Substation-area Backup Protection Scheme for the Failure of 10kV Line Protection Device

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Abstract—The research on wide-area backup protection for high-voltage transmission lines has made certain progress in recent years, but there are few reports published on substation-area backup protection for low-voltage 10kV transmission lines. Based on the characteristics of shared information in intelligent substation, a substation-area backup protection scheme to deal with the failure of 10kV line protection device is proposed in this paper. This scheme uses the device self-test information and heartbeat mechanism to monitor the operation status of 10kV line protection devices; to realize the substation-area backup protection for the 10kV transmission lines when any line protection device fails, the protection criterion is constructed by the action results of power directional elements of transformer protections and other 10kV line protections. The proposed scheme can greatly improve the speed of the fault isolation and has low requirements for data demand and synchronization. PSCAD simulation results show that the proposed method is with high correctness and feasibility.

1. Introduction

With the increasing complexity of power grid and the flexibility of operation mode, it has brought many challenges to the relay protection technology. Traditional relay protection is usually distributed according to intervals and can only use local information, resulting in many defects for traditional backup protection such as long time delay, difficulty in setting and coordination, easy to cause cascading trips [1]. To improve the adaptability of relay protection technology to power system, the substation-area backup protection which comprehensively uses the multi-interval electric quantities to detect the fault has become a research hotspot in recent years.

Substation-area protection is proposed and developed on the basis of shared information in intelligent substation. The purpose of substation-area protection is to increase the interaction of different protections, simplify the configuration of traditional backup protection, optimize the control of protection system, and improve the reliability and speed of relay protection under the complex power grid structure and operation mode [2].

In recent years, many researchers have focused on the wide-area backup protection of high-voltage transmission lines, but there is still a lack of research on the substation-area backup protection of low-voltage 10kV lines. In [3-4], the wide-area directional pilot protection and the wide-area current differential protection was proposed to realize the fast and sensitive backup protection function by collecting wide-area information and making multi-point comprehensive comparison and judgment. In
[5], a new scheme of substation-area differential backup protection is proposed, which defines four types of differential zone, the scheme can accurately locate the faulted component according to whether the differential zone lies in restraining state or operating state; In [2], the total station differential region was divided into the boundary differential region and the element differential region, and a new differential backup protection method for large substation based on current inrush variable was proposed; Literature [6] identifies the suspected fault lines according to action information of the traditional main/backup protection and direction component at both ends of all substation lines, and finally identifies the fault line by improved evidence theory fusion with the evidence information. However, communication system is the basis for the above wide-area backup protection and substation-area backup protection. Once the communication system fails, the protection function will not be completed.

If the relay protection device failure, the fault on the line needs to be cleared by the remote backup protection of the adjacent component, and the influence range will be significantly expanded [7-8]. To solve the problem, a substation-area backup protection scheme to deal with the failure of 10kV line relay protection device is proposed in this paper. This scheme uses the device self-test information and heartbeat mechanism to monitor the operation status of 10kV line relay protection device; to realize the substation-area backup protection for the transmission line when any line protection device fails, the protection criterion is constructed by the action information of power directional elements of transformer protections and the other line protections, which has low requirements for data demand and synchronization. The scheme has high feasibility and can effectively improve the reliability of 10kV line protection system.

2. System Structure of the Substation-area Backup Protection
The intelligent substation adopts the mode of "three levels and two networks", "three levels" refers to the process level, the bay level and the substation level, and "two networks" refers to the GOOSE network and the SV network. The intelligent substation realizes the digitization of information sampling and the standardization of information sharing, which can provide good conditions for improving the performance of the backup protection [9]. The system structure is shown in Fig.1.

![Fig.1 System structure of the substation-area backup protection](image-url)
As shown in Fig.1, the substation-area backup protection can obtain the electrical quantities of the whole substation through the SV network. Meanwhile, it can obtain action results of the traditional main/backup protection, the status information of circuit breakers, and can send the tripping signal to the corresponding intelligent terminal through the GOOSE network.

3. Substation-area Backup Protection Scheme for the Failure of 10kV Line Protection Device

3.1. Influence of relay protection failure for 10kV line
As an important part of power grid, 10kV transmission lines are closely related to people's electricity consumption for production and life. Due to different substations adopt different models of microcomputer protection, and the load density and load properties are also of great difference, especially during the peak period of power consumption in summer, the probability of the microcomputer protection device failure is very high.

When the microcomputer protection device of 10kV line have failed and a fault occurs in the line, the fault need to be cleared by the compound voltage over-current protection at the low voltage side of the transformer and the time delay is long. In case of the near area fault occurs in the line, the large short-circuit current for such a long time will pose a serious threat to the safety and stability of the power system. Moreover, the leapfrog tripping will cause the load loss of all the connected transmission lines. In conclusion, it is of great significance to propose a substation-area backup protection scheme for 10kV line to deal with the failure of protection device.

3.2. Principle of the substation-area backup protection scheme

3.2.1. Input conditions of the substation-area backup protection scheme
Microcomputer protection has certain self-test capability. Hardware self-test includes on-line detection and self-test of power module, CPU board, analog quantity, input quantity and output quantity; software self-test is mainly the verification of fixed value area. In case of the fixed value area is wrong, it can automatically open the blocking protection and set the watchdog circuit. The self-test information can be written into the device warning report [10]. The substation-area backup protection can collect the self-test warning information sent by the 10kV line relay protection through the GOOSE network, and then inputs the substation-area backup protection when the 10kV line protection device sends the warning information.

Considering that the line protection device will not be able to send self-test warning information if it has a serious failure, the heartbeat mechanism can be used to monitor the serious failure. It is specified that the 10kV line protection device send the "device normal" information to the GOOSE network every $t_1$ time when the device is normal. When the GOOSE network is normal and the substation-area backup protection detects that the time difference $t_2$ is greater than the specified time $t_1$, where $t_2$ represents the time difference from the last "device normal" information to the current time, it is considered that the line protection device may have a serious failure, and the substation-area backup protection shall be put into immediately.

3.2.2. Process design of the substation-area backup protection scheme
Fig.2 shows the typical topology of the 10kV system in substation. When the protection device of line $L_i$ ($i=1,2,...,6$) is detected to be invalid, considering that the 10kV bus may operate in parallel, the substation-area backup protection will collect the action information of power directional elements of transformer protections and other line protections, which are electrically connected with the line $L_i$. If the power directional element of transformer protections judge that the fault direction is to the bus, and the power direction elements of other line protections do not act (feeders) or judge that the fault direction are to the bus (small power lines), it can be determined that the fault occurs on the line $L_i$ or the bus, and the substation protection will send a tripping signal to the circuit breaker CBL$_i$ after time delay $\Delta t_i$, where $\Delta t_i$ is the longest time delay of the backup protection for line $L_i$. 


The voltage variation of bus is greater than the threshold value, that is $|\Delta U_{bus}| > U_{set}$; the current variation at the low voltage side of the transformer is greater than the threshold value, that is $|\Delta I| > I_{set}$; the directional elements of transformer protections no longer act. If none of the above three conditions can be met, the fault still exists. One possibility is that the breaker CBL$_i$ fails to operate, the other possibility is that the fault occurs on the bus. Whatever the cause, the substation-area backup protection needs to trip the breaker CBFD. If the power directional element of transformer $T_i$ judges that the fault direction is to the bus, it indicates that the fault exists on the bus section connected to transformer $T_i$ or on line $L_i$. Trip the breaker CBT$_i$ and the breakers of the lines connected to the bus section. The flow chart of the substation-area backup protection is shown in Fig.3.

![Flow chart of substation-area backup protection](image-url)

**Fig.3 The flow chart of the substation-area backup protection**
3.3. 90° connection power directional relay
It can be seen from Fig. 1 that the transformer protections and line protections at the bay level are connected to the process layer network and can output the action results of power directional elements. The substation-area backup protection can identify the fault by collecting the action results of the directional elements, so as to realize the network mining network jump mode. To meet the requirements of power directional relay, 90° connection mode is widely used and the criterion is constructed in (1):

\[
-90^\circ < \arg\left(\frac{U_{\phi}}{I_{\phi}}\right) < 90^\circ
\]

(1)

Where \(U_{\phi}\) and \(I_{\phi}\) are the line voltage and phase current. \(U_{bc}, U_{ca}\) and \(U_{ab}\) correspond to \(I_a, I_b\) and \(I_c\) respectively. \(\alpha\) is defined as the internal angle of the power directional element, \(\delta\) is defined as the phase difference between \(U_{\phi}\) and \(I_{\phi}\). When the relationship of formula (2) is satisfied, the power directional element with 90° connection can obtain the highest sensitivity.

\[
\delta = -\alpha
\]

(2)

4. Case Studies

4.1. Simulation model
To verify the correctness and feasibility of the protection scheme, the schematic diagram of the test system shown in Fig.2 was established in PSCAD simulation software. The system includes two main transformers and six transmission lines, of which four lines are feeder and two lines are small power lines. The bus operates in parallel and the sampling rate is 48 points every 20 milliseconds.

Taking the short-circuit fault F at the middle of feeder \(L_2\) in Fig.2 as an example, assuming that the protection device of line \(L_2\) has failed, testing the action results of power directional elements of the main transformer protections and the other line protections. The simulation will only give the action results of two main transformers, line \(L_1\) and \(L_3\), and the action results of line \(L_4, L_5\) and \(L_6\) is similar. It is specified that the positive direction of directional element is to the bus for the transformer, and the positive direction of directional element is to the protected line for the transmission line. Since the neutral point of the 10kV system is generally ungrounded, the short-current of single-phase-to-earth fault is small, so the phase-to-phase short-circuit faults are mainly set here:

1) \(t=0.5s\), three-phase fault occurs at F, and circuit breaker CBL2 is normal;
2) \(t=0.5s\), BC phase-phase fault occurs at F, and the circuit breaker CBL2 fails.

4.2. Simulation and verification

4.2.1. Three-phase short-circuit fault
Fig.4 (a), (b), (c) and (d) respectively show the action results of power directional elements of the No.1 main transformer, No.2 main transformer, feeder \(L_1\) and small power line \(L_3\) after three-phase short circuit occurs. Fig.5 (a) and (b) respectively show the measured bus voltage waveform and the current waveform at the low voltage side of No.1 main transformer.

It can be seen from Fig.4 that after the three-phase short-circuit fault occurs at 0.5s, the power directional elements of No.1 main transformer and No.2 main transformer enter the zone of positive direction, the power directional elements of feeder \(L_1\) do not act, and the power directional elements of small power line \(L_3\) enter the zone of opposite direction, so the power directional elements can correctly judge the fault direction. According to the protection scheme, the backup protection sends a tripping signal to CBL2 after time delay \(\Delta t\) (1s). Then the protection judged that the directional elements of No.1 main transformer and No.2 main transformer no longer act. It can be seen from Fig.5 that the bus voltage and the low-voltage side current of No.1 main transformer have a sudden change after the fault is removed. According to the above characteristics, it can be judged that the fault has been removed. The simulation results show that the substation-area backup protection can quickly and reliably remove the fault in case of line protection device failure.
4.2.2. Two-phase short-circuit fault

Fig.6 (a), (b), (c) and (d) respectively show the action results of power directional elements of the No.1 main transformer, No.2 main transformer, feeder $L_1$ and small power line $L_3$ after two-phase short-circuit occurs. Fig.7 (a) and (b) respectively show the measured bus voltage waveform and the current waveform at the low voltage side of No.1 main transformer.

It can be seen from Fig.6 that after the BC two-phase short-circuit fault occurs at 0.5s, the phase B and phase C power directional elements of No.1 main transformer and No.2 main transformer enter the zone of positive direction, the power directional elements of feeder $L_1$ do not act, and the power directional elements of small power line $L_3$ enter the zone of opposite direction, so the power directional elements can correctly judge the fault direction. According to the protection scheme, the backup protection sends a tripping signal to CBL2 after time delay $\Delta t_2$ (1s). Due to the circuit breaker CBL2 refuse to operate, it is found that the directional elements of No. 1 main transformer and No.2 main transformer are still in the zone of positive direction. It can be seen from Fig.7 that the bus voltage and the low-voltage side current of No.1 main transformer have no sudden change after the tripping signal is sent. According to the above characteristics, it can be judged that the fault still exists. According to the protection scheme, it is necessary to send a tripping signal to the bus section circuit breaker CBFD at 1.6s and then judge the action results of the power directional elements of main transformers. As can
be seen from Fig. 6 (a) and (b), the power directional element of No. 1 main transformer still points to the bus, and power directional element t of No.2 main transformer no longer acts, indicating that the fault is on bus section I or still on the $L_2$, the substation-area backup protection needs to trip the circuit breaker at the low-voltage side of No. 1 main transformer and the circuit breakers of all the outgoing lines connected bus section I at 1.7s. The simulation results show that the substation-area backup protection can quickly and reliably remove the fault when the 10kV line protection device fails, and can deal with the abnormal situation of circuit breaker failure.

![Diagram](image1)

![Diagram](image2)

Fig.6 Action results of directional elements

![Diagram](image3)

![Diagram](image4)

Fig.7 Three-phase fault on F

5. Conclusion

Aiming at the abnormal working condition that the microcomputer protection device of 10kV line fails to operate, a substation-area backup protection scheme based on the action results of power directional elements of transformer protections and other line protections is proposed in this paper, which has high feasibility and can effectively improve the reliability of 10kV line protection system. The basic conclusions are as follows:

1. The self-test information and heartbeat mechanism are used to monitor the operation status of the protection device on line. When the failure of the 10kV line protection device is detected, the substation-area backup protection scheme shall be put into immediately.
(2) It is demonstrated that the substation-area backup protection can effectively identify faults only by collecting the action results of power directional elements of transformer protections and other line protections. The scheme has low requirements for data demand and synchronization and high feasibility.

(3) Relative simulations prove that the proposed substation-area backup protection scheme can quickly and reliably identify faults, and can deal with the abnormal situation of circuit breaker failure.

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