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An Adaptive Differential Protection and Fast Auto-Closing System for 10 kV Distribution Networks Based on 4G LTE Wireless Communication

Wen An ^{1,*}, Jun Jie Ma ¹, Hong Yang Zhou ², Hong Shan Chen ², Xu Jun ³ and Xu Jian ³

¹ School of Automation, Foshan University, Foshan 528225, China; junjie952019@163.com

² Dispatching and Control Center, China Southern Power Grid Co. Ltd., Guangzhou 510080, China; zhouhy@csg.cn (H.Y.Z.); chenhs@csg.cn (H.S.C.)

³ Department of Distribution Automation, Beijing Sifang Automation Co. Ltd., Beijing 100085, China; xujun_pw@sf-auto.com (X.J.); xujian@sf-auto.com (X.J.)

* Correspondence: wenan@fosu.edu.cn

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Abstract: With the development of wireless communication technology and computer technology, more and more smart technologies have been applied in electricity distribution networks. This paper presents an adaptive current differential protection and fast auto-closing system for application in 10 kV distribution networks in China Southern Power Grid. The current differential protection can adaptively change its settings according to the topology change of the primary distribution networks, thus the system effectively reduces the operation and maintenance cost of the power distribution network. In order to restore the power supply for the healthy part of the 10 kV networks quickly after a power system fault is cleared, the protection and control system provides wide area control function for automatic fault isolation and automatic switching. The traditional overcurrent protection and control system have no fault location function, it may take several minutes or even hours to manually locate a fault and then restore the power supply. Compared with the protection and control system of the traditional 10 kV distribution networks, the system developed can locate and isolate faults within 900 ms (assuming that the operating time of the load switch is 700 ms), and can quickly restore power supply in less than one second after a power system fault is cleared.

Keywords: adaptive current differential protection; auto-closing; distribution network; wireless communication

1. Introduction

Most protection installed in China 10 kV distribution networks is mainly based on the simple three stage overcurrent protection. As more and more distributed new energy sources are connected to the distribution networks, the conventional radial distribution network is becoming an active distribution network. It has the characteristics of multi-source, multi-branch, bidirectional power and fault current flow, as well as weak infeed. It is very difficult or impossible to apply the conventional overcurrent protection in the distribution networks with distributed generations, so adaptive overcurrent protection has been developed for distributed generation [1–4]. As this type of protection is still basically an overcurrent protection, it is very difficult to provide a sensitive, fully satisfactory protection for distribution networks with distributed generations under all operation conditions. Therefore, current differential protection has been considered for application in distribution networks with distributed generations [5–9]. Compared with the traditional overcurrent protection, the principle of line current differential protection is simple. As it is a unit protection, the protection zone is

defined, it does not require time grading. Its protection performance is also not affected by distributed generation connected in the distribution networks. It can be applied for fast main protection or fault location in the distribution networks. Current differential protection requires reliable communication. With the development of 4G LTE (Long-Term Evolution) wireless communication, it is possible to apply the current differential current protection using the 4G LTE wireless communication in the distribution networks.

In recent years, research has been carried out on the application of current differential protection for distribution networks with distributed generations. Reference [5] analyzed the protection problem of distributed energy resources (DER) access to distribution network and proposed a differential protection scheme for active distribution network. The scheme uses centralized line differential protection and decentralized bus differential protection. DTU (Distribution Terminal Unit) uses built-in Ethernet port technology and dedicated fiber-optic communication channels for data transmission and simultaneous sampling. Reference [6] proposed a unit-type protection scheme that utilizes the principle of differential current protection in urban distribution networks. Multifunction line differential relays provide basic in-zone unit protection, local and remote standby overcurrent protection, and dedicated ground fault protection for downstream power systems to improve line-to-ground fault sensitivity. Reference [7] proposed a current differential protection scheme which uses positive-sequence fault component for the protection. Reference [8] proposed a pilot protection scheme which compares the phase angle variation of positive-sequence fault current; this scheme only needs to transmit numerical value of phase variation, therefore, communication channel of high synchronization is not required. Reference [9] derived a differential criterion of current amplitude; the criterion just needs current amplitude information without strict synchronization of data sampling. Reference [10] proposed an integrated protection and control system for 10 kV feeder applications based on PTN (Packet Transport Network) communication. The system uses centralized line differential protection and decentralized bus differential protection. It can be seen from these publications that these current differential protections for application in distribution networks cannot adaptively change their settings automatically if the topology of the primary distribution networks change. As the topology of primary distribution networks can change frequently, particularly in China, due to fast development of its distribution networks, this paper derived a method of automatically changing the setting of current differential protection when the topology of primary distribution networks changes.

Feeder automation technology is an important mean to improve the standard of fault handling in distribution networks. At present, various types of feeder automation have been used, including voltage–time type [11], closing quick-break type [12], intelligent distribution type, and centralized type [13]. These types are all aimed at the faults with large fault current. To solve the problem existed in the voltage–time feeder automation that the fault processing time is long, the upstream switches of the fault point need to tolerate fault current twice, and the upstream sections need to experience two short-time power outages, [14] proposed a quick fault location and isolation method for distribution network based on adaptive reclosure. However, none of these methods can really provide a fast, sensitive fault location function. They have no adaptive auto-switching function which can automatically change its switching procedure if the topology of the primary distribution networks changes.

In the 10 kV distribution networks in China Southern Power Grid, normally circuit breakers are only installed on the outgoing feeders at the 10 kV substations, and load switches with DTU are installed on the ring main unit, as shown in Figure 1. As the load switch is only capable of breaking load current, when a power system fault occurs, the circuit breakers at the 10 kV substation will operate first to break the fault current. After the fault is located, then the load switches which are the nearest to the fault location will open to isolate the fault. After the fault is isolated, the circuit breakers at the 10 kV substation will re-close to restore the power supply to the healthy part of the network. For the traditional automation system, as there is no fast fault location function, after a power system fault is cleared, it takes minutes or even hours to manually locate a fault and isolate a fault; the

restoration process is slow after a feeder is tripped out when a power system fault occurs. Therefore, it becomes necessary to find a quick fault location method and automatic closing strategy to restore power supplies to customers after a power system fault. As current differential protection is a unit protection, it can be easily applied for fault location.

This paper presents an adaptive current differential protection and a fast auto-closing system developed for the 10 kV distribution networks in China Southern Power Grid. The current differential protection can adaptively change its settings according to the topology change of the primary distribution networks, thus the system effectively reduces the operation and maintenance cost of the power distribution network. As load switches are installed on the 10 kV feeder, the current differential protection function is used for fault location. The fast auto-closing function is implemented in the existing DMS (Distribution Management System). When a fault occurs on the 10 kV feeder, the current differential protection can locate the fault quickly and accurately, and the fault can be isolated quickly. After the fault is isolated, the auto-switching function in the DMS can quickly restore the power supply to the healthy part of 10 kV feeder in less than one second.

2. System Architecture and Communication

2.1. System Architecture

The integrated protection and control system developed has been installed on a 10 kV feeder in China Southern Power Grid, as shown in Figure 1. The feeder is connected to two 110 kV/10 kV substations by CB F05 and F36, respectively. The feeder is normally run in open-ring configuration, that is, the normal open point of the 10 kV feeder is at 601 of RMU2 (Ring Main Unit 2). DTU is installed at two 110 kV/10 kV substations and each 10 kV Ring Main Unit (RMU). Each DTU communicates with the adjacent DTUs for current differential protection function, also communicating with the existing central DMS (Distribution Management System) for SCADA (Supervisory Control And Data Acquisition) function and auto-switching function to restore power supplies after a power system fault is cleared.

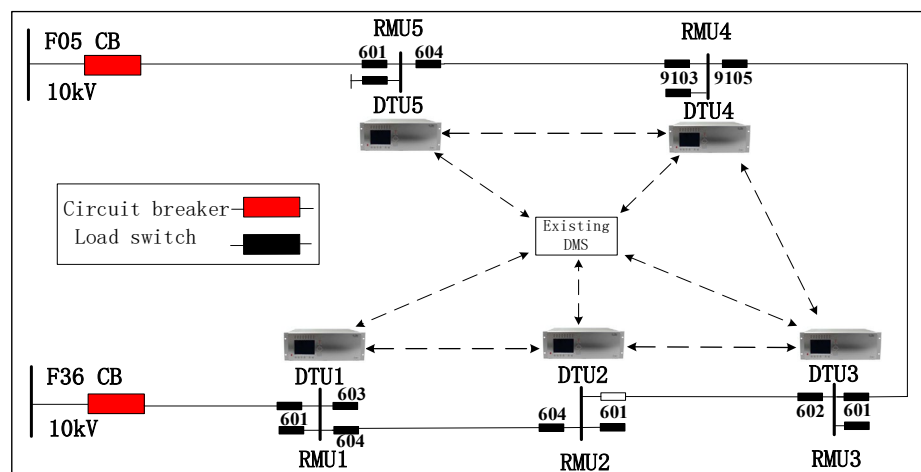


Figure 1. Topology of the distribution network. DTU, Distribution Terminal Unit; RMU: Ring Main Unit.

The adaptive current differential protection function is located in each DTU at each RMU. The protection communicates with adjacent DTU to obtain the current data from remote terminals. If the topology of the feeder changes, the DMS can detect the change and send the information to the affected DTUs. The current differential protection then changes its configuration settings according to the new topology. The DMS is responsible for modeling, real-time monitoring, and clock synchronization of the entire distribution network, and for performing topology dynamic analysis on the entire distribution network, transmitting topology change data to each DTU terminal. The DTU is

responsible for transmitting the respective sampled data and trip information to adjacent terminals, collecting the sampling data and operation information of adjacent terminals, and responding quickly to a power system fault by running its differential protection algorithm. The protection is fast and can dynamically adapt to topology change of distribution networks.

2.2. Communication

Fiber network is normally available in urban areas, but it is not readily available in remote rural areas. Due to the rapid development of 4G wireless communication, it is considered for the application of the protection and control system. Special CPE (Customer Premise Equipment) of the wireless communication equipment has been developed for current differential protection with accurate time synchronization. The IRIG B signal from the CPE is used for synchronization of the differential protection.

The DMS and DTUs are connected by setting up a 4G wireless private network, as shown in Figure 2. A CPE device is connected to each DTU for wireless communication. Communication networks also use data encryption to ensure data reliability and integrity.

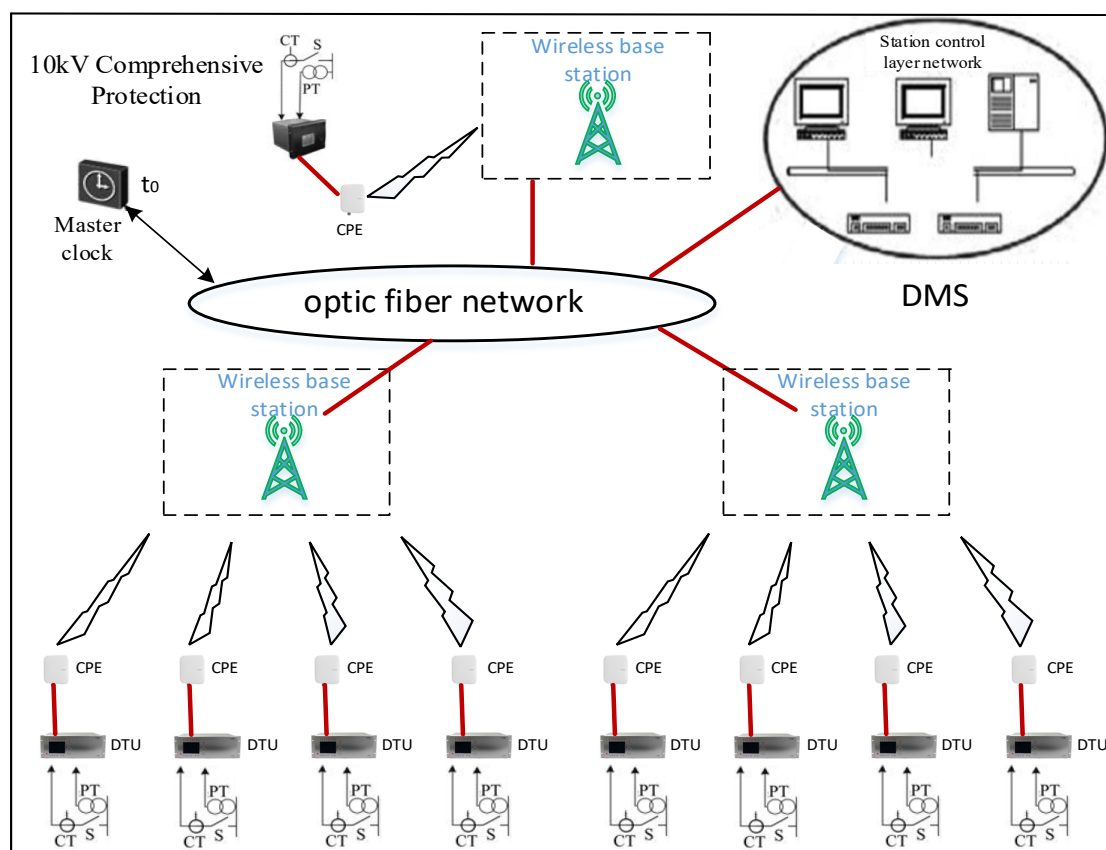


Figure 2. Communication for the differential protection system. DMS: Distribution Management System. CPE: Customer Premise Equipment.

The distribution master station transmits the distribution system model data and terminal deployment information to the DMS through TCP (Transmission Control Protocol). Through 4G wireless private network, the DMS uses Web Service to exchange topology change information with DTU terminals, and to enable or disable the current differential protection function. The 4G wireless private communication network is used between the DMS and the terminal, and a discovery/registration mechanism is used between the DMS master station and the terminal, that is, after the terminal is deployed, the terminal is registered in the DMS through a Web Service registration service, and the

terminal model information is transmitted through a file transmission service. After successfully registering with the master station, the terminal real-time data is transmitted through IEC 60870-5-104 protocol to the DMS. At the same time, IEEE 1588 protocol is adopted to perform time synchronization service for the terminal. Communication between terminals is also through the wireless private network, but because of the need to transmit sampling values and trip signals, GOOSE/SV protocol based on subscription/publishing mechanism is required to ensure the synchronization efficiency of sampled values.

2.3. Clock Synchronization Technology

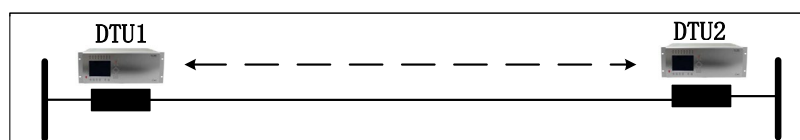
The terminal's clock synchronization uses the IEEE 1588 timing method. IEEE 1588 is an Ethernet synchronous clock that provides sub-microsecond timing accuracy. IEEE 1588 uses the Best Master Clock algorithm to determine the most accurate clock in the network to be the Master. All the remaining clocks are used as slaves, synchronized with the master clock. In the adaptive differential protection, since the sampling information and the trip information need to be transmitted, and the timing accuracy is required to be very high, the IEEE 1588 dedicated timing chip is deployed inside the terminal, that is, the timing information is processed at the MAC layer to ensure the required timing accuracy. In the application, the international common time format code is used to combine the timing of the timing pulse with the time data of the serial message to transmit time information. After CPE receives the time information, it converts to IRIG-B code with timing pulse. DTU then uses on-time edge of the timing pulse to synchronize the sampling of the currents data and perform current differential protection calculation. The accuracy of the time synchronization was tested in the factory, and the test results are shown in Table 1.

Table 1. IEEE 1588 timing test results.

Test Number	Wireless Timing Synchronization Errors (μ s)
1	Mean 2.466 μ s and standard deviation 10.093 ns for 100 samples
2	Mean 2.533 μ s and standard deviation 22.549 ns for 100 samples
3	Mean 2.507 μ s and standard deviation 3.036 ns for 100 samples

3. Topology Adaptive Differential Protection

The adaptive current differential protection developed in the paper can automatically change its configuration settings if a change of the topology of the 10 kV distribution networks is detected. For example, if a new T-line is added to a feeder, the two-terminal feeder becomes a three-terminal line, as shown in Figure 3b. Before the topology change, the DTU1 communicates with DTU2 for its current differential protection function, as shown in Figure 3a. After the topology change from a two-terminal circuit to a three-terminal circuit, DTU1 not only needs to communicate with DTU2, but also needs to communicate with DTU3 for its current differential protection, this requires change the configuration settings of current differential protection in the DTUs. For traditional differential protection, the settings are normally changed manually, but it is time-consuming to do it manually.



(a)

Figure 3. Cont.

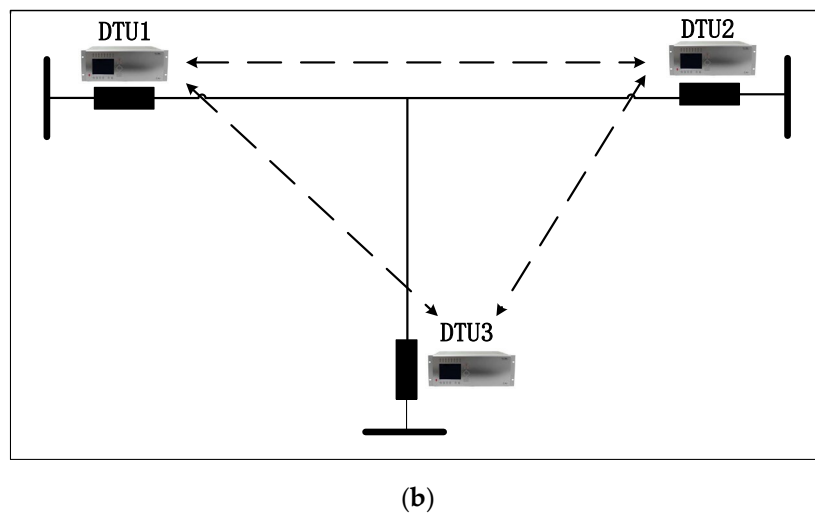


Figure 3. (a) Communication of current differential protection for a two-terminal circuit; (b) Communication of current differential protection for a three-terminal circuit.

Another scenario of changing the topology of the primary circuit could be removing or adding substations. For example, if RMU2 shown in Figure 1 is removed, DTU1 then needs to communicate with DTU3 for its current differential protection instead of DTU2. This requires changing of the configuration settings of current differential protection to reflect the change of the topology of the primary circuit. Traditionally, the settings are changed manually. In this paper, an adaptive function of the automatic changing of the setting is developed. After the topology change, the DMS knows the topology change from the information obtained by it, and then it automatically sends the new configuration settings of the differential protection to the affected DTU. Therefore, manually changing the settings of the current differential protection is not required, and this saves outage time for system operations.

3.1. Topology Adaptive Technology

Figures 4 and 5 show the flow charts of the process of obtaining the change of the topology of the distribution network and the process making the change of differential protection setting.

The operation procedure for the user is as follows:

- (1) When the site is ready for construction to carry out feeder modification, the control engineer in the control room first switches off the feeder, then issues a command to block the protection function associated with the feeder.
- (2) After the feeder is isolated and earthed, construction work then starts.
- (3) The feeder is then ready for switching on after the construction is completed.
- (4) The control engineer then issues command to send new topology information to the affected DTUs through DMS system.
- (5) After DTU receives the new topology information, the differential protection then changes its configuration settings to suit the new topology of the feeder. The control engineer then issues command to enable the differential protection, the feeder is then ready to be switched on.

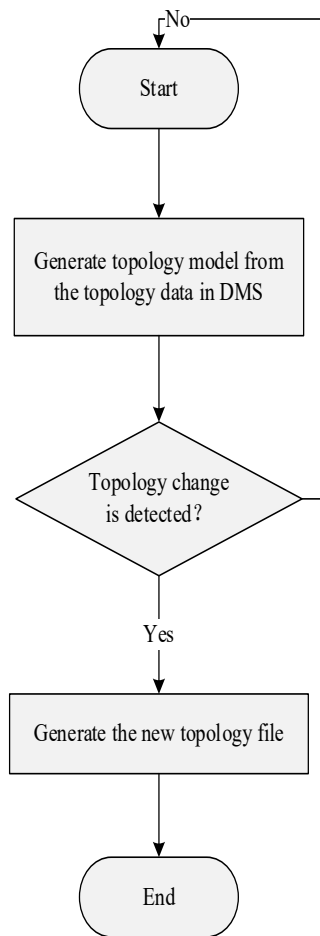


Figure 4. Flow chart for obtaining distribution network topology information.

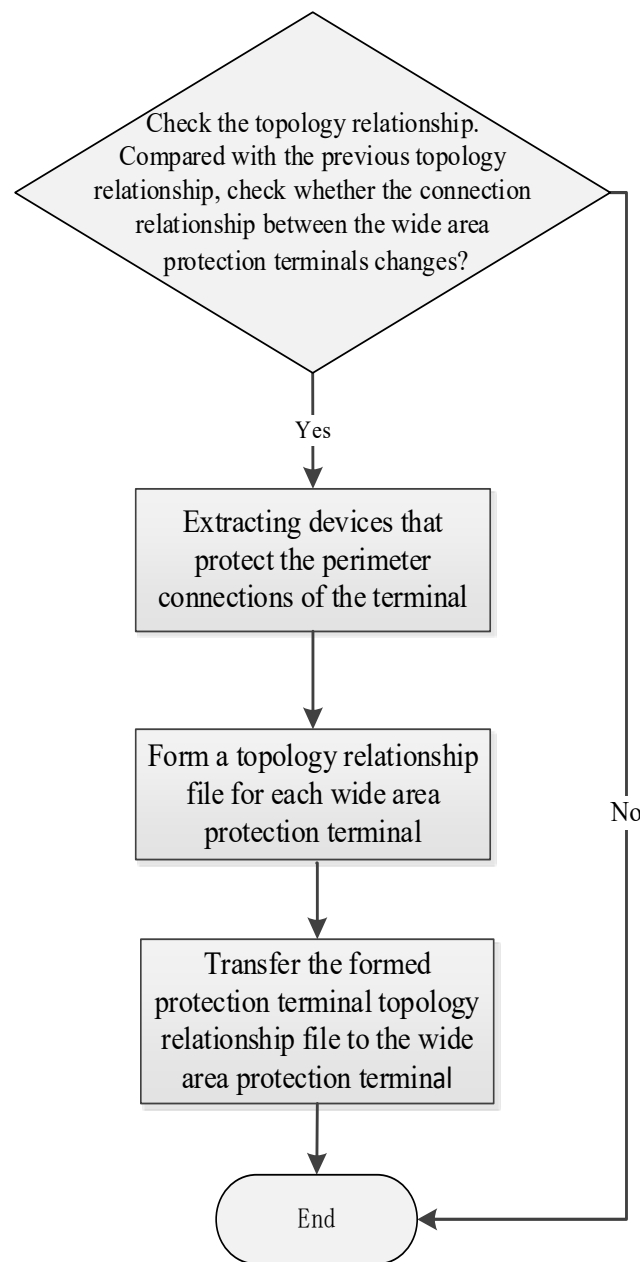


Figure 5. Flow chart of adaptive topology generation.

3.2. Distributed Current Differential Protection Technology

The current differential protection function is located in each DTU. Each DTU communicates with adjacent DTUs to perform the current differential protection function.

The algorithm of the current differential protection is as follows, that is, the differential current and restraint current are calculated as follow:

$$\begin{cases} I_d = \sum_{i=1}^N I_i \\ I_r = \frac{1}{2} |I_{max} - \sum I_i| \end{cases} \quad (1)$$

In the above formula, $\sum_{i=1}^N I_i$ is the sum of all sides phase currents; I_{max} is the largest phase current in all sides; $\sum I_i$ is the sum of the phase currents on the other sides (except the maximum phase current side).

The protection operating characteristic is shown in Figure 6. In the Figure, I_{cd} is the setting of the differential current protection.

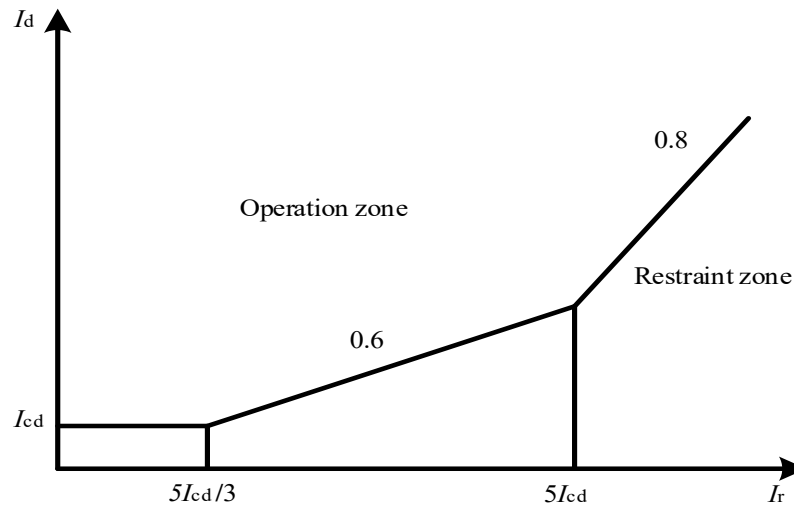


Figure 6. Differential protection operating characteristics.

3.3. Zero Sequence Current Differential Protection

The 10 kV distribution network in the urban area normally adopts the neutral grounding through small-resistance grounding method. The CTs in the RMU are normally installed on phase A, phase C, and a CT around all three phases (i.e., summation of all three phases to obtain the zero-phase sequence current). The ratio of the zero-phase sequence CT is smaller than the CT ratio of the phase A and C, so the current differential protection of the zero-phase sequence current provides sensitive differential protection for ground faults.

4. Fast Auto-Closing Function

As circuit breakers are only installed at the beginning of the 10 kV feeder (i.e., CB F36 and F05, as shown in Figure 7) and load switches are installed at each ring main unit, the current differential protection is used for fault location. The normal open point on the 10 kV feeder is at the load switch 601 at RMU2, as shown in Figure 1. When a power system fault occurs, the DMS knows the fault location by the operation of the current differential protection. After the fault is cleared, the DMS then sends open command to the two load switches which are closest to the fault location to isolate the fault. After the fault is isolated, the DMS then sends close command to close CB and the normally open point on the 10 kV feeder to restore the power supply to the healthy part of the feeder.

4.1. Fault at f1

If a power system fault occurs at f1 as shown in Figure 7, the feeder current differential protection locates the fault between RMU1 and RMU2. After CB F36 opens by operation of its protection to clear the fault, load switches 604 at RMU1 and 604 at RMU2 open to isolate the fault. As all the DTUs communicate with the central DMS, DMS knows the topology and the status of load switches on the 10 kV feeder, so the DMS sends closing command to close CB F36 and load switch of 601 at RMU2 to automatically restore the supplies to the healthy part of the feeder, as shown in Figure 7.

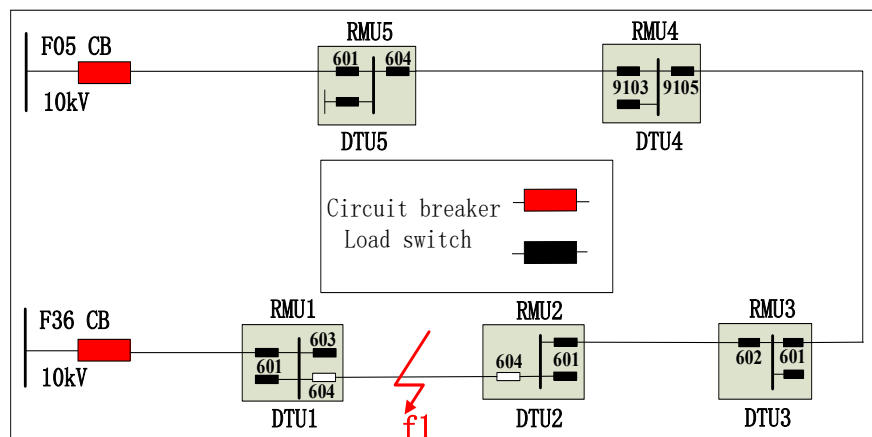


Figure 7. Final status when fault occurs at f1.

4.2. Fault at f2

If a power system fault occurs at f2, the feeder current differential protection locates the fault between RMU3 and RMU4. After CB F05 opens by operation of its protection to clear the fault, load switch 601 at RMU3 and 9105 at RMU4 open to isolate the fault, DMS then sends closing command to close CB F05 and the load switch of 601 at RMU2 to automatically restore the supplies to the healthy part of the feeder, as shown in Figure 8.

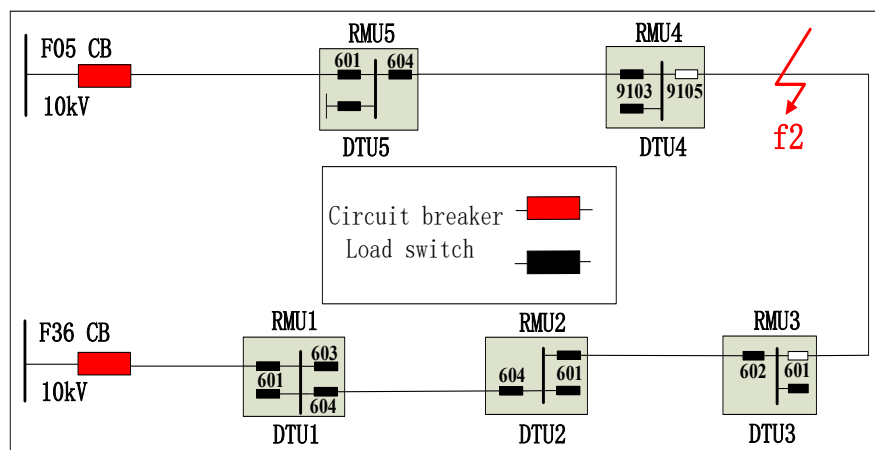


Figure 8. Final status when fault occurs at f2.

5. Factory Test of the System

5.1. Test of Auto-Switching Function

The developed protection and control system has been satisfactorily tested in the factory using Real-Time Digital Simulator (RTDS). The 10 kV network model used for the test is shown in Figure 9 below. Factory test results showed that the delay of 4G LTE communication network is less than 80 ms, and the time synchronization error is less than 10 μ s. The system's response time is within 200 ms. The system was installed and commissioned on site and was put into service at the end of 2018. The system can significantly improve the reliability of power supply in the distribution network after it is in service.

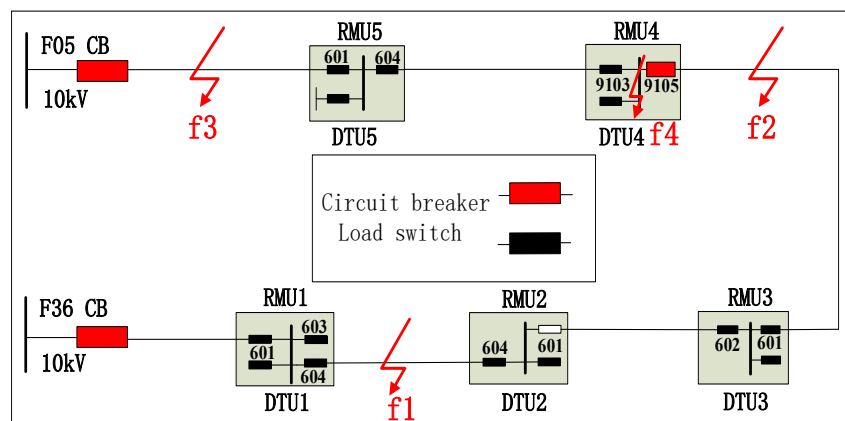


Figure 9. 10 kV Network used for the test.

5.2. Test of Topology Adaptive Current Differential Protection

A test of the topology adaptive current differential protection function was done by removing one of the RMUs. For the 10 kV feeder shown in Figure 9, RMU4 was first removed, and when a fault of f2 was applied as shown in Figure 9, CB F05 tripped, then 601 at RMU3 and 604 at RMU5 opened to isolate the fault, CB F05 then reclosed to supply the load at RMU5, 601 at RMU2 then closed to supply the load at RMU3. The sequence of all the operations was correct, as expected. After the test, the RMU4 was then restored to the primary circuit, and the fault of f2 was then repeated, the sequence of all the operations was correct, as shown in Table 2. The tests have shown that the current differential protection function can adaptively change its configuration settings according to the topology change of the primary circuit, and its configuration settings are changed automatically, without manual changing. This saves time for site operating and maintaining of the system.

Table 2. Test results of fault isolation time.

Flt	Operation Sequence of Equipment	Load Switch/CB Opening Time
f1	1. Diff. protection between RMU1 and RMU2 operates 2. CB F36 trips 3. 604 at RMU1 and 604 at RMU2 open 4. CB F36 reclose 5. 601 at RMU2 closes	At RMU1, 604 opening time: 870 ms At RMU2, 604 opening time: 870 ms
f2	1. Diff. protection between RMU3 and RMU4 operates 2. CB 9105 trips 3. 601 at RMU3 opens 4. 601 at RMU2 closes	At RMU3, 601 opening time: 860 ms At RMU4, 9105 opening time: 370 ms
f3	1. Diff. protection between F05 and RMU5 operates 2. CB F05 trips 3. 601 at RMU5 opens 4. 601 at RMU2 closes	At RMU5, 601 opening time: 870 ms
f4	1. Busbar protection of RMU4 operates 2. CB F05 and CB 9105 trip 3. 604 at RMU5, 9103 at RMU4 and 601 at RMU3 open 4. CB F05 reclose 5. 601 at RMU2 closes	At RMU4, 9103 opening time: 870 ms 9105 opening time: 340 ms

6. Conclusions

Development of an adaptive current differential protection and fast auto-closing system for application in 10 kV electricity distribution networks in China Southern Power Grid has been carried out. The system uses 4G LTE wireless communication network for its current differential protection and

control function. The system can locate and isolate faults in less than one second, while conventional overcurrent protection has no fault location capability. Manual locating and isolation of power system faults may take minutes or even hours. The system improves the accuracy of fault location of the power system, reduces the fault outage time, and improves the power supply reliability of the distribution network by implementing the differential protection function and the fast auto-closing function. As it can detect the change of the topology of the primary distribution network, the differential protection can adaptively change its configuration settings to suit the new topology of the distribution network. The settings are changed automatically according to the change of the topology of the primary circuit, whilst traditionally the setting change is done manually. This saves time for site operating and maintaining of the system. As it can quickly locate and isolate the power system faults and restore the power supplies to the healthy part of the distribution networks in less than one second, this improves the reliability of the power supplies to customers. The system has been factory tested to demonstrate the effectiveness of the system. The communication network data transmission and time synchronization are satisfactory for its application. It is expected that, with the application of the system, faults in the 10 kV distribution networks can be located and isolated quickly. It shortens the outage time of the important load and can improve the reliability of power supply significantly.

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References

1. He, J.H.; Cheng, Y.H.; Hu, J.; Yip, H.T. An Accelerated Adaptive Overcurrent Protection for Distribution Networks with High DG Penetration. In Proceedings of the 13th IET International Conference on Developments in Power System Protection, Edinburgh, UK, 7–10 March 2016. [\[CrossRef\]](#)
2. Sherbilla, N.F.; Kawady, T.A.; Elkalashy, N.I.; Taalab, A.M.I. Modified Setting of Overcurrent Protection for Distribution Feeders with Distributed Generation. In Proceedings of the IET Conference on Renewable Power Generation, Edinburgh, UK, 6–8 September 2011.
3. Pei, X.J.; Chen, Z.; Wang, S.C.; Kang, Y. Over current Protection for Inverter-based Distributed Generation System. In Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, Canada, 20–24 September 2015.
4. Chandraratne, C.; Logenthiran, T.; Naayagi, R.T. Adaptive Overcurrent Protection for Power Systems with Distributed Generators. In Proceedings of the 8th International Conference on Power and Energy Systems, Colombo, Sri Lanka, 21–22 December 2018.
5. Li, R.S.; Xe, C. Differential protection scheme to apply to active distribution network. *Power Syst. Prot. Control.* **2015**, *43*, 104–109.
6. Rintamaki, O.; Ylinen, J.H. Communicating line differential protection for urban distribution networks. In Proceedings of the China International Conference on Electricity Distribution, Guangzhou, China, 10–13 December 2008.
7. Gao, H.L.; Li, J.; Xu, B.Y. Principle and Implementation of Current Differential Protection in Distribution Networks with High Penetration of DGs. *IEEE Trans. Power Deliv.* **2017**, *32*, 565–574. [\[CrossRef\]](#)
8. Li, R.; Lu, Y.P.; Zhang, Z. A Novel Pilot Protection Scheme for Distribution Network with DGs. In Proceedings of the China International Conference on Electricity Distribution (CICED 2014), Shenzhen, China, 23–26 September 2014.
9. Zhang, Z.; Lu, Y.P.; Li, R. A Novel Sufficient Differential Criterion of Current Amplitude for Distribution Network with Distributed Generators. In Proceedings of the 2014 China International Conference on Electricity Distribution (CICED 2014), Shenzhen, China, 23–26 September 2014.

10. An, W.; Kun, L.; Jin, X.; Huang, W.F.; Wei, C.Z.; Mou, M. An Integrated Protection and Control System for 10 kV Electricity Distribution Networks Based on Package Transmission Communication Network. In Proceedings of the China International Conference Electricity Distribution, Xi'an, China, 10–13 August 2016.
11. Chen, Y.; Hai, T. Voltage type feeder automation system. *Power Syst. Technol.* **1999**, *23*, 31–33.
12. Cheng, H.L.; Zhang, W.; Liu, J. Improvement of reclosing and instantaneous protection based feeder automation and its setting approach. *Automation Electr. Power Syst.* **2006**, *30*, 35–39.
13. Ge, L.; Tan, Z.H.; Zhao, F.Q.; Weng, L.; Dong, X.Z. An improved feeder self-healing control scheme and its realization. *Power Syst. Protect. Control* **2013**, *41*, 62–65.
14. Zhang, W.; Song, G.B.; Dou, M.; Chang, Z.X.; Zhang, Z.H.; Liu, J.; Guo, S.H. A quick fault location and isolation method in distribution network based on adaptive reclosure. *Power Syst. Protect. Control* **2019**, *47*. [[CrossRef](#)]



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