Communication-Assisted Protection and Self-Healing Control Scheme for Distribution Networks Based on IEC 61850

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ABSTRACT

Communication-assisted protection and self-healing control (CAPSC) is perceived as a new alternative to ensure reliable operation of distribution networks (DNs) because of its prominent advantages of information sharing. Although the application of CAPSC based on IEC 61850 has been verified in substations, it has not yet been effectively promoted in DNs. To fully exert its advantages in DNs, a novel scheme of IEC 61850-based CAPSC is proposed in this paper. The proposed scheme enable samplings to be synchronized by propagation delay compensation without external clocks. Adaptive execution algorithms of protection and self-healing control are introduced considering changeable topology and configuration conditions. The coordination between protection and self-healing control in this scheme is simplified by component state descriptions instead of event signals. The scheme proposed in this paper has been incorporated in an engineering field application. A closed-loop test has been conducted on a real-time digital simulator (RTDS) according to the field connections and parameters to verify the rationality and effectiveness of the proposed scheme.

INDEX TERMS

Distribution networks, IEC 61850, protection and self-healing control, RTDS.

I. INTRODUCTION

The integration of distributed generators (DGs), energy storage systems and flexible loads has caused drastic changes of the generation structure, network topology and control demands of distribution networks (DNs) [1], [2]. Although localized protection has been improved to satisfy the development of DNs, it inevitably leads to complex configuration and difficult coordination of protection and self-healing control [3]. In recent years, significant breakthroughs have been made in information technology and intelligent sensing technology, which remove the communication barricade of the application of communication-assisted protection and self-healing control (CAPSC) [4]. In the meanwhile, a series of uniform communication standards have been presented to ensure the real-time communication of DNs [5]. Therefore, CAPSC has become an alternative approach for DNs.

In contrast to localized protection, CAPSC is able to achieve fast and comprehensive execution due to information integration of small time scales and large space scales [6]–[8].

IEC 61850-based CAPCS, which has been widely employed in substations [9], [10], was preliminarily introduced to DNs [11]. One of the advantages of IEC 61850-based CAPSC is to improve the protection performance. Most of the applications of IEC 61850-based CAPSC in DNs adopt generic object oriented substation event (GOOSE) messages to transmit fault signals to implement logic protection [12]–[17]. In reference [14], the overcurrent principle is adopted to generate fault signals to achieve fault location in radial DNs. But the presence of DGs may result in maloperation of this scheme. In reference [16], the distance protection principle is employed, which shows better adaptivity to DNs with high penetration of DGs. However, the implementation of high-performance logic protection depends on the improvement of local configuration. Except for logic protection, current differential principle with higher sensitivity...
provides another effective option for DN protection [17]. However, current differential protection in DNs is confronted with the challenges of sampling synchronization [19], [20].

Another advantage of CAPSC is to apply the coordination between different protection decisions and control decisions. By means of event signal sharing instead of time-step setting, CAPSC is able to reduce its execution time. To utilize better coordination between main protection and backup protection, reference [21] proposes a protection approach considering the abnormality of sampling devices and switching devices. To achieve interaction of protection and control, reference [22] introduces an integrated process of fault location, isolation and supply restoration (FLISR) by inquiring the switch status [22], [23]. However, the implementation of the above measures inevitably lead to high maintenance workload.

To make full use of the advantages of IEC 61850-based CAPSC, a novel CAPSC scheme is proposed in this paper. Sampling value (SV) messages, employed in the CAPSC scheme for DNs, are synchronized by propagation delay compensation independent of external clocks. In addition, adaptive execution algorithms and coordinated interaction between protection and control are introduced in the CAPSC scheme. The CAPSC proposed in this paper manifests the following advantages:

1) The proposed scheme is adaptive to different topologies and operating modes;
2) The execution decisions of the proposed scheme can be adjusted in accordance with the changes of configuration conditions;
3) The execution time under complex fault events can be effectively compressed. The CAPSC scheme proposed in this paper has been implemented in the engineering field.

To evaluate the effectiveness of the proposed scheme, a closed-loop test based on a real-time digital simulator (RTDS) was performed, and the rationality and validity of the proposed scheme were verified.

The sections of this paper are developed as follows: The physical architecture of the IEC 61850-based CAPSC scheme for DNs is presented in section II. The sampling synchronization for the IEC 61850-based CAPSC scheme is provided in section III. Section IV focuses on the adaptive CAPSC algorithms, and section V illustrates the coordinated interaction based on component state description. Implementation of a closed-loop test on an RTDS using the proposed IEC 61850-based CAPSC scheme is presented in section VI. Finally, Section VII concludes the paper.

II. PHYSICAL ARCHITECTURE OF THE IEC61850-BASED CAPSC SCHEME

Referring to the deployment in substations [11], a three-level two-bus physical architecture of the CAPSC scheme based on IEC 61850 for DNs is developed, as shown in Fig. 1.

The intelligent terminals (ITs) arranged on DN switches act as the process-level devices, which collect electrical sampling and switch status data and transmit them to the bay level. An integrated protection and self-healing control station (IPSCS) is deployed in the bay level. The IPSCS retains the interface to connect with the distribution automation system analogous to the station level. Notably, the centralized IPSCS deployment is adopted to fully realize the adaptation of the CAPSC scheme to different operating modes and promote the protection and control coordination.

A robust and reliable communication network guarantees realization of the IEC 61850-based CAPSC scheme. The following principles are proposed:

1) A duplicated or ring communication network structure is required to guarantee the reliability for data transmission;
2) A high-bandwidth optical fiber communication network is adopted to ensure the data transmission rate and channel capacity;
3) SV and GOOSE heartbeat messages are utilized to monitor communication links.

III. SYNCHRONIZATION BASED ON PROPAGATION DELAY COMPENSATION

The propagation delay compensation method is adopted to address the difficulty of SV message synchronization for DNs without the need to deploy a unified clock for each sampling device. To realize synchronization, when the IPSCS receives an SV message from a sampling device, it can obtain the exact sampling instant by subtracting the receipt instant and propagation delay of the SV message. This method, first mentioned in reference [24] by the coauthor of this paper, has been well proved in the applications of substations.

From reference [24], we can conclude that the propagation delay contains three parts, which are the rated delay, Ethernet-switch delay and fiber delay. The rated delay represents the fixed data processing time of ITs, which is recorded in the data sets of SV messages. The Ethernet-switch delay is the resident time of a message spent on Ethernet switches. The fiber delay equals the transmission time a message spent on fibers. However, the fiber delay is always ignored in substations because it only lasts for several nanoseconds.

FIGURE 1. Physical architecture of the CAPSC scheme based on IEC 61850 for DNs.
Therefore, the Ethernet-switch delay is the only variable part considered in reference [24].

Unlike in substations, the total fiber delay in DNs can reach up to tens of microseconds and hence, is no longer negligible. Actually, the fiber delay is fixed for a given transmission path, so the delay of each fiber segment can be measured in advance. However, there are still some difficulties in tracking the transmission paths of the messages considering the real-time changes in communication networks. Instead of calculating the transmission path of a message beforehand, it is more practical to record the delay of each fiber segment in the message by the Ethernet switches along the transmission path. To address the synchronization issue in DNs, the propagation delay compensation method should be improved.

Fig. 2 illustrates the process of obtaining the propagation delay via the delay-measurable Ethernet switch considering the fiber delay in DNs. When a message enters the Ethernet switch \( i \) via the ingress port, the delay-measurable Ethernet switch will record the instant as \( t_{i}^{\text{in}} \) and obtain the fixed fiber delay \( j \) attached to the ingress port as \( \Delta t_{i}^{j} \). After message processing in the Ethernet switch, which requires a fixed processing delay of \( \Delta t_{E} \), the message will be sent to the egress port. When the message arrives at the egress port, the delay-measurable Ethernet switch will record the instant as \( t_{i}^{\text{out}} \). Therefore, when a message passes through Ethernet switch \( i \), its propagation delay will be increased by \( \Delta t_{i} \), which can be calculated as (1):

\[
\Delta t_{i} = t_{i}^{\text{out}} - t_{i}^{\text{in}} + \Delta t_{E} + \Delta t_{i}^{j}
\]

When a message is transmitted and exchanged through \( n \) Ethernet switches, the propagation delay \( t_{n} \) recorded in the reserved field of the SV message can be calculated as \( \sum_{i=1}^{n} \Delta t_{i} \). Thus, the total propagation delay is summed up as (2):

\[
T_{pd} = t_{0} + \sum_{i=1}^{n} \Delta t_{i} + \Delta t_{\text{IPSCS}}
\]

where \( t_{0} \) is the rated delay and \( \Delta t_{\text{IPSCS}} \) is the fiber delay attached to the IPSCS. After obtaining the total propagation delay, the exact sampling instant can be calculated and the sampling synchronization can be realized accordingly.

IV. ADAPTIVE CAPSC ALGORITHMS CONSIDERING TOPOLOGY AND CONFIGURATION CONDITIONS

As topology and configuration conditions change, the CAPSC scheme should always meet the requirements of making proper operation decisions to identify, remove and isolate the faulty component in the minimum range, and enabling automatic protection setting adjustments and supply restoration options [25]. To this end, adaptive CAPSC algorithms are provided in this section.

A. ADAPTIVE FAULT IDENTIFICATION

1) DIVISION OF PROTECTION ZONES

A regional DN is divided into several protection zones according to the switch status and sampling conditions. It is assumed that the topology of the DN can be described by the directed component incidence matrix \( D \). Then, the protection zones, represented by the zone incidence matrix \( D_{M} \), are further established according to the switch status and sampling conditions. The establishment of \( D_{M} \) is shown as (3):

\[
D_{M} = \prod_{i=1}^{n_{M}} P_{i} \cdot D
\]

where \( n_{M} \) is the number of switches that remain opened or fail to obtain current samplings, and \( P_{i} \) is the row transformation matrix generated by the \( i \)-th switch. Assuming that the forward-connected component of switch \( i \) is \( a \) and the reverse-connected component is \( b \), the corresponding \( P_{i} \) can be obtained as follows:

\[
P_{i} = \begin{bmatrix}
a & b & 0 & 0 \\
0 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

The execution of row transformation \( P_{i} \) indicates that the zone with component \( b \) is merged into the zone with component \( a \). The corresponding relationship of the protection zones and the components contained in these zones, denoted as \( Y_{M} \), can be calculated as (4):

\[
Y_{M} = \prod_{i=1}^{n_{M}} P_{i} \cdot Y
\]

where \( Y \) is a unit diagonal matrix.

2) ADJUSTMENT OF PROTECTION SETTINGS

After defining different protection zones, the action vector \( I_{\text{act}} \) is formed as (5) according to \( D_{M} \):

\[
I_{\text{act}} = |D_{M} \times I|
\]

where \( I \) is the current sampling vector. From the formation of the action vector, it can be deduced that the overcurrent
protection criterion is automatically employed for the protection zone with single-terminal sampling, while the differential current protection criterion is preferred for the one with multiterminal samplings. Thus, the protection criteria for the DN components can adaptively change according to the topology and configuration conditions.

The settings vector for different protection zones can be expressed as follows:

\[ I_{\text{set}_H} = k_1 |D_M| I_e + k_2 Y_M \left( |I_N^{\text{load}}| + |I_F^{\text{source}}| \right) \]  
\[ I_{\text{set}_S} = k_S \cdot D_M \times |I| \]  

where \( I_{\text{set}_H} \) constitutes the horizontal restraint section of the current settings, whereas \( I_{\text{set}_S} \) constitutes the slope section to avoid the protection maloperation.

For the horizontal restraint section, when a complete differential current protection criterion is configured, the latter term of (6) equals 0, and the term \( I_e \) consisting of sampling errors only needs to be considered. Otherwise, the unbalanced current terms, constituted by the unmeasurable current of load branches or DG branches, should be considered. \( k_1 \) and \( k_2 \) are the coefficients for the horizontal restraint section, which should range from 1.3-1.5. \( k_S \) is the coefficient for the slope section and can be fixed to 0.3. \( I_N^{\text{load}} \) represents the current vectors of the loads, and \( I_F^{\text{source}} \) is the maximum fault current vector that the DGs can provide under fault conditions.

B. ADAPTIVE FAULT REMOVAL AND ISOLATION ALGORITHM

After the fault has been identified, proper circuit breakers and sectionalizing switches are selected to execute fault removal and fault isolation operations.

1) DECISIONS FOR FAULT REMOVAL OPERATIONS

Similar to the establishment of protection zones, the regional DN can be divided into several ranges for fault removal operations, denoted as incidence matrix \( D_B \), according to the ability of a switch to cut the fault current. The containing components of each range can be calculated as \( Y_B \). If the faulty component is identified, denoted as vector \( A_i \), the circuit breakers to remove the faulty component in the minimum range can be obtained as (8):

\[ R = A_i \cdot (Y_B)^T \cdot D_B \]  

2) DECISIONS FOR FAULT ISOLATION OPERATIONS

Similarly, for faulty component \( A_i \), the switches to isolate the faulty component in the minimum range can be obtained as (9) according to the range division for fault isolation operations, denoted as incidence matrix \( D_C \), and the containing components matrix \( Y_C \):

\[ R = A_i \cdot (Y_C)^T \cdot D_C \]  

where \( D_C \) and \( Y_C \) are formed according to the ability of a switch to be telecontrolled.

C. ADAPTIVE SUPPLY RESTORATION ALGORITHM

1) JUDGMENT FOR SUPPLY AVAILABILITY

To illustrate the electrical connections of different components, real-time topology blocks are defined according to the status of switches. The components belonging to each topology block can be calculated as \( Y_K \).

The block with power sources is considered to be efficiently supplied. Assuming that power sources are marked by vector \( S \), the blocks with effective power supply can be represented as \( Y_K \cdot S \). Furthermore, the supply availability of the components can be obtained by \( (Y_K \cdot S)^T \cdot Y_K \).

2) JUDGMENT FOR FAULT CORRELATION

We assume that the faulty component is identified, denoted as \( A_i \), and the fault block can be represented as \( Y_K \cdot A_i \). Furthermore, the components of the fault block, denoted as \( (Y_K \cdot A_i)^T \cdot Y_K \), are regarded to be fault correlated.

3) DECISIONS FOR SUPPLY RESTORATION OPERATIONS

The supply capacity of a block is defined by the total ability of its containing components to provide or receive power supply. Considering the presence of faulty component, the supply capacities of different blocks can be calculated as (10):

\[ Q = Y_K \cdot (I_N^{\text{source}} - I_N^{\text{load}} - k_f \cdot A_i) \]  

where \( k_f \) is an extremely large constant that ensures the supply capacity of the fault block to be negative.

Furthermore, the supply restoration capacity of a switch is defined by the sum of the supply capacities of the blocks on both sides of this switch, shown in (11):

\[ \Delta Q = |D_K|^T \cdot Q \]  

If the switch with the maximum supply restoration capacity is chosen as an operation option step by step, we can make the final supply restoration operation decisions accordingly.

V. COMPONENT STATE DESCRIPTION AND CAPSC COORDINATION

A. DESCRIPTION OF THE COMPONENT STATES

To establish the relationship between protection and self-healing control processes, DN components are classified into six types of component states as follows.

N indicates that the component is operating normally without any fault or power loss. \( F_{\text{ide}} \), \( F_{\text{rem}} \) and \( F_{\text{iso}} \) are three types of component states that the faulty component will cycle through during the fault handling, which represent the state of a faulty component being identified, removed, and isolated, respectively. \( L_{\text{cor}} \) and \( L_{\text{n-cor}} \) represent the component states of a component with power loss. The difference between \( L_{\text{cor}} \) and \( L_{\text{n-cor}} \) is that the \( L_{\text{cor}} \) state indicates a component with electrical connection to the faulty component, whereas the \( L_{\text{n-cor}} \) state represents the component with no electrical connection to the faulty component. State transitions can occur during protection and self-healing control processes, which are shown in Fig. 3.
Different components perform different operations according to their own states. Fig. 3 reveals that when the component is in the \( F_{\text{ide}} \), \( F_{\text{rem}} \) or \( L_{n-\text{cor}} \) state, the corresponding operations need to be executed. These operations include fault removal, fault isolation and supply restoration, the algorithms of which are provided in Section IV-B and IV-C. After the execution of the operations, the state of components will transit to the next one according to judgments provided in Section IV-A and IV-C.

**B. CAPSC COORDINATION BASED ON COMPONENT STATES**

The self-healing control process is only implemented after the protection process is finished if these processes are coordinated via event signals. Thus, the components in the \( L_{n-\text{cor}} \) state will not execute the supply restoration operations until all the faulty components have been successfully isolated. In fact, not all the components in the \( L_{n-\text{cor}} \) state appear after the completion of the protection process, which means that the execution time of these components can be compressed in the self-healing control process.

As shown in Fig. 4, the horizontal axis represents the state transitions of the components in Fig. 1 during the fault handling. A permanent fault occurs on the component B at instant \( t_f \), as shown in Fig. 1, where the boxes represent circuit breakers and the circles represent sectionalizing switches. The state transitions of component B are shown by I-axis. The circuit breaker CB2 will open during the fault removal operations, resulting in the \( L_{n-\text{cor}} \) state of the component C. The CAPSC coordinated by event signals will execute the supply restoration operations for the component C at instant \( t_{\text{res}}^\text{I} \), as shown by III-axis. However, by recognizing the component states, the CAPSC can begin the supply restoration operations as soon as the component C enters the \( L_{n-\text{cor}} \) state. The supply restoration operations can be initiated at instant \( t_{\text{res}}^\text{C} \) rather than at instant \( t_{\text{res}}^\text{I} \), as shown by II-axis. The time lag \( \Delta t \) between \( t_{\text{res}}^\text{I} \) and \( t_{\text{res}}^\text{C} \) indicates the reduction of the fault handling time.

In complex scenarios, such as a dead zone fault or breaker rejection, prolongation of the fault removal and isolation operations may result in \( \Delta t \) lasting up to tens of seconds. Moreover, in the case of multiple faults, the time lag \( \Delta t \) may further increase. Thus, CAPSC coordination based on the component states plays a significant role in reducing the fault handling time in the scenarios mentioned above.

**VI. SYSTEM IMPLEMENTATION AND CLOSED-LOOP TEST**

**A. SYSTEM IMPLEMENTATION**

According to the proposed scheme, a series of devices, including functionalized ITs, IPSCSs and delay-measurable Ethernet switches, have been developed. The proposed scheme has also been applied in a regional DN of China Southern Power Grid. A closed-loop test was conducted on the RTDS using the field connections and parameters. The simplified simulation models and installation methods are shown in Fig. 5.

**B. CLOSED-LOOP TEST SYSTEM ON THE RTDS**

The closed-loop test system is shown in Fig. 6. Different scenarios are run on the RTDS, and the electrical samplings and switch status are output as the simulation results. The electrical samplings are output by GTNET cards in the form of IEC 61850-9-2 SV messages, including 32 sets of three-phase current samplings. The switch status is output by GTDO cards, and the teleclosing and teletripping control commands are input by GTDI cards.

To take the influence of the communication delay into account, SV messages obtained by the RTDS are not directly input to the IPSCS. Instead, they are connected to a signal detection and fault simulation device, which converts the SV messages into different channels of analog signal outputs.
Power amplifiers regenerate the secondary current or voltage signals matching the analog signal outputs, and the secondary current or voltage signals are input to the ITs. The switch status and control commands are directly transmitted between the RTDS and ITs.

The ITs regenerate IEC 61850-9-1-standardized SV and GOOSE messages to communicate with the IPSCS through the delay-measurable communication networks, and the control commands of the IPSCS are issued through the form of GOOSE messages to the ITs.

C. TEST OF DIFFERENT OPERATING MODES
1) CONVENTIONAL OPERATING MODE
As shown in Fig. 5, the regional DN operates in the three-supply-one-backup operating mode. A three-phase short-circuit fault is imposed on Line #D. The operation decisions are shown in Fig. 7. When the fault occurs, the faulty component Line #D enters the F_{ide} state and instructs the circuit breakers CB5 and CB6 to perform fault removal operations. After the fault is removed, Line #D jumps into the F_{rem} state, and the sectionalizing switches S32 and S41 are tripped to isolate Line #D. As soon as S32 is open, the component Bus #3 attains the L_{n-cor} state, and the breaker CB5 is instructed to reclose to offer supply, whereas sectionalizing the switch S12 remains unclosed until S41 is detected to be opened.

The operation decisions and execution time when faults occur on Bus #3, Load #L3 and DG1 are listed in Table 1. The results show that the proposed scheme can adopt proper operation decisions in conventional operating mode. The fault
TABLE 1. Operation decisions and execution time of different faults in the conventional operating mode.

| Faulty component | Operation decision | Execution time |
|------------------|-------------------|----------------|
| Line #D          | Trip#CB5. CB6      | 68ms           |
|                  | Trip#S32. S41      | 142ms          |
|                  | Close#CB5          | 246ms          |
|                  | Close#S12          | 252ms          |
| Bus #3           | Trip#CB5. CB6      | 67ms           |
|                  | Trip#S30. S32      | 143ms          |
|                  | Close#S12          | 241ms          |
| Load #L3         | Trip#CB5. CB6      | 67ms           |
|                  | Trip#S30           | 140ms          |
|                  | Close#CB5          | 248ms          |
| DG1              | Trip#CB6           | 66ms           |

A permanent three-phase short-circuit fault is imposed on Line #D, and the operation decisions are shown in Fig. 8. The results indicate that the fault will be removed within 137 ms and finally be isolated in the extended range.

TABLE 2. Operation decisions and execution time of different faults in the unconventional operating mode.

| Faulty component | Operation decision | Execution time |
|------------------|-------------------|----------------|
| Line #D          | Trip#CB1. CB6      | 65ms           |
|                  | Trip#S32. S41      | 137ms          |
|                  | Close#CB1          | 242ms          |
|                  | Close#CB5          | 251ms          |
| Bus #3           | Trip#CB1. CB6      | 67ms           |
|                  | Trip#S30. S32      | 142ms          |
| Load #L3         | Trip#CB1. CB6      | 65ms           |
|                  | Trip#S30           | 138ms          |
|                  | Close#CB1          | 246ms          |
| DG1              | Trip#CB6           | 64ms           |

TABLE 3. Operation decisions and execution time of different faults in the closed-loop operating mode.

| Faulty component | Operation decision | Execution time |
|------------------|-------------------|----------------|
| Line #D          | Trip#CB1. CB5. CB6| 68ms           |
|                  | Trip#S32. S41     | 140ms          |
|                  | Close#CB5         | 251ms          |
|                  | Close#CB1         | 255ms          |
| Bus #3           | Trip#CB1. CB5. CB6| 65ms           |
|                  | Trip#S30. S32     | 142ms          |
|                  | Close#CB1         | 248ms          |
| Load #L3         | Trip#CB1. CB5. CB6| 70ms           |
|                  | Trip#S30          | 148ms          |
|                  | Close#CB1         | 256ms          |
| DG1              | Trip#CB6          | 69ms           |

2) UNCONVENTIONAL OPERATING MODE
The topology in Fig. 5 is adjusted to the unconventional operating mode by closing the sectionalizing switch S12 and opening the circuit breaker CB5. A three-phase short-circuit fault is also applied to the above four components, and the corresponding operation decisions and execution time are listed in Table 2. It can be deduced from the results that the operation decisions can be automatically adjusted according to the real-time topology changes.

3) CLOSED-LOOP OPERATING MODE
To evaluate the performance of the proposed scheme in the closed-loop operating mode, the above topology is adjusted by closing sectionalizing switch S12. Thus, the feeders of Sub1 and Sub2 realize the closed-loop operating mode. The same four types of faults in Table 1 are also applied, and the corresponding operation decisions and execution time are summarized in Table 3. The result shows that the scheme proposed in this paper can adapt to the closed-loop operating mode as well.

D. TEST WITH DIFFERENT CONFIGURATION CONDITIONS
1) SAMPLING FAILURES
During the operation of DNs, sampling failures may occur due to a transformer failure, a merging unit being out of service, or a communication error. Under the condition of a sampling failure, the protection zones need to be redivided, and the operation decisions should be adjusted accordingly.

To evaluate the performance of the proposed scheme under sampling failures, the merging unit at Bus #3 is set to be deactivated at the beginning. Thus, fault identification of Line #C, Line #D, Bus #3 and Load #L3 according to the original protection zones will fail due to the absence of sampling access. However, a new protection zone, containing Line #C, Line #D, Bus #3 and Load #L3, will be automatically divided for extended differential current protection.

2) SWITCH OUT OF SERVICE
With the proposed scheme, fault removal and fault isolation operation decisions will not occur on the switch that is already out of service. In this simulation scenario, the breaker CB5 is assumed to be out of service. A permanent three-phase short-circuit fault is imposed on Line #D, and the operation decisions are shown in Fig. 9. The results indicate that the fault will be removed within 137 ms and finally be isolated in the extended range.

This means that in the case of sampling failures, the proposed scheme can achieve fast backup extended protection without time-stepped settings. The whole operation time still remains within 300 ms.

E. TEST FOR COMPLEX FAULT EVENTS
1) DEAD ZONE FAULT
When a fault occurs between a switch and its current sampling devices, the main networks may still have an electrical...
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FIGURE 8. Operation decisions when a fault occurs on Line #D with sampling failures.

FIGURE 9. Operation decisions when a fault occurs on Line #D with a switch out of service.

FIGURE 10. Operation decisions in the case of a dead zone fault.

FIGURE 11. Operation decisions in the case of multiple faults.

connection with the fault after fault removal or fault isolation. Thus, additional operations are required.

Assuming that the fault occurs between the sectionalizing switch S41 and its corresponding current sampling devices, the following operations will be executed, as shown in Fig. 10.

i) Differential current protection configured on Bus #4 is put into effect, and Bus #4 is recognized as the faulty component at first. Corresponding fault removal and fault isolation operations are executed, which cause Bus #4 to enter the F\textsubscript{iso} state, and Line #D and Line #E to enter the L\textsubscript{n−cor} state;

ii) Supply restoration operations are performed. Since Line #E is completely isolated from the fault, Line #E is repowered immediately by closing S12;

iii) However, since Line #D is not isolated from the fault, reclosing the breaker #CB5 will reinject the fault current to the fault;

iv) An additional fault identification process is conducted to address fault reappearance. Overcurrent protection of Line #D will be automatically triggered according to the topology changes. Thus, Line #D will be recognized as the faulty component, whose fault removal and fault isolation processes will thus be carried out.

The results indicate that changes in topology can be quickly reflected in the adjustment of protection configuration of the proposed CAPSC scheme. Additional fault identification process can be conducted without any delay in the case of the dead zone fault. It can also be deduced that, the supply restoration operations of different components are
executed separately, which means that the execution time of certain components can be reduced in the self-healing control process via the proposed CAPSC scheme.

2) MULTIPLE FAULTS
Assuming that the permanent fault on Line #D occurs at 1.0 s and is not effectively isolated, another permanent fault occurs on Line #A at 1.1 s subsequently. In this case, Line #E, currently without power supply, cannot be repowered through Sub1. The supply restoration operation decisions need to be regenerated as follows, the details of which are shown in Fig. 11.

i) The first fault is located on Line #D at first. Fault removal operations on breakers CB5 and CB6 is followed by activating the sectionalizing switches S32 and S41 to isolate Line #D;

ii) In the meantime, the second fault on Line #A is detected. The faulty component Line #A will be removed and isolated by tripping the circuit breaker CB1 as well as the sectionalizing switch S11;

iii) Bus #3 will quickly restore power supply, which will not be affected by the fault on Line #A;

iv) Since Bus #1 has lost power supply, Line #E is not able to restore the power supply from Sub1;

v) Power supply of Bus #1 is restored by reclosing S81;

vi) After Bus #1 is repowered, a closing command will be sent to S12 to execute supply restoration operations for Line #E.

It can be concluded from the results that the proposed CAPSC scheme can achieve the coordination of protection and self-healing control even in the case of multiple faults, and reduce the execution time of certain components as much as possible.

VII. CONCLUSION
In this paper, a novel CAPSC scheme based on IEC 61850 for DNs is proposed. The synchronization based on propagation delay compensation method is adopted, which is independent of the external clocks and creates the utilization conditions for SV messages. Furthermore, adaptive protection and self-healing control algorithms are introduced for operation decision making. Finally, to achieve better interaction between protection and self-healing control, the protection and self-healing control is coordinated based on component state description. With the scheme mentioned above, a closed-loop test has been conducted on an RTDS according to the implementation conditions of a field engineering application of China Southern Power Grid. The proposed scheme presents the following advantages to DNs:

1) The proposed scheme can be automatically applied to different operating modes, including the closed-loop operating mode. Notably, it does not require voltage sampling device installation or time-stepped settings, which enables that the proposed scheme can be better popularized in DNs;

2) The proposed scheme can be adapted to different configuration conditions. This also indicates that the proposed scheme is able to address sampling or switching device failures;

3) The proposed scheme can be adapted to certain complex scenarios and realize the automatic interaction between protection and self-healing control processes. The connections in the protection and self-healing control are strengthened, and the fault handling time is effectively reduced.

REFERENCES
[1] M. E. Baran and I. El-Markaby, “Fault analysis on distribution feeders with distributed generators,” IEEE Trans. Power Syst., vol. 20, no. 4, pp. 1757–1764, Nov. 2005.
[2] J. Morren and S. W. H. de Haan, “Impact of distributed generation units with power electronic converters on distribution network protection,” in Proc. IET 9th Int. Conf. Develop. Power Syst. Protection (DPSP), 2008, pp. 664–669.
[3] N. A. Bari and S. D. Jawale, “Smart and adaptive protection scheme for distribution network with distributed generation: A scoping review,” in Proc. Int. Conf. Energy Efficient Technol. Sustainability (ICEETS), Nagercoil, Tamil Nadu, Apr. 2016, pp. 569–572.
[4] F. Zhang, L. Mu, and W. Guo, “An integrated wide-area protection scheme for active distribution networks based on fault components principle,” IEEE Trans. Smart Grid, vol. 10, no. 1, pp. 392–402, Jan. 2019.
[5] H. F. Habib, N. Fawzy, M. M. Esfahani, O. A. Mohammed, and S. Brahma, “An enhancement of protection strategy for distribution network using the communication protocols,” IEEE Trans. Ind. Appl., vol. 56, no. 2, pp. 1240–1249, Mar. 2020.
[6] M. Pipattanasomporn and H. Ferezie, “Multi-agent systems in a distributed smart grid: Design and implementation,” in Proc. Power Syst. Conf. Expo., Seattle, WA, USA, Mar. 2009, pp. 1–8.
[7] L. A. Oquendo Class, K. M. Hopkinson, X. Wang, T. R. Andel, and R. W. Thomas, “A robust communication-based special protection system,” IEEE Trans. Power Del., vol. 25, no. 3, pp. 1314–1324, Jul. 2010.
[8] Y. Xu and P. Han, “Review on methods of wide area backup protection in electrical power system,” in Proc. Int. Conf. Mechatronics, Apr. 2015, pp. 502–506.
[9] G. Kunz, J. Machado, E. Perondi, and V. Vyatkin, “A formal methodology for accomplishing IEC 61850 real-time communication requirements,” IEEE Trans. Ind. Electron., vol. 64, no. 8, pp. 6582–6590, Aug. 2017.
[10] Y. Liu, H. Gao, W. Gao, and F. Feng, “Development of a substation-area backup protective relay for smart substation,” IEEE Trans. Smart Grid, vol. 8, no. 6, pp. 2544–2553, Nov. 2017.
[11] Q. Song, “Smart substation integration technology and its application in distribution power grid,” CSEE J. Power Energy Syst., vol. 2, no. 4, pp. 31–36, Dec. 2016.
[12] D. Della Giustina, F. Dedé, G. Invernizzi, D. P. Valle, F. Franzoni, A. Pegotiani, and L. Cremonaci, “Smart grid automation based on IEC 61850: An experimental characterization,” IEEE Trans. Instrum. Meas., vol. 64, no. 8, pp. 2055–2063, Aug. 2015.
[13] M. A. Afshar, S. Roostaei, S. M. Suhail Hussain, I. Ali, M. S. Thomas, and S. Mefhuz, “Performance evaluation of IEC 61850 GOOSE-based inter-substation communication for accelerated distance protection scheme,” IET Gener., Transmiss. Distrib., vol. 12, no. 18, pp. 4089–4098, Oct. 2018.
[14] E. Sorrentino and M. Navas, “Two improvements related to overcurrent functions for bus protection in distribution systems,” IEEE Trans. Power Del., vol. 30, no. 3, pp. 1634–1635, Jun. 2015.
[15] F. Cuffele, C. Booth, and A. Dyko, “An adaptive overcurrent protection scheme for distribution networks,” IEEE Trans. Power Del., vol. 30, no. 2, pp. 561–568, Apr. 2015.
[16] J. Ma, X. Xiang, R. Zhang, P. Li, J. Liu, and J. S. Thorp, “Regional protection scheme for distribution network based on logical information,” IET Gener., Transmiss. Distrib., vol. 11, no. 17, pp. 4314–4323, Nov. 2017.
[17] H. Gao, J. Li, and B. Xu, “Principle and implementation of current differential protection in distribution networks with high penetration of DGs,” IEEE Trans. Power Del., vol. 32, no. 1, pp. 565–574, Feb. 2017.
[18] L. Qin, C. Qin, and F. Jiao, “Research and design of industrial Ethernet switch based on IEEE1588 standard,” in Proc. Int. Conf. Adv. Power Syst. Autom., Beijing, China, Oct. 2011, pp. 1583–1586.
[19] H. Y. Li, E. P. Southern, P. A. Crossley, S. Potts, S. D. A. Pickering, B. R. J. Caunce, and G. C. Weller, “A new type of differential feeder protection relay using the global positioning system for data synchronization,” IEEE Trans. Power Del., vol. 12, no. 3, pp. 1090–1099, Jul. 1997.

[20] W. Li, Y. Tan, Y. Li, Y. Cao, C. Chen, and M. Zhang, “A new differential backup protection strategy for smart distribution networks: A fast and reliable approach,” IEEE Access, vol. 7, pp. 38135–38145, 2019.

[21] T. Yip, B. Xu, Z. Zhu, Y. Chen, and C. Brunner, “Application of IEC 61850 for distribution network automation with distributed control,” J. Eng., vol. 2018, no. 15, pp. 993–996, Oct. 2018.

[22] W. Li, Y. Tan, Y. Li, Y. Cao, C. Chen, and M. Zhang, “A new differential backup protection strategy for smart distribution networks: A fast and reliable approach,” IEEE Access, vol. 7, pp. 38135–38145, 2019.

[23] T. Yip, J. Wang, B. Xu, K. Fan, and T. Li, “Fast self-healing control of faults in MV networks using distributed intelligence,” Open Access Proc. J., vol. 2017, no. 1, pp. 1131–1133, Oct. 2017.

[24] Y. Zhang, Z. Cai, X. Li, and R. He, “Propagation delay measurement and compensation for sampled value synchronization in a smart substation,” CSEE J. Power Energy Syst., vol. 3, no. 2, pp. 196–202, Jul. 2017.

[25] Y. Cai, Z. Cai, C. Guo, Y. Huang, and G. Dai, “Research on adaptive protection and control algorithm for distribution network based on network description model,” in Proc. Int. Conf. Power Syst. Technol. (POWERCON), Guangzhou, China, Nov. 2018, pp. 142–147.

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