The Effects of Arc Protection of 10-kV Switchgear Based on the Principle of Voltage Latching up

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Abstract. The reasons of the no-action of conventional protection and arc protection based on current latching up criterion when phase-to-ground fault occurs in the internal of switchgear or external cable resulting in the increase of line voltage which causes switchgear ground discharging and damages with the further development of the fault are analysed in this paper based on the accidents of the 10-kV switchgear in the substation. Therefore, it is concluded that the switchgear should be tripped when single-phase grounding happens and accompanied by arc discharging. On the basis of it, a new type of 10-kV switchgear arc protection based on the principle of voltage latching up is proposed and compared with the arc protection based on the principle of the current latching up. The results demonstrate that the new voltage latching up arc protection has higher sensitivity than arc protection based on the conventional principle of the current latching up in the 10-kV switchgear.

1. Introduction

In accordance with the regulations of China, the isolated neutral system is temporarily allowed to run for 2 hours when the single-phase-to-earth fault happens. The operation and maintenance personnel should try to find out the grounding fault within two hours and remove the failure [1]. It is shown that the energy generated by the short circuit increases exponentially when the arc is produced by insulation discharging in the switchgear and lasts for more than 100ms [2]. Therefore, it is indispensable to quickly remove the arc fault in the switchgear. As a kind of non-electric protections, 10kV bus arc protection can remove bus-bar fault quickly and accurately based on the inherent localization function of arc, which greatly reduces the degree of damage to the switchgear and slows down the impact on transformers [3-5].

Statistics suggest that the phase-to-earth faults account for more than 80% of all faults in the distribution lines, and most of the interphase faults are evolved from the single-phase fault. Therefore, the protection of grounding fault is crucial for the safe operation of power lines and even the whole power system. In the 10-kV switchgear system, there is a defect that the system will still operate when the traditional phase-to-ground fault (short circuit in the switchgear or the short circuit of the external overhead cable) happens. Phase-to-ground faults cause the increase of the phase voltage of switchgear and lead to arc discharging in switchgear. Conventional single-phase grounding protection will not act in 10kV isolated neutral system when phase-to-ground fault happens. The traditional current latching
up arc protection will not act when the arc is detected due to current locking is not open, and the phase-to-earth fault would develop into interphase fault. Then, the conventional protection acts while the switchgear has been burned out at this moment. Therefore, it is necessary to configure a new type of arc protection for the 10-kV switchgear.

2. Case analysis

In the last two years, many arc discharge accidents of switchgear have occurred. These accidents have caused huge damages to switchgears and further caused the transformer protection and line protection to trip. Two cases are listed for analysis.

Case 1:

At 20:30 in March 6, 2016, three-phase voltage unbalance was reported in 10kV bus I of Shanhe substation. The line #318 was shut off by remote control and the failure was eliminated. However, important load was switched in line #318 when three-phase voltage unbalance fault still existed. After running for 1 hour and 30 minutes, the $3 \times 14$ switchgear in 10kV bus I burst into flames. The switchgear 310 tripped under the instruction of backup protection of #1 main transformer protection. The DC loop network power supply for 10kV buses I and II disappeared, and failed to be forcibly switched in.

The #1 main transformer and #2 transformer in the Shanhe substation were in parallel operation. The two branches of the low voltage side of main transformer #1 and #2 connected with two 10kV bus respectively. Before the failure occurred, 10kV bus I is non-load (only connected with capacitors and reactors). The three-phase current of the low voltage side is 0A, the voltage of phase A is close to 0V, and the voltages of phase B and C rise to line voltage (close to 100V).

The results of the on-site inspection is: the $3 \times 14$ 10kV bus I switchgear has been burned out; the adjacent switchgear #310 and #305 were affected by the spread burning heat and smoke; a set of protection device and a set of integrated intelligent indicating device were burnt; the cabinet was blackened and totally ruined. The damage situation of $3 \times 14$ switchgear is shown in figure 1-figure 2, and the recording wave of the #1 main transformer protection are shown in figure 3.

![Figure 1. The back of the burned switchgear of 10-kV bus I.](image1)

![Figure 2. The frontage of the burned switchgear of 10-kV bus I.](image2)
Figure 3. The recording wave of #1 main transformer protection.

In the accident investigation, the cause of the accident was deduced based on the SOE message, recorded data and equipment burned on the spot. According to the inspection situation of the primary equipment and analysis of protection and fault recorder, conclusions can be drawn that the phase-to-ground fault inside the switchgear led to the burning of the 3×14 switchgear, resulting in the elevation of the voltages of phase B and C (reaching the value of line voltage). Then, the explosion of the C phase arrester of the 3×14 switchgear caused three phase short circuit. Fire and burning gradually spread upward, and destroyed the equipment in the cabinet. The backup protection of the low voltage side of #1 main transformer handled the fault correctly. Although the main transformer protection operated correctly when three phase short circuit occurred, the switchgear had been burned out and missed the best time for tripping.

Case 2:

At 13:31:22 on January 11, 2017, circuit breaker #312 of 10-kV bus I in 110kV Pingyang substation tripped under the instruction of line current protection in section I. At the same time, the differential instantaneous protection and the ratio differential protection of the #2 main transformer acted. Then, the circuit breaker #520 and #360 on both sides of the #2 main transformer tripped.

The accident caused damages to the contact on the circuit breaker #360 and part of the equipment in 110kV Pingyang, and the 10kV bus I, II, and III simultaneously suffered the voltage loss.

The photos of the accident scene are shown in figure 4-figure 6.
By checking the pile head on the phase A static contact of the switchgear #360, it is found that the static contact has been melt with the plum blossom contact of the phase A moving contact of the circuit breaker #360 (as shown in figure 4). The upper part of moving contact of the phase A in the circuit breaker has been melt, the finger spring has fallen off, and the injury of the upper left corner of the finger arm is the most serious. At the same time, obvious point discharge burned-out traces were found in some of the fixing bolts of the phase A, B, and C of the circuit breakers #360 (as shown in figure 5).

Due to the unqualified material of the phase A dynamic and static contact parts of the circuit breaker #360 and large deviation of installation position, the fever is quite serious in the contact part of the contact when large load was in operation. At 13:31 on January 11th, the phase-to-ground fault occurred in phase C of the line #312 of the Pingyang bus I (external overhead cable) and caused the abnormal rise of the voltages of the ungrounded phase. The overvoltage caused the top bolt of the upper terminal of the circuit breaker #360 to point discharge to the tip of the metal stent above the circuit breaker chamber. The differential protection of the #2 main transformer correctly operated and tripped the circuit breaker #520 and circuit breaker #360 on both sides of the #2 main transformer.

According to the pictures of the accident, it is found that the differential protection of the main transformer didn’t act at the initial stage of the arc combustion, causing serious discharge combustion phenomenon.

3. Voltage latching up arc protection and solution

The 10kV substation system is isolated neutral or neutral grounding via arc suppression coil. The two cases mentioned above are all caused by the transient grounding of external cables, resulting in the increase of the voltage inside the cabinets, resulting in the breakdown of the insulation in the switchgear, and the location of the discharge is inside the switchgear circuit breaker room. When the phase-to-ground fault occurs inside the switchgear internal or the external overhead cable transmission, the currents and the line voltages basically remain unchanged. But the phase voltages would increase, resulting in discharge to ground in the switchgear and the position of discharge generally locates in the bus room, the circuit breaker chamber and the cable chamber which would destroy the switchgear, and then developed into other faults. Based on the two cases above, conclusions can be drawn that conventional protection and conventional current latching up arc protection missed the time of tripping when failure has not developed into interphase short circuit and that it is not possible for these two protections to give the instructions of tripping in time in the above cases. However, arc protection based on the principle of voltage latching up can open the voltage latching up to trip.

3.1. Arc protection based on the principle of voltage latching up

Arc protection based on the principle of voltage latching up is a switchgear protection system which integrates bus protection and feeder protection. In the design of the protection scheme, all the switchgear bus room, circuit breaker chambers and cable chambers are provided with the arc sensor.
Once arc discharge happens in the switchgear bus bar room, circuit breaker room, and the cable room, it will immediately be detected by the arc sensor. The two-criteria of arc and voltage are applied in the arc protection based on the principle of voltage latching up.

3.1.1. Criterion of voltage locking. When a simple fault occurs, the line voltage and the zero-sequence voltage will change. In order to present the principle of voltage latching up in detail, a voltage locking action condition is defined.

\[ u_{\phi \phi} < u_{\text{set}} \text{ or } u_0 > u_{0\text{set}} \]  \hspace{1cm} (1)

Where \( u_{\phi \phi} \) is line voltage; \( u_{\text{set}} \) is the setting value of the line voltage; \( u_0 \) is zero-sequence voltage; \( u_{0\text{set}} \) is the setting value of the zero-sequence voltage.

Line voltage and zero sequence voltage are adopted as the criterion in voltage latching up. When either of them reaches the setting value, the open condition of voltage latching up is satisfied.

The logic diagram of arc protection based on the principle of voltage latching up is shown in figure 7.

**Figure 7.** The logic diagram of arc protection based on the principle of voltage latching up.

3.1.2. Analysis of the action of voltage latching up element. When a phase-to-ground fault occurs in switchgear, no matter it is the metallic single-phase grounded fault in switchgear, or the single-phase metallic and non-metallic grounded fault of feeder, zero sequence voltage will emerge. Therefore, zero sequence voltage outburst \( \Delta u_0 \) would be produced. If the traditional current latching up is adopted, the setting value of the latching up cannot be reached due to the low capacitive short circuit current and current outburst. At this time, the power supply is equivalent to a weak power supply, and the sensitivity of the current outburst on the weak power side is rather low [6].

According to the PSCAD simulation modelling, the waveform of the current and voltage of phase-to-ground fault is shown in Figure 8-Figure 10 [7].
Figure 8. The current waveform of metallic phase-to-ground fault.

Figure 9. The line voltage waveform of metallic single phase short-circuit.

Figure 10. The zero-sequence voltage waveform of the metallic single-phase short-circuit.
When the phase to phase fault occurs in the switchgear, the zero sequence loop cannot be completed because the 10kV line is isolated neutral system, but the line voltage will achieve the requirement of latching up.

When the two phase earth fault happens in the switchgear, there is zero sequence loop in the circuit. Both the zero-sequence voltage and the line voltage will achieve the condition of latching up.

When the three-phase short circuit fault occurs in the switchgear, the line voltage will be lower than $u_{\text{ph}}$, and the phase voltage can be used as the setting value.

Theoretically, no matter what kind of earth or interphase fault arises in the 10kV switchgear, the proposed arc protection based on the principle of voltage latching up which is composed of the line voltage and zero sequence voltage is able to meet the requirements of protection well.

3.2. Conventional current latching up bus arc protection

The conventional current arc protection system is consisted of the main control unit, the arc unit and the current unit [4], and the design of arc protection scheme is shown in Figure 11.

![Figure 11. Arc protection based on the principle of current latching up.](image)

To prevent misoperation, the principle of conventional current latching up adopts arc and current as double-criteria. If the over current or current outburst variables can reach the setting value, the current criterion is satisfied [8–10]. When the protective device detects arc and current at the same time, it can send out alarm signals and the command of the tripping of the related circuit breaker; When the protection device only detects the arc or the current, the protection device only emits alarm signals and will not send the command of the tripping of the related circuit breaker.

3.3. The necessity of arc protection based on the principle of voltage latching up

When single-phase metallic grounding short circuit happens on the 10kV switchgear bus, the phase current doesn’t change in 40ms and cannot meet the current requirements of opening the latching up. Consequently, the problem arises that the sensitivity of the current latching up arc protection is not enough when single-phase short circuit happens on the 10kV bus of the switchgear. When the phase-to-ground fault occurs, the voltage value of the phase A turns to zero, while the voltage of phase C increases to the times of the voltage of phase B and the three-phase line voltages remain unchanged.
[11, 12]. At this time, the low interphase voltage triggers no action command. The zero-sequence voltage is generated by phase-to-ground fault, so the zero-sequence overvoltage can meet the open requirement of the voltage latching up even if the interphase low voltage won’t cause any action command when phase-to-ground fault happens. The zero-sequence voltage rises to the maximum value in about 20ms. If the zero-sequence threshold is set to the 40% of the rated voltage, the time of action of the zero-sequence element will be less than 10ms. At present, the outlet time of arc protection is about 10ms, and the time of action of voltage latching up elements can meet the requirements of the rapid action of arc protection. When the short-circuit fault with high resistance grounding happens, there is no difference between the waveform of current and line voltage and that of the metallic short-circuit. But the relevant zero-sequence voltage is still highly sensitive, and the voltage latching up criterion is suitable for short-circuit fault with resistance grounding. The arc protection based on the principle of voltage latching up proposed in this paper is more sensitive than the arc protection based on the principle of current latching up.

When the line-to-line fault or three-phase short circuit occurs on the bus bar of the switchgear, the zero-sequence voltage won’t lead to the action command, but the low interphase voltage is highly sensitive. When the phase-phase to ground fault occurs, the low interphase voltage and zero sequence voltage are also highly sensitive. Based on the above analysis, when the line-to-line fault, phase-phase to ground fault and three-phase short circuit happens, two-phase generating cabinet, the power supply is equivalent to the strong power, current criterion in strong power supply side of high sensitivity [4]. And the current break variable and overcurrent can reach the action setting value of the arc protection. When a phase-to-ground fault occurs, the short-circuit current is a small capacitive current, and the phase current and the current break variable are very small, which cannot reach the setting value of protective action. The probability of single phase grounding fault in power system is generally greater than that of phase-to-phase fault. The arc can be produced quickly within the 1ms. The phenomenon of arcing will happen not only under the condition of low impedance short circuit, but also in the case of high impedance and low current. Once the condition of arc ignition is satisfied, arcing will also happen [13-16]. Because of the effect of air ionization, the nearby resistance will change rapidly. The arc resistance will gradually reduce to 0 ohm. Therefore, if the single-phase grounding fault causes the arc discharge which is not eliminated in time, it will quickly develop into interphase short circuit, resulting in greater loss. The current of single-phase short-circuit grounding, especially non-metallic grounded short circuit is too small for the conventional arc protection based on the principle of current latching up. Although the arc is detected by the protection device, it is mistakenly latched up because the conditions of the current don’t meet the requirements. Therefore, the conventional arc protection based on the principle of current latching up cannot quickly eliminate the short circuit fault caused by the phase-to-ground fault in the early stage. With better in reliability and sensitivity, the arc protection based on the principle of voltage latching up can complete all the tripping actions of the conventional current latching up arc protection. Voltage latching up arc protection can operate in the situation of different kinds of short circuit faults (including phase-to-ground fault), and can avoid further development of the fault.

To sum up, voltage latching up arc protection can adapt to all kinds of single-phase short-circuit or interphase short circuit faults. It can also adapt to all kinds of non-metallic short circuits, and its sensitivity is almost not affected by transition resistance. Compared with current latching up arc protection, arc protection has higher reliability and sensitivity. Especially in the case of the above cases, it’s necessary to configure voltage closed arc protection.

4. Conclusion
Based on the actual case and theoretical analysis, it is concluded that the 10kV system should be tripped when single-phase-to-ground fault occurs with arc discharge in switchgear. In the condition of single-phase-grounding fault without arc in the switchgear, the isolated neutral system is allowed to continue to operate for a period of time. An arc protection based on the principle of voltage latching
up is presented in this paper. The new arc protection of the 10kV switchgear is able to act like the traditional current latching up arc protection when the interphase short circuit fault happens, and quickly react to the phase-to-ground fault with arc discharge. Based on lots of practical cases, theoretical analysis and simulation experiments, the effectiveness of voltage latching up arc protection based on interphase low voltage and zero sequence overvoltage in 10kV switchgear is proved and the necessity that arc protection based on the voltage latching up should be configured in the 10kV switchgear is emphasized.

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Reference
[1] Electrical equipment operation and accident treatment procedures.2014
[2] Zhang Tao, Wang Junbo, Li Guowei. 10kV switchgear partial discharge detection technology research and application. High Voltage Apparatus, 2012, 48(10): 100-104
[3] Chen Yuan. Study on voltage switchgear protection pre-alarm system. 2014
[4] Huang Peng. High-speed electric arc protection system and application research. 2012
[5] Fan Jianjun. Arc Protection System and its Application in Low Voltage Switchgear and Bus Protection. 2007
[6] Lu Wenjun, Lin Xiangning, Huang Xiaobo. A novel adaptive phase selector based on fault component. Proceedings of the CSEE, 2007, 27(28): 53-58
[7] Fan Liping, Yuan Zhaoqiang, Zhang Kai. Single-phase ground fault based on wavelet transform arc model and PSCAD / EMTDC Simulation Research. Power System Protection and Control, 2011, 39(5): 51-56
[8] Li Chongfei, Chen Fan, Lu Yabin. The design of DPR360ARC arc protection system. Power System Protection and Control, 2010, 38(12): 125-128
[9] Zhang Tao. Low-voltage switchgear the arc protection systems and engineering applications based on DSP.
[10] Zhang Xiling, Yang Huixia, Jiang Guangqian. Study on key technologies of electric arc protection. Power System Protection and Control, 2013, 41(14): 130-135.
[11] He Yangzan, Wen Zengying. Power System Analysis. Huazhong University of Science and Technology Press, 2002: 202-208.
[12] Zhu Shengshi. Protection principles and techniques of high voltage power grid. China Electric Power Press, 2014
[13] Lan Huiili, Zhang Rencheng. Status and trends of switchgear internal arc fault detection method. High Voltage Engineering, 2008, 34(3): 496-499
[14] Zhou Nianchen, Zhou Chuan, Wang Qiang. Switchgear fault feature selection and diagnosis methods based on the improved Laplacian score. Power System Technology, 2015, 39(3): 850-855
[15] Li Ling, Liu Xuecheng. Medium voltage switchgear internal arc fault calculation and protective measures. High Voltage Apparatus, 2014, 50 (9): 131-138
[16] Zhang Jie, Ma Hongwei. Mine High Voltage Switchgear arc and arc detection system. Power System Protection and Control, 2013, 41 (11): 141-146