 200 ohm, 300 ohm, and 500 ohm) are tested. The results are depicted in Fig. 9(f). One can observe that the proposed method is more accurate than the existing method. The maximum absolute fault location errors are 0.1699 km for the proposed method and 23.2527 km for the existing method.

VI. DISCUSSION

To prove the effectiveness of the proposed method, the performance of the method is further discussed, including the calculation burden of the algorithm, the effect of measurement errors, the effect of parameter errors and unrealistic solutions of the algorithm.
A. Calculation Burden of the Algorithm

The calculation burden of the proposed method is evaluated to ensure that it is applicable in practice. Here the calculation burden test is performed in a standard personal computer with the i7-7700 CPU. Different fault events in test case 10 (high impedance faults in the three-terminal non-homogeneous transmission line system) are selected as examples. For each fault, the test calculates 80 fault location results of the last cycle using 80 groups of phasor measurements (which are calculated from the instantaneous measurement data stored in the COMTRADE file with the sampling rate of 80 samples per cycle). The fault location is estimated by calculating the average value of the 80 fault location results in the last cycle.

Fig. 10 shows the calculation time with different fault events in test case 10. The calculation time varies between 0.3950 seconds to 0.6310 seconds. The average calculation time is 0.5208 seconds. The computation time can be much reduced if the 80 fault location results in the last cycle are calculated in parallel (in this case the calculation time is in the order of milli-seconds). Nevertheless, considering the fact that fault location is an offline procedure, the calculation time without the aforementioned parallel computing techniques is still acceptable in practice.

B. Effect of Measurement Errors

The effect of measurement errors is studied via different fault events in test case 10 (high impedance faults in the three-terminal non-homogeneous transmission line system). The measurement errors are added to the instantaneous measurements in the COMTRADE file. The measurement errors obey Gaussian distribution with 1%, 2%, 5% and 10% standard deviations, respectively. The fault location results with different fault impedances, different fault locations and different measurement errors are depicted in Fig. 11. It can be observed that the fault location errors are generally higher with larger measurement errors and larger fault impedances. The maximum fault location errors are 0.9731 km, 2.3865 km, 6.9175 km and 14.5242 km, with 1%, 2%, 5% and 10% measurement errors, respectively.

C. Effect of Parameter Errors

The effect of parameter errors is studied via different fault events in test case 10 (high impedance faults in the three-terminal non-homogeneous transmission line system). The 1%, 2%, 5% and 10% parameter errors are added to all the parameter matrices of the non-homogeneous transmission line, respectively. The fault location results with different fault impedances, different fault locations and different parameter errors are depicted in Fig. 12. It can be observed that the fault location errors are generally higher with larger parameter errors and larger fault impedances. The maximum fault location errors are 1.3598 km, 3.0673 km, 10.5755 km and 26.6504 km, with 1%, 2%, 5% and 10% parameter errors, respectively.

D. Unrealistic Solutions of the Algorithm

For a non-homogeneous transmission line with fault, the proposed method finds the faulted homogeneous line section by establishing different line models. Each model assumes that the fault is inside each homogeneous line section. Afterwards, these models are solved simultaneously. Among all these results,
Fig. 13. Fault location results with unrealistic values, two-terminal transmission line. 0.01 ohm phase A-N fault in Section I, 130 km from side A1. (a) Estimated fault location, assuming the fault is in Section I. (b) Value of J, assuming the fault is in Section I. (c) Estimated fault location, assuming the fault is in Section II. (d) Value of J, assuming the fault is in Section II.

VII. CONCLUSION

A novel phasor domain fault location approach has been presented to accurately determine the fault location in non-homogeneous transmission lines. Voltage and current synchrophasor measurements at terminals of the line are typically required. The method first proposes a generalized compact model of one homogeneous line section. Afterwards, a systematic methodology to generate the overall model of any non-homogeneous transmission line with fault is provided, where the location of the fault is introduced as an additional state of the system. No assumption is made during the derivation of the model, resulting in full consideration of three phase distributed parameters as well as transmission line asymmetry. State estimation algorithm is adopted to solve the states of the non-homogeneous line, inclusive of the fault location. Numerical experiments on a two-terminal and a three-terminal three phase circuits, the proposed methodology can also be applied to multi-terminal, polyphase and mutually coupled non-homogeneous lines.

Since the proposed method is a model based fault location approach, large measurement errors and parameter errors could potentially result in compromised fault location accuracy. Therefore, for practical implementation, best performance of the proposed method requires high-quality synchrophasor measurements as well as accurate transmission line parameters. Moreover, if synchrophasor measurements are not available, the proposed method should be modified to also consider phase angle differences between terminals of the line. In addition, validation through real world data will be valuable to ensure the effectiveness of the algorithm. These issues will be studied in future publications.

APPENDIX A
PROOF OF EQUIVALENCE

The model in (9) is mathematically equivalent to methods in group 2 (as defined in part II) when the number of conductors \( n = 3 \). This equivalence is proved next.

From methods in group 2, \( T_V \) should satisfy,

\[
T_V^{-1} (R_1 + j\omega L_1) (G_1 + j\omega C_1) T_V = diag([\gamma_1^2 \gamma_2^2 \gamma_3^2]^T) \tag{A-1}
\]

where \( diag([\gamma]) \) is the diagonal matrix with column vector \([\gamma]\) as the diagonal elements, and the variable definitions are consistent with those in (2).

After selecting \( T_I = T_V^T \), the following equations hold,

\[
T_I^{-1} (G_1 + j\omega C_1) (R_1 + j\omega L_1) T_I = diag([\gamma_1^2 \gamma_2^2 \gamma_3^2]^T) \tag{A-2}
\]

\[
T_V^{-1} (R_1 + j\omega L_1) T_I = diag([r_1 + j\omega l_1 r_2 + j\omega l_2 r_0 + j\omega l_0]^T) \tag{A-3}
\]

Therefore,

\[
B = \begin{bmatrix} 0 & I_{3\times3} \\ (R_1 + j\omega L_1) (G_1 + j\omega C_1) & 0 \end{bmatrix} = T_6 F T_6^{-1}
\]

where \( T_6 = [T_V^T 0] \) and \( F = \begin{bmatrix} 0 & I_{3\times3} \\ diag[\gamma_1^2 \gamma_2^2 \gamma_3^2] & 0 \end{bmatrix} \).
Apply eigenvalue decomposition to matrix $F$,

$$ F = PAP^{-1} \quad \text{(A-5)} $$

where

$$ \Lambda = \text{diag} \begin{pmatrix} \gamma_1 & \gamma_2 & \gamma_0 \\ -\gamma_1 & -\gamma_2 & -\gamma_0 \end{pmatrix}, \quad P = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} $$

From (A-4) and (A-5),

$$ e^{jB} = \sum_{m=0}^{\infty} \frac{[jB]^m}{m!} = \sum_{m=0}^{\infty} \frac{(T_6PAP^{-1}T_6^{-1})^m}{m!} $$

$$ = T_6P \sum_{m=0}^{\infty} \frac{[\Lambda]^m}{m!} P^{-1}T_6^{-1} $$

$$ = T_6P \delta diag \left( e^{j\gamma_1} e^{-j\gamma_2} e^{j\gamma_0} e^{-j\gamma_0} \right) P^{-1}T_6^{-1} $$

$$ = T_6 \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} T_6^{-1} \quad \text{(A-6)} $$

where $Q_{11} = Q_{22} = \text{diag}(\cosh(\gamma_1 l) \cosh(\gamma_2 l) \cosh(\gamma_0 l)), Q_{12} = \text{diag}(\sinh(\gamma_1 l) / \gamma_1 \sinh(\gamma_2 l) / \gamma_2 \sinh(\gamma_0 l) / \gamma_0),$ and $Q_{21} = \text{diag}(\gamma_1 \sinh(\gamma_1 l) / \gamma_1 \gamma_2 \sinh(\gamma_2 l) / \gamma_2 \gamma_0 \sinh(\gamma_0 l) / \gamma_0).$

Substitute (A-6) into (9) and apply mode transformation,

$$ \begin{bmatrix} \tilde{V}_{S120} \\ \tilde{I}_{S120} \end{bmatrix} = \begin{bmatrix} T_V & 0 \\ 0 & T_I \end{bmatrix}^{-1} \begin{bmatrix} I_{3x3} & 0 \\ 0 & A \end{bmatrix}^{-1} e^{jB} \begin{bmatrix} I_{3x3} & 0 \\ 0 & A \end{bmatrix} \begin{bmatrix} \tilde{V}_{R120} \\ \tilde{I}_{R120} \end{bmatrix} $$

$$ = \begin{bmatrix} T_V & 0 \\ 0 & T_I \end{bmatrix}^{-1} \begin{bmatrix} T_V & 0 \\ 0 & A^{-1}T_V \end{bmatrix} \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} T_V^{-1} & 0 \\ 0 & T_V^{-1}A \end{bmatrix} \begin{bmatrix} \tilde{V}_{R120} \\ \tilde{I}_{R120} \end{bmatrix} $$

$$ = \begin{bmatrix} I_{3x3} & 0 \\ 0 & T_I \end{bmatrix}^{-1} \begin{bmatrix} I_{3x3} & 0 \\ 0 & T_V^{-1}AT_I \end{bmatrix} \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} I_{3x3} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \tilde{V}_{R120} \\ \tilde{I}_{R120} \end{bmatrix} $$

$$ \begin{bmatrix} \tilde{V}_{S120} \\ \tilde{I}_{S120} \end{bmatrix} = \begin{bmatrix} Q_{11} & S_{12} \\ S_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} \tilde{V}_{R120} \\ \tilde{I}_{R120} \end{bmatrix} \quad \text{(A-7)} $$

where $\begin{bmatrix} \tilde{V}_{S120} \\ \tilde{I}_{S120} \end{bmatrix} = \left[ \tilde{V}_{S1} \tilde{I}_{S1} \tilde{V}_{S0} \right]^T, \begin{bmatrix} \tilde{V}_{R120} = \left[ \tilde{V}_{R1} \tilde{I}_{R1} \tilde{V}_{R2} \tilde{I}_{R2} \tilde{V}_{R0} \right]^T, \end{bmatrix} \begin{bmatrix} I_{S120} \end{bmatrix} = \left[ \tilde{I}_{S1} \tilde{I}_{S2} \tilde{I}_{S0} \right]^T, \begin{bmatrix} I_{R120} = \left[ \tilde{I}_{R1} \tilde{I}_{R2} \tilde{I}_{R0} \right]^T. \end{bmatrix}$

Substitute (A-3) into (A-7),

$$ \begin{bmatrix} \tilde{V}_{S120} \\ \tilde{I}_{S120} \end{bmatrix} = \begin{bmatrix} Q_{11} & S_{12} \\ S_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} \tilde{V}_{R120} \\ \tilde{I}_{R120} \end{bmatrix} \quad \text{(A-8)} $$

where $S_{12} = \text{diag}\left( Z_1 \sinh(\gamma_1 l) Z_2 \sinh(\gamma_2 l) Z_0 \sinh(\gamma_0 l) \right), \text{and} S_{21} = \text{diag}\left( \sinh(\gamma_1 l) Z_1 \sinh(\gamma_2 l) Z_2 \sinh(\gamma_0 l) Z_0 \right).$

We can observe that (A-8) is equivalent to (2) with varying transformations. Q.E.D.


Yu Liu (Member, IEEE) received the B.S. and M.S. degrees in electrical power engineering from Shanghai Jiao Tong University, Shanghai, China, in 2011 and 2013, respectively, and the Ph.D. degree in electrical and computer engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 2017. He is currently a Tenure-Track Assistant Professor with the School of Information Science and Technology, ShanghaiTech University, Shanghai, China. His research interests include modeling, protection, fault location, and state/parameter estimation of power systems, and power electronic systems.

Binglin Wang (Student Member, IEEE) received the B.S. degree in electrical engineering and intelligent control from Xi’an University of Technology, Xi’an, China, in 2018. He is currently working toward the Ph.D. degree in electrical engineering with the School of Information Science and Technology, ShanghaiTech University, Shanghai, China. His research interests include protection, fault location and state estimation of HVac and HVdc transmission lines.

Xiaodong Zheng (Senior Member, IEEE) was born in Anhui, China, on January 1985. He received the Ph.D. degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 2013, and the Joint Ph.D. degree in electrical power from Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, in 2012. He was a Postdoctoral Researcher with the Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University. He is currently an Associate Professor with the Department of Power Electrical Engineering, Shanghai Jiao Tong University. His research interests include HVdc transmission system and smart grid.

Dayou Lu (Student Member, IEEE) received the B.S. degree in electrical engineering and automation from Huazhong University of Science and Technology, Wuhan, Hubei, China, in 2017. He is currently working toward the Ph.D. degree in electrical engineering with the School of Information Science and Technology, ShanghaiTech University, Shanghai, China. His research interests include modeling, protection and fault location of transmission lines.

Minfan Fu (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical and computer engineering from the University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, China, in 2010, 2013, and 2016, respectively. From 2016 to 2018, he held a Postdoctoral position with the Center for Power Electronics Systems, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA. He is currently an Assistant Professor with the School of Information Science and Technology, ShanghaiTech University, Shanghai, China. His research interests include megahertz wireless power transfer, high frequency power conversion, high-frequency magnetic design, and application of wide-bandgap devices.

Nengling Tai (Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 1994, 1997, and 2000, respectively. He is currently a Professor with the Department of Power Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China. His research interests include the protection and control of active distribution systems, microgrids, smart grid, and renewable energy.