A Design of Integrated Protection Principle for Box-type Substation

Yunchi Zhang¹, Houlei Gao¹* and Shichang Du²

¹ Key Laboratory of Power System Intelligent Dispatch and Control of Ministry of Education, Shandong University, Jinan, Shandong, 250061, China
² Shandong Lusheng Electrical Equipments Company Limited, Rizhao, Shandong, 276800, China
*Corresponding author’s e-mail: houleig@sdu.edu.cn

Abstract. Box-type substation plays a very important role in distribution network. The protection of traditional box-type substation needs to be equipped with multiple equipment, and there is often a lack of selectivity between protections of low-voltage side and low-voltage outgoing lines of transformer. In order to solve these problems, an integrated protection principle of box-type substation is proposed, which uses relay protection to replace the traditional protection form. An adaptive fault component overcurrent protection is proposed to improve the sensitivity of protection, and an operation time selection criterion is put forward to ensure selectivity and clear fault quickly in some cases. Finally, the performance of proposed protection principle is verified by PSCAD simulation.

1. Introduction
Box-type substation, also known as prefabricated substation, has the characteristics of low equipment cost, high integration, short construction and installation cycle, and is widely used in current urban power grid [1]. At present, the protection mode of load switch and current limiting fuse is mainly adopted on high voltage side of box-type transformer. On low voltage side, due to the complex connecting type and large number of outgoing lines, low-voltage circuit breakers are often configured [2]. Transformers with capacity above 800kVA, will also be configured with circuit breakers which are controlled by relay protection. Due to capacity limitations, they are mainly equipped with current instantaneous trip protection, over-current protection, and overload protection [3-5]. However, protection configuration above, especially at low-voltage side of transformer and low-voltage outgoing lines, is faced with the problem of no selectivity. When an outgoing line faults, it is easy to lead both upper and lower circuit breakers tripping at the same time, or even leapfrog tripping, which expands power failure scope and affects power supply reliability [6].

With the increasing demand for electricity, more attention is paid to reliability and power quality. The extension of power failure scope caused by lack of selectivity or improper coordination should be avoided as far as possible. Therefore, it is necessary to apply relay protection principle with time coordination in box-type substation. However, the simple use of traditional time coordination protection will cause new problems:
• When the low-voltage bus faults, it needs to be removed by the transformer's backup over-current protection, which will cause a time delay [7].
For low voltage outgoing lines of box-type substation, which are located at the end of system, fault current is generally small, and the protection often has problems of insufficient sensitivity or even refusal to operate [8].

There is not enough space to install many devices in box-type substation, which also reduces the economy.

With the continuous development of power distribution network automation, box-type substations will inevitably develop in the direction of intelligence and networking, among which the design of integrated comprehensive protection devices with powerful functions and excellent performance is very necessary [1-3]. [5] developed a set of embedded protection device for prefabricated substations, which can realize the monitoring of power quantities, temperature and humidity, transformer protection and other auxiliary functions, but did not improve the protection principle. [1] applied the digital protection and integrated control system in conventional substation to prefabricated substation, which is more comprehensive and intelligent, but occupies a large space and has complex configuration.

Based on above analysis, considering protection performance and economy comprehensively, this paper proposes a kind of integrated protection principle for box-type substation, which uses integrated relay protection device to replace traditional protections to ensure selectivity. Firstly, we analyze the fault characteristics on the low voltage side of box-type substation. Then, an adaptive fault component overcurrent protection principle is proposed in this paper, which greatly improves sensitivity. Aiming at the delay removal of low-voltage bus faults, an operation time selection criterion is put forward. Combined with time limit, it realizes a fast removal of low-voltage bus fault and also serves as the backup protection of low-voltage outgoing line, which reduces the risk of leapfrog tripping. Finally, PSCAD is used to build a model of box-type substation system, and the reliability of our protection principle is verified.

2. Fault characteristics of box-type substation

The internal electrical schematic diagram of box-type substation is shown in figure 1. It integrates three parts, high voltage incoming line, transformer and low-voltage outgoing lines into a closed box. Assuming that a fault occurs at k in figure 1 at time $t_0$ and fault removal time is $\Delta t$, the rms values of power frequency current flowing through QF2, QF3 and QF4 are shown in figure 2.

As can be seen from figure 2, when fault occurs at k, current flowing through QF4 first increases. After the fault is judged by protection, QF4 trips immediately, and the current becomes 0. When fault occurs, the bus voltage will reduce to a certain extent, which will make the current value decrease. After fault removal, the current value will increase compared with that before fault occurs as a result of self-starting process of the load. QF2 is located on the low-voltage side of transformer and current flowing through it is the sum of all outgoing lines currents. When fault occurs at 0.4kV bus, fault current only flows through QF2.
3. Improvement of protection principle

3.1. Adaptive fault component overcurrent protection

For the low-voltage outgoing line, the sensitivity of traditional over-current protection is insufficient due to the influence of load and operation mode. This paper proposes a principle of over-current protection based on fault component, which uses the change of current to design protection. Integrated protection device collects, calculates and stores the rms current value in real time. If the starting element operates at time \( t \), protection device starts to calculate the fault component \( \Delta I \), which is defined as:

\[
\Delta I = I_t - I_{t-T}
\]

where \( I_t \) is the rms value of current within the calculation period with \( t \) as the initial point, and \( I_{t-T} \) starts from \( t-T \); \( T \) is the power frequency period.

Protection criterion of low-voltage outgoing line is defined as criterion 1:

\[
\Delta I > I_{set}
\]

where \( I_{set} \) is the threshold value, which theoretically should be set as the maximum current fault component that may occur under normal conditions. However, considering that load change is not a centralized process and has discreteness in time, so \( I_{set} \) is set to 0.4\( I_N \) to avoid the impact of load fluctuation, and \( I_N \) is rated load current of the line.

In view of the self-starting process of load, combined with the convenience of collecting information provided by integrated protection, we adopt the method of self-adaptive raising threshold after fault to avoid the influence of self-starting. During normal operation, \( I_{set} \) is set to 0.4\( I_N \). When a circuit breaker trips due to fault, the setting value is temporarily raised to 3\( I_N \), and \( I_{set} \) always takes the current value before fault occurs. When the time limit of high setting value is reached, protection will return to normal operation state.

3.2. Multi-time adaptive fault component overcurrent protection

Considering the problem of time delay in removing transformer low-voltage bus fault, we propose a multi-time adaptive fault component overcurrent protection principle based on the theory in 3.1. Taking advantage of integrated protection, an operation time selection criterion is designed, which not only ensures the fast removal of low-voltage bus fault, but also can be used as backup protection of low-voltage outgoing line.

The calculation of fault component \( \Delta I \) is similar to equation (1), only the current is changed from low-voltage side of transformer, which is denoted as \( I_l \).

\[
\Delta I = I_{1,t} - I_{1,t-T}
\]

where the setting principle is the same as equation (2). After a certain delay, this protection can be used as a backup protection for the low-voltage outgoing line. Considering the cooperation with traditional overcurrent protection, time limit is set to 0.15s [6].

However, for low-voltage bus fault of transformer, we hope the delay can be as small as possible, so this paper proposes an operation time selection criterion based on current amplitude comparison combined with the principle of integrated protection, which is defined as criterion 3:

\[
C_t = \left| I_l - \sum I_{load} \right| / I_l < C_{t set}
\]

where \( \sum I_{load} \) is the sum of current amplitude of all low-voltage outgoing lines; \( C_{t set} \) is set to 0.15.
In single source system, assuming that the load power factor of each outgoing line has little difference, the amplitude of transformer low voltage side current is compared with the sum of each low-voltage outgoing line current amplitude through integrated protection device. If there is no significant difference between the two values, it indicates that fault occurs at the low voltage outgoing line. In this case, the operation time limit is set to 0.15s, and \( I_{l,t} \) always takes the current value before fault during this period. On the contrary, if there is a big difference between them, it means that fault occurs at transformer low-voltage side, and protection operates without delay.

4. Integrated protection principle design

Based on above theoretical analysis, the microcomputer integrated protection principle of box-type substation is designed as shown in figure 3. Two dashed line areas A and B are measured and controlled by the protection, and the coordination with 10kV feeder protection time limit is considered. The adaptive fault component over current protection is designed as the main protection of low-voltage outgoing line to solve the problem of insufficient sensitivity, involving area B. The multi-time adaptive fault component over current protection is designed as the main protection of transformer low-voltage side, and also as the backup protection of low-voltage outgoing line, involving area A and B. All of these are controlled by only one device, and the integrated protection process is shown in figure 4.

5. Simulation studies

In order to verify the feasibility of the integrated protection principle proposed in this paper, a simulation model as shown in figure 5 is built in PSCAD/EMTDC. Box type transformer is Dyn11 connection, 10/0.4kV, and its capacity is 800kVA. There are two induction motors with rated power of 300kW and two outgoing lines L1 and L2 with a length of 0.5km and unit impedance of 0.18+j0.39Ω/km at the low voltage side. The load on L1 is about 61 kVA, and that on L2 is about 30.5 kVA. Different fault types are set in different locations, and the protection logic proposed in this paper is implemented in PSCAD to comprehensively test the proposed protection principle.
5.1. Fault at low voltage outgoing line

In order to test the protection principle comprehensively, faults such as AB two-phase short circuit (case 1), A-phase grounding (case 2) and three-phase short circuit (case 3) are considered. These faults occur at k2 in 1.5s, and k2 is located at the end of L2. Taking AB two-phase short circuit as an example, the status of circuit breakers QF2, QF3 and QF6 and rms value of phase A current flowing through them are shown in figure 6. The operation time of circuit breaker is set to 0.1s.

Calculation results of phase A under different fault types are shown in table 1.

| System state | Protection location | criterion | case 1   | case 2   | case 3   | Setting value |
|--------------|---------------------|-----------|----------|----------|----------|--------------|
| Fault occurring | QF2      | criterion 2:ΔI_l | 536.23   | 806.26   | 843.77   | 462         |
|              | criterion 3:C_l  | 0.05      | 0.01     | 0.06     | 0.15     |
|              | QF3      | criterion 1:ΔI_l | -38.46   | -101.02  | -65.49   | 210.8       |
|              | QF6      | criterion 1:ΔI_l | 692.25   | 1017.6   | 1093.5   | 17.6        |
| Fault clearing | QF3      | criterion 2:ΔI_l | -1.33    | 41.78    | 104.14   | 3465        |

It can be seen from the results in figure 6 and table 1 that when fault occurs at k2, the fault current on QF6 satisfies criterion 1, and protection operates instantaneously. The calculation time of protection is one cycle, and operation time of circuit breaker is 0.1s, so QF6 trips and fault is cleared at 1.62s. Current of other outgoing lines decreases during the fault, and the fault component is negative, which obviously will not satisfy criterion 1. After fault removal, current on QF3 is increased by self-starting,
but our adaptive criterion can overcome this problem effectively, and QF3 does not trip reliably. In addition, current flowing through QF2 will also satisfy criterion 2, but the result of criterion 3 is 0.15s delay operation. After the delay, fault has been cleared by QF6, self-starting is overcome by adaptive criterion, and finally QF2 does not trip. We can also find that when low-voltage outgoing circuit breakers cannot trip normally, protection at QF2 can completely clear fault after 0.15s delay, which realizes the backup protection.

5.2. Fault at low voltage side of transformer

Similarly, we consider that AB two-phase short circuit fault occurs at k1 in 1.5s, where k1 is the low voltage bus. In this case, setting values of protection are the same as those in Table 1, and the results of protection calculation are $\Delta I_l = 1403.3A$, which is greater than the setting value of fault component $I_{set}$, and $C_t = 0.823$, greater than $C_{set}$. QF2 trips with no delay, which can quickly remove transformer low voltage bus fault and reduce the damage to transformer.

6. Conclusion

Aiming at the problems of scattered configuration, low economy and poor selectivity of existing protection in box type substation, this paper proposes an integrated protection principle of box type substation. This principle aims to ensure the selectivity of low-voltage side protection in box type substation, and integrates low-voltage bus protection and low-voltage outgoing lines protection into a microcomputer device, which replaces traditional protection mode in it and avoids the decline of economy and safety caused by independent protection equipment. Protection principle proposed in this paper not only ensures the selectivity, but also reduces the time limit as much as possible without affecting existing protections in system.

Acknowledgments

This work was supported by the project named “Research and development of integrated protection device for intelligent box-type substation”. (No. 2019CX2X1202).

References

[1] Crompton L., Stokoe J. (2004) Integrated control and protection solution in 33 and 11 kV package substations. In: Eighth IEE International Conference on Developments in Power System Protection. Amsterdam, Netherlands. pp. 494-497.

[2] Wang H.J., Li H.T., Ge T., et al. (2018) Research and Application of 10kV Built-in High Voltage Protection Distribution Transformer. In: 2018 China International Conference on Electricity Distribution (CICED). Tianjin. pp. 280-284.

[3] Zhang H., He J.H., Li B., et al. (2009) An improved transformer protection scheme based on integrated protection system. In: Universities Power Engineering Conference. Glasgow. UK. pp. 1-4.

[4] Grabovickic R., Labuschagne C., Fischer N., et al. (2012) Protection of transformer-ended feeders using multifunction relays. In: Pes T&D 2012. Orlando. USA. pp. 1-10

[5] Liu S.G., Rong J.W., Wang H.B. (2013) Design and implementation of integrated protection apparatus in prefabricated substation. Automation of Electric Power Systems, 27:90-93.

[6] Kong L.L., Chen X.G., Zhang X., et al. (2018) Protection Configuration Scheme for 10 kV Distribution Network Branch Line. Distribution & Utilization, 35: 21-24.

[7] Sari I.M., Tryollinna A., Sudin A.D.P. and Deka Permata D. (2017) Through fault current effects on distribution transformer and prevention actions using backup protection : Case study of Kelapa Gading transformer. In: 2017 International Conference on High Voltage Engineering and Power Systems (ICHVEPS). Sanur. pp. 247-251.

[8] Huang J.G., Ding Q., Zheng S.W., et al. (2018) A new adaptive over current protection principle based on current mutation. Power System Protection and Control, 46: 49-55.