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Protection and Control of Modern Power Systems

ORIGINAL RESEARCH

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A new coordinated backup protection scheme for distribution network containing distributed generation

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Abstract

This paper proposes a new backup protection scheme, named coordinated backup protection (CBP) scheme, for distribution networks containing distributed generation. The proposed protection scheme takes into account the issues faced by traditional backup protection, such as difficulty in setting parameters and complex cooperation, and considers the features of distribution networks, such as changeable power flow because of high penetration of distributed generation sources and insufficient measuring quantities. The CBP scheme includes two aspects: coordinated substation protection and regional master substation protection, who also work as nearby backup protection and remote backup protection respectively. The two protections support each other by local information coordination and regional information sharing, in order to improve the reliability of fault identification. The configuration principles and performances of the proposed backup protection scheme are addressed in the paper. Different fault conditions in the IEEE 14-node system have been used to illustrate and verify the feasibility of the CBP scheme.

Keywords: Distribution network, Backup protection, IEC61850, Tabu search

1 Introduction

Modern power systems are facing great challenges due to the deregulation of the electricity market, environmental concerns and energy policy change. With a number of major blackouts occurred around the world, customers' expectation of system reliability and power quality has also gradually increased. The growth of renewables as energy source has promoted the development of distributed generation [1, 2]. However, traditional electrical infrastructure cannot satisfy these development requirements, and thus a new grid infrastructure is urgently needed. To address the challenges facing the existing power grid, the new concept of smart grid has emerged [3, 4].

With the wide spread application of intelligent electronic devices (IEDs), information digitization and the IEC61850 protocol, the development of protection using comprehensive information is greatly impelled. Extensive studies have been carried out by researchers on how to improve the protection performance and functionalities by better utilization of digital and communication technologies. From the division of protection information domain, wide area protection is based on wide area measurement system (WAMS) to implement large-scale system protection and control [4–9]. This kind of system is developed from early special protection systems (SPS) [10] and broadens traditional relay protection function from point to surface. Narrow-sense wide area protection is a system level protection aimed at reflecting various system disturbances through analyzing power system wide area information and evaluating system states. This kind of protection has better sensitivity and effectiveness compared with traditional SPS [11]. Generalized wide area protection including wide area relay protection (WARP) helps to assist main protection to improve adaptability, simplify cooperation strategy and shorten action time [12]. At present, because of the communication delays, wide area protection is mainly applied to the backup protection and integral control of large-scale gird. On the other hand, protection systems whose information domain is within a substation or within a local area network have been proposed. These protection schemes analyze the integrated information and make use of adaptive setting principle to realize

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comprehensive relay protection. Integrated protection (IP) (as in [13] and [14]) integrates all the information from a digital substation into one computer system to form a reliable, flexible and complementary integrated protection system. Integrated network protection (INP) is based on IP but its information range is extended to several correlative substations. There are some other protections that use similar concept, referred to as aggregate protection (AP) which uses other relays' information to improve its own protection performance, centralized protection [15], and protection based on multi-sources [16]. All these studies have driven the protection and control system to utilize comprehensive information to achieve better performance and to satisfy modern grids' functional requirements. Compared with traditional protection, there have been marked improvements.

Studies above indicate that protection based on comprehensive information can adapt to power network development. Current researches mainly focus on analyzing integrated comprehensive data whereas protection considering coordination of different units and functions needs further study. Moreover, comprehensive data depends on global information acquisition. However, the network states are sometimes immeasurable and only partial information is available from the distribution network in practice, especially the node voltage information. Thus the protection unit can only get information of several important nodes and it is a challenge to propose protection strategy based on insufficient measuring quantities.

This paper proposes a solution to the above issues. Retaining the information acquisition mode and communication network of smart grid, this paper presents a coordinated backup protection (CBP) scheme and corresponding protection configuration principles. It includes coordinated substation protection and regional master substation protection. Coordinated substation protection pays more attentions to the coordination and cooperation among different IEDs and substations, and works as the nearby backup protection. Compared to the existing protection schemes, distributed IED has advantages in terms of functional support, information utilization, and achieving higher protection reliability. Master substation protection mainly analyzes regional comprehensive information and works as the remote backup protection. Considering the likelihood of insufficient state measurements, an integrated MS protection based on centralized searching method is proposed in master substation protection.

In this paper, an introduction on the framework of CBP scheme is presented in Framework of coordination backup protection scheme section. Protection principles section depicts the configuration of CBP and its principles are discussed in details. Case studies are carried out in Test and results section to prove the reliability and effectiveness. Finally, Conclusion section draws conclusions.

2 Framework of coordination backup protection scheme

The CBP scheme includes coordinated substation (CS) protection and regional master substation (MS) protection who also work as nearby backup protection and remote backup protection, respectively. The two protections support each other by local information coordination and regional information sharing, in order to improve the reliability of fault identification. Compared with traditional backup protection scheme, the CBP scheme has stronger independence and higher reliability, and at the same time, the cooperation between CS protection and MS protection helps to decrease the risk of protection malfunction.

2.1 Coordinated substation (CS) protection

The CS is an application concept that uses the unified communication protocol and strong information network of smart grid, and at process level, accomplishes synchronous sample value acquisition, action command execution and breaker states uploading. Based on the needed local information, bay level includes a number of protection IEDs to implement protection. At the same time, modularization structure of IED helps in harmonious interaction and coordination of functions to support reliable fault identification which is independent to backup protection. The coordination of IEDs includes information sharing, redundant CPU space utilization and coordinated backup tripping. Station level is the top one which integrates useful data and events for substation management and communication with dispatching center or MS.

Part of Fig. 1 shows the structure of CS which pays more attentions on the coordination and cooperation among different protection IEDs. In this paper, the IED is an extended concept which combines local protection function with coordination concept. Every IED is an integration of functional modules and has three main parts: function module (FM), local coordination module (LCM) and remote coordination module (RCM). FM mainly is the protection algorithm part, which processes the samples received from the process bus and sends action commands to the breaker. At the same time, FM can communicate with other IEDs to share information or provide coordinated trip signal in order to improve protection reliability and security. LCM monitors the requirements of local IED, establishes appropriate tasks and sends task commands. RCM receives remote command from other IEDs and analyzes their requirements, or receives remote information and uses it in local processing. The protection of CS uses ownerless structure [17] and can work reliably even if one IED fails. In this

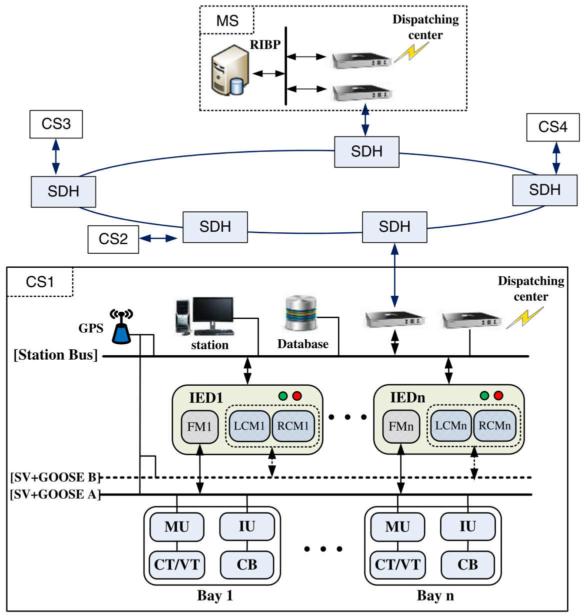

Fig. 1 Structure of coordinated backup protection scheme

paper, installation of the IEDs is in the standard bay as in traditional protection devices and the IEDs are based on block-based design principle which makes it easy to recombine or extend functions through standard module interface.

CS protection is a distributed substation-domain protection, and its protection range is the elements within the substation and outgoing-lines. Some coordinated IEDs implement local rapid protection judgment and other IEDs exchange information with adjacent substations for protection judgment of the outgoing-lines. If primary equipment (CT/VT/CB) is in abnormal working states, IEDs work in coordination mode and their data sharing and coordinated tripping help to improve the reliability of local substation protection.

2.2 Master substation (MS) protection

MS protection is a regional integrated backup protection (RIBP) and its protection range is the network composed of several CSs. The RIBP acquires every CS's available data through wide area communication network to analyze regional comprehensive information. Likewise, if primary equipment (CT/VT/CB) is in abnormal working states, RIBP can acquire valid data through coordinated information analysis in corresponding CS. For power systems up to 110 kV, the protection scheme usually consists of single main protection and has no breaker failure protection [18]. The RIBP can help to realize dual-configuration protection and improve reliability. In addition, backup protection based on wide area information optimizes general backup protection in action time while still ensuring reliability.

RIBP of MS parses the data packages and integrates all the regional information. By analyzing the integrated data, the protection algorithm unit calculates and outputs fault judgment results. Output tripping signals are sent back to communication network to reach the corresponding objective CS. Station level of CS obtains the tripping signals and relative IED in process level sends the tripping command to intelligent units (IU) and circuit breakers (CB) to isolate fault.

2.3 Communication network

In order to implement the CBP scheme, communication network is one of the key technologies. The CBP communication system includes three parts: process level communication network within CS, network communicated with adjacent substations, MS integrated data communication network.

Process level communication network within CS is shown in Fig. 1. Based on the IEC61850-9-2LE standard, the communication between bay level and process level is via high performance local area network (LAN) [7] which is the process bus (SV + GOOSE). Considering large quantities of information and network load capacity, dual process network is set in CS (shown in Fig. 1). The function module which is the protection calculation part communicates with primary equipment through LAN “SV + GOOSE A”. The coordination part, including LCM and RCM, communicates with the same part from other IEDs through LAN “SV + GOOSE B”. In order to synchronize different data sources, LAN communication needs have accurate GPS synchronous time-marker.

One CS can exchange information of outgoing-lines with adjacent substations to implement cooperation work among different substations. Network communicated with adjacent substations uses synchronous digital hierarchy (SDH) [19] technology and works in self-healing ring transmission mode. The CSs and MS connect with each other in a ring and flexible data acquisition is available. As shown in Fig. 2, CS_2 and CS_3 upload data to SDH network by SDH device, and CS_1 can download the necessary data from SDH network for CS substation-domain protection judgment.

Because the quantity of multi-CS transmission data is large and communication has high real-time requirement, MS integrated data communication network also uses SDH technology as special communication network of wide area protection (shown in Fig. 3). As communication network terminals, CS accomplishes local protection judgment and at the same time, its IEDs preprocess the sample values and package necessary data. For those data that needs to be synchronized, unified GPS synchronous time-marker should be tagged to packaged

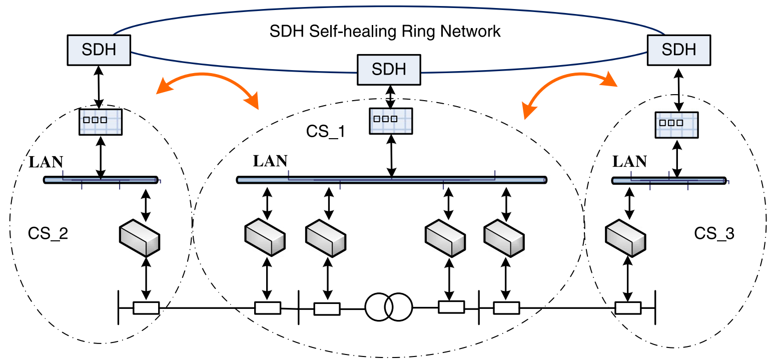

Fig. 2 Communication mode of adjacent substations

message. All the shared data is uploaded to SDH network through SDH method, and MS could download the needed data from the network. Computer simulation shows that SDH fiber communication network can satisfy transmission delay requirements of WARP [19].

The latency is another concern, which includes the sensor delay (5 ms), communication delay, processor computational time (dependent on the protection principle), and circuit breaker operation time (90 ms). The communication delay of the process level is about 5 μs which is negligible, whereas the possible longest communication delay of wide-area optic fiber network is 24 ms. For regional distribution networks, the communication delay will not be longer than 24 ms. Therefore, the protection principle should ensure the calculation to be carried out efficiently in order to isolate fault as soon as possible.

3 Methods

CS protection implements local rapid fault judgment and coordination working mode and can help to improve protection reliability. MS integrated backup protection, which is known as RIBP in previous discussion, analyzes regional comprehensive information to recognize fault effectively in case CS protection fails to clear the fault.

The following discusses the detailed CS protection and MS protection configuration principles.

3.1 CS protection based on differential principle

The principle of current differential protection is not affected by changeable power flow. Therefore, this type of protection can identify faults correctly and rapidly without the need for VTs at every node to provide directionality. In CS protection, differential principle is applied and multiple IEDs can cooperate by information sharing and function coordination to implement extended differential protection. The basic principle is to use the nearest non-fault data when local data has failure and to broaden trip boundary when protection or breaker does not operate correctly.

Based on the CS concept in Framework of coordination backup protection scheme section, the IEEE 14-node system is divided into two substations (CS_1 and CS_2) in Fig. 4, and the two CSs dispose substation domain protection separately based on differential principle. As an example, fault 1 (F1) in the IEEE 14-node system as shown in Fig. 4 is considered and the coordination working mode is analyzed. In this paper, positive current direction is defined as from bus to the line. $\dot{I}_{471}$, $\dot{I}_{781}$ and $\dot{I}_{791}$ are the first-terminal currents of line4-7, line7-8 and line 7–9, respectively. $\dot{I}_{472}$, $\dot{I}_{782}$ and $\dot{I}_{792}$ are the second-terminal currents of the same three lines, respectively. The basic differential current dif_1 of line 7–8 is $\left|\dot{I}_{781}+\dot{I}_{782}\right|$. If the local data $\dot{I}_{781}$ has failure, it can be

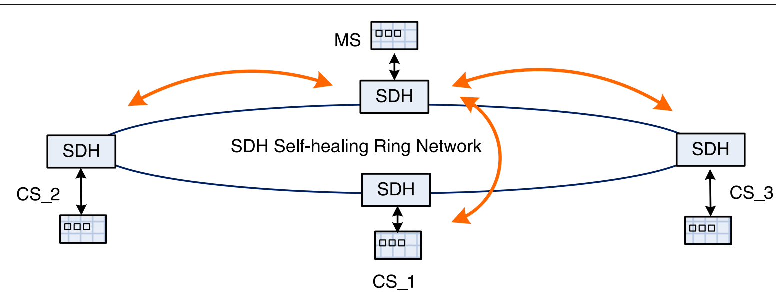

Fig. 3 Communication mode of MS

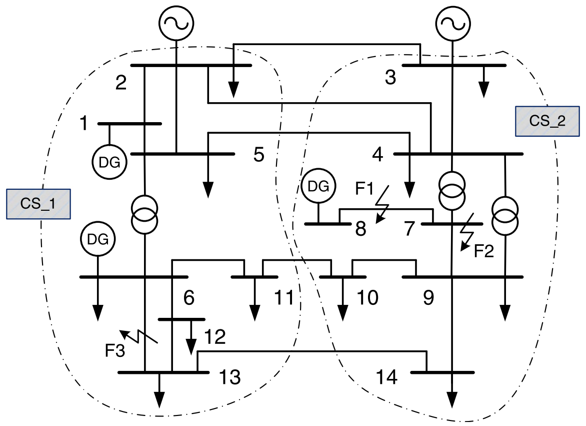

Fig. 4 IEEE 14-node system diagram

replaced by $\dot{I}_{472}$ and $\dot{I}_{791}$ through information coordination with other IEDs. The information sharing is achieved through the process bus LAN "SV + GOOSE B", and the differential current dif_2 should change to $\left|\dot{I}_{782}-\left(\dot{I}_{472}+\dot{I}_{791}\right)\right|$. Furthermore, the differential current dif_3 can also be expressed by replacing $\dot{I}_{472}$ with $\dot{I}_{471}$.as $\left|\dot{I}_{782}-\dot{I}_{791}+\dot{I}_{471}\right|$.

3.2 MS protection based on centralized searching method

For a large-scale network, only some key nodes have PMU measurements due to the cost. In general, those key buses and buses having several feeders should be regarded as the key nodes. As DG node voltages are necessary for their converter control and condition monitoring, the DG nodes should also be the key nodes.

When there is a fault in the network, node voltages have no directionality according to fault sequence analysis. This is because that voltage drops occur at the nodes at or around the fault and low voltage protections will all act. The fault point has the lowest voltage and voltage increases with the increase of the electrical distance. Thus voltage information can reflect fault location to some extends, though when voltage data is only available at the key nodes, it is difficult to diagnose the fault. Obviously, when there is a fault, most power from the power sources will go to the fault point through a minimum impedance path, referred to as the fault power path in this paper. The fault power flow of this path is the biggest and direction is to the fault point. Based on the selection of the fault power path and search tree model, together with current information comparison, fault location can be identified effectively. Thus this paper proposes a MS protection based on centralized searching method, and based on that backup protection can be realized.

The key nodes sequence from initial results are searched and the node with the maximum objective function value (Z^* shown in formula 1) is found to be the fault power path. The termination condition is $c \geq (k+p+1)$ where k and p are the number of general key nodes and DG nodes respectively.

$$\begin{cases} Z^* = Z(x^*) = \sum_j re\left[\dot{U}_i * \dot{I}_{i,j}\right] - \sum_j re\left[\dot{U}_{i.load} * \dot{I}_{i.j.load}\right] \\ c = c+1 \\ s.t.\ re\left[\dot{U}_i * \dot{I}_{i,j}\right] < 0 \& re\left[\dot{U}_{i.load} * \dot{I}_{i.j.load}\right] < 0 \\ c_0 = 0 \end{cases} \tag{1}$$

Where,
x^*: feasible solution
$\dot{U}_i$: voltage vector of node i
$\dot{I}_{i,j}$: current vector of the line between node i and j
$\dot{U}_{i.load}$: voltage vector of node i (normal operation)
$\dot{I}_{i.j.load}$: current vector of the line between node i and j (normal operation)
$re[\ ]$: calculation of real component
c: iteration counter

The second-step search appoints fault power path as the search target and works to find the fault using current information.

① When it is a node fault, voltage at the fault point is approximately zero and the vector sum of the node currents is not zero based on Kirchhoff's current law. The features discussed above can be used to judge node fault. ②When it is a branch fault, the fault current flows through non-fault branches which is the same as load current. For the fault branch, the contralateral line current is zero if it is a single-terminal power network. On the contrary, if it is a double-terminal power network, the contralateral line current is positive but the direction information is hard to calculate due to the lack of voltage data. Thus, a fault criterion based on current data for double-terminal power network is necessary.

Neglect the line charging capacitance and system impedance, line impedance and generator transient reactance are inductive. In this paper, phase angle change is defined as the absolute value between the positive sequence component of the fault current and the non-fault current. For the non-fault branch, the phase angle changes of the two terminals are small whereas for the fault branch, the phase angle change of one terminal is small but the other is large. Thus the fault criterions based on current information are given as

$$\left\|\arg\left(\frac{\dot{I}_{K_{(1)}}.i}{\dot{I}_{normal.i}}\right)\right| - \left|\arg\left(\frac{\dot{I}_{K_{(1)}}.j}{\dot{I}_{normal.j}}\right)\right\| > A_{rel} \tag{2}$$

where, A_{rel} is around $5^{\circ} \sim 10^{\circ}$. The branch, whose

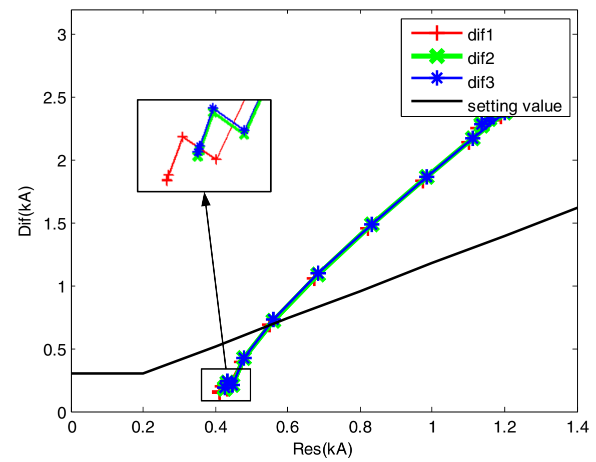

Fig. 5 Differential currents with F1

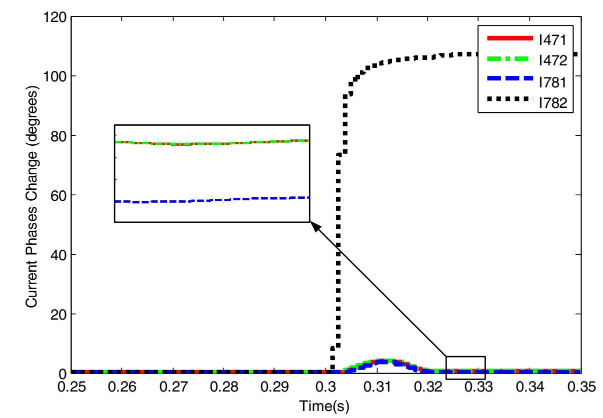

Fig. 6 Current phase changes of fault power path (F1 and ABC)

two-terminal current data satisfies either criterion, can be judged as the fault line. In this paper, the criterion is named as two-terminal current phase comparison (TCPC) criterion for line protection. The criterion needs no voltage data and fault judgment is independent from directional element.

If the line is connected with single-terminal power system, the second-terminal current of the feeder line is compared with unbalanced current to judge whether it is a line fault. If the line is connected with two-side power system, line fault is judged by the TCPC criterion. The second-terminal node is judged by bus differential criterion to decide whether it is the fault node.

3.3 Time coordination analysis

CS protection judges fault independently and coordination of information and functions helps to trip reliably. The two-step search of MS protection needs small calculation time, and thus the tripping output works with minimum delay. When the CS protection has judgment failure, backup protection will operate. However, if CS protection needs coordination among many IEDs, time required for communication and coordinated judgment will be long and tripping output time may be longer than that of the backup protection. In that case, the backup protection should output tripping signals immediately in order to clear the fault.

Table 1 Voltage amplitude and objection function values of key nodes (Fault 1)

	Node	1 (DG)	4	5	6 (DG)	8 (DG)
ABC	Voltage Amplitude (kV)	98.92	5.62	68.98	64.69	127.02
	Z^* (MW)	3.25	11.86	1.14	−9.85	0

4 Results

A test case using the IEEE 14-node network (shown in Fig. 3) is simulated to evaluate the performance of the CBP scheme. The IEEE 14-node network is a complex radial network with 3 DGs. There are current transformers (CT) at both terminals of the lines and only the key nodes have voltage transformers (VT). As the network is complex, markings of the CT/VTs are omitted in Fig. 3. In this paper, it defines that VT is named by the node number, and CT is named by the two-terminal nodes and location terminal. For instance, U_4 is the voltage of node 4, I_{471} is the current of line 4–7 at the node 4 terminal, and I_{472} is the current of line 4–7 at the node 7 terminal. Set 1, 4, 5, 6, 8 nodes as the key nodes and the fault inception is at 0.3 s. Simulations are performed using MATLAB. Measurement data is based on the results of power flow analysis and Gaussian random number (expectation is zero and variance is 0.01) is superimposed as measurement error.

4.1 Fault 1

An ABC fault is applied at line 7–8 (fault 1). According to the coordinated differential protection discussed in Protection principles section the three differential currents (dif_1, dif_2, dif_3) are calculated.

Table 2 Evaluation data and result (portion) Current phase changes of fault power path (Fault 1)

Fault type	Positive sequence current phase change of A phase (degrees)			
	$\|\Delta\varphi_{471}\|$	$\|\Delta\varphi_{472}\|$	$\|\Delta\varphi_{781}\|$	$\|\Delta\varphi_{782}\|$
ABC	0.5637	0.5358	0.7231	107.1168
A to G	0.2223	0.2272	0.3313	105.9737
AB	0.1407	0.1495	0.2447	108.1144
AB to G	0.3501	0.3985	0.2281	106.8386
BC	0.1908	0.1366	0.2761	108.1041
BC to G	0.3799	0.3851	0.1861	106.8296

Table 3 Voltage amplitude and objection function values of key nodes (Fault 2)

	Node	1 (DG)	4	5	6 (DG)	8 (DG)
ABC	Voltage Amplitude (kV)	98.44	3.79	68.09	63.74	127.02
	Z^* (MW)	2.52	7.40	−1.63	−9.92	0

Figure 5 shows the calculation results, and it can be seen that the differential currents increase significantly after fault occurrence. It is obvious that, differential protection using information sharing can judge the fault effectively. From the partial enlarged waveforms shown in Fig. 5, differential current dif_2 and dif_3 have larger unbalance currents compared with dif_1. The reason is that information coordination brings greater measurement error and distributed capacitance current [20]. In real application, the unbalance current can be significant considering IED communication error and data conversion error. Thus, in order to maintain reliability, protection setting should consider the effect of information sharing and coordination.

The MS protection based on centralized searching method is applied in the same simulation case. The voltage amplitudes and first-search objection function values are shown in Table 1. The key nodes by voltage amplitudes are sorted and node 4 has the lowest value. The key nodes are searched from node 4 and the maximum objection function value is found to be at node 4. Thus the fault power path is from node 4 which is then set as the beginning node for the second-step search. The phase angle changes of the fault power path are calculated and the two terminal phase angle changes of one line are compared to judge the fault.

Figure 6 shows the current phase changes of the fault power path. After the fault occurrence at 0.3 s, the phase changes of I_{471} and I_{472} are almost identical but the sum of the phase changes of I_{781} and I_{782} is about 108°. Judged by the criterion in Test and results section, the fault is on line 7–8 (fault 1).

In order to further analyze the accuracy of the criterion, several typical fault types are tested and the two terminal phase angle changes are compared. Table 2 shows the current phase changes. Obviously, the fault criterion can judge different faults accurately.

4.2 Fault 2

An ABC fault is applied at node 7 (fault 2). As the main protection based on differential principle is simple and reliable, this case only analyzes the MS protection based on centralized searching method.

The voltage amplitudes and first-search objection function values are shown in Table 3. The key nodes by voltage amplitudes are sorted and node 4 has the lowest value. The key nodes from node 4 are then searched and the maximum objection function value is found to be at node 4. Thus the fault power path is from node 4 and it is the beginning node of the second-step search.

The phase angle changes of the fault power path are calculated and the two terminal phase angle changes of one line are compared to judge the fault. Figure 7 shows the current phase changes of the fault power path. After fault occurrence at 0.3 s, phase changes of I_{471} and I_{472} are almost identical and so as for I_{781} and I_{782}. The line fault criterion is not satisfied and thus it can be concluded that there is no fault in lines 4–7 and 7–8. According to the second search, the currents sum of the second terminal of line 4–7 is calculated and the result is shown in Fig. 8.

The result in Fig. 8 shows that the node differential current increases when fault occurs at 0.3 s. Thus it can be identified that the second terminal of line 4–7 is the fault location and it is a node fault.

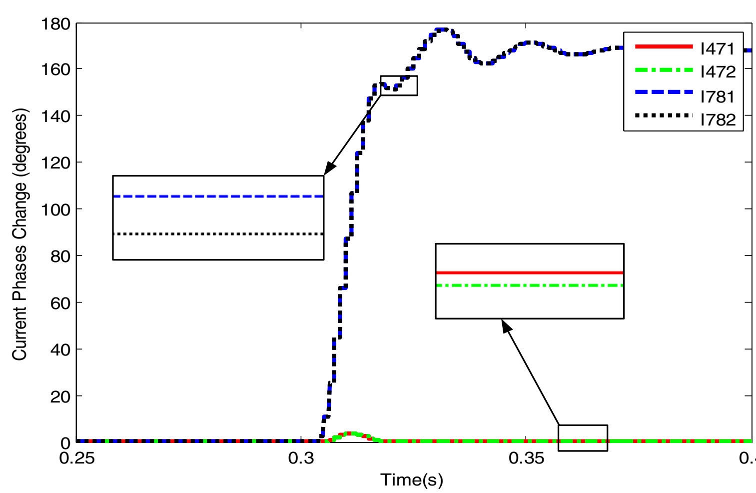

Fig. 7 Current phase changes of fault power path (F2 and ABC)

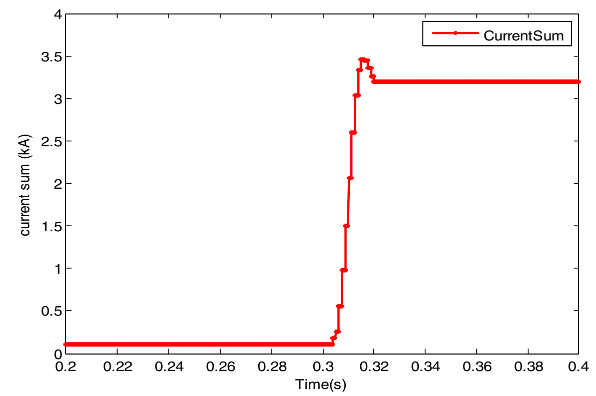

Fig. 8 Current sum (F2 and ABC)

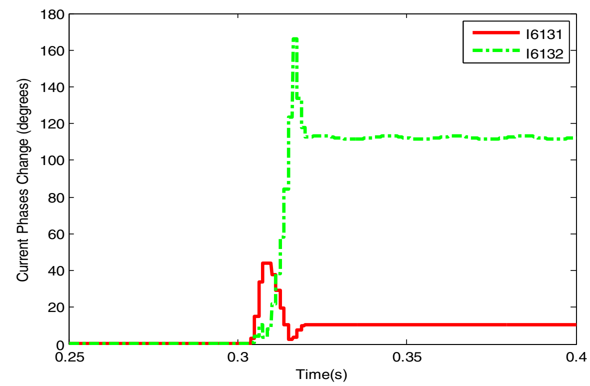

Fig. 9 Current phase changes of fault power path (F3 and ABC)

4.3 Fault 3

An ABC fault is applied at line 6–13 (fault 3). This case also analyzes the MS protection based on centralized searching method only.

The voltage amplitudes and first-search objection function values are shown in Table 4. The key nodes by voltage amplitudes are searched and node 6 has the lowest value. The key nodes from node 6 are searched and the maximum objection function value is found to be at node 6. Thus the fault power path is from node 6 and it is the beginning node of the second-step search. The phase angle changes of the fault power path are calculated and the two terminal phase angle changes of one line are compared to judge the fault.

Figure 9 shows the current phase changes of the fault power path. After fault occurrence at 0.3 s, the sum of the phase changes of I_{6131} and I_{6132} is about 122°. Judged by the criterion in Test and results section, the fault is identified to be on the line 6–13 which is fault 3.

5 Discussion

This paper presents the concept of coordinated backup protection in order to solve the issues brought by traditional backup protection and adapt to the changes of distribution networks. The framework is discussed including coordinated substation backup protection and regional master substation backup protection, working as nearby and remote backup protection respectively. The cooperation of the two backup protections contributes to CBP's higher reliability and better adaptability. The communication network of CBP is fully explored in the likely scenarios, including network within substation, and communication network among adjacent substations and master substation.

Table 4 Voltage amplitude and objection function values of key nodes (Fault 3)

	Node	1 (DG)	4	5	6 (DG)	8 (DG)
ABC	Voltage Amplitude (kV)	117.66	124.90	104.29	73.05	127.02
	Z^* (MW)	0.94	−1.19	2.41	5.03	0

6 Conclusions

The configuration principles of CBP consider the changeable power flow and insufficient measuring quantities in distribution networks. CS protection is based on current differential principle and its coordination ensures the reliability of nearby backup protection. MS protection is based on centralized searching protection principle which analyzes integrated regional comprehensive information.

From the simulation tests and results, the CBP scheme can be seen as an effective and promising solution for distribution network backup protection optimization. The strong independence and high reliability of CBP can help decrease the risk of protection malfunction.

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Authors' contributions

JH contributed to the study design and analysis and drafted the manuscript; LL was involved in data acquisition, analysis and revision of the manuscript; FD worked on aspects of the study relating to inter-substation information protection system; CL was involved in data acquisition and revision of the manuscript; DZ contributed to the revision of the manuscript. All authors have read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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