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# A Novel 10kv Switchgear Bus Arc Protection Based on the Principle of Voltage Lockout

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# A Novel 10kv Switchgear Bus Arc Protection Based on the Principle of Voltage Lockout

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**Abstract**. 10kV switchgear bus arc protection based on current lockout criterion has the disadvantage of insufficient sensitivity when single-phase fault occurred. This paper proposes a new type of 10kV switchgear arc protection on the basis of voltage lockout. The electrical characteristics of 10kV ungrounded systems of various short-circuit fault are analyzed by simulation calculation. Analysis results show that the new 10kV switchgear voltage lockout arc protection has a higher sensitivity than arc protection based on the current lockout.

## 1. Introduction

The arc generated in the short-circuit fault of the medium and low voltage busbars causes great harm to equipment and personnel, and may cause chain accidents [1]-[2]. However, according to China's current design standards for relay protection, medium and low voltage busbar systems are generally not equipped with dedicated rapid bus protection, but rely on the backup overcurrent protection of the upper component to cut off the bus short-circuit fault, resulting in a longer time to remove the fault. The data shows that when the arcing time in the switch cabinet exceeds 100 ms, the energy generated by the short-circuit increases exponentially [3]. Therefore, how to quickly remove arc faults in the switchgear becomes particularly important [4]. The 10kV busbar arc protection is a non-electrical protection [5]. Using the natural positioning function of the arc [6], it can cut off the bus fault quickly and accurately, reducing the degree of damage of the switch cabinet and slowing down the impact on the transformer. In order to prevent misoperation caused by various kinds of external light sources, such as lighting, flashlights, etc., which is caused by the arc protection during the inspection, the bus arcs adopt the double-criterion principle of arc and current generally. That is, when the arc is detected and the increase of the current is detected, it is considered that a short-circuit fault has occurred [7].

The 10kV distribution network is a neutral point ungrounded system [8]. When a single-phase ground short circuit occurs on the 10kV bus in the switchgear, although the current is very small, it still generates arcs [9]-[10]. If the arc probe can detect the arc, the current change does not reach the setting value, the arc protection will not act [11]. If the single-phase short-circuit fault is not removed at this time, the arc fault will quickly develop into an interphase short-circuit [12]. Once it develops into an interphase short circuit, it will cause a major accident. How to quickly and accurately determine the fault in the early stage of failure is worth studying [13]. However, the current-blocking busbar arc protection has the disadvantage of insufficient sensitivity. In order to solve the above problem, this paper will discuss an arc protection based on the principle of voltage lockout.

## 2. Principle of current 10kV Bus Arc Protection Current lockout and Analysis of Existing Problems

### *2.1. Current-locked bus arc protection*

The arc protection system is composed of a main control unit, an arc unit and a current unit. The arc protection design scheme is shown in figure 1.

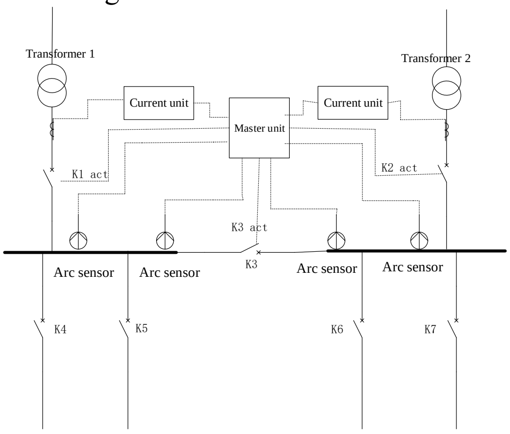


**Figure 1.** Arc protection based on the current lockout.

In order to prevent misoperation, the arc protection principle of current lockout adopts arc and current as dual criteria, and any one of the overcurrent and current abrupt changes reaches the setting value to satisfy the current criterion. When the protection device detects arc and current at the same time, the protection device will send an alarm signal and issue a command for tripping of the relevant circuit breaker; when the protection device detects only one of the arc and current, the protection device will only send an alarm signal. No breaker trip command will be issued.

### *2.2. Bus fault current and voltage variation characteristics*

For the convenience of analysis, a simple system is used as an example. The system model is shown in figure 2. Among them: T is a 110/10kV step-down transformer; S, S1~Sn are 10kV switchgear; T1~Tn are 10/0.4kV step-down transformers; Z1~Zn are loads.

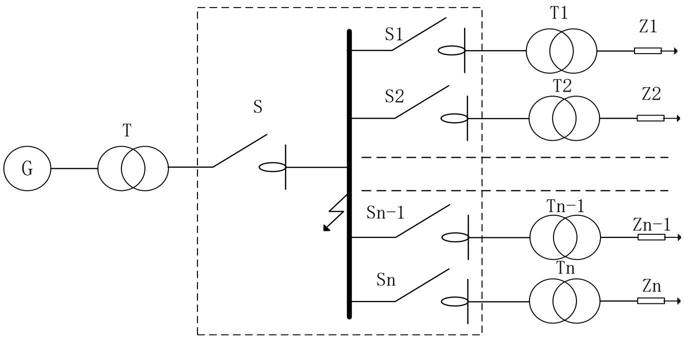


**Figure 2.** Model of simple system.

In a simple system, assuming a single-phase ground fault occurs in the a-phase bus of the 10kV switchgear. The boundary conditions are:

$$\boldsymbol{V}_{fa} = 0, \boldsymbol{I}_{fb} = 0, \boldsymbol{I}_{fc} = 0 \tag{1}$$

In the equation, $V_{fa}$ is a-phase short-circuit voltage; $I_{fb}$ is b-phase short-circuit current; $I_{fc}$ is c-phase short-circuit current.

The equation (1) can be used to calculate the fault phase current:

$$\boldsymbol{I}_f^{(1)} = \frac{3\boldsymbol{V}_f^{(0)}}{\boldsymbol{j}(\boldsymbol{X}_{ff(1)} + \boldsymbol{X}_{ff(2)} + \boldsymbol{X}_{ff(0)})} \tag{2}$$

In the equation, $I_f^{(1)}$ is the short-circuit current of the fault phase; $V_f^{(0)}$ is the short-circuit voltage before the fault; $X_{ff(1)}$, $X_{ff(2)}$ and $X_{ff(0)}$ are respectively the positive, negative and zero sequence input impedances of the short-circuit point. Because the neutral point of the 10kV line is an ungrounded system, $X_{ff(0)}$ tends to infinity, the single-phase short-circuit current to ground is zero, and the fault phase current variation approaches zero. The neutral point potential rises to the phase voltage, the fault phase voltage becomes zero, and the non-fault phase voltage rises to the line voltage.

Assuming a two-phase short circuit occurs between the b-phase and the c-phase bus of the 10kV switchgear. The boundary conditions at the short-circuit are:

$$\boldsymbol{I}_{fa} = 0, \boldsymbol{I}_{fb} + \boldsymbol{I}_{fc} = 0, \boldsymbol{V}_{fb} = \boldsymbol{V}_{fc} \tag{3}$$

Through calculation, it can be seen that the non-failure phase voltage is equal to the pre-fault voltage, and the fault phase voltage amplitude is reduced by half. Assuming a two-phase ground short circuit occurs between the b-phase bus and the c-phase bus of the 10kV switchgear. The boundary conditions for the short-circuit are:

$$I_{fa} = 0, V_{fb} = 0, V_{fc} = 0 \tag{4}$$

When a three-phase short circuit occurs in a 10kV switchgear, the short-circuit current is

$$\boldsymbol{I}_f = \frac{1}{\boldsymbol{jX}_j + \boldsymbol{z}_f} \tag{5}$$

In the equation (5), $X_j$ is the equivalent impedance of the grid to the short-circuit point; $Z_f$ the three-phase short-circuit grounding impedance.

### *2.3. Problems with current lockout criteria*

From the above analysis, it can be known that when a two-phase short circuit, a two-phase grounding short circuit, and a three-phase short circuit occur in a 10kV switchgear, the power source is equivalent to a strong power source, and the current criterion has a high sensitivity on the strong power supply side, and abrupt current and over-current can reach setting value of arc protection action. When a single-phase ground fault occurs, the short-circuit current is a very small capacitive current, and the fault phase current and the sudden change of the current are very small, failing to reach the setting value of the protection action. The probability of occurrence of a single-phase earth fault in a power system is generally greater than that of an interphase short circuit. Arc can be generated quickly within 1ms. Not only in the case of low impedance short circuit will produce arcing phenomenon, in the case of the corresponding high impedance and low current, once arcing conditions are met, arc will also be burned. Moreover, due to the effect of air ionization, it will prompt rapid changes in the resistance nearby. Arc resistance will gradually approach 0 ohms. Therefore, if the arc discharge caused by a single-phase earth fault is not removed in time, it will quickly develop into an interphase short circuit, resulting in greater losses. Current-lockout arc protection, when the single-phase short-circuit grounding, especially non-metallic grounding, the current is too small. Although the protection device detects the arc, it is erroneously blocked because the current condition does not meet the requirements. Therefore, the current-locked arc protection cannot quickly cut off the short circuit caused by the single-phase ground fault at the early stage of the fault.

## 3. 10kV switchgear voltage lockout arc protection

### *3.1. Criterion of voltage lockout*

Through the analysis of the current and voltage in the single-phase ground fault, two-phase short circuit, two-phase ground short circuit and three-phase short circuit in the 10kV switchgear, it can be found that the current lockout is not comprehensive in the 10kV switchgear. An arc protection based on principle of voltage lockout is proposed. The interphase voltage and the zero-sequence voltage will change when a simple fault occurs. To fully explain the principle of voltage lockout, a voltage lockout action condition is defined.

$$\boldsymbol{u}_{\varphi\varphi} < \boldsymbol{u}_{set} \ \text{or} \ \boldsymbol{u}_0 > \boldsymbol{u}_{0set} \tag{6}$$

Where $u_{\phi\phi}$ is the interphase voltage; $u_{\text{set}}$ is the interphase voltage setting; $u_0$ is zero-sequence voltage; $u_{0\text{set}}$ is zero-sequence voltage setting. The voltage lockout adopts the interphase voltage and the zero-sequence voltage as criteria, and when either of them reaches a setting value, the voltage lockout opening condition is satisfied. Voltage lockout arc protection logic diagram is shown in figure 3.

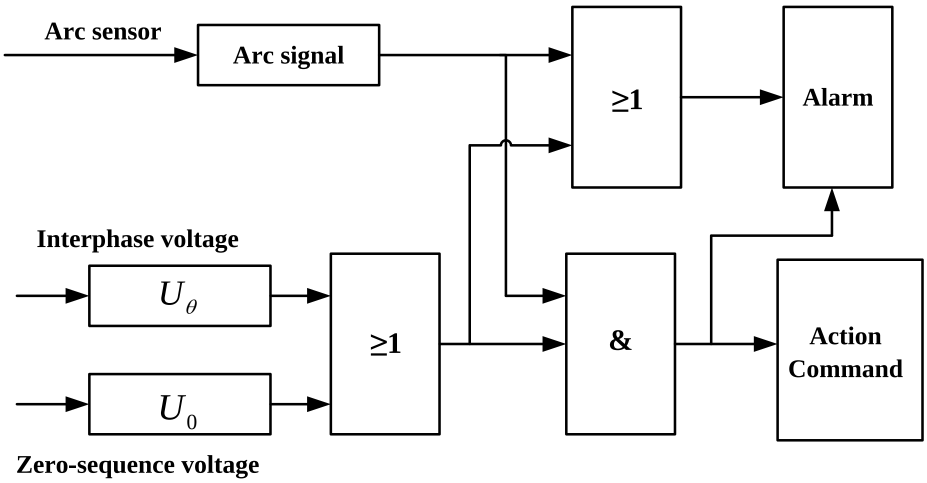


**Figure 3.** Voltage lockout arc protection logic diagram.

*3.2. Criterion of voltage lockout*

When a single-phase ground short-circuit fault occurs in the switchgear, no matter whether it is a single-phase metallic ground fault in the switchgear or a single-phase metallic or non-metallic ground fault in the feeder, a zero-sequence voltage will be generated. Therefore, there is a zero-sequence voltage mutation $\Delta u_0$. If the traditional current blocking is adopted, because the short-circuit capacitor current is very small, the current is abruptly small, and there is no overcurrent at the same time, the closed-loop setting value cannot be reached. At this time, the power supply is equivalent to a weak power supply, and the sensitivity of the current mutation on the weak power supply side is not enough [14].

When a two-phase short circuit occurs in switchgear, since the 10kV line is a neutral point ungrounded system, the zero sequence cannot form a loop, but the interphase voltage can meet the requirement of blocking. When a two-phase ground fault occurs in the switchgear, a zero-sequence loop exists in the line at this time and the zero-sequence voltage $u_0$ can reach the locked condition, and the interphase voltage can also reach the latched condition. When a three-phase short-circuit fault occurs in the switchgear, the interphase voltage can reach $u_{\phi\phi}$, and the interphase voltage can be used as the setting value of the action.

Theoretically, regardless of what type of short-to-ground or interphase fault occurs in the 10kV switchgear, the proposed arc-based voltage protection principle consisting of interphase voltage and zero-sequence voltage can well meet the protection requirements.

## 4. Simulation verification

Create the model shown in figure 4 in PSCAD [15] according to the schematic shown in figure 2. The model specification and the specific parameters of each component are as follows:

Model consists of synchronous generator, 110/10kV step-down transformer, circuit breaker, busbar, fault module, 10/0.38kV step-down transformer, load and line composition. The rated phase voltage of the generator is 63.510kV, the iron loss resistance is 300 ohms, the mechanical torque speed is 3600r/min; the capacity of the 110/10kV step-down transformer is 100MVA; the capacity of the 10/0.38kV distribution transformer is 50MVA.

In the process of PSCAD simulation, the fault occurrence time is set to 0.2s, and the fault duration is 0.2s. Figure 5- figure 10 show the phase current, line voltage, and zero-sequence voltage waveforms when the bus in the 10kV switchgear fails.

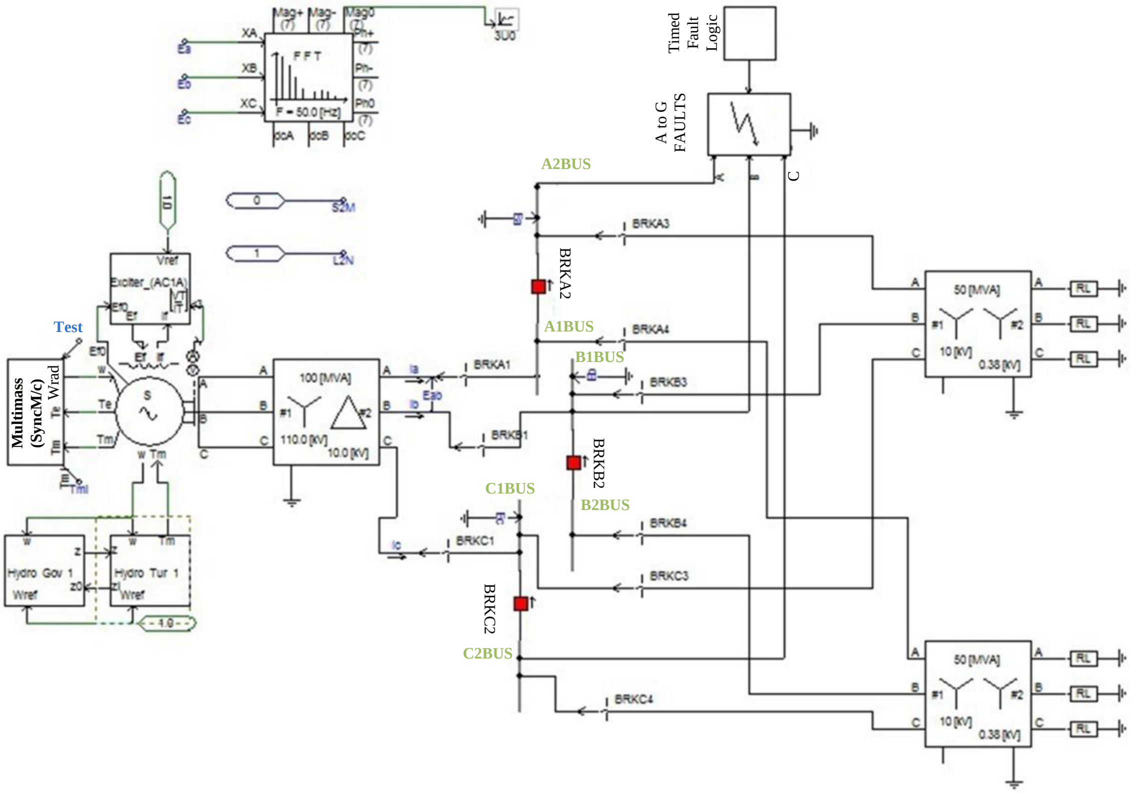


**Figure 4.** 10kV switchgear bus fault simulation model.

### *4.1. Single-phase metallic short circuit*

In the PSCAD simulation, a metal-to-ground short circuit is set to the a-phase bus. Short-circuit current and voltage waveforms are shown in figure 5, figure 6, and figure 7, respectively.

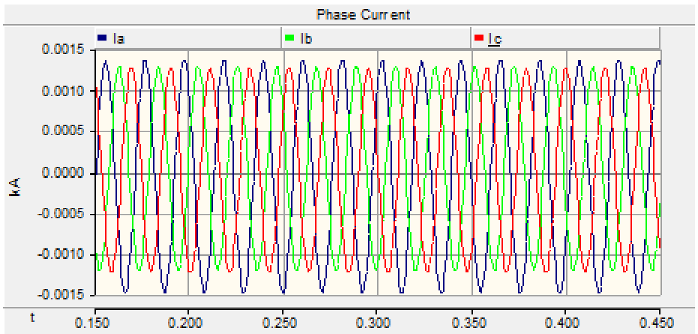


**Figure 5.** Single-phase metal short-circuit phase current waveform

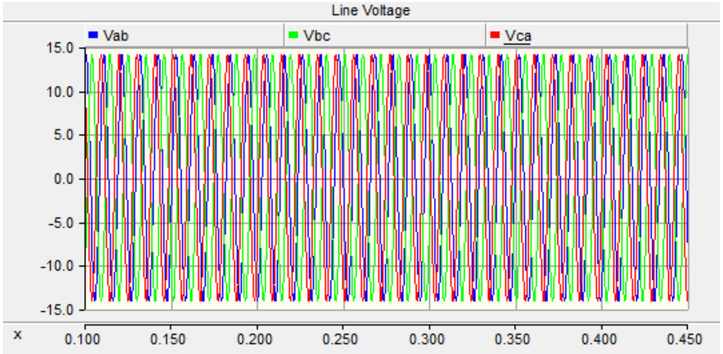


**Figure 6.** Single-phase metal short-circuit line voltage waveform

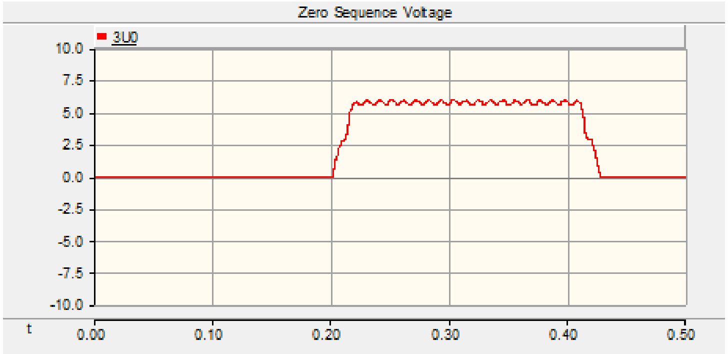


**Figure 7.** Single-phase metal short-circuit zero-sequence voltage waveform

*4.2. Single-phase non-metallic short circuit*

In the PSCAD simulation, a non-metallic high-resistance grounding short circuit is set to the a-phase bus, and a 400 ohm resistor is used instead of the high-resistance in the PSCAD. Short-circuit current and voltage waveforms are shown in Figure 8, Figure 9, and Figure 10, respectively.

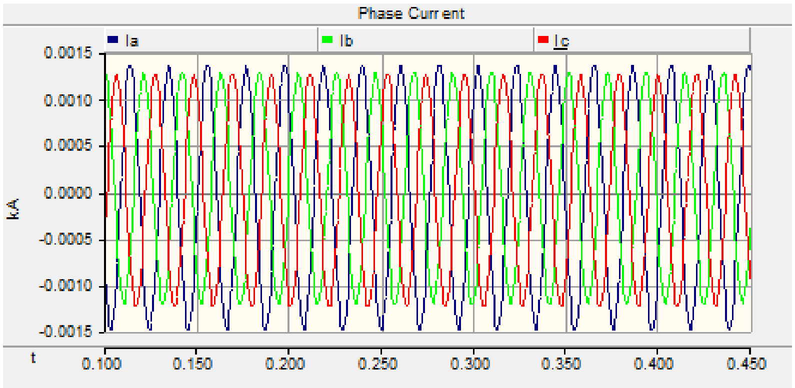


**Figure 8.** Single-phase non-metal short circuit phase current waveform

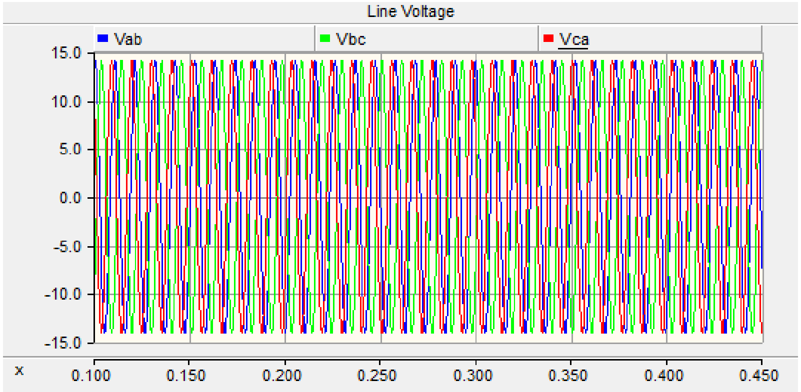


**Figure 9**. Single-phase non-metal short circuit line

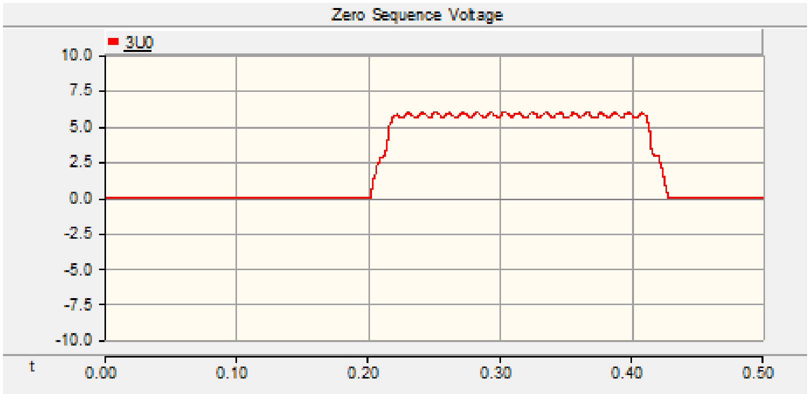


**Figure 10.** Single-phase non-metal short circuit zero-sequence voltage waveform

### *4.3. Single-phase non-metallic short circuit*

Table 1 lists the phase current, line voltage and zero-sequence voltage values of the bus in the 10kV switchgear under the other three short-circuit conditions.

**Table 1.** Other short circuit current, line voltage, zero sequence voltage data tables

| Short circuit type. | Phase current （kA） | | | line voltage （kV） | | | zero sequence voltage （kV） |
|---|---|---|---|---|---|---|---|
| | $I_a$ | $I_b$ | $I_c$ | $U_{ab}$ | $U_{bc}$ | $U_{ca}$ | $3U_0$ |
| two-phase short circuit （Phase b and Phase c） | 0.0013 | 36.6 | 36.6 | 10 | 0 | 10 | 0 |
| two-phase grounding short circuit（Phase b and Phase c） | 0.0013 | 36.8 | 36.8 | 10 | 0 | 10 | 3 |
| three-phase short circuit | 41.1 | 41.1 | 41.1 | 0 | 0 | 0 | 0 |

According to the simulation results, when a single-phase metal-to-ground short circuit occurs in the 10kV switchgear, Figure 5 shows that the phase current does not change within 40ms of the short circuit and the current cannot meet the requirements for open blocking. Therefore, there is a problem that the current lockout arc protection is insufficient sensitivity in the single-phase grounding short circuit of the bus in the 10kV switchgear. Figure 6 shows that in the event of a single-phase-to-ground short-circuit fault, the A-phase voltage becomes 0, and the B-phase C-phase voltage rises 3 times and the three-phase line voltage remains unchanged. At this time, the interphase low voltage does not act. Figure 7 shows that the single-phase ground short circuit produces a zero-sequence voltage, so that although the interphase low voltage does not act when a single-phase ground fault occurs, the zero-sequence voltage overvoltage meets the voltage lockout open requirement. In addition, as can be seen from Figure 7, the zero-sequence voltage rises to a maximum of only about 20ms. If the zero-sequence threshold is set to about 40% of the rated voltage, the zero-sequence element operation time is less than 10ms. At present, arc protection outlet time is generally about 10ms, and the action time of the voltage blocking element satisfies the requirement of rapid protection of arc protection. Figure 8 and Figure 9 show that the high-resistance grounding short-circuit has little difference between the current waveform and the interphase voltage waveform and the metallic short-circuit, but the zero-sequence voltage still has high sensitivity, and the voltage lockout criterion can adapt to the fault that is grounded by the transition resistor. It can be seen from the simulation results that the voltage lockout arc protection proposed in this paper has higher sensitivity than the current blocking arc protection.

From the data analysis in Table 1, when two-phase short circuit or three-phase short-circuit occurs in the busbar of the switchgear, although the zero-sequence voltage will not act, the interphase low voltage has high sensitivity. A two-phase ground short circuit occurs, and the interphase low voltage and zero-sequence voltage have high sensitivity. In summary, the simulation results verify that the voltage blocking arc protection can adapt to various single-phase short-circuit or inter-phase short-circuit faults, and can adapt to various non-metallic short-circuits, and its sensitivity is hardly affected by the transition resistance. Compared with current lockout arc protection, it has higher reliability and sensitivity.

## 5. Conclusions

In the 10kV switchgear, the traditional current-locked arc protection is normally blocked in two-phase, two-phase grounding and three-phase short-circuit. But in the event of a single-phase earth fault, the short-circuit current is too small to set the protection operation value. Excessively high operating values result in reduced sensitivity of the protective action. In the initial phase of a single-phase ground fault, the current lockout element cannot be opened and the fault cannot be quickly removed. This will cause the fault to expand and upgrade, so there is a certain defect in the current lockout element. In this paper, an arc protection based on the principle of voltage lockout is proposed. In the 10kV switchgear, this new type of arc protection can act in the same way as the current lockout arc protection in the case of interphase short-circuit faults, and it can also act quickly in single-phase earth faults. In this paper, the theoretical analysis and a large number of simulation experiments demonstrate the effectiveness of voltage-locked arc protection based on interphase low voltage and zero-sequence overvoltage in a 10kV switchgear.

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