

Model-based Location of Segmental Aging for Underground Power Cables in Distribution Grids

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Abstract—Power cable in distribution grids usually operates in nonuniform environments, leading to segmental aging of cable insulation. Location of segmental aging is highly desirable for early maintenance of power distribution grids, which can avoid severe insulation faults and improve system reliability. In this paper, a novel segmental aging location method based on voltage and leakage current measurements under multi-frequency common-mode (CM) monitoring signal injection is proposed. Segmental aging models for various types of cables are first developed, and a model-based location algorithm of segmental aging is then designed. Comprehensive simulations and case studies in PSCAD/EMTDC are conducted to prove the effectiveness of the proposed method. Compared with existing approaches, the proposed method achieves more accurate location of aging accounting for various measurement noises, parameter uncertainties, and distribution grid structures.

Index Terms—Distribution grids, power cables, location algorithm of segmental aging, segmental aging model.

I. INTRODUCTION

URBANIZATION has led to the rapid expansion of power distribution grids, whose reliability has become a most critical issue [1]. As the main power carrier, underground cable plays a critical role in distribution grids. Due to electrical and thermal stresses, cable insulation undergoes irreversible aging during operation, which will lead to incipient faults and system outages [2]. Nowadays, routine maintenance is still the most popular way to monitor cable aging conditions, which requires removing the cable from service and disrupting normal system operation. Therefore, condition-based maintenance based on online estimation of cable insulation parameters has become an urgent need in power distribution systems [3]–[5].

Segmental aging is a common aging form of power cables in distribution grids, as reported in [6]–[8]. Due to nonuniform operation environments, electric fields, and load-current-induced thermal effects, some segments of a cable may present a noticeable electrical parameter variation while other counterparts remain intact. Location of segmental aging in underground power cables can assist targeted maintenance at an early stage, avoiding insulation faults and ensuring reliable operation of the system.

To date, there have not been any satisfying solutions reported for online location of cable segmental aging due to the following challenges. First, the parameter variation of segmental aging is small and hard to observe under normal working conditions [9]. Moreover, the relationship between electrical measurements and cable insulation parameters is highly nonlinear, making accurate estimation difficult. A comprehensive model is still lacking to describe this relationship for various types of cables, and a location algorithm with high accuracy and fast convergence speed is also needed.

Existing cable segmental aging location methods are mostly based on travelling waves [10]. As cable aging will lead to insulation dielectric parameter variation, characteristic impedance discontinuity may appear at segmental aging terminals. Therefore, aging location can be realized by injecting high-frequency travelling waves into inspected cables and analyzing reflected signals. Based on the types of injected signal, these methods can be further classified into two categories: namely, time-domain-reflectometry-based method (TDR) [11] and frequency-domain-reflectometry-based method (FDR) [12]. For TDR method, a high-frequency travelling wave with a single frequency is injected into the inspected cable, and the time delay of the reflected wave is used to determine the location. However, in segmental aging situations, variation of dielectric parameters will be rather small, resulting in a weak reflected wave which is hard to detect [13]. Besides, TDR method also fails to provide an estimation of insulation aging severity. Moreover, it is hard to apply in ring-structured distribution grids [14].

FDR method injects a set of signals that step over a selected frequency range into the cable, and characteristic impedance variation is obtained using an inverse Fourier transform based on the measured terminal impedance spectrum [15]. FDR usually performs better than TDR due to more information collected [16]. Location accuracy of FDR can also be improved by using a wider frequency range and a smaller measurement frequency interval, which leads to a broadband impedance

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spectrometry (BIS) method in some research [7], [8]. However, methods based on FDR have the following shortcomings. First, aging severity cannot be easily obtained, which also fails in detecting segmental aging with one end at the cable terminal. Moreover, the location accuracy of the FDR highly relies on the selected frequency range. A wide frequency range covering hundreds of MHz to GHz is always needed, making online implementations difficult.

To solve the problems of the above methods, a novel segmental aging location method based on voltage and leakage current measurements under multi-frequency common-mode (CM) monitoring signal injection is proposed in this paper. Key contributions are threefold:

1) Segmental aging models for various types of cables under the injected monitoring signal are derived, which lay the foundation of the location method.

2) A model-based location algorithm of segmental aging is proposed. Segmental aging parameters can be estimated based on voltage and leakage current measurements at cable terminals.

3) Comprehensive numerical experiments prove the effectiveness of the proposed method under various measurement noises, parameter uncertainties, and distribution grid structures.

Compared with the traditional TDR and FDR methods, the main advantage of the proposed method lies in non-intrusiveness, the ability to estimate aging severity online, and a much lower measurement frequency range.

The rest of this paper is organized as follows. Segmental aging models for various types of cables are derived in Section II. The location algorithm is designed in Section III. Evaluations of the proposed method are included in Section IV, with case studies in PSCAD/EMTDC developed in Section V. Section VI provides some comparison results, and Section VII gives the conclusion.

II. SEGMENTAL AGING MODELS FOR POWER CABLES

A. Online Location of Segmental Aging Based on Multi-Frequency CM Monitoring Signal Injection

The dominant characteristic of segmental aging in underground power cables is the increase in cable insulation capacitance [9], [17]. It is also found that the capacitance increase pattern remains almost unchanged in a wide frequency range, for example, larger than 50 Hz for cross-linked polyethylene (XLPE) cables [18]. Therefore, estimation of cable segmental aging parameters based on wide-frequency range measurements becomes possible.

For a typical radial distribution grid as shown in Fig. 1(a), the distributed-element model of cable L1 with segmental aging is shown in Fig. 1(b). R_0 represents the per-unit-length resistance of the conductor, and L_0 represents the per-unit-length inductance of the conductor. C_0 represents the per-unit-length insulation capacitance of intact segments, and C_{aged} represents the per-unit-length insulation capacitance of aged segments. Insulation conductance is neglected due to a much smaller value compared with insulation capacitance at inspected frequencies larger than 50 Hz [19]. The aim of the

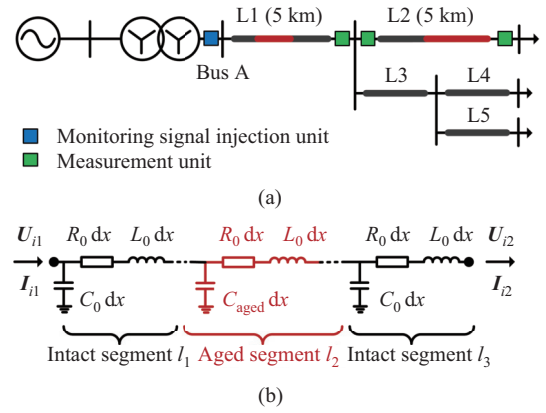


Fig. 1. A typical radial distribution grid. (a) With segmental aging in power cable L1 and L2. (b) The distributed-element model of L1.

proposed location scheme is to give an estimation of aging location and severity, C_{aged}/C_0 .

When segmental aging appears in power cables, the variation of electrical parameters is always small, and the insulated nature of cables is preserved. Therefore, it is difficult to locate under normal working conditions, and additional injection of monitoring signals proves to be necessary. An online location scheme based on multi-frequency CM monitoring signal injection is used in this paper. A diagram of the used CM monitoring signal is shown in Fig. 2. As the monitoring signal is equally exerted on all phases, induced current only flows through cable insulation as leakage current, and no current will be induced in the connected load [20], [21], ensuring non-intrusiveness of the proposed method for normal ungrounded distribution grids.

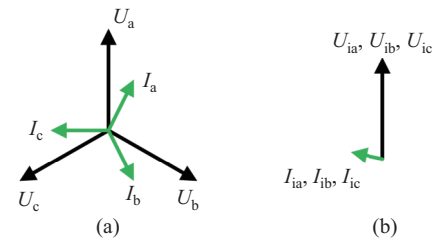


Fig. 2. Phasor diagram. (a) Phase voltage and current. (b) Injected CM monitoring signal and induced leakage current on each phase.

For industry applications, the monitoring signal can be injected by neutral-point voltage injection [22], [23] or inductive coupling methods [24], [25]. Recently, monitoring signal injection methods based on power line communication (PLC) modems have also been reported [26]. A bandwidth of 3~500 kHz can be achieved in PLC [27], enough to implement the proposed method. Besides, measurement of voltage and leakage current induced by injected monitoring signals can also be achieved in a contactless manner using electric or magnetic sensors, as in [28] and [29]. As the aging of power cables is usually a long-term process that may last several years, injecting a monitoring signal does not need to be carried out frequently and will not influence normal system operation.

B. General Segmental Aging Model for Power Cables

The segmental aging model is derived as follows to describe the relationship between electrical measurements at the cable terminal and segmental aging parameters. As all phases in distribution grids usually share a similar segmental aging pattern and endure identical stress under CM monitoring signal injection, induced voltage and leakage current remain almost the same for all phases. Therefore, the following analysis is based on a single-phase cable for a simpler demonstration. According to transmission line theory, the relationship between voltage and induced leakage current at two terminals can be expressed as (1).

$$\begin{bmatrix} U_{i1} \\ I_{i1} \end{bmatrix} = \begin{bmatrix} \cosh \tau_0 l_1 & \frac{\sqrt{Z_0}}{\tau_0} \sinh \tau_0 l_1 \\ \frac{\tau_0}{\sqrt{Z_0}} \sinh \tau_0 l_1 & \cosh \tau_0 l_1 \end{bmatrix} \times \begin{bmatrix} \cosh \tau_{\text{aged}} l_2 & \frac{\sqrt{Z_0}}{\tau_{\text{aged}}} \sinh \tau_{\text{aged}} l_2 \\ \frac{\tau_{\text{aged}}}{\sqrt{Z_0}} \sinh \tau_{\text{aged}} l_2 & \cosh \tau_{\text{aged}} l_2 \end{bmatrix} \times \begin{bmatrix} \cosh \tau_0 l_3 & \frac{\sqrt{Z_0}}{\tau_0} \sinh \tau_0 l_3 \\ \frac{\tau_0}{\sqrt{Z_0}} \sinh \tau_0 l_3 & \cosh \tau_0 l_3 \end{bmatrix} \times \begin{bmatrix} U_{i2} \\ I_{i2} \end{bmatrix} \quad (1)$$

where U_{i1} and I_{i1} represent voltage and leakage current at the sending end. U_{i2} and I_{i2} represent voltage and leakage current at the receiving end. Z_0 is the conductor impedance, which can be expressed as $Z_0 = R_0 + j\omega L_0$. $\omega = 2\pi f$, where f represents the injected signal frequency. $\tau_0 = \sqrt{j\omega C_0 Z_0}$ is the transmission coefficient of intact segments, and $\tau_{\text{aged}} = \sqrt{j\omega C_{\text{aged}} Z_0}$ is the transmission coefficient of the aged segment. l_1 , l_2 , and l_3 represent the lengths of intact and aged segments, as shown in Fig. 1(b). The main idea is to realize estimation of aging location and severity using the segmental aging model based on voltage and leakage current measurements under multiple injected frequencies.

C. Segmental Aging Model for Cables with Metal Sheaths

Apart from the above general segmental aging model, applications for cables with metal sheaths need further consideration. The illustration of a cable with metal sheath is shown in Fig. 3(a) [30], with the distributed-element model shown in Fig. 3(b). Unlike the model above, per-unit-length sheath resistance and inductance should be considered, which are denoted as R_s and L_s , respectively. U_{S1} and I_{S1} represent voltage and current on the sheath layer at the sending end, while U_{S2} and I_{S2} represent voltage and current on the sheath layer at the receiving end.

The segmental aging model needs to be modified for cables with metal sheaths due to a more complicated relationship between measurements and cable aging parameters. Consider the metal sheath as a separate conductor [31]. According to multi-conductor transmission line (MTL) theory, the relationship between voltages measured at each terminal under the injected monitoring signal can be expressed as (2).

$$\begin{bmatrix} U_{i1} \\ U_{S1} \end{bmatrix} = \mathbf{H}_1 \times \mathbf{H}_{\text{aged}} \times \mathbf{H}_2 \times \begin{bmatrix} U_{i2} \\ U_{S2} \end{bmatrix} \quad (2)$$

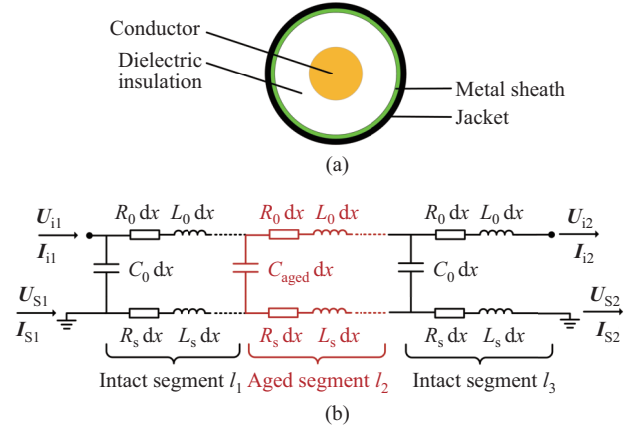


Fig. 3. Studied cable structure. (a) Illustration and (b) Distributed-element model of a power cable with metal sheath.

Currents at sending end can be expressed as (3).

$$\begin{bmatrix} I_{i1} \\ I_{S1} \end{bmatrix} = \mathbf{Y}_R \times \begin{bmatrix} U_{i1} \\ U_{S1} \end{bmatrix} \quad (3)$$

where $\mathbf{H}_1$ and $\mathbf{H}_2$ represent transfer function matrices of the intact segment at the sending end and receiving end, respectively. $\mathbf{H}_1 \in \mathbb{C}^{2 \times 2}$, $\mathbf{H}_2 \in \mathbb{C}^{2 \times 2}$. $\mathbf{H}_{\text{aged}}$ represents the transfer function matrix of the aged segment and $\mathbf{H}_{\text{aged}} \in \mathbb{C}^{2 \times 2}$. $\mathbf{Y}_R$ represents the equivalent admittance matrix at the sending end, $\mathbf{Y}_R \in \mathbb{C}^{2 \times 2}$. Derivation of $\mathbf{H}_1$, $\mathbf{H}_2$, $\mathbf{H}_{\text{aged}}$, and $\mathbf{Y}_R$ can be found in [32], which is omitted in this paper for a simpler demonstration. As terminals of metal sheath are always connected to ground directly or through a small resistance, U_{S1} and U_{S2} can be assumed as zero. Therefore, the segmental aging model for power cables with metal sheaths can be expressed as (4).

$$\begin{cases} U_{i1} = [1 \ 0] \times \mathbf{H}_1 \times \mathbf{H}_{\text{aged}} \times \mathbf{H}_2 \times \begin{bmatrix} U_{i2} \\ 0 \end{bmatrix} \\ I_{i1} = [1 \ 0] \times \mathbf{Y}_R \times U_{i1} \end{cases} \quad (4)$$

As analyzed in [32], segmental aging only leads to an increase of per-unit-length system admittance, which will increase to C_{aged}/C_0 times normal value for all inspected frequencies. Therefore, the location of segmental aging based on voltage and leakage current measurements at different frequencies will still be feasible for cables with metal sheaths.

D. Typical Voltage and Leakage Current Distribution under Segmental Aging

An example of voltage and leakage current distribution with segmental aging under monitoring signal injection is shown below for clearer demonstration. Cable parameters are as in [33]. Cable length is set as 5 km with segmental aging located from 1 km to 2 km, whose insulation capacitance increases to 1.2 times the normal value. Load admittance is set as zero, as no current is induced in the connected load under CM monitoring signal injection. Monitoring signal is injected from the sending end with unit amplitude of 1 V. Measured U_{i2} and I_{i1} for power cables under intact and aged situations in 1~200 kHz are shown in Fig. 4.

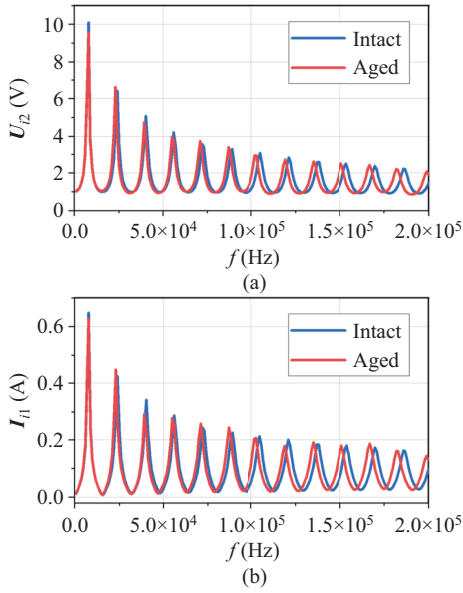


Fig. 4. Measurements under cable aging. (a) U_{i2} and (b) I_{i1} of power cables under intact and aged situations.

It is shown that measured voltage and leakage current present variation when segmental aging exists, which can probably be used for location. However, this variation is rather small with large nonlinearity, making accurate estimation of segmental aging parameters difficult. A novel location algorithm is needed to solve this complicated problem.

III. LOCATION ALGORITHM OF SEGMENTAL AGING

A novel location algorithm of segmental aging based on voltage and leakage current measurements is proposed in this section. Assume n monitoring frequencies are used, which are $f_1, \dots, f_k, \dots$ and f_n . Voltage and leakage current measured at each terminal can be denoted as $U_{i1}(f_1), \dots, U_{i1}(f_n)$, $I_{i1}(f_1), \dots, I_{i1}(f_n)$, $U_{i2}(f_1), \dots, U_{i2}(f_n)$, $I_{i2}(f_1), \dots$, and $I_{i2}(f_n)$. Assume all monitoring signals are injected from the sending end, and unit amplitudes are used, which satisfy $U_{i1}(f_1) = \dots = U_{i1}(f_n) = 1$ V.

Three parameters are to be estimated in the location procedure, which include the beginning position of segmental aging L_b , the end position of segmental aging L_e , and aging severity γ . γ is defined as $\gamma = C_{\text{aged}}/C_0$. A model-based location approach is proposed in this paper. The main idea is that when estimated parameters approximate real values, measured voltage and leakage current at cable terminals will approach calculated values based on derived models. Therefore, location can be realized by solving an optimization problem as (5).

$$\begin{aligned} \min_{L_b, L_e, \gamma} \sum_{k=1}^n [(U_{i2}(f_k) - U_{m2}(f_k))^2 + \lambda(I_{i1}(f_k) - I_{m1}(f_k))^2] \\ \text{s.t. } 0 \leq L_b < L_e \leq L, \gamma \geq 1 \end{aligned} \quad (5)$$

where $I_{i1}(f_k)$ represents leakage current amplitude measured at the sending end, and $U_{i2}(f_k)$ represents voltage amplitude measured at the receiving end. $U_{m2}(f_k)$ and $I_{m1}(f_k)$ represent amplitudes of voltage at the receiving end and leakage current

at the sending end, which are calculated by models in (1) or (4) based on estimated segmental aging parameters. L represents the entire length of the inspected cable. λ is used to adjust the weight between the voltage and leakage current difference terms, which can be determined by the measurement sensitivity of each item in real industry applications. In the following analysis and simulations, λ will be set as 1. As only amplitudes of measurements are used, location does not require real-time communication between terminals, ensuring simple and low-cost implementation.

The main difficulty in solving (5) lies in the following aspects. First, the relationship between measurements and parameters to be estimated is highly nonlinear and strongly coupled, which will lead to a local minimum problem if using optimization algorithms directly. Moreover, variation in measurements under segmental aging conditions is usually small, resulting in a flat gradient field and a long search time. To solve these problems, a combined grid-searching and sequential quadratic programming (SQP) optimization method is proposed in this paper, which mainly consists of two steps, as shown in Fig. 5. The detailed description is presented below.

Step I: Grid Searching. First, the entire cable is evenly divided into p segments, with $p + 1$ separation positions (including sending end and receiving end). By choosing two positions randomly as L_b and L_e with $L_b < L_e$, a location set $\mathbf{L}$ is generated that contains all possible position combinations. Optimization is then carried out on each position group in $\mathbf{L}$. Take the j th position group ($L_{b,j}, L_{e,j}$) as an example. The optimization problem to be solved can be expressed as (6).

$$\begin{aligned} \min_{\gamma_j} \sum_{k=1}^n [(U_{i2}(f_k) - U_{m2}(f_k))^2 + \lambda(I_{i1}(f_k) - I_{m1}(f_k))^2] \\ \text{s.t. } L_b = L_{b,j}, L_e = L_{e,j}, \gamma_j \geq 1 \end{aligned} \quad (6)$$

where γ_j represents the estimated aging severity with j th position group. It is shown that the number of unknown parameters reduces to one for each position group, which makes the problem easier to be solved. SQP method, which is commonly used for medium-sized nonlinear optimization problems [34], is then used to solve (6) for each position group. By conducting grid searching, the original optimization problem in the entire searching space has been converted into many sub-optimization problems on the location set $\mathbf{L}$. Therefore, computation accuracy and efficiency can be largely improved.

Step II: Evaluation and Iteration. After aging severity is estimated for each position group, voltage and leakage current amplitude at cable terminals are calculated according to the obtained parameters, and the estimation error for each group will be evaluated. Estimation error E_j for the j th position group is defined as (7).

$$E_j = \sum_{k=1}^n [(U_{i2}(f_k) - U_{m2}(f_k))^2 + \lambda(I_{i1}(f_k) - I_{m1}(f_k))^2] \quad (7)$$

where $L_b = L_{b,j}$, $L_e = L_{e,j}$, $\gamma = \gamma_j$.

As position groups with smaller estimation error will normally be closer to real segmental aging positions, t position

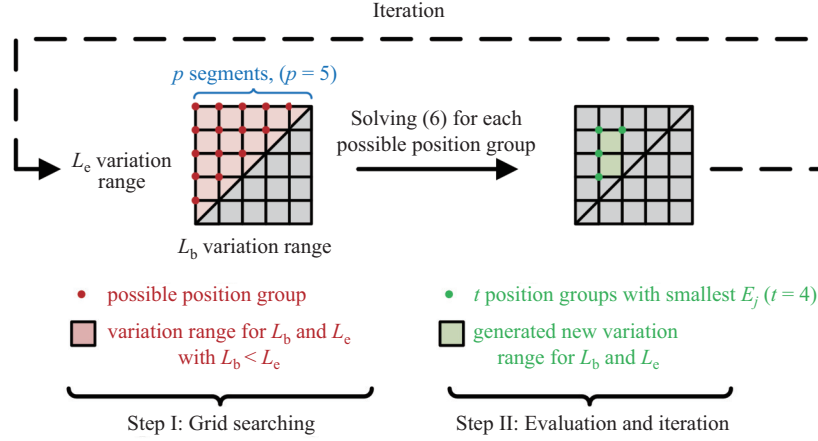


Fig. 5. Schematic diagram of the proposed location algorithm.

groups with smallest estimation errors are selected, and new variation ranges of L_b and L_e are then generated as $[L_{b1}, L_{b2}]$ and $[L_{e1}, L_{e2}]$. L_{b1} is the smallest beginning position in t position groups, while L_{b2} is largest. L_{e1} and L_{e2} are also obtained similarly. If $L_{b2} - L_{b1} < \alpha$ and $L_{e2} - L_{e1} < \alpha$, the algorithm will be terminated, and the two variation ranges will be output as the location result. α represents the required sensitivity of location. Aging severity is also obtained by averaging estimated aging severities of t position groups. If the above conditions are not satisfied, the generated variation range will be divided into p segments, and a new iteration will begin. The algorithm will also terminate when a maximum iteration number N is exceeded.

The overall flow chart of the proposed location algorithm of segmental aging is shown in Fig. 6. As aging of power cables is usually a slow process, the proposed method only needs to be carried out on a certain time span, such as every three months.

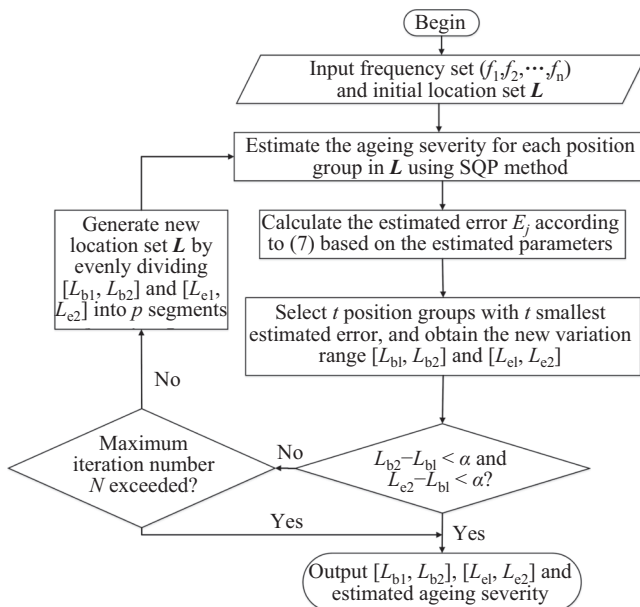


Fig. 6. Flow chart of the proposed location algorithm for segmental aging.

Aging parameter γ serves as an effective indicator for power cable aging [2], [9]. In accelerated thermal aging tests [18], per-unit-length insulation capacitance can increase to approximately 1.3 times the normal value when cables are aged under 150 °C environments for 120 h, and will further increase to more than 1.5 times when aging time becomes longer than 180 h. It is also recommended in [33] that cable maintenance should be conducted if the aging parameter γ reaches 1.15. Based on estimated aging location and severity, targeted maintenance can be conducted conveniently.

IV. EVALUATIONS OF THE DESIGNED ALGORITHM

Simulations in MATLAB are first carried out to evaluate the designed algorithm.

A. Simulation Setup and Monitoring Frequency Selection

A PLC simulator proposed in [6] is used to emulate a power cable under different segmental aging situations, with cable parameters shown in Table I. Z_0 , C_0 , and other parameters in models can be calculated based on the listed values as in [33]. The proposed method is validated on both power cables without and with metal sheaths. For a simpler demonstration, the following analysis mainly focuses on power cables without metal sheaths, and validations for power cables with metal sheaths will be presented in Section IV-C.

TABLE I
PARAMETERS OF THE POWER CABLE IN SIMULATIONS

Items	Parameters	Value
Basic parameters	conductor radius r_C	22 mm
	conductor resistivity ρ_C	$1.68 \times 10^{-8} \Omega \cdot m$
	insulation radius r_{in}	39.5 mm
	insulation relative permittivity ϵ_r	4.1
For cables with metal sheaths	length L	5 km
	sheath radius r_s	44 mm
	sheath resistivity ρ_s	$2.2 \times 10^{-7} \Omega \cdot m$

The monitoring frequency for the proposed method is first selected. Frequencies at which voltage and leakage current measurements present larger variation when insulation capacitance increases should be used. Therefore, the sensitivity of U_{i2} and I_{i1} at frequency f is defined as (8).

$$\text{Sensitivity}_{U_{i2}}(f) = \left| \frac{U_{i2}(1.01C_{\text{aged}}, f) - U_{i2}(C_{\text{aged}}, f)}{0.01C_{\text{aged}}/C_0 \times U_{i2}(C_{\text{aged}}, f)} \right| \quad (8)$$

$$\text{Sensitivity}_{I_{i1}}(f) = \left| \frac{I_{i1}(1.01C_{\text{aged}}, f) - I_{i1}(C_{\text{aged}}, f)}{0.01C_{\text{aged}}/C_0 \times I_{i1}(C_{\text{aged}}, f)} \right| \quad (9)$$

Sensitivity represents the relative variation of measurements when the insulation capacitance of the aged segment presents a 1% increase. C_0 is included in the denominator for normalization. Various test cases are carried out. Sensitivity of U_{i2} and I_{i1} for different aging severities in 1~200 kHz when $L_b = 1$ km and $L_e = 2$ km is shown in Fig. 7.

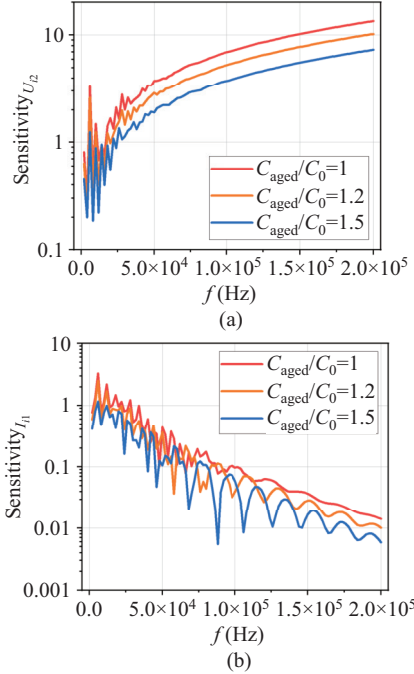


Fig. 7. Sensitivity analysis. (a) The sensitivity of U_{i2} and (b) The sensitivity of I_{i1} for different aging severities when $L_b = 1$ km and $L_e = 2$ km.

It is shown that the sensitivity of U_{i2} increases and sensitivity of I_{i1} decreases with larger frequency, and measurement difficulty will also increase. When frequency is below 50 kHz, the sensitivities of voltage and leakage current measurements are in a similar range and complement each other. Therefore, monitoring frequency is selected as 2.5 kHz to 50 kHz with an interval of 2.5 kHz in the following simulations.

The effectiveness of the selected monitoring frequency range for different segmental aging locations is further studied. In this paper, monitoring frequency is selected when the length of the aged cable segment is rather short ($L_b = 1000$ m, $L_e = 2000$ m). With a short aging length, the cable aging phenomenon is harder to observe, and the accurate location becomes more difficult. Therefore, if selected monitoring frequencies can meet requirements with a short aging length, they will most likely be suitable for other aging situations, as well.

For example, two different aging locations are studied with aging segments at 0 ~ 5000 m and 2500 m ~ 4000 m. Sensitivity of U_{i2} and I_{i1} for different aging locations is plotted in Fig. 8. C_{aged}/C_0 is set as 1.

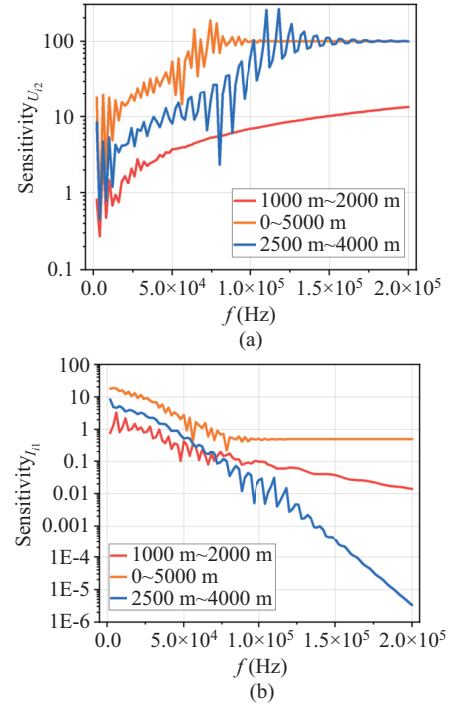


Fig. 8. Sensitivity analysis. (a) The sensitivity of U_{i2} and (b) The sensitivity of I_{i1} for different aging locations when C_{aged}/C_0 is set as 1.

It is shown that both the sensitivity of U_{i2} and I_{i1} below 50 kHz increase with larger aging length. Variation patterns for the sensitivity of U_{i2} and I_{i1} are also quite similar to the originally analyzed situation. Therefore, sensitivity on the selected monitoring frequency range can also be ensured for different aging locations.

B. Validations of the Location Algorithm of Segmental Aging

A segmental aging sample set is first generated with 275 measurement samples of different segmental aging situations. Beginning position L_b is set as 0 to 4.5 km with an interval of 0.5 km, and end position L_e is set as 0.5 km to 5 km with an interval of 0.5 km. Aging severity γ is set as 1.1 to 1.5 with an interval of 0.1. The proposed location algorithm of segmental aging is then validated on the segmental aging sample set. As analyzed in the above sections, the beginning position and end position are estimated by a combined grid-searching and SQP algorithm, which outputs estimated varying ranges for two positions. The maximum deviation between estimated ranges and real positions for each sample is used for evaluations. Therefore, the performance of the proposed method for the worst case can be ensured. Location errors of beginning position E_{L_b} and end position E_{L_e} are defined as (9), and the error of estimated aging severity E_γ is defined as (10).

$$\begin{cases} E_{L_b} = \frac{1}{N_S} \sum_{i=1}^{N_S} \max(|L_b^{(i)} - L_{b1}^{(i)}|, |L_b^{(i)} - L_{b2}^{(i)}|) / L \\ E_{L_e} = \frac{1}{N_S} \sum_{i=1}^{N_S} \max(|L_e^{(i)} - L_{e1}^{(i)}|, |L_e^{(i)} - L_{e2}^{(i)}|) / L \end{cases} \quad (10)$$

$$E_\gamma = \frac{1}{N_S} \sum_{i=1}^{N_S} |\gamma^{(i)} - \hat{\gamma}^{(i)}| / \gamma^{(i)} \quad (11)$$

where N_S represents the number of samples. $L_b^{(i)}$ represents segmental aging beginning position for the i th sample, and $[L_{b1}^{(i)}, L_{b2}^{(i)}]$ is the estimated beginning position range using the proposed method. $L_e^{(i)}$, $L_{e1}^{(i)}$ and $L_{e2}^{(i)}$ are defined similarly for the end position. $\gamma^{(i)}$ represents the real aging severity of the i th sample, and $\hat{\gamma}^{(i)}$ represents the estimated aging severity using the proposed method. The maximum value of E_{L_b} and E_{L_e} can then be selected to present an overall location error of the proposed algorithm.

Location performance on the segmental aging sample set with different measurement noises is first studied. Selection of algorithm parameters is introduced as follows. Grid division number p determines the number of possible position groups in the grid searching step. To ensure computation efficiency of grid searching, the value of p should not be too small, which is set as 8 in this paper. t represents the number of selected position groups with the smallest estimation error in the evaluation and iteration step. As the position group with the smallest estimation error in the grid searching step will not necessarily be closest to the real position due to many existing local optimums, t is introduced to maintain robustness of the designed algorithm. The value of t should also be larger with a larger value of p , and is set as 4 in the calculation.

Apart from the above parameters, the maximum iteration number N and location sensitivity α are used for the termination of the algorithm. When the lengths of estimated position ranges $[L_{b1}, L_{b2}]$ and $[L_{e1}, L_{e2}]$ are smaller than α , algorithm will stop, and estimation results can be obtained. α can be set according to industry requirements and is set as 0.05 km in this paper. Besides, it is shown in simulations that an average iteration time is 6 when α is set to 0.05 km. Therefore, maximum iteration number N is set as 10 in this paper to ensure the convergence of location algorithm. The location result is shown in Table II.

TABLE II
PERFORMANCE OF THE PROPOSED LOCATION METHOD

States	E_{L_b}	E_{L_e}	E_γ
No noise	0.0124	0.0213	0.0264
$\pm 0.5\%$ noise	0.0163	0.0244	0.0275
$\pm 1\%$ noise	0.0202	0.0276	0.0267
$\pm 2.5\%$ noise	0.0316	0.0360	0.0363

Table II shows that the proposed method can accurately locate segmental aging in power cables. When the strength of the noises is within $\pm 2.5\%$, the location error is smaller than 3.6% and the error of the estimated aging severity is smaller than 3.63%. The average iteration time is 6. Computation is conducted in MATLAB on a standard PC with Intel Core i7-10700F CPU running at 2.90 GHz. The average calculation time for the location of each sample is 7.63 s. The computation burden is not very large and can be easily fulfilled in industry applications.

As parameters of cables in distribution grids may present some deviations from data provided by manufacturers, the

performance of the proposed method under parameter uncertainties of Z_0 is also studied and shown in Fig. 9.

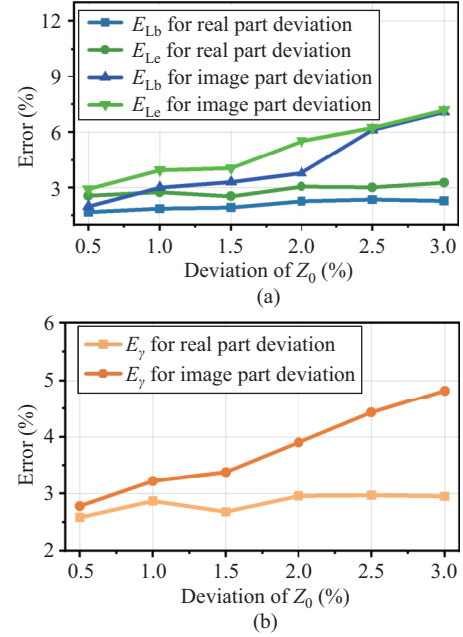


Fig. 9. Segmental ageing location results. (a) Location error and (b) Aging severity estimation error under uncertainties of Z_0 .

It is shown that the method's performance deteriorates a little with increasing parameter uncertainties, but the location error is kept within 7.18% and the estimation error for aging severity is smaller than 4.82%. It is proven that an accurate location can still be realized when parameter uncertainty reaches 3%, which can be ensured in the industry.

C. Validations for Power Cables with Metal Sheaths

The proposed location algorithm of segmental aging is further validated on power cables with metal sheaths. Sheath parameters are also shown in Table I. Parameters for the segmental aging sample set are the same as in Section IV-B. Using the model derived in Section II. C, performance of location method is also validated, as shown in Table III. Location error is smaller than 3.05% and the error of the estimated aging severity is smaller than 2.19%. It is proven that the proposed method can realize the accurate location of segmental aging in underground power cables of different types.

TABLE III
PERFORMANCE FOR CABLES WITH METAL SHEATHS

Sates	E_{L_b}	E_{L_e}	E_γ
No noise	0.0210	0.0225	0.0175
$\pm 0.5\%$ noise	0.0222	0.0231	0.0170
$\pm 1\%$ noise	0.0256	0.0260	0.0196
$\pm 2.5\%$ noise	0.0285	0.0305	0.0219

D. Implementation of the Proposed Method for Short Lines

Implementation of the proposed method for short lines in the industry needs to be further discussed. The above analysis has

shown that the location of segmental aging is based on measured voltage and leakage current distribution pattern at cable terminals, which is solely determined by cable parameters and frequency range of injected signals. Therefore, to retain as much information in long cable situations, the frequency range used can be enlarged for short line situations. At the same time, the used frequency number and the following calculation procedure remain unchanged, making the proposed method convenient to be adopted for power cables of different lengths.

Numerical simulations are further conducted to validate the effectiveness of the proposed method for short lines. A short cable without a metal sheath is used as an example, with parameters shown in Table I, and cable length L is set as 1 km. The segmental aging sample set still contains 275 measurements with different segmental aging situations. Beginning position L_b is set as $0 \sim 0.9L$ with an interval of $0.1L$, and end position L_e is set as $0.1L \sim L$ with an interval of $0.1L$. Aging severity ranges from 1.1 to 1.5 with an interval of 0.1. Location procedure is the same as the above sections, and the only difference is that the used frequency range is set as 12.5 kHz to 250 kHz with an interval of 12.5 kHz. Location results are shown in Table IV.

TABLE IV
PERFORMANCE OF THE PROPOSED LOCATION METHOD FOR
1-KM CABLES

States	E_{L_b}	E_{L_e}	E_γ
No noise	0.0032	0.0033	0.0126
$\pm 0.5\%$ noise	0.0066	0.0074	0.0118
$\pm 1\%$ noise	0.0112	0.0123	0.0147
$\pm 2.5\%$ noise	0.0214	0.0207	0.0171

It is shown that the proposed method realizes an accurate location of segmental aging in short lines with a cable length of 1 km. Location error is smaller than 2.14% and aging severity estimation error is smaller than 1.71%. Therefore, the effectiveness of the proposed method for cables of different lengths can be ensured. This is because the measured voltage and leakage current at cable terminals are determined by the voltage distribution along the cable under different frequencies. Therefore, for cables of different lengths, the injected signal frequency can be adjusted proportionally. Measurements can be kept within a similar range, and the effectiveness of the proposed method with different measuring point distances can then be ensured.

V. CASE STUDIES

Test cases in PSCAD/EMTDC are further implemented to validate location method in power distribution grids with different structures.

A. Test Cases for Power Cables Without Metal Sheaths

Test cases for power cables without metal sheaths are first conducted. Frequency range is still set as 2.5 kHz to 50 kHz with an interval of 2.5 kHz. Voltage and leakage current at the terminal of the inspected cable are collected. Used parameters are the same as in Table I. Segmental aging position and aging severity are set as in Table V.

TABLE V
SEGMENTAL AGING POSITION AND AGING SEVERITY OF THE
TEST CASES

Cases	L_b (m)	L_e (m)	γ
Case 1	1000	2000	1.463
Case 2	1000	4000	1.342
Case 3	3000	4000	1.585
Case 4	0	2000	1.463
Case 5	2000	5000	1.463
Case 6	1200	3700	1.463

Validation for derived models is first presented. Take Case 1 as an example. Voltage and leakage current distribution patterns obtained by the proposed model and PSCAD simulations are shown in Fig. 10.

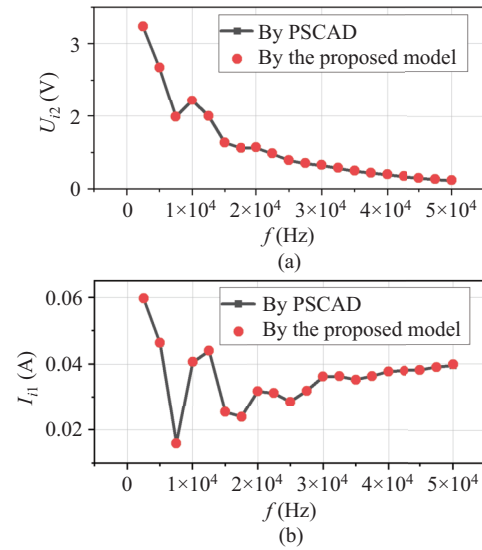


Fig. 10. Measurements for the location. (a) Measured voltage and (b) Leakage current distribution for cables without metal sheaths by PSCAD and the proposed model.

It is shown that the measurements calculated by the proposed models are identical to values obtained by PSCAD, validating the effectiveness of the proposed models.

Location is then conducted, and the estimated segmental aging position variation in iterations is shown in Fig. 11. It is shown that the estimated range of segmental aging beginning position and end position converges to the real value during iterations. Location and aging severity estimation error are shown in Fig. 12. Location error is smaller than 5.12% and aging severity estimation error is smaller than 3.84% for all test cases, validating the effectiveness of the proposed method.

B. Test Cases for Power Cables with Metal Sheaths

Test cases for power cables with metal sheaths are also conducted. Cable parameters are set as in Table I, and segmental aging situations are set the same as in Table V. For Case 1, voltage and leakage current distribution patterns obtained by the proposed model and PSCAD simulations are shown in Fig. 13, which proves the proposed model can describe segmental aging in power cables with high accuracy.

Location and aging severity estimation error are shown in Fig. 14. It is shown for power cables with metal sheaths;

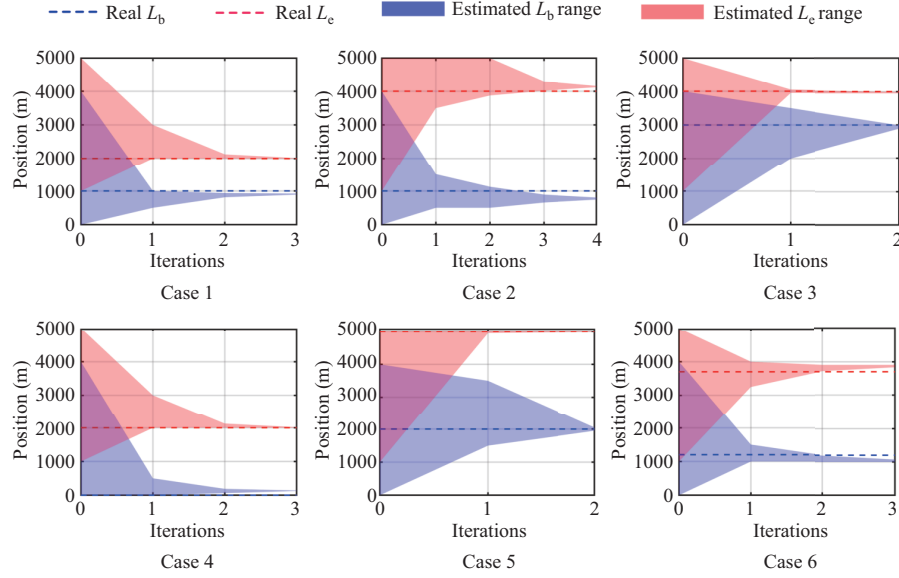


Fig. 11. Location performance of segmental aging test cases for power cables without metal sheaths in PSCAD.

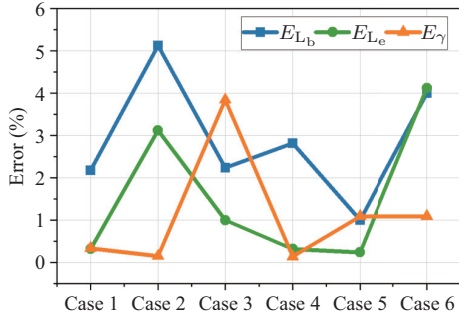


Fig. 12. Estimation error for power cables without metal sheaths in PSCAD.

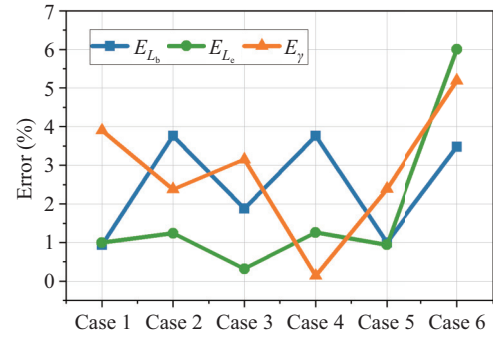


Fig. 14. Estimation error for power cables with metal sheaths in PSCAD.

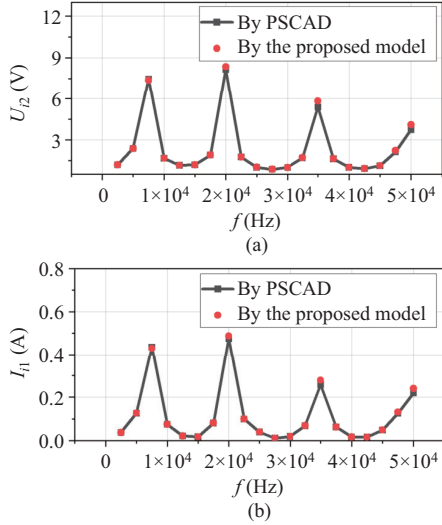


Fig. 13. Measurements for the location. (a) Measured voltage and (b) Leakage current distribution for cables with metal sheaths by PSCAD and the proposed model.

the location error is smaller than 6% and the estimated aging severity error is smaller than 5.19%, fulfilling industry demands.

C. Test Cases for Different Distribution Grid Structures

The performance of the proposed method for different distribution grid structures is further studied. To monitor segmental aging of power cables in distribution grids, CM monitoring signal should be injected from a selected bus, and the induced voltage and leakage current on both terminals of the inspected cable are measured. The proposed algorithm is then conducted to realize location.

Segmental aging location in a radial distribution grid is first implemented with the structure shown in Fig. 1(a). The high-frequency monitoring signal is injected from Bus A, and the voltage and leakage current at each bus are recorded. Two test cases are carried out, which are denoted as Case 1 and Case 2. Segmental aging parameters and location results are both shown in Table VI. Simulation results show that segmental aging location in the radial distribution grid can be realized with high accuracy. As cable L2 locates farther from the monitoring signal injection point, the measured signal becomes weaker, and the error becomes larger in Case 2. However, the location error is still smaller than 4.73% and the aging severity estimation error is smaller than 6.6%, fulfilling industry demands. In real applications, the monitoring signal injection

location can be adjusted according to different operation states and the environments of the distribution grid.

Segmental aging location in a ring-structured distribution grid is also studied, as shown in Fig. 15. High-frequency monitoring signal is injected from Bus A. The voltage and leakage current at both terminals of cable L1 are measured. The location result is shown in Table VI as Case 3.

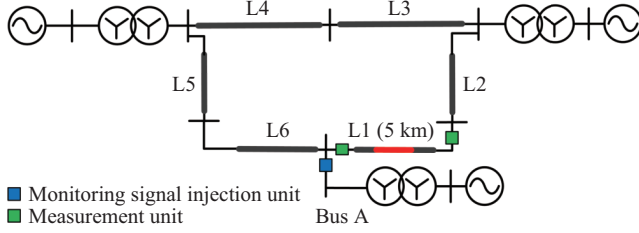


Fig. 15. Ring-structured distribution grid established in PSCAD.

TABLE VI
PERFORMANCE FOR DIFFERENT DISTRIBUTION GRID STRUCTURES

Cases	Aged Cable	L_b (m)	L_e (m)	γ	E_{L_b}	E_{L_e}	E_γ
Case 1	L1	2000	5000	1.463	0.25%	1.87%	0.89%
Case 2	L2	1000	4000	1.463	4.73%	4.73%	6.6%
Case 3	L1	1000	2000	1.463	0.47%	1%	6.1%

It is shown that the location of segmental aging in ring distribution grids can be realized with an error of 1% and the error of aging severity estimation is 6.1%, proving the effectiveness of the proposed method.

VI. COMPARISONS WITH THE EXISTING METHODS

Improvements of the proposed method compared with existing methods are further studied. In the following analysis, BIS method is mainly used for comparison due to highest location accuracy among existing methods.

A. Improvement of Accuracy When the Same Frequency Range is Used

Take test cases in Section V. A as an example. The inspected frequency range is set as 2.5 kHz to 50 kHz. FDR method [7] is used in location for Cases 3 and 4 for comparison, where voltage and leakage current measurements at the sending end are used to calculate insulation admittance spectrum Y . Inverse Fourier transform is then conducted to track impedance variation on the entire length of the inspected cable. Location results are shown in Fig. 16.

It is shown that no obvious peak exists in the BIS method for selected test cases. BIS method fails to locate segmental aging due to the few frequencies used in monitoring. As a conclusion, the accuracy of the proposed method is much higher than BIS method when the same frequency range is used. In other words, to achieve better location accuracy, BIS method needs to raise the frequency range and increase the used measurement frequencies dramatically. This will lead to significant hardware investment in data sampling and storage, which is also difficult to implement online.

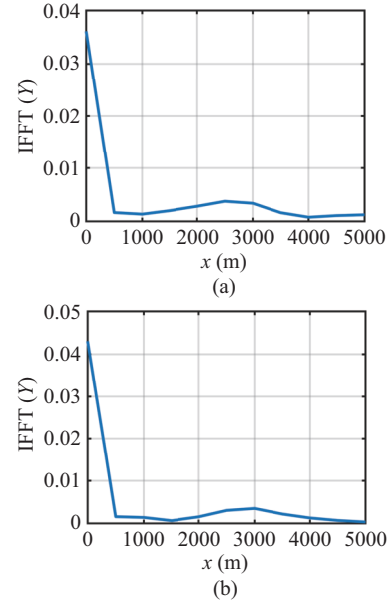


Fig. 16. Location results of the BIS method for (a) Case 3 and (b) Case 4.

B. The Ability to Estimate Aging Severity and Therefore Locate Segmental Aging Situations with one End at the Cable Terminal

As travelling-wave-based methods and BIS method all rely on signal reflection at segmental aging terminals and cannot realize aging severity estimation, these methods will fail in locating segmental aging situations with one end at the cable terminal. For example, when segmental aging locates from the sending end to the middle of the cable, only one peak at the middle of the cable will exist in the BIS method, which cannot tell which half is aged. By contrast, the proposed method realizes estimation of aging location and severity at the same time, and can certainly deal with segmental aging situations with one end at the cable terminal (such as Case 4 in Section V-A).

C. The Ability to Realize the Location for Gradually Appearing Segmental Aging

Segmental aging for power cables in the industry may not start from a single point, and may gradually appear across the cable. Under such circumstances, reflected signals in travelling-wave-based methods or BIS method will be very weak due to small characteristic impedance variation on the aged segment, which will certainly deteriorate method performance. By comparison, the proposed method uses terminal voltage and leakage current measurements, which realize location based on electrical parameters along the entire cable. Therefore, the proposed method can cope with gradually appearing segmental aging, outperforming existing methods.

For example, a segmental aging pattern as shown in Fig. 17 is applied, and cables without a metal sheath are used for demonstration, whose parameters are shown in Table I. Beginning position of segmental aging L_b is set as 1 km, and end position of segmental aging L_e is set as 2 km. Unlike situations originally discussed in this paper, insulation capacitance is

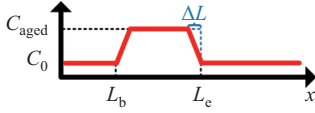


Fig. 17. Gradually appeared segmental aging pattern.

gradually increased from C_0 to C_{aged} , and the length of the capacitance variation segment ΔL at both terminals is set to 200 m. Other parameters and calculation procedure remain unchanged. When aging severity ranges from 1.1 to 1.5, the location results obtained using the proposed method are shown in Table VII.

TABLE VII
LOCATION RESULTS FOR GRADUALLY APPEARED AGING SITUATIONS
USING THE PROPOSED METHOD

Aging severity C_{aged}/C_0	E_{L_b}	E_{L_e}	E_γ
1.1	0.0098	0.015	0.0028
1.2	0.0111	0.005	0.0026
1.3	0.005	0.005	0.0221
1.4	0.0148	0.005	0.0047
1.5	0.0148	0.005	0.0066

It is shown that an effective location can still be realized by the proposed method with a maximum location error of 1.5% and a maximum aging severity estimation error of 2.21%. Therefore, although the proposed method is not especially designed to solve gradually appearing segmental aging problems, accurate location can be achieved for such situations due to the entire cable insulation information being used in the calculation.

However, location of gradually appeared segmental aging using existing methods proves to be difficult. Take the BIS method as an example. Terminal admittance Y is collected from 1 kHz to 500 kHz with an interval of 1 kHz, and the inverse Fourier transform is then conducted for location [7]. Location results for the above five situations are shown in Fig. 18.

Figure 18 shows that almost no peak can be observed

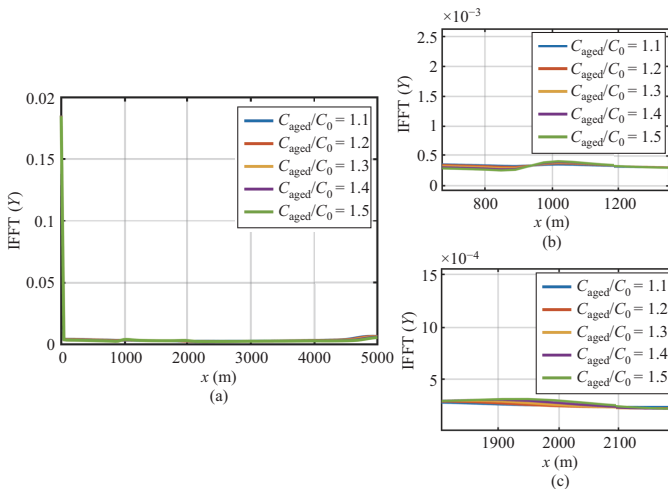


Fig. 18. Comparison with BIS method. (a) Location results using the BIS method for gradually appeared segmental aging situations, with the magnified view around the segmental aging terminals shown in (b) and (c).

using the BIS method for gradually appearing segmental aging situations due to no abrupt variation of insulation capacitance, and is outperformed by the proposed method.

As a conclusion, compared with existing methods, the proposed method proves to be more effective and suitable for cable segmental aging location in the industry [35]–[38].

VII. CONCLUSION

Locating segmental aging in underground power cables will lead to targeted maintenance, which can improve the reliability of distribution grids and reduce system maintenance costs. In this paper, a novel segmental aging location method based on voltage and leakage current measurements under multi-frequency CM monitoring signal injection has been proposed. Segmental aging models for various types of cables under the injected signal have been developed, and a model-based location algorithm has been proposed. Comprehensive simulations have been conducted, validating the effectiveness of the proposed method. For various types of cables, segmental aging location can be realized with an error smaller than 3.6% and aging severity can be estimated based on the insulation parameter of the cable with an error smaller than 3.63%. Test cases in PSCAD have validated the effectiveness of the proposed method for different distribution grid structures. Compared with existing methods, the proposed method achieves more accurate location with a far smaller measurement frequency range.

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