Jestr

Journal of Engineering Science and Technology Review 7 (2) (2014) 80 – 86

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

Fault Identification Algorithm Based on Zone-Division Wide Area Protection System

Xiaojun Liu[1,*] , Youcheng Wang[1] and Hub Hu[2]

[1]*School of Electrical Engineering, Northeast Dianli University, Jilin 132012, China*
[2]*School of Electrical and Electronic Engineering, University of Manchester, Manchester M13 9PL, UK*

Received 16 January 2014; Accepted 2 April 2014

Abstract

As the power grid becomes more magnified and complicated, wide-area protection system in the practical engineering application is more and more restricted by the communication level. Based on the concept of limitedness of wide-area protection system, the grid with complex structure is divided orderly in this paper, and fault identification and protection action are executed in each divided zone to reduce the pressure of the communication system. In protection zone, a new wide-area protection algorithm based on positive sequence fault components directional comparison principle is proposed. The special associated intelligent electronic devices (IEDs) zones which contain buses and transmission lines are created according to the installation location of the IEDs. When a fault occurs, with the help of the fault information collecting and sharing from associated zones with the fault discrimination principle defined in this paper, the IEDs can identify the fault location and remove the fault according to the predetermined action strategy. The algorithm will not be impacted by the load changes and transition resistance and also has good adaptability in open phase running power system. It can be used as a main protection, and it also can be taken into account for the back-up protection function. The results of cases study show that, the division method of the wide-area protection system and the proposed algorithm are effective.

Keywords: Wide-area Protection System, Region Division, Fault Identification, Positive Sequence Fault Component, IED

1. Introduction

Relay protection is an important defense line for grid security, its reliability and quick action will directly affect the safe operation of the grid. Cascading outages or blackout at home and abroad in recent years show that in different extents the back-up protection incorrect tripping is the main reason for the grid collapse in large area, and any failure of electrical components or wrong operation during equipment checks may cause power flow transferring which contributes to the rapid depravation of back-up protection[1]. At the same time, complicating and expanding of grid structure will also increase the risk of large-scale power outages to a certain extent. Therefore, relay protection is facing more severe challenges[2].

With the development of wide-area measurement system and communication technology, a kind of wide-area protection system based on multi-point information in power system has been paid more and more attention from scholars all over the world[3]. It can identify the fault location in a short time and provide a new idea to solve above-mentioned problems. According to CIGRE, wide-area protection not only can take advantage of wide-area information to real-time monitoring and control for power grid's security and stability, but also can use the information for fault location and removal in order to realize the function of relay protection.

At present, research on the wide-area protection system has mainly focused on the use of wide-area information to improve the performance of backup protection, or to expand the main protection to backup protection system, such as pilot protection, distance protection algorithms and other traditional main protection, or to extend to a wide-area backup protection system in order to improve the reliability of backup protection performance[4], [5], [6].

In order to make the conversion of wide-area protection from rational exploration to engineering application, in recent years, the concept of limited wide-area protection system[7], [8] is continually raised and has developed very rapidly. It has been divided wide-area protection system from a macro perspective and can reduce the pressure in large communication transmission systems.

From the point of view of reducing network traffic, the complexity of large power grids is orderly divided, so that the data collection and processing, the fault identification, and the protection actions are all completed in the division area, which reduces the pressure of the communication system by exchanging of information blindly. For the divided area, a new wide-area protection algorithm based on positive sequence fault components directional comparison principle is proposed. Positive sequence fault component directional element has been employed due to its irreplaceable advantages; for example, it will not be affected by transition resistance and load changing. As fault affected scope is often limited, the special associated IEDs (*Intelligent Electronic Devices*) zones need to be discussed in order to share and transmit fault information in specific area to reduce communication volume.

* E-mail address: lxjnedu@126.com
ISSN: 1791-2377

2. Structure of Wide-Area Protection System

Wide-area protection system often takes two structural forms: centralized form and distributed form[9], [10]. Centralized form is composed of decision-making centers and dispersed IEDs. IED is responsible for collecting the electrical information from the installation through the network and sends it to control center, then control center analyzes the data, determines the fault location and sends the control commands. In the distributed structure, data collection, data analysis, fault judgment and decision control are accomplished by the IED. Each IED is a relatively independent individual and can be shared in a specific area of other IEDs information. According to the characteristics of the division principle and fault identification algorithm, a combination form of two structures above is employed in this paper, namely distrusted centralized decision-making structure. Its form is shown in figure 1.

Figure 1(a) is wide-area protection system structure, in which the complex power grid is divided into several small areas. IEDs will collect the fault information and upload the handled fault information to the regional control center. Combining with fault identified algorithm, control center uses fault direction information to determine the fault location and sends the tripping signals to each IED. At the same time, the results of processing upload wide-area control center to optimal control, shown in Fig.1 (b).

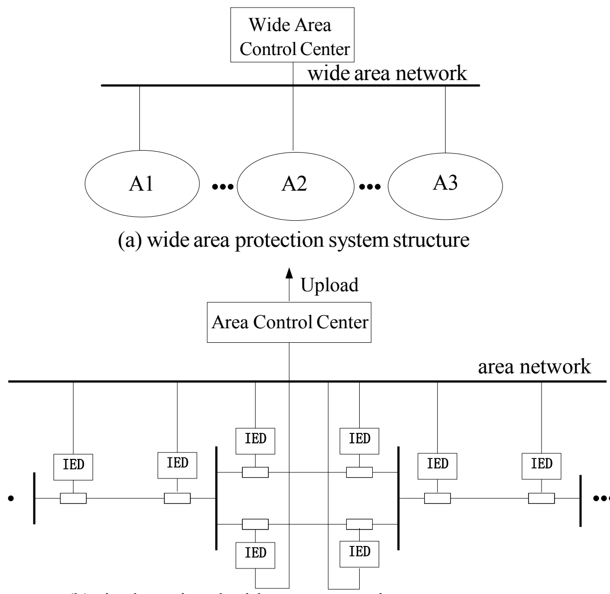


Fig.1 Distributed centralized decision-making wide-area protection system structure

The distributed centralized decision-making wide-area protection system structure not only has the advantages of information situ treatment in distributed form, but also has retained the global optimal control in centralized form, so it lays a safe and stable operation foundation of grid structure.

3. Division Method of Wide-Area Protection System

The partition of wide-area protection system has been a hot research field in recent years, and many scholars have made a lot of studies. On the basis of the concept of wide-area limited, reference [8] has given the specific zoning principle and methods and taken advantage of graph theory to express it in the form of a matrix. On this basis, combining with its own characteristics of fault identification algorithm, a new wide-area division method is applied.

3.1 Select the Central Station

The central station is the place where the RCC (*Region Control Center*) is located. It is used to collect the certain IEDs message in the divided area and to send the commands after the fault is identified by itself; at the same, the results are transmitted to WCC (*Wide-area Control Center*) in order to optimal control.

As for the selection of central station, many factors should be considered, such as the relationship between individual nodes and central station, the position of geography, communication environment and climate type. Therefore, the following principles should be met:

1) A good external environment is required to satisfy staffs maintenance and repairing.

2) The central station should be as important or center transformer substation as possible and should maintain close electrical contact with other transformer substation or transmission lines in the certain area.

3) Try to avoid being too close between the central stations to prevent excessive cross-regional interoperability among regions that the central stations control.

4) Adjacent substation or power plant can be taken for its backup central station

3.2 Division Method

Division of the protection area should try to consider the actual grid. Generally, to take the central station as the center, the scope of protection area can be extended to the end of the next transmission line. This can meet backup protection requirement in traditional protection and coordinate well. However, actual grid dividing radius of protection may have some margins, and some boundary nodes that do not meet the dividing principles should be contained in the sub-region in order to achieve the reliability and economy of unity.

On the issue of interactive in the area, after summarizing existing regional interactive method[11], [12], combined with the characteristics of own fault identification algorithm, the region interactive method, shown in Fig.2, is adopted in this paper, where, L2 is interactive areas.

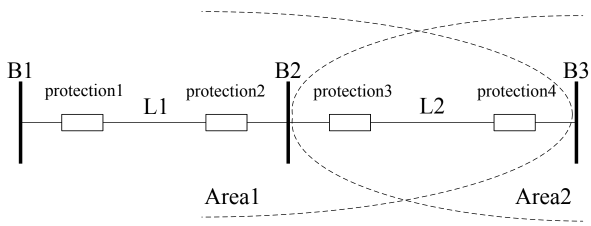


Fig.2 Region interactive method diagram

In order to explain the selection principle of center station and region interactive method, 11 node power system is taken as an example to analyze in detail, shown in Fig.3. Bus 6 and Bus 9 are the center stations. When Bus 6 is taken as the center station, protection area extends to the end of next line, forming a protection Area 1. Similarly, Bus 9 can constitute protection Area 2.

With the dividing method mentioned above, the fault situation can be reflected well. In addition, the method can reduce unnecessary redundant information, and it is simple and convenient.

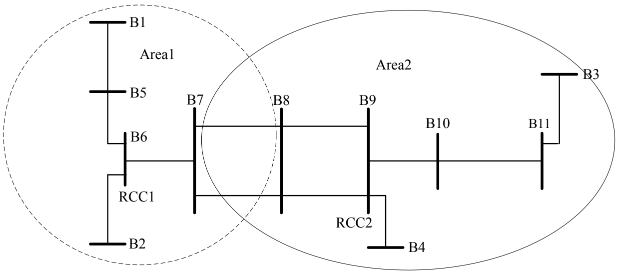


Fig. 3. Division area diagram

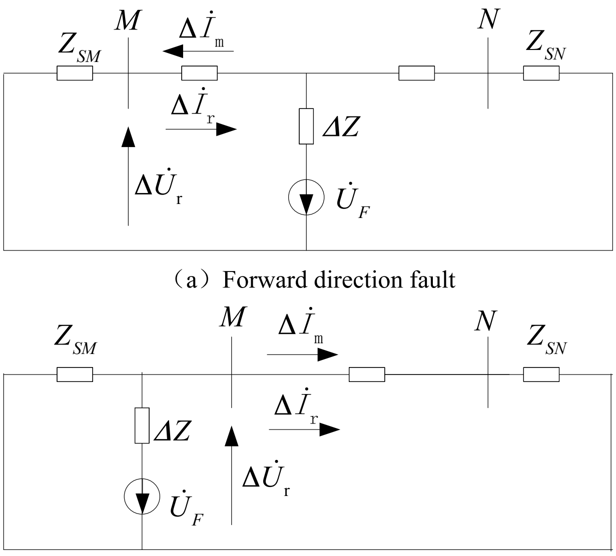
Even so, in the process of constant development and expansion, actual grid has to take dispatch system and communication system into account, so the division of protection areas should meet the needs of actual system planning and design continuously in order to have more practical application value.

4. Wide-Area Protection Algorithm Based on Positive Sequence Fault Component

For the divided area, a new regional protection algorithm based on positive sequence fault components directional comparison principle is proposed.

4.1 Positive Sequence Fault Component Directional Element

Figure 4 is a positive sequence fault component equivalent network of dual power supply system, supposing that Point F faults, and protection is installed at Point M.



（a）Forward direction fault

（b）Reverse direction fault

Fig.4 Equivalent network of positive sequence fault component

Suppose the positive direction of electric current flows from bus to line. When a fault occurs at Point F at the forward direction of the protection, as shown in Fig.4 (a), it can be described as follow:

$$\Delta\dot{U}_{\mathrm{r}} = -\Delta\dot{I}_{\mathrm{r}} Z_{\mathrm{SM}} \tag{1}$$

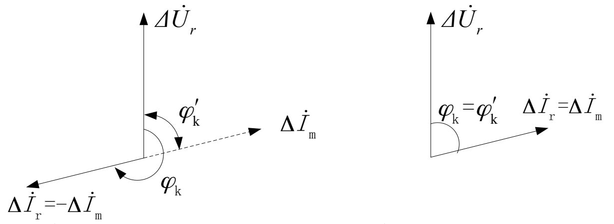
Its vector diagram is shown in Fig.5 (a), φ_k' is the back system impedance angle of the protection. φ_k is the angle that $\Delta\dot{U}_r$ leads $\Delta\dot{I}_r$, and

$$90^\circ < \arg\frac{\Delta\dot{U}_{\mathrm{r}}}{\Delta\dot{I}_{\mathrm{r}}} < 270^\circ \tag{2}$$

When a fault occurs at Point F at the reverse direction of the protection, we can explain (3) and (4) from Fig.4 (b) and Fig.5 (b).

$$-90^\circ < \arg\frac{\Delta\dot{U}_{\mathrm{r}}}{\Delta\dot{I}_{\mathrm{r}}} < 90^\circ \tag{3}$$

$$-90^\circ < \arg\frac{\Delta\dot{U}_{\mathrm{r}}}{\Delta\dot{I}_{\mathrm{r}}} < 90^\circ \tag{4}$$



（a）Forward direction fault vector diagram

（b）Reverse direction fault vector diagram

Fig.5 Positive sequence voltage and current fault component vector diagram

From (2) and (4), we can find that when a fault occurs at the forward direction of the protection, $\varphi_k \in (90°,270°)$ and $\cos\varphi_k < 0$. When a fault occurs at the reverse direction of the protection, $\varphi_k \in (-90°,90°)$ and $\cos\varphi_k > 0$. In order to improve the sensitivity of direction element, we define the sensitive angle $\varphi_{sen} = \varphi_k'$, so the direction of direction element can be expressed as:

$$\begin{cases} P = \Delta U_r \Delta I_r \cos(\varphi_k - \varphi_{sen}) > 0 \\ P = \Delta U_r \Delta I_r \cos(\varphi_k - \varphi_{sen}) < 0 \end{cases} \tag{5}$$

Therefore, we can easily conclude that it is forward direction fault when P<0 and it's reverse direction fault when P>0.

Wide-area protection system often takes two structural forms: centralized form and distributed form. In order to meet the needs of algorithm, distrusted centralized decision-making structure has been taken in the paper. In this structure form, every direction IED which contains positive sequence fault components direction element is installed in the same place as the circuit breaker, analyzing and processing the local fault information independently instead of dealing it by control center. And at the same time, every IED also needs to share information with other associated IEDs via wide-area network. When a fault occurs, IEDs get fault information from associated zone itself and detect and remove the fault by way of fault identification principle and action strategy that defined in advance.

4.2 Division of the Associated Zone

Every IED should not only perceive the fault from local transmission line, but also respond the bus fault that behind it. The division principle of the associated zone is described as follow:

1) A certain IED associates with the IED in its opposite site, and they are provided with the same ID.
2) A certain IED associates with the IEDs that are connected in the same bus.
3) If a certain IED faults, its associated IEDs defined in (1) and (2) make up new associated zone.

Every IED should be together with the associated IEDs to form the associated zone and share information with them mutually in order to reduce the communication volume effectively. For the purpose of explaining the division principle in detail, a simple power network is shown in Fig.6 as the example. Number 1 to 8 represents serial number of IEDs. And taking IED3 as the example, IED3 associates with IED4 which is installed in its opposite site, and it also associates with IED2 and IED5 which connect directly in the same Bus B, shown in figure 6(a).

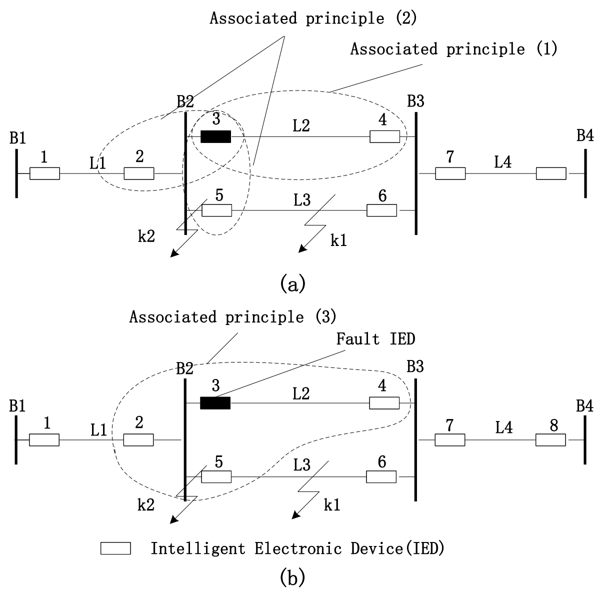


Fig.6 Simple power network

If IED3 faults, it will not be perceived in its associated zone by other IEDs, and its associated IEDs, IED2, IED3, IED5 will make up new associated zone, as Fig.6 (b) indicates.

4.3 Fault Identification Principle

Longitudinal comparison protection is widely used in bus and transmission line protection, and positive sequence fault component directional element has become one of the most popular direction elements that is applied to longitudinal comparison protection, attributed to numerous advantages, such as non-effect by load changing and transition resistance and good adaptability to open phase running power system. According to the characteristic of associated zone, two circumstances should be discussed: main protection and back-up protection.

4.3.1 Main protection situation

a. Line fault

$$\begin{cases} ID_{\text{IEDi}} = ID_{\text{IEDj}} \\ P_{\text{IEDi}} = P_{\text{IEDj}} \end{cases} \quad (6)$$

Where, j≠i, j=1,2,…,n, n is the number of the IEDs involved in associated zone of IEDi, and PIEDi is the fault direction of IEDi. When certain IED is satisfied with (6), it can be judged as line fault and the fault location is between IEDi and IEDj.

b.Bus fault

$$\begin{cases} ID_{IEDi} \neq ID_{IEDj} \\ P_{IEDi} = P_{IEDj} \end{cases} \cap \cdots \cap \begin{cases} ID_{IEDi} \neq ID_{IEDn} \\ P_{IEDi} = P_{IEDn} \end{cases} \quad (7)$$

Where, j≠i, j≠k(where IDIEDk = IDIEDi), j=1,2,…,n, n is the number of the IEDs involved in associated zone of IEDi, and PIEDi is the fault direction of IEDi. When certain IED satisfied with (7), it can be judged as bus fault and the public bus that IEDi connected is the fault location.

4.3.2 Back-up protection situation

a. Protection rejecting action

This situation means that IEDs can receive tripping signal and succeed in sending it to the protections, but the protections act unsuccessfully. To solve this problem, the matching IEDs of the protections send signal to other IEDs that are involved in its associated zone, shown in Fig.7.

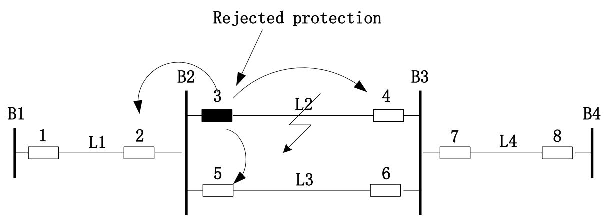


Fig.7 Action strategy for rejected protection

b. IED fault

Communication accident is the main cause of this situation, and fault IEDs can not receive the information from its associated zone, meanwhile they also fail to send signal to their matching protections. Under this situation, a new associated zone can be formed according to the principle (3), and (8) can be found.

$$\begin{cases} P_{adjIED} \neq P_{conIED} \\ P_{par1IED} \neq P_{par2IED} \end{cases} \quad (8)$$

Where, adjIED and conIED represent adjacent IED and connected IED of fault IED, respectively. And par1IED and par2IED represent the parallel IEDs which are installed at either end of the parallel line, shown in Fig.8 in detail. If (8) is satisfied, a fault occurs between adjIED and conIED.

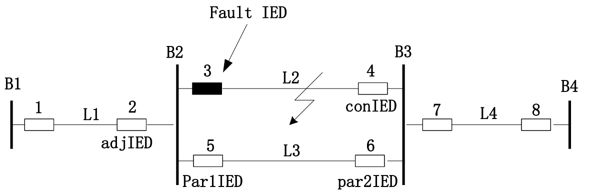


Fig.8 IEDs relationship diagram

4.4 Action Strategy of IEDs

Fault identification principle is the key in the paper in order to express its meaning better. IED5 in Fig.6 is taken as the example to analyze the implementation process in main protection and back-up protection while a fault occurs. And two steps are applied for this process.

Step 1: If IED5 communicates well and meets (6) while collecting fault information in its associated zone, the fault may be located in L3. If IED5 meets (7), the fault may be located in bus B. Then IED5 trips its matching circuit breaker. If the situation in step 1 can not be met, then turn to step 2.

Step 2: If the breaker which matches with IED5 rejects action, IED5 will send tripping signal to other IEDs in its own associated zone according to the rejected information sent from the breaker and the algorithm returns. If IED5 faults, IEDs in its associated zone can not perceive its information and they will form a new associated zone followed by principle (3) and check whether the IEDs in the new associated zone satisfy with (8). If yes, tripping their own breakers, if no, return.

5. Case Study

In this paper, IEEE 10 39-bus network model is taken as the example to verify regional division method. According to the principle of the division method, the system can be divided into six pieces, in which the central stations are located in the Bus 16, Bus 26, Bus 2, Bus 6, Bus 13, and Bus 22 respectively, and they disperse well which are shown in Fig.9. We note that the Bus 34 is divided into Region 1, which should be contained in the area according to the division principle because of the boundary bus.

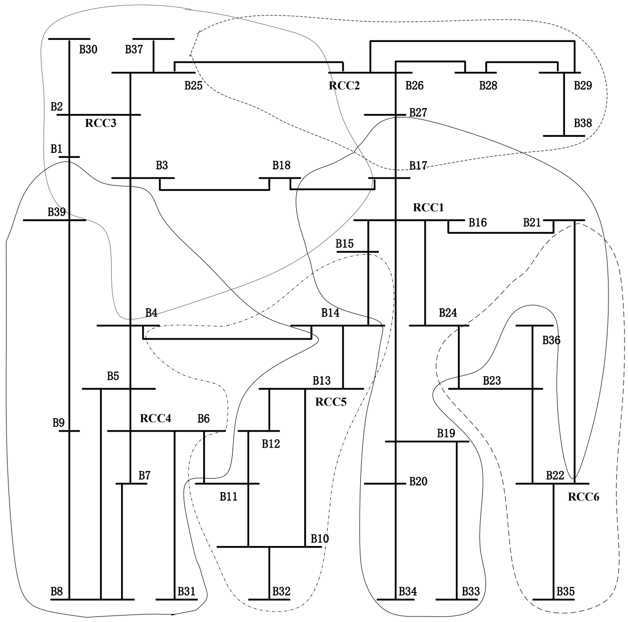


Fig.9 Division area of IEEE 10-machine 39-bus system

According to the system shown in Fig.9, Region 5 is taken as the fault algorithm simulation system, and the Bus and the transmission line are shown in Fig.10 after reordering. The dashed Bus in Fig.10 is the Bus which is outside the scope of the region. Line 9, Line 12, and L13 are the interactive areas.

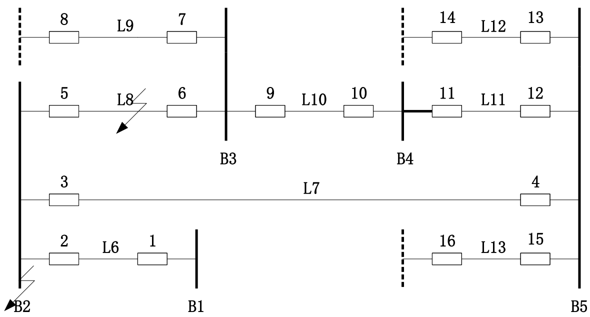
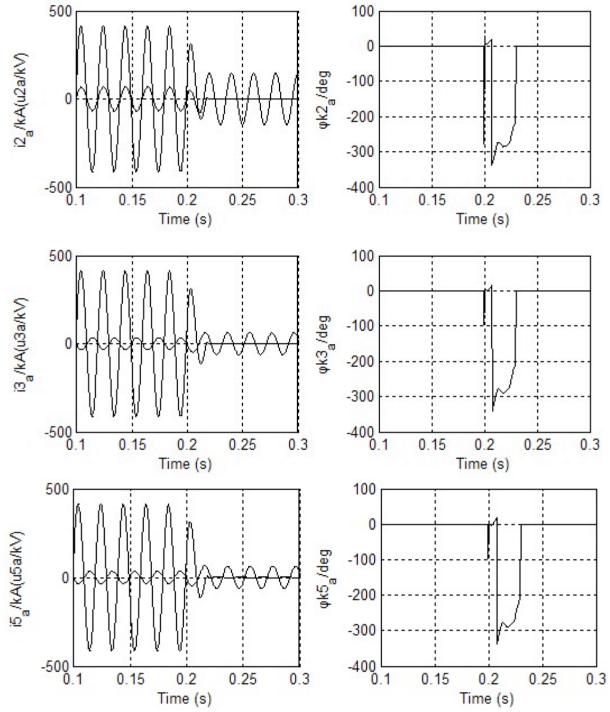


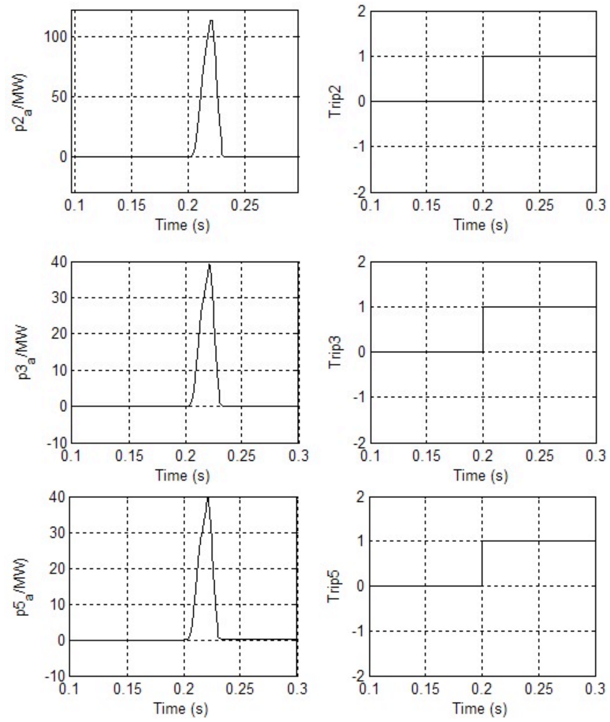
Fig.10 Region simulation system

If Bus 2 A phase faults, and all IEDs communicate well. Fig.11(a) shows the simulation information of IED2, IED3 and IED5, and the ordinate represents fault voltage u and fault current i and the angle φk between Δu and Δi. From Fig.11(a), we know that φk is between -1800 and -900 , and the fault can be located in Bus 2 according to the fault identification principle in formula(7). Fig.11 (b) shows the simulation results of the IEDs and their trip messages.

If IED5 faults or its circuit breaker rejects action at this time, step 1 will be not satisfied to remove the fault, so the algorithm will turn to step 2 automatically, removing the fault based on action strategy of step 2.



(a) Simulation information

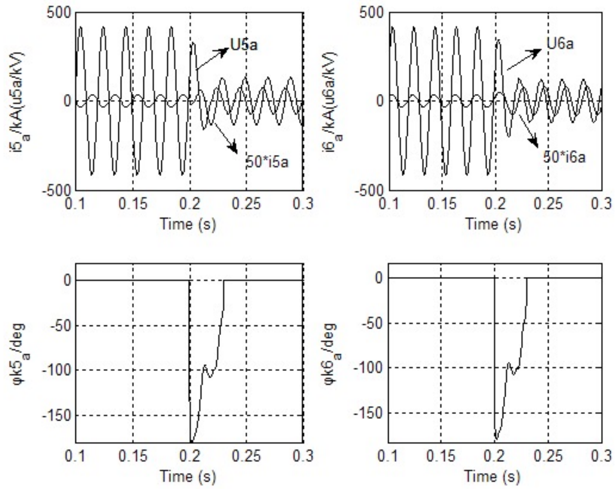


(b) Simulation results and tripping message

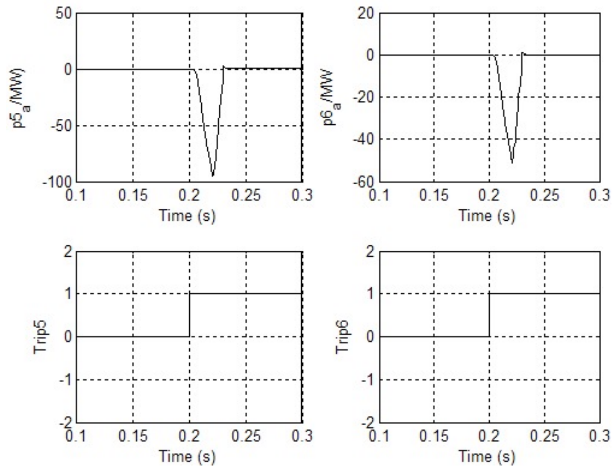
Fig.11 Output of IED2, IED3 and IED5

If Line 8 A phase faults, and the simulation information and results are shown in Fig.12 (a) and Fig.12 (b), the fault can be located at Line 8.

We can easily find from the simulation result that IED5 and IED6 satisfy (8) and the fault can be located in L3, so the matching circuit breakers are tripped successfully.



(a) Simulation information



(b) Simulation results and tripping message

Fig.12 Output of IED5 and IED6

6. Conclusions

Relay protection system, as the first line of defense in power system, has been put forward higher requirements than ever before owing to the complex structure of power grid nowadays. Wide-area protection system based on wide-area multi-point information is bound to be increased by the communication level in the process of conversion to engineering practice. Based on the concept of limitedness of wide-area protection system, the grid with complex structure is divided orderly. And in the division area, a new wide-area protection algorithm based on positive sequence fault components directional comparison principle is proposed. Fault identification and protection action are executed in each divided area to reduce the pressure of the communication system. The protection algorithm proposed in this paper can be used as the main protection; at the same time, it has the back-up protection function.

IEEE 10 39-bus network model is taken as the example to verify regional division method. Case study result further verifies the effectiveness of the division method and the identification algorithm.

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