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METHODS

Sequence Control Mechanism for the Handover of Distribution Networks Under Disaster Recovery

CHENG LONG[1,2], **JIAN ZHANG**[3], **HUA ZHANG**[1], **XING LIU**[4], **YIWEN GAO**[1], **XUENENG SU**[1], **AND SHILONG LI**[1]

[1]State Grid Sichuan Electric Power Company Electric Power Research Institute, Chengdu 610041, China
[2]Power Internet of Things Key Laboratory of Sichuan Province, Chengdu 610041, China
[3]Department of Equipment Management, State Grid Sichuan Electric Power Company, Chengdu 610000, China
[4]College of Electrical Engineering, Sichuan University, Chengdu 610065, China

Corresponding author: Cheng Long (Chenglong202311@163.com)

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ABSTRACT In the distribution network under the background of disaster, the distribution terminal embodies the characteristics of disorder. Therefore, when the distribution terminal node accesses the backup network, there will be congestion, delay and other phenomena. In order to solve this problem, this paper proposes a distribution terminal access mechanism based on sequence control. Then, a family of control sequences is constructed based on the trace function in the finite field. The control sequences can realize the rapid access of distribution terminal node users and the safe transmission without interference. Finally, the program algorithm for the process of distribution terminal node accessing and exiting the backup network based upon the control sequences is given. The fast and stable information transmission of distribution terminal node can be realized by means of the sequence control mechanism.

INDEX TERMS Control sequences, prime sequences, no-hit, distribution network, disaster recovery.

I. INTRODUCTION

A. BACKGROUND

As is known to all, a disaster is a discrete event triggered by natural or human factors [1]. It is unpredictable so that the damage object can not be recovered accurately and immediately. In the power network, the role of the distribution network is to distribute electrical energy to various users step by step according to the voltage. As an important component of the power network, the distribution network is easily affected by natural disasters. This will lead to power outages in daily life and work which cause considerable economic losses. However, for distribution networks the damages have occurred frequently due to the increase of natural disasters. For example, 69 percent of Texans lost power during the storm and their average disruption was 42 hours [2]. It not only caused huge economic losses, but also brought inconvenience in daily life. Besides, as the large-scale growth of distribution terminals in the future, the failure rate of the distribution network will become higher under natural disasters. This makes the recovery of the distribution network under disasters increasingly difficult. Hence, it is important to study the disaster recovery strategy and how to repair the distribution network accurately and immediately.

For disaster monitoring, [3] used wireless mesh network in artificial intelligence of things (AIoT) to offer a strong self-healing capability and network robustness against disaster damages. In order to monitor distribution network disasters, it is necessary to make short-term predictions for distribution network disasters (see [4], [5], [6], [7]). By analyzing and processing predicted data, anomalies such as line overload, equipment overheating, short circuit faults, etc. can be detected as early as possible. Thus triggering the warning mechanism and taking timely measures for intervention. Hence, short-term predictions can help the distribution network avoid disasters to a certain extent. However, the short-term prediction relies on prior probabilities which leads

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to estimation errors sometimes. Once an estimation error occurs, it will result in the inability of the distribution network to recover promptly. This will bring huge losses to industrial production and people's lives. Thus, it is necessary to study the disaster recovery mechanism for distribution networks. For the disaster recovery mechanism of distribution networks, the backup network plays an important role. It is crucial to quickly and accurately make the distribution terminals handover to the backup network.

In the condition of disaster recovery, it is difficult for distribution terminals to quickly access the backup network, and the transmission and access mechanism of large-scale distribution terminals under disaster recovery is an urgent problem to be solved [8], [9], [10], [11]. In large-scale distribution terminal node networks, data transmission and access need to have the following characteristics [12], [13], [14]: 1) Distribution terminal node access requires a short response time to meet the timely needs of users; 2) Data transmission should avoid mutual interference to ensure the reliability of transmission; 3) Terminal data transmission should ensure its security.

B. RELATED WORK

At present, most of the existing access mechanisms for distribution terminal access networks are traditional request response mechanisms [15], [16], [17], [18]. Due to factors such as network congestion and electromagnetic interference during the access process, there is a time delay in the access speed, which cannot achieve instantaneous access and meet the timely needs of users. Additionally, conflicts may occur if the same time slot is selected for different terminal nodes, and mutual interference often occurs due to such conflicts. However, the channel chosen for each terminal is usually fixed, and its security cannot be guaranteed [19], [20], [21], [22], [23], [24].

In order to ensure the security of channel access, channel hopping sequences were considered to be used to control the access of user terminals. The channel hopping sequences must satisfy excellent randomness so that the security of channel access can be guaranteed. There are some researches on channel sequences in the literature. In [25], symmetric-asynchronous channel sequences were used to replace each node. In [26], each user was assigned a sequence that comprises hop pattern subsequences. By using subsequences the patterns were divided into jump and stay patterns. Besides, some literature used quadratic-congruence sequences as base sequences and prime sequences as stay-sequences, such as [27], [28], and [29]. Reference [27] used disjoint relaxed difference sets to access channel. Reference [28] combined the rows of the default matrix in a specific sequence. In [29], distinct arrangements of elements were used to manage channel access. In [30], each user swaps unavailable channels with accessible channels randomly. In [31], the users can switch to any available channel while the other users remain on a specific channel. Reference [32] employed the similar way to generate their channel sequences. Reference [33] used a pure prime matrix to move horizontally and vertically. In [34], based on interleaving techniques in finite fields, channel hopping sequences were constructed. However, all of those channel sequences have large Hamming correlation values so that they are not suitable for the access of the distribution network.

TABLE 1. **Comparison of channel sequences in the literature and this paper.**

Reference	Period	MTTR	MFTTR
[25]	$6lN^2$	$6lN^2-N+1$	$\leq 6lN^2$
[26]	$3(l+1)Np$	$3(l+1)Np-N+1$	$\leq 3(l+1)Np$
[27]	$3p^2$	$3p^2-p+1$	$\leq 3p^2$
[28], [29]	$2p^2+p\lfloor\frac{p}{2}\rfloor$	$2p^2+p\lfloor\frac{p}{2}\rfloor-p+1$	$\leq 2p^2+p\lfloor\frac{p}{2}\rfloor$
[30]	$2p^2$	$2p^2-p+1$	$\leq 2p^2$
[31]	$3Np^2$	$4p$	$3p$
[32]	$2N^3+N^2$	$2N^2+N$	$\leq 2N^3+N^2$
[33]	$2p^2$	$2p$	$2p$
[34]	wp^2	$2p-1$	p
This paper	p^2-1	$p-1$	$\leq p$

Besides, we list the channel sequences in Table 1 where the maximum time to rendezvous (MTTR) denotes the maximum time interval for two nodes coinciding again [33]. Maximum first time to rendezvous (MFTTR) denotes the waiting time required for any two sequences to rendezvous for the first time [33]. It is easily seen that our control sequences have smaller MTTR than those in the literature.

C. CONTRIBUTIONS

This paper proposes a new access control mechanism for distribution terminal access the backup network under disaster recovery, and constructs a new family of control sequences to control it. In this mechanism, the control sequence generator uses the sequence elements corresponding to the sequence to synthesize time slots. After that, it sends the generated time slot instructions to the time slot allocation module and controls the distribution terminal user node to obtain the current time slot position information. By performing operations in the finite field according to the current slot position and the slot of previously accessed user, the access to the backup network is achieved.

The control sequences can solve the following problems: 1) Fast access can be achieved through finite field operations between sequences; 2) Due to the pseudorandomness of the control sequence, the secure transmission of information can be guaranteed; 3) The sequences satisfy no-hit characteristics, which ensure that there is no interference between any users;

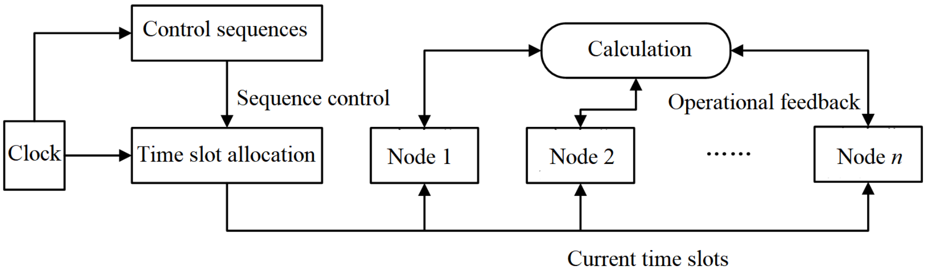


FIGURE 1. Access control mechanism model for distribution terminal node to access backup network.

4) Time slot resources can be fully utilized among users. This access control mechanism is suitable for large-scale access of any distribution terminal nodes.

D. ORGANIZATION OF THIS PAPER

The paper is organized as follows: Section II proposes a new access control mechanism model for distribution terminal node to access backup network; In Section III, a construction of control sequences is given; Section IV introduce the handover process using the control sequence and the exit strategy for the distribution terminal node. Then some simulation results are presented. Some conclusion remarks are given in Section V.

II. A NEW ACCESS CONTROL MECHANISM MODEL FOR DISTRIBUTION TERMINAL TO ACCESS BACKUP NETWORK

Here, a new access control mechanism model for distribution terminal node to access backup network is proposed, as shown in Figure 1.

As shown in the above figure, under clock control, the control sequence generator uses the sequence elements corresponding to the sequence to synthesize time slots, and sends the generated time slot instructions to the time slot allocation module. Then the time slot allocation module controls the distribution terminal user node to obtain the current time slot position information. The ith node user who is ready to access the backup network performs operations in the finite field according to the current slot position and the slot of previously accessed user. Then it obtain the access slot instruction, that is, the position of the actual access slot in the control sequence. The ith node uses this position in the control sequence as the starting slot to start access, and then performs slot transformation according to the slot synthesized by the control sequence. By analogy, large-scale access of any distribution terminal nodes can be achieved.

In principle, the control sequence should meet the following requirements:

1) The control sequences should meet strict no-hit conditions [35], [36];

2) The randomness of the control sequence should be as good as possible;

3) The control sequence has the time slot position judgment function, that is, the ith control sequence can perform finite field operation with the previous control sequence to obtain the actual access time slot position;

4) The number of control sequences should be as large as possible;

5) The period of the control sequence should be as long as possible.

III. CONSTRUCTION OF CONTROL SEQUENCES

Firstly, we give some notations.

p: a prime;

q: a prime power $q = p^n$;

GF(q): finite filed with q elements;

$\mathtt{L}(x)$: a one-to-one linear function from GF(p) to GF(p);

$\langle a\rangle_b$: the least non-negative residue of a module b;

Z_m: integral ring with size m;

(L, N, λ): control sequence set with period L and size N over the time slot set with size λ;

$d(x, y)$: $d(x, y) = 1$ if $x = y$ and 0 otherwise;

First, we give a proposition on the (L, N, λ) control sequence set.

Proposition 1: For the (L, N, λ) control sequence set $C = \{c^1, c^2, \cdots, c^N\}$ where $c^i = (c^i_0, c^i_1, \cdots, c^i_{L-1})$, $1 \le i \le N$, and $c^i_j \in \{0, 1, \cdots, \lambda - 1\}$, $0 \le j \le L - 1$, we have $N \le \lambda$.

If the $N = \lambda$ is met, then the (L, N, λ) control sequence set is optimal.

A. CONSTRUCTION METHOD

For the control sequence suitable for distribution terminal node access, the construction method is as follows:

Step 1: Choose a sequence

$$a = (a_0, a_1, \cdots, a_{p-1}), \tag{1}$$

where $a_i \in$ GF(p) for $0 \le i \le p - 1$ and a_i's are distinct.

Step 2: Construct a sequence set $B = \{B^0, B^1, \cdots, B^{p-1}\}$ with

$$B^i = (b^i_0, b^i_1, \cdots, b^i_{p^2-1}), \tag{2}$$

and

$$b^i_j = \left(a_{\left\lfloor \frac{j}{p} \right\rfloor}, \mathtt{L}(a_{\langle j\rangle_p} + i)\right), \tag{3}$$

where $0 \le i \le p - 1$ and $0 \le j \le p^2 - 1$.

Step 3: Let $g(a, b) = a + bp$ be a one-to-one function from (GF(p), GF(p)) to Z_{p^2}. Generate a control sequence

$$c^{ip+k} = (g(b_0^i) + k, g(b_1^i) + k, \cdots, g(b_{p^2-1}^i) + k) \tag{4}$$

where $0 \le i, k \le p - 1$. Then the control sequence set is as follows:

$$C = \{c^{ip+k} | 0 \le i \le p - 1, 0 \le k \le p - 1\}. \tag{5}$$

For the control sequence set C, we have the following result.

Theorem 1: The set C contains p^2 control sequences over the time slot set with size p^2 with strict no-hit and pseudo-randomness. In addition, it satisfies that $c^{ip+j_1} - c^{ip+j_2}$ is a constant sequence for any $0 \le j_1, j_2 \le p-1$. Moreover, there is a function $f(x)$ such that $f(g(b_{k_1}^i) - g(b_0^i)) \neq f(g(b_{k_2}^i) - g(b_0^i))$ for any $0 \le k_1 \neq k_2 \le p^2 - 1$, i.e. it has time slot position judgment ability.

Proof: It is clear that

$$\begin{aligned} &c^{ip+j_1} - c^{ip+j_2} \\ &\quad = (j_1 - j_2, j_1 - j_2, \cdots, j_1 - j_2) \end{aligned} \tag{6}$$

is a constant sequence. Let $f'(x) = g^{-1}(x) = (g_L^{-1}, g_R^{-1})$ be a linear function from Z_{p^2} to (GF(p), GF(p)) such that g^{-1} is the inverse function of g. For $0 \le k_1 \neq k_2 \le p^2 - 1$, we have

$$\begin{aligned} &f'(g(b_{k_1}^i) - g(b_0^i)) \\ &\quad = g^{-1}(g(b_{k_1}^i) - g(b_0^i)) \\ &\quad = b_{k_1}^i - b_0^i \\ &\quad = \left(a_{\left\lfloor \frac{k_1}{p} \right\rfloor} - a_0, \mathtt{L}(a_{\langle k_1 \rangle_p}) - \mathtt{L}(a_0)\right) \\ &\quad = \left(a_{\left\lfloor \frac{k_1}{p} \right\rfloor} - a_0, \mathtt{L}(a_{\langle k_1 \rangle_p} - a_0)\right). \end{aligned} \tag{7}$$

Similarly, we have

$$\begin{aligned} &f'(g(b_{k_2}^i) - g(b_0^i)) \\ &\quad = \left(a_{\left\lfloor \frac{k_2}{p} \right\rfloor} - a_0, \mathtt{L}(a_{\langle k_2 \rangle_p} - a_0)\right). \end{aligned} \tag{8}$$

Case 1: $tp \le k_1, k_2 \le (t+1)p - 1$ for some $0 \le t \le p - 1$. In this case, we know $\left\lfloor \frac{k_1}{p} \right\rfloor = \left\lfloor \frac{k_2}{p} \right\rfloor = t$ and $\langle k_1 \rangle_p \neq \langle k_2 \rangle_p$. Since a_i's are distinct for $0 \le i \le p-1$, we have $a_{\left\lfloor \frac{k_1}{p} \right\rfloor} = a_{\left\lfloor \frac{k_2}{p} \right\rfloor}$ and $a_{\langle k_1 \rangle_p} \neq a_{\langle k_2 \rangle_p}$. It indicates that $\mathtt{L}(a_{\langle k_1 \rangle_p}) \neq \mathtt{L}(a_{\langle k_2 \rangle_p})$.

Let $f(x) = \chi(f'(x)) = \chi(g_L^{-1}, g_R^{-1})$ be a one-to-one function from (GF(p), GF(p)) to Z_{p^2}. Since

$$\begin{aligned} &f'(g(b_{k_1}^i) - g(b_0^i)) - \left[f'(g(b_{k_2}^i) - g(b_0^i))\right] \\ &\quad = \left(0, \mathtt{L}(a_{\langle k_1 \rangle_p}) - \mathtt{L}(a_{\langle k_2 \rangle_p})\right) \\ &\quad \neq (0, 0), \end{aligned} \tag{9}$$

we have

$$f(g(b_{k_1}^i) - g(b_0^i)) - \left[f(g(b_{k_2}^i) - g(b_0^i))\right] \neq 0. \tag{10}$$

Then $f(g(b_{k_1}^i) - g(b_0^i)) \neq f(g(b_{k_2}^i) - g(b_0^i))$.

Case 2: $tp \le k_1 \le (t+1)p - 1$ and $sp \le k_2 \le (s+1)p - 1$ for some $0 \le t \neq s \le p - 1$. In this case, we know $t = \left\lfloor \frac{k_1}{p} \right\rfloor \neq \left\lfloor \frac{k_2}{p} \right\rfloor = s$. Then we have $a_{\left\lfloor \frac{k_1}{p} \right\rfloor} \neq a_{\left\lfloor \frac{k_2}{p} \right\rfloor}$ which indicates that

$$\begin{aligned} &f(g(b_{k_1}^i) - g(b_0^i)) - \left[f'(g(b_{k_2}^i) - g(b_0^i))\right] \\ &\quad = \left(a_{\left\lfloor \frac{k_1}{p} \right\rfloor} - a_{\left\lfloor \frac{k_2}{p} \right\rfloor}, \mathtt{L}(a_{\langle k_1 \rangle_p}) - \mathtt{L}(a_{\langle k_2 \rangle_p})\right) \\ &\quad \neq (0, 0). \end{aligned} \tag{11}$$

Then

$$f(g(b_{k_1}^i) - g(b_0^i)) - \left[f(g(b_{k_2}^i) - g(b_0^i))\right] \neq 0, \tag{12}$$

that is $f(g(b_{k_1}^i) - g(b_0^i)) \neq f(g(b_{k_2}^i) - g(b_0^i))$.

For any sequences $c^{i_1 p + j_1}$, $c^{i_2 p + j_2}$, consider the $h(g(b_k^{i_1}) + j_1, g(b_k^{i_2}) + j_2)$, $0 \le k \le p^2 - 1$, $0 \le j_1, j_2 \le p - 1$, $0 \le i_1, i_2 \le p - 1$.

Case 1: $i_1 = i_2$. In this case, we have $h(g(b_k^{i_1}) + j_1, g(b_k^{i_2}) + j_2) = 0$ for $j_1 \neq j_2$.

Case 2: $i_1 \neq i_2$. Then

$$\begin{aligned} &h(g(b_k^{i_1}) + j_1, g(b_k^{i_2}) + j_2) \\ &\quad = h(g(b_k^{i_1}) - g(b_k^{i_2}), j_2 - j_1) \\ &\quad = h(g(b_k^{i_1} - b_k^{i_2}), j_2 - j_1). \end{aligned} \tag{13}$$

Now we consider the range of $b_k^{i_1} - b_k^{i_2}$. We know that

$$\begin{aligned} &b_k^{i_1} - b_k^{i_2} \\ &\quad = \left(a_{\left\lfloor \frac{k}{p} \right\rfloor} - a_{\left\lfloor \frac{k}{p} \right\rfloor}, \mathtt{L}(a_{\langle k \rangle_p}) - \mathtt{L}(a_{\langle k \rangle_p}) + \mathtt{L}(i_1) - \mathtt{L}(i_2)\right) \\ &\quad = (0, \mathtt{L}(i_1) - \mathtt{L}(i_2)) \\ &\quad = (0, \neq 0). \end{aligned} \tag{14}$$

Since $g(a, b) = a + bp$, we have

$$g(b_k^{i_1} - b_k^{i_2}) \le -p \text{ or } g(b_k^{i_1} - b_k^{i_2}) \ge p. \tag{15}$$

Since

$$-(p-1) \le j_2 - j_1 \le p - 1, \tag{16}$$

then we have

$$g(b_k^{i_1} - b_k^{i_2}) \neq j_2 - j_1. \tag{17}$$

Hence $h(g(b_k^{i_1}) + j_1, g(b_k^{i_2}) + j_2) = 0$.

Then C is with strict no-hit and pseudo-randomness under the action of the linear function $\mathtt{L}(x)$ [37], [38]. □

B. PRIME SEQUENCES AS BASE SEQUENCES

The prime sequence over GF(p) is defined as follows [39], [40]:

$$a^i = (i, 2i, \cdots, (p-1)i, pi), \text{ for some } i \in \{1, 2, \cdots, p-1\}. \tag{18}$$

Let a^i be the base sequences in (1), and we can obtain the special control sequence set C' (called *prime control sequence set*). Let $g(a, b) = a + bp$ be a one-to-one function from $(\mathrm{GF}(p), \mathrm{GF}(p))$ to Z_{p^2} where $a, b \in \mathrm{GF}(p)$.

Theorem 2: The set C' contains p^2 control sequences over the time slot set with size p^2 with strict no-hit and pseudo-randomness. In addition, it satisfies that $c^{ip+j_1} - c^{ip+j_2}$ is a constant sequence. Moreover, we have $g(b^i_{k_1}) \neq g(b^i_{k_2})$ for any $0 \leq k_1 \neq k_2 \leq p^2 - 1$, i.e. it has time slot position judgment ability.

Proof: Similar to the proof of Theorem 1, we can get that C' has strict no-hit and $c^{ip+j_1} - c^{ip+j_2}$ is a constant sequence. We only prove that $g(b^i_{k_1}) \neq g(b^i_{k_2})$ for any $0 \leq k_1 \neq k_2 \leq p^2 - 1$.

Since $g(a, b) = a + bp$, then we have

$$\begin{aligned} g(b^i_{k_1}) - g(b^i_{k_2}) &= a_{\left\lfloor \frac{k_1}{p} \right\rfloor} + \mathtt{L}(a_{\langle k_1\rangle_p} + i)p \\ &\quad - \left(a_{\left\lfloor \frac{k_2}{p} \right\rfloor} + \mathtt{L}(a_{\langle k_2\rangle_p} + i)p\right) \\ &= a_{\left\lfloor \frac{k_1}{p} \right\rfloor} - a_{\left\lfloor \frac{k_2}{p} \right\rfloor} \\ &\quad + \mathtt{L}(a_{\langle k_1\rangle_p} - a_{\langle k_2\rangle_p})p. \end{aligned} \tag{19}$$

Case 1: $tp \leq k_1, k_2 \leq (t+1)p - 1$ for some $0 \leq t \leq p - 1$. In this case, we have

$$\begin{aligned} g(b^i_{k_1}) - g(b^i_{k_2}) &= ti' - ti' + \mathtt{L}(a_{\langle k_1\rangle_p} - a_{\langle k_2\rangle_p})p \\ &= \mathtt{L}(a_{\langle k_1\rangle_p} - a_{\langle k_2\rangle_p})p, \end{aligned} \tag{20}$$

where $1 \leq i' \leq p - 1$. Since $a_{\langle k_1\rangle_p} \neq a_{\langle k_2\rangle_p}$ by the property of the prime sequence, we have

$$g(b^i_{k_1}) - g(b^i_{k_2}) \neq 0. \tag{21}$$

Case 2: $tp \leq k_1 \leq (t+1)p-1$ and $sp \leq k_2 \leq (s+1)p-1$ for some $0 \leq t \neq s \leq p - 1$. In this case, we have

$$\begin{aligned} g(b^i_{k_1}) - g(b^i_{k_2}) &= ti' - si' + \mathtt{L}(a_{\langle k_1\rangle_p} - a_{\langle k_2\rangle_p})p, \end{aligned} \tag{22}$$

where $1 \leq i' \leq p - 1$. We can get that

$$-(p-1) \leq ti' - si' < 0 \tag{23}$$

or

$$0 < ti' - si' \leq p - 1. \tag{24}$$

Since $\mathtt{L}(a_{\langle k_1\rangle_p} - a_{\langle k_2\rangle_p})p = \widehat{i}p$ for some integer $\widehat{i}$, we have

$$g(b^i_{k_1}) - g(b^i_{k_2}) \neq 0. \tag{25}$$

□

Remark 1: By choosing different prime sequences, we can get $p - 1$ different prime control sequence sets. This can ensure that up to $p - 1$ different prime control sequence sets can be used in adjacent distribution terminal communities.

IV. ANALYSIS OF HANDOVER ACCESS PROCESS BASED ON SEQUENCE CONTROL

For $p = 7$ and $q = 49$, choose $a = (0, 2, 4, 6, 1, 3, 5)$ and $g((a, b)) = ap + b$. Then the following sequence set can be obtained:

$$\begin{aligned} &\{(0, 24, 9, 12, 37, 19, 23, 42, 14, 10, 33, 15, 28, 44, 3, \cdots), \\ &(1, 25, 10, 13, 38, 20, 24, 43, 15, 11, 34, 16, 29, 45, 4, \cdots), \\ &(2, 26, 11, 14, 39, 21, 25, 44, 16, 12, 35, 17, 30, 46, 5, \cdots), \\ &\cdots\cdots\cdots, \\ &(48, 37, 29, 4, 15, 11, 16, 2, 39, 22, 18, 7, 6, 8, 30, \cdots)\}. \end{aligned}$$

It can be seen that the sequence set contains 49 control sequences over the time slot set with size 49. The control sequences also have strict no-hit and pseudo-randomness. The difference between every 7 sequences is a constant sequence. Besides, let $f(x) = (g_L^{-1}, g_R^{-1})$ where g^{-1} is the inverse function of g and we can check that for each $0 \leq k \leq 48$ the time slot position can be determined.

The program algorithm flow of the distribution terminal node handover process using the above control sequence is implemented by Algorithm 1.

Algorithm 1 Distribution Terminal Node Handover Process Using the Control Sequence

```
Require: initialize $C = (0, 0, \cdots, 0)$ and $i \geq 1$
 1: the $i$th user requested handover
 2: assign the $i$th sequence $c$ to the user from the control
    sequence set
 3: if $i|7$ then
 4:     $D \leftarrow (i-1)$th sequence minuses $(i-2)$th sequence
 5:     $C \leftarrow D+$ $i$th sequence $c$ in $Z_{p^2}$
 6: else
 7:     $e \leftarrow (i-1)$th sequence minuses $i$th sequence $c$
 8:     if $e$ is a constant sequence then
 9:         $C \leftarrow$ $i$th sequence $c$
10:     else
11:         $c \leftarrow c$ shift a bit cyclically
12:         goto Step 7
13:     end if
14: end if
15: return $C$
```

At present, there are $i - 1$ distribution terminal nodes accessing the backup network. If the ith distribution terminal node initiates an access request, then assigning the ith sequence c to the user from the control sequence set. There are two situations: 7 can divide i and 7 cannot divide i. When the ith distribution terminal node initiates an access request, the ith sequence is assigned first. If i can be evenly divided by 7, then the difference sequence between the $(i-1)$th distribution terminal node and the $(i-2)$th distribution terminal node is used to perform addition operation in Z_{p^2} to the allocated sequence and then a new sequence is obtained to be its control sequence. If i cannot be evenly divided by 7, subtracting the sequence c from the $i-1$th sequence and the sequence e is obtained, and determining whether the sequence is a constant sequence. If so, the current sequence C ($=$ ith sequence c) can be used as its control sequence. If not, let the sequence c shift a bit cyclically and make it as a new sequence c. Subtracting the sequence c from the $i-1$th sequence and the sequence e is obtained and this step is repeated until the obtained difference sequence is a constant sequence. Then the current sequence C can be used as its control sequence. By the program, the distribution terminal node access process can be achieved.

Algorithm 2 shows the exit strategy for the distribution terminal node. When the $(i-k)$th user requested exit, the $(i-k)$th sequence is labelled as "idle sequence". The idle sequence is reserved for the access of future users. If the $i+1$th distribution terminal node initiates an access request, then judging whether there is a reserved idle sequence. If yes, then assigning the idle sequence to the user. Otherwise, assigning the $(i+1)$th sequence c' to the user from the control sequence set. Next, the distribution terminal node access process is executed by Algorithm 1. Finally, wait for the next user requesting exit and repeat the procedure. If there is not any distribution terminal node initiating access request, then also repeating the procedure. Then the exit strategy for the distribution terminal node can be achieved.

Algorithm 2 The Exit Strategy for the Distribution Terminal Node

```
Require: initialize $i \geq 1, k < i, j = 0$
1:  if the $(i-k)$th user requested exit then
2:      label the $(i-k)$th sequence as "idle sequence"
3:      $j = j + 1$
4:      if the $(i+1)$th user requested handover then
5:          if $j \neq 0$ then
6:              assign the idle sequence to the user
7:              $j = j - 1$
8:          else
9:              assign the $(i+1)$th sequence $c'$ to the user from
                the control sequence set
10:         end if
11:         $i = i + 1$
12:         execute Algorithm 1 from Step 3
13:     else
14:         goto Step 1
15:     end if
16: else
17:     goto Step 1
18: end if
```

Next, we discuss the Hamming correlations of the control sequences in this section. Hamming correlations can describe the similarity between two sequences. Small Hamming correlation value indicates a high degree of similarity between the two sequences. For a sequence $a = (a_0, a_1, \cdots, a_{L-1})$,

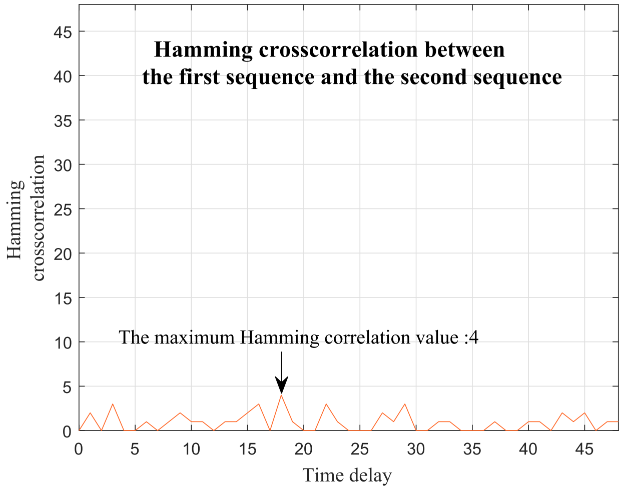


FIGURE 2. The Hamming crosscorrelation between the first sequence and second sequence.

the Hamming autocorrelation can be defined as follows:

$$C_a(t) = \sum_{i=0}^{L-1} d(a_i, a_{i+t}), \tag{26}$$

where $0 \leq t \leq L-1$ is time delay. The Hamming crosscorrelation between $a = (a_0, a_1, \cdots, a_{L-1})$ and $b = (b_0, b_1, \cdots, b_{L-1})$ is defined as follows:

$$C_{ab}(t) = \sum_{i=0}^{L-1} d(a_i, b_{i+t}), \tag{27}$$

where $0 \leq t \leq L-1$ is time delay.

Figure 2 illustrates the Hamming crosscorrelation between the first sequence and second sequence, and Figure 3 illustrates the Hamming crosscorrelation between the first sequence and last sequence. It is known that the difference between the first sequence and second sequence is constant sequence while that between the first sequence and last sequence is not. It can be seen that the Hamming crosscorrelation between the first sequence and second sequence is 0 at time delay 0 which is same as that between the first sequence and last sequence. Although the Hamming crosscorrelation between them is not 0 at time delay $\neq 0$, it can be maintained at a very low value which does not exceed 4. Thus, these control sequences are suitable for the handover of distribution terminal nodes.

In order to compare our new control sequences with those in the literature. We compare their MTTRs and average Hamming correlations. The MTTRs can be found in Table 1 and [34], and the average Hamming correlations are the average values of Hamming correlations between each two sequences at different time delays. Figures 4 and 5 show the MTTRs and the average Hamming correlations of control sequences respectively in the literature and this paper.

As shown in Figure 4, our new control sequences have smaller MTTR than those in the literature if the number of

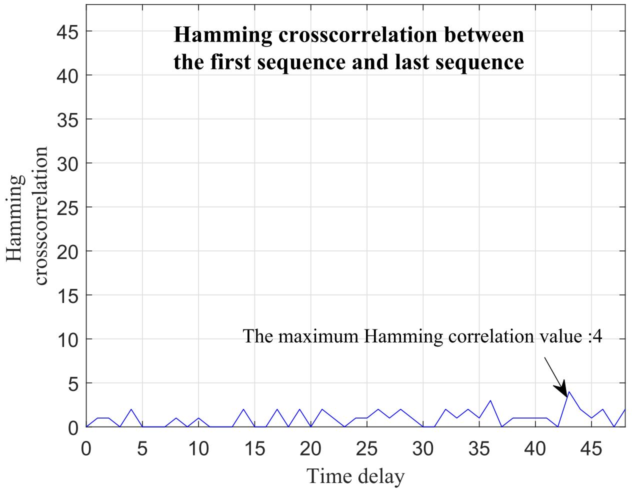


FIGURE 3. The Hamming crosscorrelation between the first sequence and last sequence.

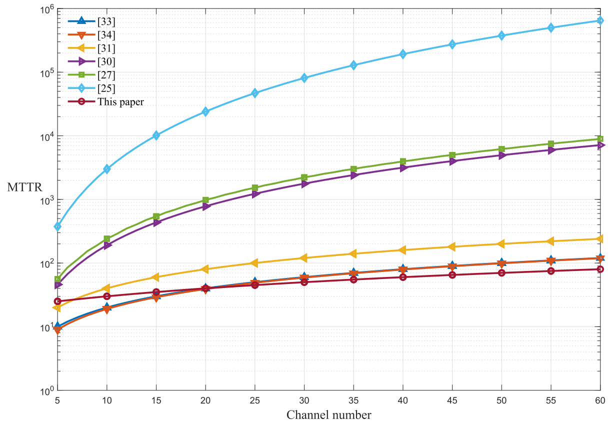


FIGURE 4. Comparison of the MTTRs of control sequences.

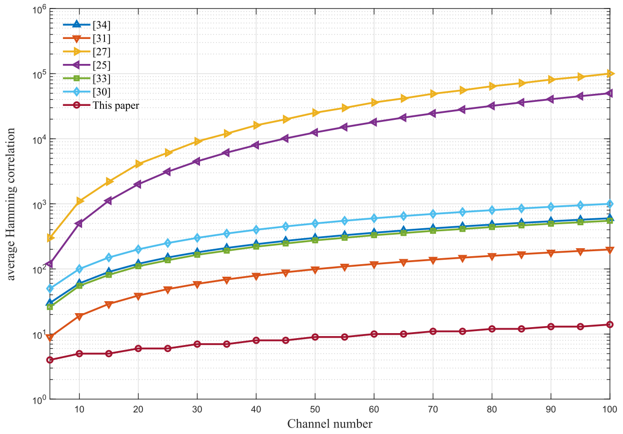


FIGURE 5. Comparison of the average Hamming correlations of control sequences.

channels is greater than 20, although have little larger MTTR than those in [33] and [34] if the number of channels is less than 20. Generally speaking, there are many channels in practice. This indicates that our new control sequences can manipulate distribution terminal nodes to access the backup network in less time. In Figure 5, we can see that our new control sequences also have smaller value of average Hamming correlations than those in the literature. It implies that the new control sequences have less mutual interference than those in the literature, which ensures the reliability of transmission by using our new control sequences.

V. CONCLUSION

In this paper, we first proposed a distribution terminal access mechanism based on sequence control. In this mechanism, the control sequence generator uses the sequence elements corresponding to the sequence to synthesize time slots and then sends the generated time slot instructions to the time slot allocation module. It controls the distribution terminal user node to obtain the current time slot position information. By performing operations of the current slot position and the slot of previously accessed user in the finite field, the access to the backup network can be achieved.

Then, a family of control sequences satisfying the requirements was constructed based on the trace function in the finite field. The control sequence can realize the rapid access of distribution terminal nodes and the safe transmission without interference. Specially, by choosing prime sequences as base sequences, the prime control sequence sets were obtained which can ensure that different prime control sequence sets can be used in adjacent distribution terminal communities. Finally, the program algorithm for the access process of distribution terminal nodes by control sequences was presented. Besides, the exit strategy for the distribution terminal node was also presented. To compare our new control sequences with those in the literature, we gave the simulations on their MTTRs and average Hamming correlations which can be found in Figures 4 and 5. By the simulations, it was showed that our new control sequences have smaller MTTR in most cases and smaller value of average Hamming correlations than those in the literature. It makes distribution terminal nodes access the backup network in less time and ensures the reliability of transmission.

REFERENCES

[1] A. J. Soto-Vergel, J. C. Velez, R. Amaya-Mier, and M. Pardo, "Transforming ground disaster response: Recent technological advances, challenges, and future trends for rapid and accurate real-world applications of survivor detection," *Int. J. Disaster Risk Reduction*, vol. 98, Nov. 2023, Art. no. 104094.

[2] Z. Liu, Q. Wu, X. Shen, J. Tan, and X. Zhang, "Post-disaster robust restoration scheme for distribution network considering rerouting process of cyber system with 5G," *IEEE Trans. Smart Grid*, vol. 15, no. 5, pp. 4478–4491, Sep. 2024.

[3] M.-L. Tham, Y. J. Wong, B.-H. Kwan, X. H. Ng, and Y. Owada, "Artificial intelligence of things (AIoT) for disaster monitoring using wireless mesh network," in *Proc. 6th Int. Conf. Softw. Eng. Inf. Manage.*, New York, NY, USA, Jan. 2023, pp. 234–239.

[4] W. Yuan, J. Wang, F. Qiu, C. Chen, C. Kang, and B. Zeng, "Robust optimization-based resilient distribution network planning against natural disasters," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2817–2826, Nov. 2016.

[5] Y. Zhang, D. Wang, Q. Xu, Q. Li, Z. Liu, S. Jiang, and D. Zhao, "A resilience evaluation index system and evaluation method for regional distribution networks facing typhoon disasters," *J. Phys., Conf. Ser.*, vol. 2782, no. 1, Jun. 2024, Art. no. 012064.

[6] C. Chen, J. Wang, F. Qiu, and D. Zhao, "Resilient distribution system by microgrids formation after natural disasters," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 958–966, Mar. 2016.

[7] L. Zheng, C. He, Y. Lin, and Y. Ning, "Research on pre-disaster reinforcement of distribution network system in extreme weather," in *Proc. 7th Int. Conf. Electron. Technol. (ICET)*, May 2024, pp. 1168–1173.

[8] J. Han, Y. Fang, E. Du, P. Yong, N. Zhang, and N. Liu, "Eliminating distribution network congestion based on spatial–temporal migration of multiple base stations," *IEEE Trans. Smart Grid*, vol. 15, no. 6, pp. 5638–5652, Nov. 2024.

[9] J. Xu, Z. Wu, X. Yu, Q. Hu, C. Zhu, X. Dou, W. Gu, and Z. Wu, "A new method for optimal FTU placement in distribution network under consideration of power service reliability," *Sci. China Technolog. Sci.*, vol. 60, no. 12, pp. 1885–1896, Dec. 2017.

[10] J. M. Nahman and M. R. Tanaskovic, "Probability models for optimal sparing of distribution network transformers," *IEEE Trans. Power Del.*, vol. 24, no. 2, pp. 758–763, Apr. 2009.

[11] K. Pang, C. Wang, N. D. Hatziargyriou, and F. Wen, "Microgrid formation and real-time scheduling of active distribution networks considering source-load stochasticity," *IEEE Trans. Power Syst.*, vol. 39, no. 2, pp. 2801–2813, Mar. 2024.

[12] U. C. Yilmaz and A. Abur, "A robust parallel distributed state estimation for large scale distribution systems," *IEEE Trans. Power Syst.*, vol. 39, no. 2, pp. 4437–4445, Mar. 2024.

[13] A. Moreira, M. Heleno, A. Valenzuela, J. H. Eto, J. Ortega, and C. Botero, "A scalable approach to large scale risk-averse distribution grid expansion planning," *IEEE Trans. Power Syst.*, vol. 39, no. 1, pp. 2115–2128, Jan. 2024.

[14] Y. Bansal, R. Sodhi, S. Chakrabarti, and A. Sharma, "A novel two-stage partitioning based reconfiguration method for active distribution networks," *IEEE Trans. Power Del.*, vol. 38, no. 6, pp. 4004–4016, Dec. 2023.

[15] P. Shi, Y. Li, Y. Du, Q. Cai, and H. Chen, "Distribution network planning considering uncertainty of incremental distribution network access," in *Proc. IEEE 4th Conf. Energy Internet Energy Syst. Integr. (EI2)*, Wuhan, China, Oct. 2020, pp. 2244–2247.

[16] S. Zhang, L. Yu, and Q. Li, "Research on high permeability photovoltaic access distribution network architecture and protection configuration," in *Proc. 7th Asia Conf. Power Electr. Eng. (ACPEE)*, Hangzhou, China, Apr. 2022, pp. 1052–1061.

[17] J. Jiang, P. Xin, N. Xiao, and Q. Li, "A multi-domain protection for reliable slicing in network coding based 5G/B5G RAN enabled power distribution network," in *Proc. 22nd Int. Conf. Opt. Commun. Netw. (ICOCN)*, Jul. 2024, pp. 1–3.

[18] H. Li, Y. Tong, C. Zhao, Z. Wang, and Y. Chi, "Reactive power coordinated control strategy for hybrid cascaded systems with large-scale renewable power hierarchical access," in *Proc. 6th Int. Conf. Power Renew. Energy (ICPRE)*, Shanghai, China, Sep. 2021, pp. 33–40.

[19] H. Hu, L. Wen, J. Li, Z. Sun, K. Zheng, and J. Li, "Optimal dispatch of CHP units at the plant level with wind power access," in *Proc. 12th Int. Conf. Power Energy Syst. (ICPES)*, Guangzhou, China, Dec. 2022, pp. 780–784.

[20] T.-T. Nguyen, V.-D. Nguyen, J.-H. Lee, and Y.-H. Kim, "Sum rate maximization for multi-user wireless powered IoT network with non-linear energy harvester: Time and power allocation," *IEEE Access*, vol. 7, pp. 149698–149710, 2019.

[21] B. Liu, J. Li, S. Zhang, M. Gao, H. Ma, G. Li, and C. Gu, "Economic dispatch of combined heat and power energy systems using electric boiler to accommodate wind power," *IEEE Access*, vol. 8, pp. 41288–41297, 2020.

[22] B. Ding, L. Du, Z. Xia, and S. Wang, "Security protection method for the edge equipment of power Internet of Things based on blockchain," in *Proc. 7th Asia Conf. Power Electr. Eng. (ACPEE)*, Hangzhou, China, Apr. 2022, pp. 369–374.

[23] J. Wu, X. Zhang, Y. Liu, and X. Feng, "Information security intelligent access system for high-skilled talents in electric power enterprises based on big data," in *Proc. Int. Conf. Knowl. Eng. Commun. Syst. (ICKES)*, Chickballapur, India, Dec. 2022, pp. 1–4.

[24] D. Xie, F. Hu, M. Huang, Y. Liu, S. Duan, and X. Tang, "Research on the power purchasing strategy and its economics of provincial power grid adapting to new energy access," in *Proc. 11th Int. Conf. Power Energy Syst. (ICPES)*, Shanghai, China, Dec. 2021, pp. 861–865.

[25] K. Bian and J.-M. J. Park, "Maximizing rendezvous diversity in rendezvous protocols for decentralized cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 12, no. 7, pp. 1294–1307, Jul. 2013.

[26] I.-H. Chuang, H.-Y. Wu, and Y.-H. Kuo, "A fast blind rendezvous method by alternate hop-and-wait channel hopping in cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 10, pp. 2171–2184, Oct. 2014.

[27] Z. Gu, Q.-S. Hua, Y. Wang, and F. C. M. Lau, "Nearly optimal asynchronous blind rendezvous algorithm for cognitive radio networks," in *Proc. IEEE Int. Conf. Sens., Commun. Netw. (SECON)*, Jun. 2013, pp. 371–379.

[28] G. Y. Chang, J. F. Huang, and Y. S. Wang, "Matrix-based channelhopping algorithms for cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 5, pp. 2755–2768, May 2015.

[29] B. Yang, M. Zheng, and W. Liang, "A time-efficient rendezvous algorithm with a full rendezvous degree for heterogeneous cognitive radio networks," in *Proc. IEEE INFOCOM 35th Annu. IEEE Int. Conf. Comput. Commun.*, Apr. 2016, pp. 1–9.

[30] C.-S. Chang, J.-P. Sheu, and Y.-J. Lin, "On the theoretical gap of channel hopping sequences with maximum rendezvous diversity in the multichannel rendezvous problem," *IEEE/ACM Trans. Netw.*, vol. 29, no. 4, pp. 1620–1633, Aug. 2021.

[31] H. Liu, Z. Lin, X. Chu, and Y. W. Leung, "Jump-stay rendezvousalgorithm for cognitive radio networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 10, pp. 1867–1881, Oct. 2012.

[32] J.-P. Sheu, C.-W. Su, and G.-Y. Chang, "Asynchronous quorum-based blind rendezvous schemes for cognitive radio networks," *IEEE Trans. Commun.*, vol. 64, no. 3, pp. 918–930, Mar. 2016.

[33] L.-H. Yang, G.-C. Yang, and W. C. Kwong, "New asynchronous channel-hopping sequences for cognitive-radio wireless networks," *IEEE Trans. Cognit. Commun. Netw.*, vol. 8, no. 2, pp. 842–855, Jun. 2022.

[34] Y. Wang, X. Niu, Z. He, C. Qi, and B. Zeng, "A construction of an asynchronous channel hopping sequence sets for cognitive radio networks," *IEEE Commun. Lett.*, vol. 28, no. 2, pp. 268–272, Feb. 2024.

[35] Q. Zeng, Z. Zhou, X. Liu, and Z. Liu, "Strong no-hit-zone sequences for improved quasi-orthogonal FHMA systems: Sequence design and performance analysis," *IEEE Trans. Commun.*, vol. 67, no. 8, pp. 5336–5345, Aug. 2019.

[36] Q. Zeng, J. Chen, X. Niu, L. Zhou, and X. Liu, "Optimal no-hit-zone sequences with wide-gap for improved FHMA systems under follower jamming," *IEEE Trans. Commun.*, early access, Sep. 12, 2024, doi: 10.1109/TCOMM.2024.3459852.

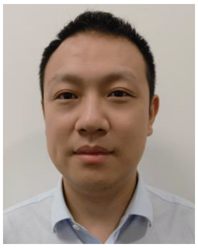
[37] T. Qayyum, T. Shah, A. Y. Hummdi, A. Aljaedi, and Z. Bassfar, "An innovative feasible approach for multi-media security using both chaotic and elliptic curve structures," *IEEE Access*, vol. 12, pp. 10411–10427, 2024.

[38] S. S. Jamal, Z. Bassfar, O. Lahlou, A. Aljaedi, and M. M. Hazzazi, "Image encryption based on elliptic curve points and linear fractional transformation," *IEEE Access*, vol. 12, pp. 53335–53347, 2024.

[39] K. Ono, T. K. Matsushima, S. Yamasaki, and H. Tanaka, "Multirate optical CDMA systems combining generalized modified prime sequence code and bi-orthogonal code," *IEEE Access*, vol. 12, pp. 56789–56798, 2024.

[40] K. Ono, S. Yamasaki, S. Miyazaki, and T. K. Matsushima, "Optical CDMA scheme using generalized modified prime sequence codes and extended bi-orthogonal codes," *IEICE Trans. Fundam. Electron., Commun. Comput. Sci.*, vol. E104.A, no. 9, pp. 1329–1338, 2021.

CHENG LONG received the Ph.D. degree in electrical engineering and its automation from Huazhong University of Science and Technology, Wuhan, China, in 2017. He is currently a Senior Engineer with the State Grid Electric Power Research Institute of Sichuan Province. His research interests include the Internet of Things in power distributions and distribution network operation and its analysis.



JIAN ZHANG received the master's degree in electrical engineering and its automation from Southwest Jiao Tong University, Chengdu, China, in 2011. He is currently a Senior Engineer with the Department of Equipment Management, State Grid Sichuan Electric Power Company. His research interests include the power Internet of Things and distribution network operation and its analysis.

HUA ZHANG received the M.S. degree in electrical engineering from Tsinghua University, Beijing, China. He is currently a Senior Engineer with the State Grid Sichuan Electric Power Research Institute of Sichuan Province, Chengdu, China. His research interest includes distribution network automation.

XING LIU received the B.S. and Ph.D. degrees in communication engineering from Southwest Jiaotong University, Chengdu, China, in 2009 and 2014, respectively. He is currently an Associate Professor with the College of Electrical Engineering, Sichuan University, Chengdu. His research interest includes electric power communication technology.

YIWEN GAO received the B.S. and M.S. degrees in electrical engineering from Sichuan University, Chengdu, China, in 2007 and 2014, respectively. He is currently an Engineer with the State Grid Sichuan Electric Power Research Institute of Sichuan Province, Chengdu. His research interest includes power systems and its automation.

XUENENG SU received the B.S. and Ph.D. degrees in electrical engineering from Sichuan University, Chengdu, China, in 2014 and 2019, respectively. From 2017 to 2018, he was a Visiting Ph.D. Student with Clarkson University, Potsdam, NY, USA. He is currently an Engineer with the State Grid Sichuan Electric Power Research Institute of Sichuan Province, Chengdu. His research interests include parallel computing and its application on power systems.

SHILONG LI received the Ph.D. degree in electronic engineering from Huazhong University of Science and Technology, Wuhan, China, in 2018. He is currently a Senior Engineer with the State Grid Sichuan Electric Power Research Institute of Sichuan Province, Chengdu, China. His research interest includes the protection of power systems.

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