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Research on Single-Phase to Ground Fault Simulation Base on a New Type Neutral Point Flexible Grounding Mode

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ABSTRACT There are some problems existing in the traditional grounding mode of the distribution network. To solve them, this paper proposes a flexible grounding method for neutral point. This paper analyzes the advantages and the disadvantages of single-phase ground faults occurring at different neutral grounding points and summarizes the characteristics of several existing grounding arc elimination technologies for distribution networks. Depending on the actual data of a 10-kV substation, the ATP-EMTP was used to build a 10-kV distribution network model, and an arc model based on arc length control was used for single-phase ground fault simulation. According to the simulation results, it was known that the overhead line network of arc suppression coils was compared. Permanent ground faults occur in pure cable networks which are grounded by small resistances. Flexible grounding systems have significant benefits in suppressing the inrush currents at fault points when an intermittent arc single-phase-to-ground fault occurs, the flexible grounding system causes intermittent arcing. The voltage is clearly inhibited. The flexible grounding method has certain reference value for improving the reliability of distribution network power supply and providing the safe operation of the system.

INDEX TERMS Flexible grounding, arc suppression coil, ineffective grounding system, arc ground overvoltage.

I. INTRODUCTION

Distribution network is the terminal of a power system which has complex structure, frequent earthing faults, wide variation range of ground parameters and fault parameters. Besides, it is difficult to predict the operation status and fault status. Over the years, there is still no comprehensive solution for the fast treatment and overvoltage in distribution network, and there is no effective suppression of grounding fault [1]–[3].

In order to run and operate normally, ordinarily, it is necessary to connect the neutral point of the power system to the earth. Investigation shows that about 85% of the faults in distribution network are single-phase grounding faults [4]. Therefore, the connection mode of the neutral point in power system is generally distinguished by the fault current when the single-phase grounding short-circuit fault occurs in the system. There are two grounding modes: large current grounding system and ineffective grounding system. Nowadays, in China, distribution networks with voltage levels below 35kV are mostly ineffective grounding systems.

In the research of neutral grounding mode in low current grounding system, some scholars believe that neutral grounding mode can be adopted [5], [6]. This mode which is simple to operate has small displacement voltage of neutral point. However, when single-phase grounding fault occurs, it can not extinguish arc by itself, which will lead to more serious accidents and it can not guarantee the reliability and safety of power supply.

Some scholars also believe that the current flowing through the grounding point increases significantly when single-phase grounding fault which is caused by the soar of cable

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susceptibility in urban distribution network occurs [7]. And they also believe cable faults are mostly permanent faults. Therefore, it is suggested that small resistance grounding mode would be used in distribution network [8]. Although this method has a good restraint effect on arc grounding overvoltage with an improved accuracy of fault line selection [9], the reliability of the power supply system is reduced greatly because of the way of removing the fault line, and the high current at the fault point may also expand the accident and cause new safety problems.

Other scholars believe that the small resistance grounding mode is not a wise choice for the distribution network. Because if the distribution network is dominated by overhead lines and the number of grounding faults is frequent, the annual trip rate will be significantly increased by adopting small resistance grounding mode [10]. The small current grounding method compensated by arc suppression coil can equalize the fault current [11], which makes the grounding arc easy to extinguish. In practical application, the problem of arc suppression coil is also very prominent: the traditional arc suppression coil can not compensate the harmonic and high frequency components in the residual current of the fault, which makes it difficult for the arc to extinguish itself and realize arc suppression in single-phase grounding fault.

In order to avoid the defects caused by traditional arc suppression coil, some scholars have proposed that a new type of arc suppression coil grounding compensation method based on power electronic components can be adopted. When single-phase grounding fault occurs, the power electronic switch module will be controlled to turn on the circuit and the arc suppression coil will be put into operation, so that the inductance current can be adjusted without error [12], [13]. However, this grounding mode will greatly increase the cost of distribution network construction.

For the small current grounding mode compensated by arc suppression coil, some scholars have analyzed the compensation's principle of arc suppression coil, summarized several common principles of automatic tracking full compensation arc suppression coil, analyzed their respective advantages and disadvantages and application situation, and given the principle of realizing full compensation under various operating conditions in view of the existing problems [14], [15]. Some scholars [16] emphatically analyzed the control strategy of arc suppression coil ground star power electronic transformer, but the above literature did not solve the problem of arc's reliable extinguishing.

For the treatment of grounding fault arc, some scholars [17] proposed a modeling method and harmonic optimization strategy of two-stage saturated magnetron reactor with arc suppression coil. Some other scholars [18] put forward the concept of electromagnetic hybrid flexible grounding distribution system, which not only has arc extinguishing function, but also can select, locate and isolate permanent single-phase grounding fault. On the basis of unbalanced voltage flexible suppression method [19], some scholars have proposed a flexible zero-sequence voltage control method [20], a future multi-port flexible interconnection device (FID) [21] based on modular multi-level converter (MMC), and a flexible arc suppression device based on three-phase cascaded H-bridge (CHB) converter [22]. However, the design of key parameters in flexible grounded distribution system has not been thoroughly analyzed or discussed in the above research.

This paper presents a comprehensive flexible grounding mode. It combines the characteristics of arc suppression coil and small resistance grounding mode. By judging the fault type of fault detection technology, the delay input time is set to control its working mode. The advantages of small resistance to suppress transient overvoltage and compensation current of arc suppression coil are brought into full play, so that this grounding mode can be used more flexibly in different transmission networks. The reliability and safe operation ability of power supply in the system can be improved.

II. FLEXIBLE GROUNDING MODEL IN DISTRIBUTION NETWORK

Neutral point flexible grounding technology is based on the traditional grounding mode, considering that some resistances are connected in series or in parallel on the arc suppression coil, and it will be put into operation after a certain delay in the event of a fault. At the same time, the advantages of the arc extinguishing coil grounding and the resistance grounding are acquired, and the disadvantages are compensated by each other.

Compared with the traditional mode of grounding by parallel resistance of arc suppression coil at neutral point, the required equipment of this mode cost is higher and need certain control strategy. However, its good fault response makes it suitable for the important distribution network with high reliability and safety requirements.

Its structural schematic is given in Fig 1.

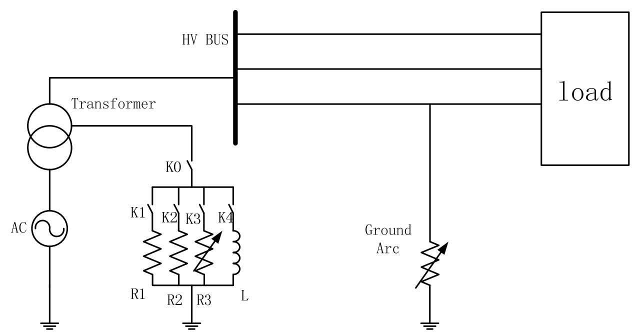


FIGURE 1. Neutral composite flexible grounding system structure diagram.

According to the schematic diagram, k0∼ k3 is the power electronic control switch, and the neutral ground mode is controlled by system detection fault current and system parameters.R1 is 0∼20 Ω small resistance, inhibiting the transient overvoltage and avoiding fault point current is too large. R0 is 1500 Ω big resistance which can prevent the neutral point voltage virtual ground [23]. R2 is 5~500 Ω adjustable selecting resistance.

In normal operation, k_0, k_1 and k_2 are closed, k_3 and k_4 are disconnected, and the system is in the state of brotherly controllable resistance grounding.

When a single-phase grounding fault occurs, k_2 is delayed to disconnect, k_4 is closed in due time, and the arc suppression coil is put into operation. The system should be switched to a large resistance and parallel connection of the arc suppression coil to deal with the working state.

When a permanent ground fault is determined, k_1 is disconnected for a certain time, and a resistor is connected to limit transient overvoltage at the fault point. After a period of time, the k_3 switch is closed and the selected line resistance R_2 is put into operation. When necessary, k_0 is disconnected to make the neutral point enter an ungrounded state and carry out relay protection action or troubleshooting.

When the intermittent arc grounding occurs, k_1 is cut off, k_2 and k_3 are put in at the right time, and the k_4 switch is closed to select fault lines. The equivalent circuit is shown in Fig 2.

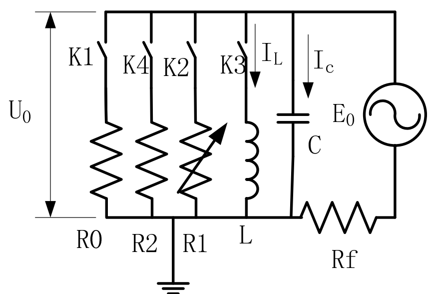


FIGURE 2. Flexible grounding system equivalent circuit diagram.

When the system is operating normally, the neutral point displacement voltage is

$$U_0 = \frac{U_{00}}{\sqrt{d^2 + v^2}} \tag{1}$$

where d is the system damping rate.

v is Arc suppression coil detuning.

U_{00} is consequence of unbalanced phase-to-ground voltages.

In this grounding system

$$d = d_0 + d_R + d_L \tag{2}$$

where d_0 is d_0 is fundamental damping ratio;

$d_R = {}^1/_{\omega C R_0}$, ω is rotational frequency;

R_0 is resistance in parallel with the arc suppression coil;

d_L is damping factor of coil, generally negligible.

During normal operation, when the resistance in parallel with the arc suppression coil is 20Ω, how to adjust the R_1 resistance is depending on system conditions. This can make the system has a higher damping rate and avoids ghost grounding. When a single-phase ground fault occurs, the neutral point is grounded by a small resistance-reducing coil in parallel with the arc suppression coil, which can fully release the energy at the grounding time and reduce its transient overvoltage. After the system delays access to large resistors, $R0 = R1 + R2 = 1520\Omega$, which can make d smaller. The fault recovery voltage initial speed is

$$v_0 = U_{pmh} \frac{\omega}{2} \sqrt{d^2 + v^2} \tag{3}$$

where U_{pmh} is phase voltage amplitude.

τ means recovery time of fault phase recovery voltage, is calculated by:

$$\tau = \frac{2}{\omega} \times \frac{1}{\sqrt{d^2 + v^2}} \tag{4}$$

The smaller damping rate can reduce the initial speed of the fault phase voltage recovery and prolong the voltage recovery time, thereby, the reduction of the probability of occurrence of intermittent arc grounding, and reasonable adjustment of the damping ratio will not lead to too high neutral point displacement voltage.

III. SIMULATION OF SINGLE-PHASE GROUNDING FAULT IN DISTRIBUTION NETWORK

The system is composed of three feeders. This wiring mode is commonly used in the current distribution system. The transformation ratio of the main transformer T is 110/10kV. The high voltage side is connected with an unlimited power supply. In order to study the fault characteristics, under different line conditions, three different line conditions are set for system outgoing line: overhead line, cable line, overhead line and cable hybrid line. L1 is overhead line, L2 is cable line, and the length is 15km respectively.

TABLE 1. Overhead line parameter.

Overhead line	R	L	C
Positive sequence parameter	*0.17Ω/km*	*1.21mH/km*	*9.7nF/km*
Zero sequence parameter	*0.23Ω/km*	*5.48mH/km*	*6.0nF/km*

TABLE 2. Cable route parameters.

Cable line	R	L	C
Positive sequence parameter	*0.193Ω/km*	*0.322mH/km*	*308nF/km*
Zero sequence parameter	*1.93Ω/km*	*1.127mH/km*	*203nF/km*

L3 is an association of overhead line and cable. The cable length is 5km and the overhead line length is 10km. System for capacitive current was about 70A, 150A, 100A, arc suppression coil compensation degree was 8%, small resistance grounding resistance tolerance in 0 ~ 20Ω, this article takes 15Ω. As shown in table 1 and table 2, actual system load difference is bigger, but for single-phase grounding fault current the impact is not big, thus to simplify the load, load impedance with $Z_L = 400 - 20j$, in the model using the star connection RLC simulation module. According to the energy balance of the arc gap theory, this paper uses an arc model based on reference [24]. Considering the effect of arc length parameter on main arc parameters, this model can be flexibly applied to resonant grounding system, and small resistance grounding system as well. The single phase grounding fault simulation model of 10kV distribution system is shown in Fig 3.

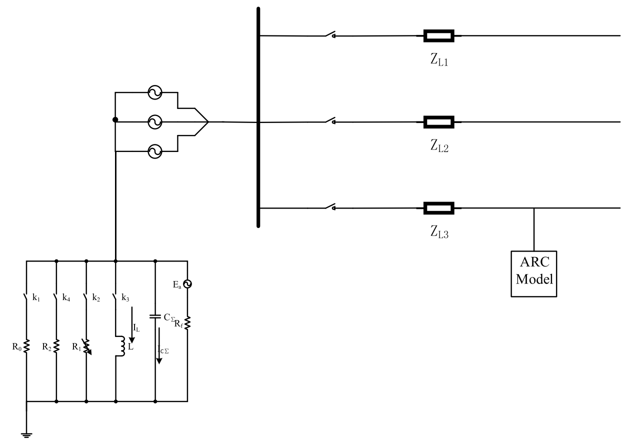


FIGURE 3. Single phase ground fault model for 10kV distribution network system.

IV. SIMULATION RESULTS AND DISCUSSION

A. OUTLINE OF THE ARC MODEL

The arc model is the cybernetic model [23]. It is a combination of Mayr model and Cassie model. The cybernetic model introduces the length of the arc to the cybernetic model, because the Mayr model and the Cassie model do not contain this critical parameter. And the Cybernetic model is defined in (5).

$$\frac{dg}{dt} = \frac{1}{\tau_c}(G_c - g) \tag{5}$$

$$P_{loss} = i^2 G_c \tag{6}$$

where i is the current of arc, G_c is the conduction of arc in steady-state, and it is defined in (7).

$$G_c = \frac{|i|}{V_c \cdot L_c} \tag{7}$$

where V_c is the field strength of arc column, L_c is the length of arc, and the I_c is the maximum current of arc.

In a real single-phase grounding fault, the length of arc is variable, in order to simplify the model and ignore the progress of the development of arc, the most desirable Lc is 100 cm. And the Vc which is $2.85*10^{-5}$ is constant. The value of Ic in this model selects the maximum current value of the single-phase ground fault model used in this paper, and Ic = 1.86 kA.

$$\tau_c = \beta \frac{I_c}{L_c} \tag{8}$$

where β is based on the empirical value of $2.85*10^{-5}$, therefore the time is constant, $\tau_c = 5.30\times10^{-4}$ s.

B. PERMANENT METAL GROUND FAULT SIMULATION

Some analysis show that the single phase ground fault and fault line selection process are influenced by many factors such as short-circuit time, network structure, line length, location of the grounding point and arc resistance. The single phase ground fault occurs when the transient voltage is close to the maximum value of the transient zero-sequence current, or when the phase voltage is near the zero-crossing point. Set the random location of phase A of the hybrid L2 hybrid line (set to 5km), take the ground fault at the peak phase of phase A of the fault phase, and set the Arc time constant of 5.30×10^{-4} s, the length of the arc of 100 cm. The simulation results are presented in Fig 4, analyzing the flexible grounding system for permanent grounding is a fault condition. Separate transmission networks are set up, and different ground fault locations are compared with the overhead line network via the arc suppression coil grounding system. The cable line network compares to a small resistance grounding system. The results are presented in table 3 and table 4.

C. INTERMITTENT ARC GROUND FAULT SIMULATION

The frequency arc extinguishing theory is based on the assumption that single phase frequency voltage peaks when the power frequency voltage reaches the peak. The switch controls the time of arc reignition, the first arcing and arc extinguishing time is tcl = 0.02s, top = 0.03s; the second time is tcl = 0.04s, top = 0.05s; the third time is tcl = 0.06s, top = 0.07s. The system experiences three phases of ground arcing in Phase A and zero extinction of zero frequency current. The simulation results of the three-phase overvoltage of each grounding system are illustrated in Fig.5.

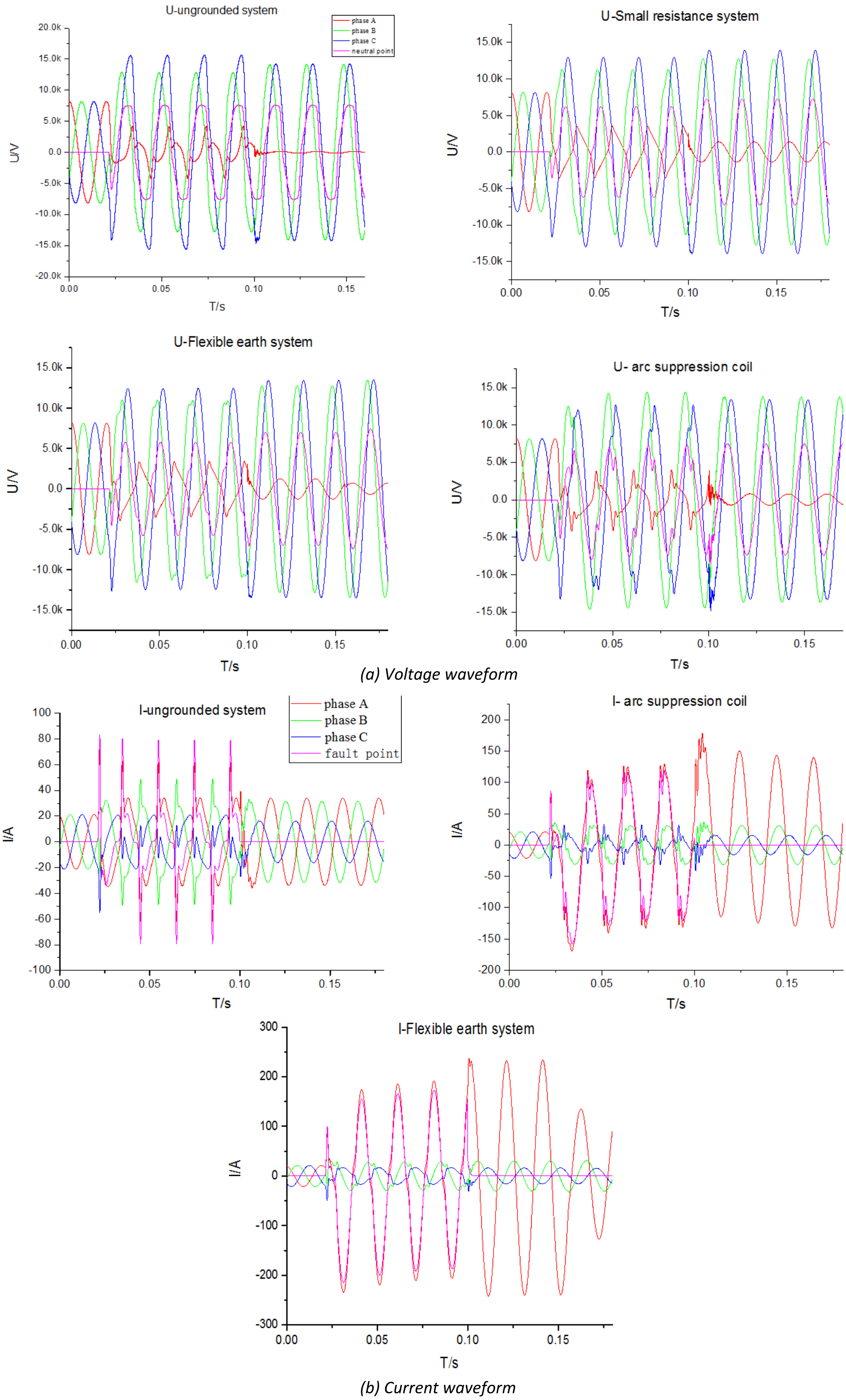
To analyze the influence of the randomness of the arc fault in the flexible grounding system, setting the arc parameters of different integrated time remain constants and dissipated power, and comparing them with ungrounded systems. The results are presented in Table 5 and Fig 6.

D. ANALAYSIS AND DISCUSSION

The study of ground fault characteristics mainly includes fault current, transient voltage and variation.

Compared with traditional grounding single phase ground fault, metallic single-phase fault, when it happened in hybrid power line network, has a maximum of 242.02A flexible point grounding way, running system with fault phase current stability of a maximum of 133.68A, 137A is lower than the average arc suppression coil. Flexible ground system has more benefits in overvoltage limitation. The maximum non-fault phase overvoltage of the system is 13.487kV, and the faulty phase runs stably with the line voltage.

In the distribution network, the location of permanent ground fault in discrete transmission lines will also have a great influence on the system. By comparing overhead lines, the failure of cable lines at 5km and 10km is contrasted.



(a) Voltage waveform

(b) Current waveform

FIGURE 4. **Four types of grounding simulation of the current and voltage.**

TABLE 3. Permanent ground fault parameters of flexible grounding system in different transmission line networks.

(A)

Parameters Conditions	Pure overhead line		Cable line	
	fault at 5km	fault at 10km	fault at 5km	fault at 10km
Neutral overvoltage peak/kV	7.877	7.392	8.051	8.007
Three-phase over-voltage peak/kV	13.53	13.31	13.88	14.01
Fault current/A	145.3	96.59	171.2	152.3

Single phase grounding fault parameters at different positions of different power transmission lines in flexible grounding system

(B)

Parameters Conditions	Pure overhead line Suppression coil		Cable line Small resistance	
	fault at 5km	fault at 10km	fault at 5km	fault at 10km
Neutral overvoltage peak/kV	8.396	7.557	6.813	6.555
Three-phase over-voltage peak/kV	14.62	14.09	12.89	12.77
Fault current/A	187.8	169.4	217.8	210

Single phase grounding fault parameters at different positions of different power transmission lines in Arc suppression coil and small resistance to ground.

TABLE 4. Flexible ground single phase grounding fault parameter drop.

Parameters Conditions	Compared with Suppression coil (Pure overhead line)		Compared with Small resistance (Cable line)	
	fault at 5km	fault at 10km	fault at 5km	fault at 10km
Neutral overvoltage peak drop	6.18%	2.54%	-17.6%	-22.15%
Three-phase over-voltage peak drop	7.45%	5.54%	-7.68%	-9.63%
Fault current drop	22.6%	43%	20.9%	27.48%

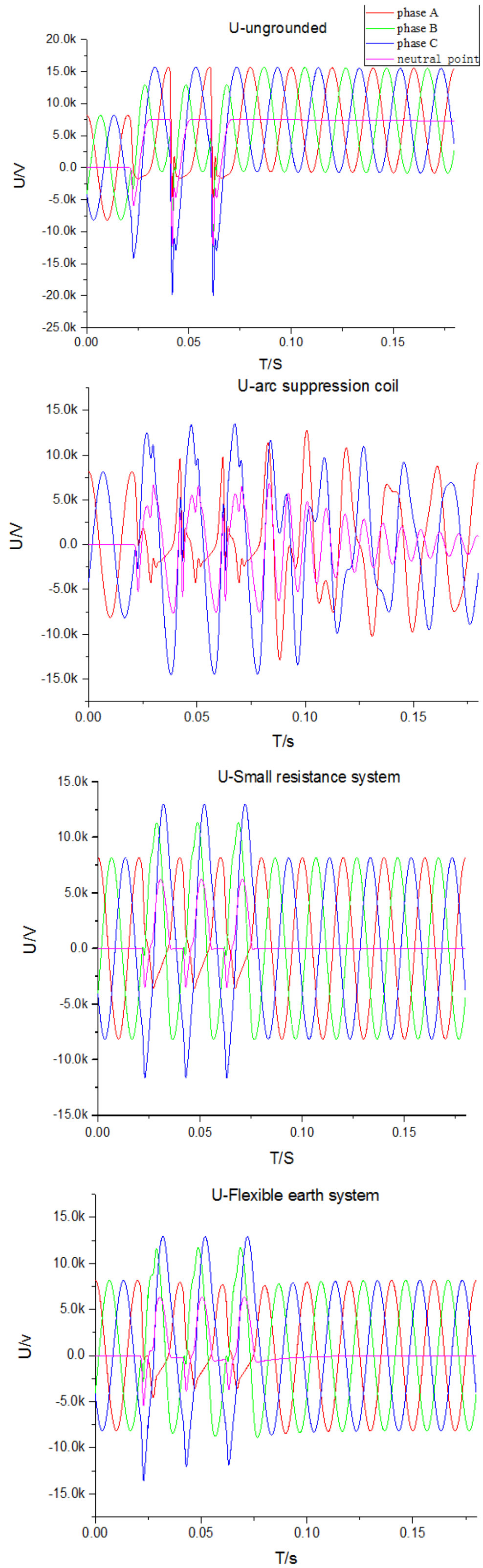


FIGURE 5. Simulation of current and voltage waveforms.

Compared with the overhead line network via arc suppression coil grounding system, the flexible grounding system has obvious advantages in suppressing the impact on current at fault point, the average fault point influence current of overhead lines decreased by 32.8% and that of cable lines decreased by 24.19%. Recovery speed of fault phase voltage

TABLE 5. 10 kV system intermittent arc grounding three-phase overvoltage data.

Rekindling time /ms Grounding mode	Three-phase maximum overvoltage /kV			
	Un-grounded	Arc suppression coil	Small resistance	Flexible grounded
1 Reburn to 2 Reburn	14.124	13.339	12.975	13.562
2 Reburn to 3 Reburn	19.904	14.202	12.972	12.097
3 Reburn	19.909	14.677	12.979	11.858

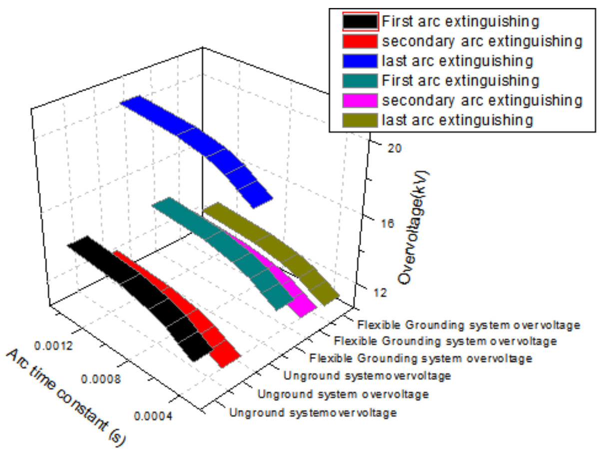


FIGURE 6. Intermittent arc overvoltage value of grounding system under different arc length parameters.

was reduced by small resistance switching and arc suppression coil compensation system. The over-voltage suppression level of fault was preferable to that of arc suppression coil, with a decrease of about 4.21%.

With the simulation results of intermittent arc grounding, the system has different response capability with different neutral grounding modes. Two power frequency arcs extinguishing failures and three reunited intermittent earth failures occurred, and the ungrounded neutral system had the most serious overvoltage problem, with the maximum overvoltage of 19.909kV and the overvoltage multiple of 2.5times. The neutral point which is grounded by arc suppression coil follows behind the ungrounded neutral system. Maximum overvoltage is 14.677kV, and the overvoltage multiple is 1.79times. Maximum overvoltage of the resistance ground system is about 12.97kV, and the overvoltage multiple is 1.58times. If more power frequency blowouts and rekindling failures occur, the system may accumulate a higher level of isolated ground overvoltage. Maximum overvoltage of flexible ground fault system is 13.562V(after the input of line selection resistance), and the overvoltage multiple is 1.6 times.

Compared with the ungrounded system, the maximum three-phase overvoltage is decreased by 38%. Compared with the intermittent arc grounding in the ungrounded system, the springy earth system has a very obvious inhibitory effect on the intermittent arc grounding overvoltage. With arc extinguishing and reignition, the accumulated charge of the system increases the overvoltage level continuously, and the increase rate of overvoltage of an ungrounded system is about 37.82%. If it is not eliminated, the power grid will be greatly impacted and it will take time to recover. The flexible ground system reasonably uses small-resistance to release the accumulated fault charge, and then uses arc suppression coil compensation to eliminate arc. The arc reignition overvoltage showed a decreasing trend, to 11.32%.

Due to the fact that the switching devices might be refused to move or turn to false operation in actual engineering, the working state of the grounding mode will be directly affected. Therefore, in the next research, fuzzy reasoning algorithm and other evaluation algorithms will be considered to evaluate and select the influence of neutral ground mode on power supply reliability of distribution network, and verify the reliability advantage of this mode.

V. CONCLUSION

Based on the analysis of the advantages and disadvantages of traditional grounding mode of single phase earth fault, a combination of arc suppression coil and small-resistance of flexible grounding mode which is built by the simulation soft ATP-EMTP, into an arc fault model of arc length control theory, power single phase earth fault simulation analysis, as to conclusions:

1) The combination of Mayr arc model and Cassie arc model can correctly simulate the actual working conditions in a hybrid distribution network.
2) When the gold attribute permanent ground fault occurs, the flexible ground system is superior to the traditional neutral ground mode for restraining fault current and neutral overvoltage.
3) When intermittent arc grounding occurs, the flexible grounding mode is superior to the suppression of neutral overvoltage. Non-fault phase overvoltage and fault point shock current.
4) By calculating and comparing the recovery speed of fault phase voltage of different grounding modes, flexible grounding modes release charge energy with small-resistance and arc suppression coil which can reasonably compensate current and reduce arc rate.

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