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New Residual Current Compensation Method for Single-Phase Grounding Fault in Power Network Based on Capacitive Current Detection and Analysis

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Abstract

Residual current compensation problem in power network was focused on with the increases of city distribution network capacity, city distribution network nonlinear load and cable line. Based on the analysis of the single-phase grounding fault system, the sources of the resistive and harmonic components in harmonic voltage and current were analyzed, and the influences of harmonic source types and fault point position on them were discussed theoretically. The measuring principle and steps of capacitive current detection in coal mine power network were given. Based on the analysis of the grounding current detection results of XieQiao coal mine, the conclusion that harmonic components of grounding current are dominated by higher harmonics for coal mine power network system with complex harmonic sources was obtained. A new thought of residual current prediction, the selections of model and control method were proposed on this basis finally.

Key words

Residual current compensation, Capacitive current detection, Full compensation arc suppression coil, Zero sequence voltage detection

1. Introduction

Resonance grounding method meets the requirements of reliability and safety for the operation of power network, and has broad prospects [1-4]. Resistive current and harmonic current components of ground residual current increase with the increases of city distribution network capacity, city distribution network nonlinear load and cable line. Traditional arc suppression coil can't compensate resistive current and harmonic current components of ground residual current. These components may cause that residual current isn't controlled within a reasonable and proper range, which cause serious threat to safe operation of electric power system. So the correct detection, the investigation on grounding fault current in power network and the solution of the problem of residual current compensation are important for ensuring power network safety.

Existing research of ground residual current has limitation, so this paper presents that the single phase earth fault system for double harmonic sources need to be analyzed. The sources of the resistive and harmonic components in harmonic voltage and current were analyzed, and the influences of harmonic source types and fault point position on them were discussed theoretically.

The most frequently used methods of measuring insulation parameters to ground for power system include: additional power supply measurement, AC voltammetry, AC-DC voltammetry, neutral to ground voltage method, resonance measurement and etc [5-7,9]. The first method can measure the insulation parameters at measuring frequency, and reflect the insulation parameters at power frequency indirectly. Other methods measure with working power frequency and reflect the real insulation parameters of power network [8-10]. A very simple, safe, reliable, and useful new indirect measuring method is proposed. For getting practical data of ground residual current, dozens of power system capacitive currents were tested. Grounding experimentals of XieQiao coal mine were researched as an example, experimental results and analysis conclusion are given as the research foundation of the analysis on the single-phase grounding fault system.

The research work of residual current compensation had been done at home and abroad [11-13].Based on the experiment conclusion of XieQiao coal mine, a new device for compensating residual current named full compensation arc suppression coil has been designed. Full current compensation arc suppression coil can solve the problem of residual current compensation, can also suppress the arc-earthing over-voltage effectively when the network is grounded through an arc-extinguishing coil. It can ensure power supply security and reliability in distribution network. Finally, the proposed principle and master-slave control strategies of full current compensation arc suppression coil are calculated, electrical properties of it are analyzed, and system evaluation is given.

2. Analysis on the single-phase grounding fault system [14]

The system model of the grounding fault feeder line can be equivalent to the circuit shown in Fig1， where the equivalent power harmonic voltage source is u_S, the internal resistance of it is Z_S and the equivalent load harmonic current source is i_{lh}. X is the fault point, and xZ_l is the line impedance between bus and fault point. Before a fault occurs, the voltage at fault point can be derived from Fig.1.

$$u_X = u_S \cdot \frac{(l-x)Z_l}{Z_S + lZ_l} + i_{lh} \cdot (xZ_l + Z_S) \tag{1}$$

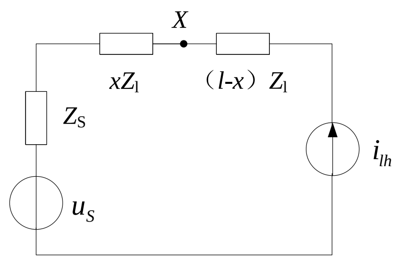


Fig.1 Simplified equivalent circuit of power system

The voltage at fault point can be represented by the following equation (2), which contains harmonic component:

$$u_X = \sum_{k=1}^{\infty} u_k \tag{2}$$

Where u_1 is fundamental component, u_k is k-th harmonic voltage component.

Fig.2 gives the circuit which is equivalent to the system of neutral point to earth via full compensation arc suppression coil. The master part of master-slave full compensation arc suppression coil is L, the slave part is equivalent to a controlled current source. The capacitance to ground of the grounding fault feeder line C_Σ, the conductance to ground of it g_Σ and the earth resistance R_E are given.

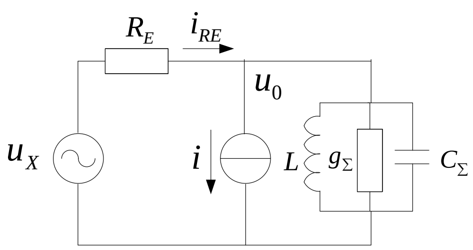


Fig.2 Equivalent circuit of single-phase grounding fault system

The relationship between zero sequence voltage u_0 and voltage at fault point u_X is derived from Fig.2, where g_k is equivalent conductance when specific k-th harmonic is produced by the converters. The conclusion that u_0 contains harmonic components is easily verified using (2) and (3).

$$u_0 = -\frac{u_X}{R_E\left(\frac{1}{R_E} + g_k + j\omega C_\Sigma + g_\Sigma + j\omega L\right)} \tag{3}$$

Suppose there are n feeder lines in the system, grounding fault occurs in the *h*-th feeder line. $C_{\Sigma i}$ is the capacitance to ground of the *i*-th feeder line, $g_{\Sigma i}$ is the conductance to ground of it. The current which flows through the current transformer in non-fault feeder line is given by the following expression when fault occurs.

$$i_{0i} = u_0(j\omega C_{\Sigma i} + g_{\Sigma i}) \tag{5}$$

The current which flows through the current transformer in fault feeder line can be written as:

$$i_{0h} = -u_0\left[\sum_{i=1}^{n}(j\omega C_{\Sigma i} + g_{\Sigma i}) - (j\omega C_{\Sigma h} + g_{\Sigma h}) + \frac{1}{j\omega L}\right] \tag{6}$$

The current at fault point is given as:

$$i_{RE} = -u_0\left[\sum_{i=1}^{n}(j\omega C_{\Sigma i} + g_{\Sigma i}) + \frac{1}{j\omega L}\right] \tag{7}$$

Expression (7) implies that the current at fault point contains active component and harmonic component, the amplitude of it is influenced by the voltage at fault point.

3. Capacitive current detection and analysis of power network

For getting the data of harmonic component of grounding residual current，the experiments of high resistance grounding and bolted grounding fault were conducted on dozens of coal mines respectively, the line test results of 6kV I bus of XieQiao coal mine were obtained by power quality measurement instrument.

3.1 The measuring principle, method and steps

The measuring model for the insulation parameters of a neutral point ungrounded electric network is shown in Fig. 3.

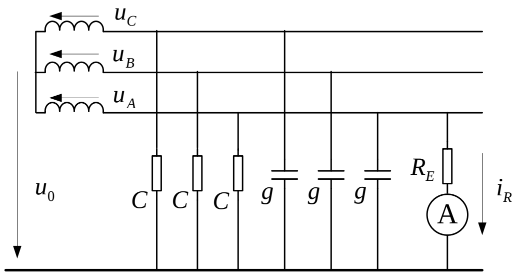


Fig.3 The measuring model for the insulation parameters of a neutral point ungrounded electric network

C and *g* denote single-phase capacitance and conductance to earth, respectively. Phase A of system is earthed via transition resistance R_E, the current flowing through R_E can be measured by ammeter A, obtained as (8). The value range of R_E is 50~1000Ω, it can hold grounding current value within a range of 10A.

$$i_R = -u_0(j\omega C_\Sigma + g_\Sigma) \tag{8}$$

When the bolted grounding fault occurs, namely R_E is almost equal to zero, zero sequence voltage changes into the phase voltage of power source u_φ, can be described as (9).

$$u_0 = u_\Phi \tag{9}$$

Grounding current can be expressed as:

$$i_{RE} = -u_\Phi(j\omega C_\Sigma + g_\Sigma) \tag{10}$$

According to (8), zero sequence current value is proportional to zero sequence voltage value, and (10) can be calculated as:

$$i_{RE} = \frac{u_\Phi}{u_0} \times i_R \tag{11}$$

Single-phase grounding current can be calculated by the current measured with the ammeter A, the zero sequence voltage of system and the phase voltage of power source.

Phase voltage and zero sequence voltage of power network were measured by voltage transformer in experiment. Considering the probability of voltage fluctuation appearance is high in system, so we can obtain the following equality from (11):

$$i_{RE} = \frac{u_{l2}}{u_{02}} i_R \tag{12}$$

Where, u_{l2} is the secondary line voltage of voltage transformer, u_{02} denotes the zero sequence voltage of the secondary open delta winding of voltage transformer.

When arc suppression coil is using operationally, let be neutral grounding inductor *L*, it is used to compensate the grounding capacitance current of whole power network, and the current which flows through R_E can be written as:

$$i_R = -u_0 (j\omega C_\Sigma + g_\Sigma + \frac{1}{j\omega L}) \tag{13}$$

When bolted grounding fault occurs, residual current is:

$$i_{RE} = -u_\Phi (j\omega C_\Sigma + g_\Sigma + \frac{1}{j\omega L}) \tag{14}$$

The equations (13) and (14) show that the operations of arc suppression coil can not affect the ratio between the grounding capacitance currents which measured before and after the single-phase grounding fault. So the equations (11) and (12) apply to the situation that arc suppression coil is in full-load operation.

The wiring diagram for measuring single-phase grounding current in coal mine power network is shown in Fig.4.Where TV denotes three phase five pole voltage transformer, QF denotes circuit breaker, QS denotes disconnector. Grounding current i_R is measured by ammeter A. The objective that the voltmeters are accessed at the secondary side of TV is the measure of u_{l2} and u_{02}.

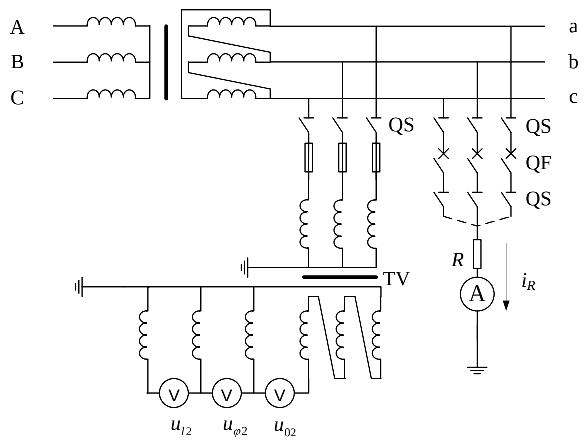


Fig.4 The wiring diagram for measuring single-phase grounding current

The concrete measuring steps are given as follows:

1) The phase voltage and line voltage of system should be measured when the grounding fault doesn’t happen in power network system.

2) The commonly used measuring point of substation should be selected, we must ensure the suitable measuring point have no electric charge.

3) The grounding transition resistance of system should be calculated. The reasonable values of test equipments can be judged and selected, and they will be accessed power network. Ensure the switch is closed, the data of test equipments can be read.

4) Open the switch.

5) According to (12), the required grounding current will be calculated.

3.2 Detection results and analysis

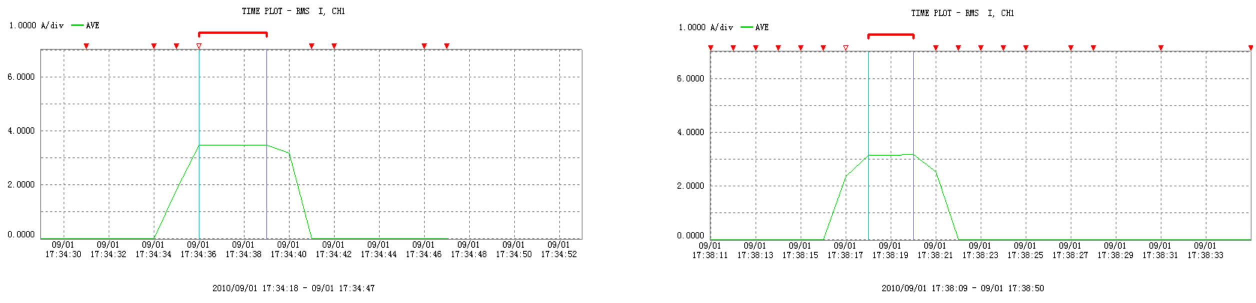
3.2.1 High resistance grounding fault occurring

Under the conditions that arc suppression coil was in operation or not, we tested the grounding current of 6kV I bus by the single-phase high resistance grounding measurement, and the test results are given as follows:

Table 1 The measurement result

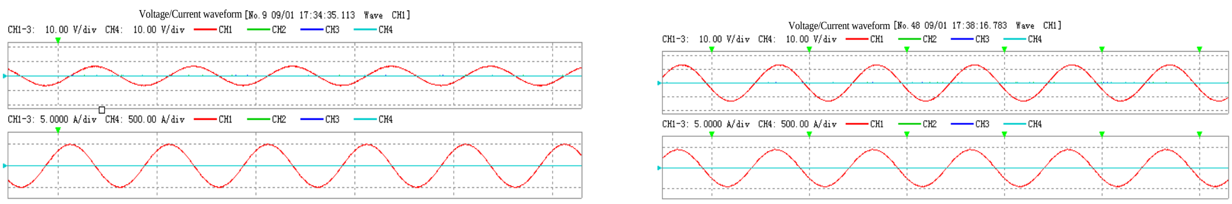
Test item	Maximum		Minimum	
	Not runing	runing	Not runing	runing
Grounding current(A)	3.46	3.16	3.46	3.16
zero sequence voltage(V)	4.68	9.33	4.67	9.32
active component P(W)	0	28.72	0	28.63
reactive component Q(Var)	16.20	6.87	16.13	6.83

Based on conversion and calculation, the grounding currents of the two conditions are 74A and 34A respectively, the trend charts of grounding current, the waveforms of zero sequence voltage and grounding current, the diagrams shown the phase relation between zero sequence voltage and grounding current are given as shown in Fig.5~Fig.7 in the case of the two conditions.



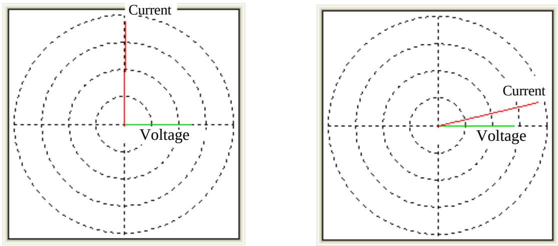
(a)When arc suppression coil wasn’t running (b)When arc suppression coil was running

Fig.5 The trend charts of grounding current



(a)When arc suppression coil wasn't running (b)When arc suppression coil was running

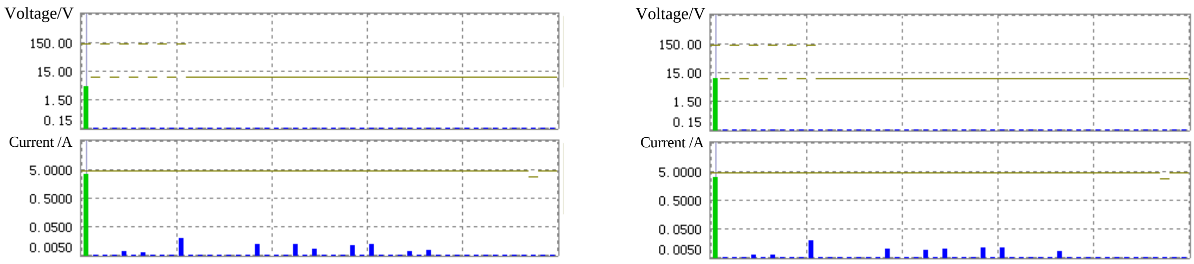
Fig.6 The waveforms of zero sequence voltage and grounding current



(a) Angle is 89.09° (b) Angle is 13.34°

Fig.7 The diagrams shown the phase relation between zero sequence voltage and grounding current

Fig.8 shows the harmonic histograms of zero sequence voltage and grounding current. Where, the fundamental amplitudes of zero sequence voltage are 4.68V and 9.3V respectively, the fundamental amplitudes of grounding current are 3.4638A and 3.1591A respectively. The contents of the main harmonics in grounding current are given in Table 2



(a)When arc suppression coil wasn't running (b)When arc suppression coil was running

Fig.8 The harmonic histograms of zero sequence voltage and grounding current

Grounding current contained almost no active component (contained harmonic component) when arc suppression coil was not running. The harmonic component of 6kV I bus was composed mainly of 11th、19th 、23rd 、29th and 31st harmonic, the proportions of each harmonic were all low. When arc suppression coil was working, grounding current contained active component. The harmonic component of 6kV I bus was composed mainly of 11th、19th 、25th 、29th and 31st harmonic, and the proportions of each harmonic were also low.

Table 2 The contents of the main harmonics in grounding current

Condition	Harmonic number and amplitude								
Not running	number	1	5	11	19	23	25	29	31
	amplitude	3.4638	0.0072	0.0201	0.0123	0.0125	0.0081	0.0112	0.0125
Running	number	1	11	19	23	25	29	31	37
	amplitude	3.1591	0.0203	0.0107	0.0092	0.0100	0.0109	0.0117	0.0087

High resistance grounding fault has little influence on power system, and the voltage amplitude of ground phase does not decrease significantly. When arc suppression coil isn’t working, the damping resistances of it aren’t cut off and do result in the existing of active component. These conclusions are verified by Fig.7.

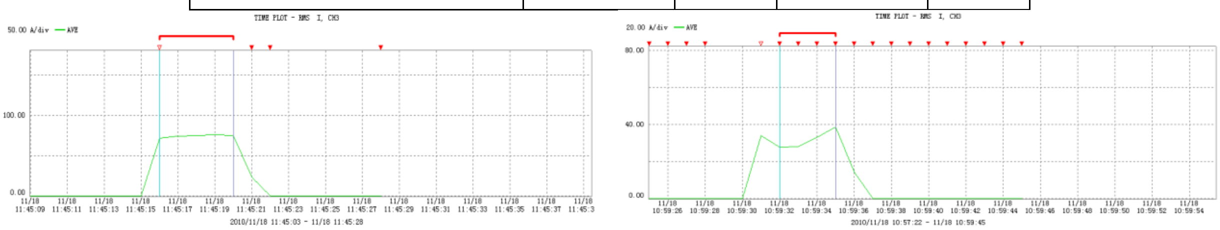
3.2.2 Bolted grounding fault occurring

Under the conditions that arc suppression coil was in operation or not, we tested the grounding current of 6kV I bus by the single-phase bolted grounding measurement, and the test results are given as follows:

Based on conversion and calculation, the grounding currents of the two conditions are 75A and 32A respectively, the trend charts of grounding current, the waveforms of zero sequence voltage and grounding current, the diagrams shown the phase relation between zero sequence voltage and grounding current are given as shown in Fig.9~Fig.11 in the case of the two conditions.

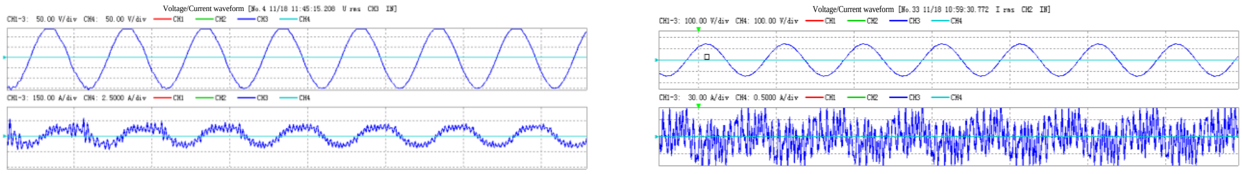
Table 3 The measurement result

Test item	Maximum		Minimum	
	Not runing	runing	Not runing	runing
Grounding current(A)	76.41	38.96	71.97	27.9
zero sequence voltage(V)	104.9	99.41	102.1	98.6
active component P(W)	0.36	0.73	0.18	0.69
reactive component Q(Var)	8	3.78	7.36	2.68



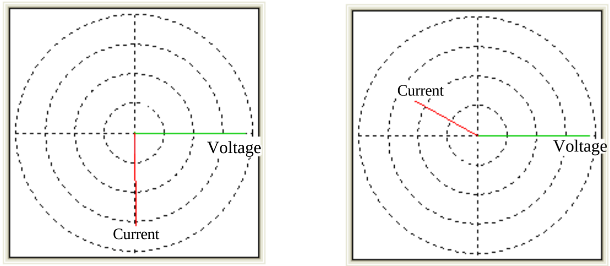
(a)When arc suppression coil wasn’t running (b)When arc suppression coil was running

Fig.9 The trend charts of grounding current



(a)When arc suppression coil wasn't running　　(b)When arc suppression coil was running

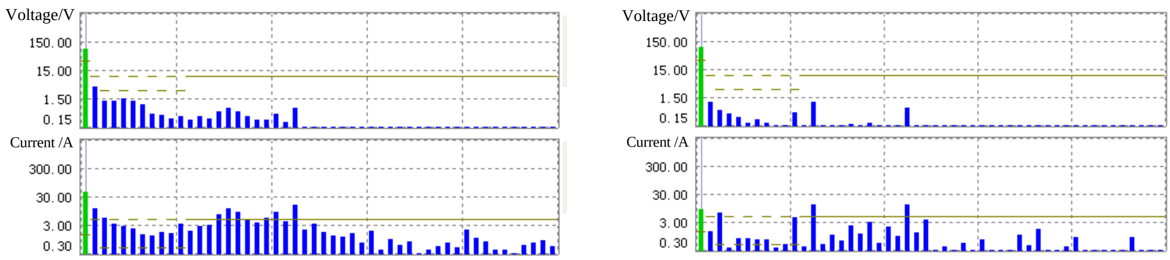
Fig.10 The waveforms of zero sequence voltage and grounding current



(a) Angle is -88.89°　　(b) Angle is 151.07°

Fig.11 The diagrams shown the phase relation between zero sequence voltage and grounding current

Fig.12 shows the harmonic histograms of zero sequence voltage and grounding current. Where, the fundamental amplitudes of zero sequence voltage are 85.16V and 99.03V respectively, the fundamental amplitudes of grounding current are 48.29A and 9.04A respectively. The contents of the main harmonics in grounding current are given in Table 3.



(a)When arc suppression coil wasn't running　　(b)When arc suppression coil was running

Fig.12 The harmonic histograms of zero sequence voltage and grounding current

Table 4 The contents of the main harmonics in grounding current

Condition	Harmonic number and amplitude									
Not running	number	1	2	3	4	5	6	11	13	15
	amplitude	48.29	12.34	5.38	3.45	2.73	2.35	3.60	2.79	7.77
	number	16	17	18	19	20	21	23	25	31
	amplitude	11.63	8.97	4.63	3.79	5.38	8.83	15.38	3.51	2.04
running	number	1	2	3	11	13	15	17	19	21

	amplitude	9.04	1.53	6.73	4.60	13.24	1.14	2.31	3.15	2.08
	number	23	25	35	37					
	amplitude	13.91	3.94	1.12	1.71					

When arc suppression coil was not working, grounding current contained almost reactive component and was rich in each harmonic. As shown in Fig.12, active component of grounding current of 6kV I bus increased when arc suppression coil was running, harmonic current was composed of higher harmonics primarily, and the 13th and 23rd harmonic current were acute particularly. Active component of grounding current was small when arc suppression coil was not working, on the contrary, there was a sensible increase in active component visibly.

The harmonic component of grounding current is the result of the voltage distortion caused by harmonic sources of power side and load side, and it has a high content of 23rd harmonic current. This is because the capacitance to ground has amplifying action to harmonic, and the harmonic current at the grounding point which is induced by harmonic voltage becomes n times of itself. This implies that the harmonic current at the grounding point caused by the harmonic voltage which the frequency of it is higher is bigger.

3.3 Analysis on the Source of the 23rd Harmonic in Grounding Current

When bolted grounding fault occurs on 6kV I bus of 110 kV XieQiao coal mine transformer substation, grounding current contains harmonic component, and the 23rd harmonic is behaved relatively significantly. In order to analyze the causes of the 23rd harmonic, some lines of the transformer substation become main monitoring object by using HIOKI-3196 and Fluke-1760 power quality analyzer.

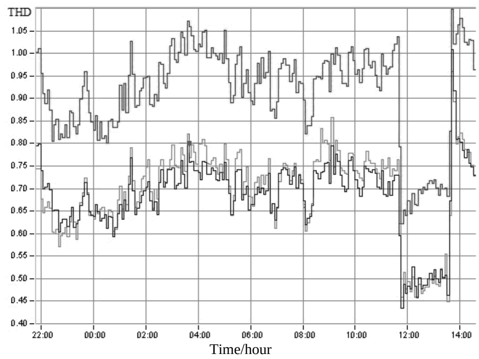


Fig.13 The trend chart for the total harmonic distortion (THD) values of the three phase voltages in 110kV entering line

In order to analyze harmonic component of grounding current intuitively, the related test waveforms are given for comparison and analysis. The trend charts for the total harmonic distortion (THD) values of the three-phase voltages in 110kV entering line, the trend charts for the 23rd harmonics of the three phase voltages in 110kV entering line and the trend charts for the three phase loads in 110kV entering line are shown in Fig.13~Fig.15.

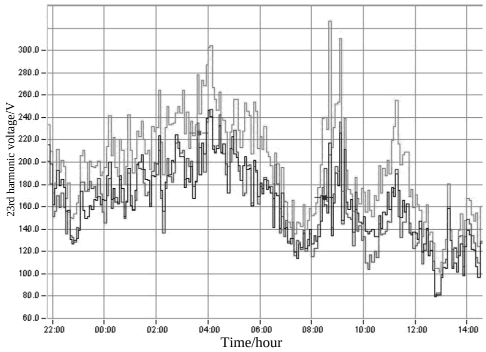


Fig.14 The trend chart for the 23rd harmonics of the three phase voltages in 110kV entering line

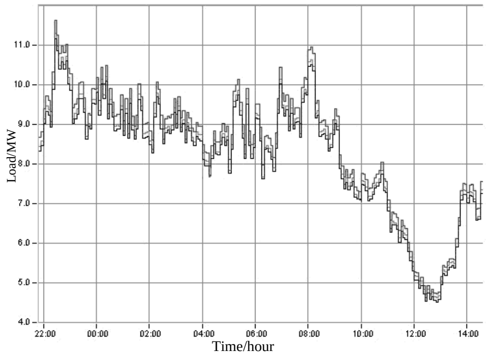


Fig.15 The trend chart for the three phase loads in 110kV entering line

The harmonic status of 6kV side of three main transformers is monitored by using analyzer for comparative analysis, the harmonic voltage changes of 6kV side of 1#, 2# and 3# main transformer are depicted as follows:

(1) 6kV side of 1# main transformer

The 23rd harmonic voltage contained ratios of B and C phase always fluctuate nearby 0.32%, the 23rd harmonic voltage contained ratio of A phase fluctuates nearby 0.15%, they have no obvious changes with the changes of loads. So the loads of 6kV I bus have a small effect on 23rd harmonic voltage, it is caused by superior system.

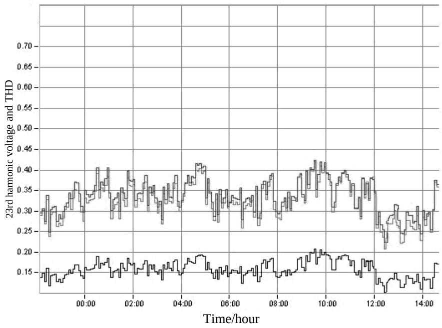


Fig.16 The trend chart for the content rates of the 23rd harmonic voltages on the 6kV side of 1# main transformer

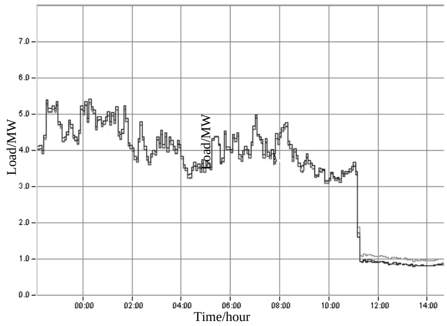


Fig.17 The trend chart for the loads on the 6kV I bus

(2) 6kV side of 2# main transformer

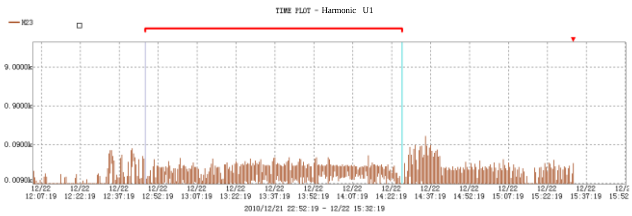


Fig.18 The trend chart for the 23rd harmonic voltages on the 6kV side of 2# main transformer

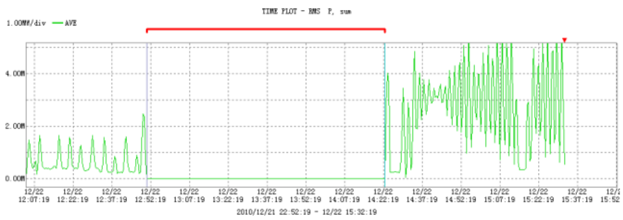


Fig.19 The trend chart for the loads on the 6kV II bus

2# main transformer has been overhauled for some time in the testing process, there's no load on 6kV II bus of it, and 23rd harmonic voltage still varies with seasonal pattern at present. Obviously we can see that the 23rd harmonic voltage of 6kV II bus should be independent of the load variations of this bus.

(3) 6kV side of 3# main transformer

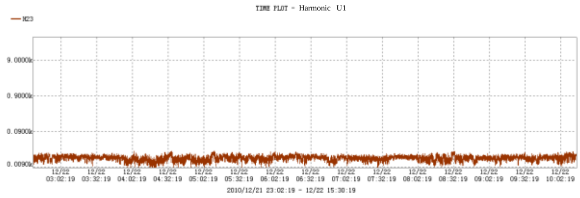


Fig.20 The trend chart for the 23rd harmonic voltages on the 6kV side of 3# main transformer

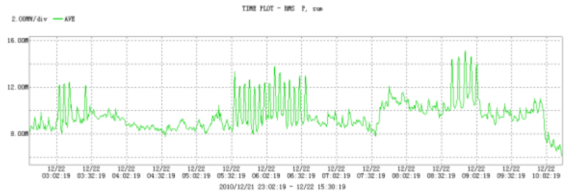


Fig.21 The trend chart for the loads on the 6kV III bus

Identical to the above conclusion, the 23rd harmonic voltage variations of 6kV III bus are independent of the load variations of this bus.

Due to the amplification effect of capacitance to ground on harmonic wave, the harmonic current caused by the higher harmonic voltage becomes bigger at the grounding point. The 23rd harmonic voltage distortion of the bus caused the 23rd harmonic component of ground current. The 23rd harmonic voltage distortion of 6kV I bus is resulted from the bus harmonic voltage caused by power side harmonic source and load side harmonic source. This conclusion can verify the theoretical derivation of section 2 at the situation realistically. As a high-order harmonic, 23rd harmonic current can lead to too small of the equivalent capacitive reactance to ground, so its amplitude can not be ignored. 23rd harmonic is the representative high-order harmonic of residual current in XieQiao coal mine power network merely, it isn’t the representative high-order harmonic of other power network. However, some high-order harmonics of other power network may have significant amplitude and influence, this characteristic is analogous, and becomes a widespread problem.

4. Proposal of full current compensation arc

For the experimental results and analysis conclusion of the capacitive current in XieQiao coal mine, we can have the basic understanding of the ground residual current data and their present situation in coal mine. Compensation objective of full current compensation arc suppression coil isn't strictly limited to the lower-order parts in high-order harmonic components, it can also select a certain signal frequency for analysing on purpose.

4.1 the proposed principle and structure of full current compensation arc suppression coil

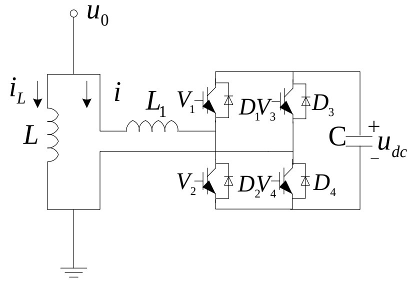


Fig.22 Simplified block diagram of full current compensation arc suppression coil

Fig.22 shows the simplified block diagram of full current compensation arc suppression coil. The essential structure of master-slave full current compensation arc suppression coil is the parallel operation of traditional arc suppression coil and inverter. The master arc suppression coil is traditional arc suppression coil *L*. It provides the inductor current that can neutralize the ground capacitive current for the system. The slave arc suppression coil is single phase bridge inverter. It can supply the reverse ground residual current for achieving the purpose of ground residual current compensation.

4.2 The control strategies of full current compensation arc suppression coil

Based on the inherent topological structure of full current compensation arc suppression coil and the different types of master arc suppression coil, a master-slave control strategies of full current compensation arc suppression coil is proposed.

It concludes that, whether for master arc suppression coil is pre-coordinated mode or adjustable mode, the tuning process, response speed and motional success rate of master arc suppression coil had a great impact on the compensation of slave arc suppression coil under the same condition. So the control key is that the movement of slave arc suppression coil is not influenced by the master part.

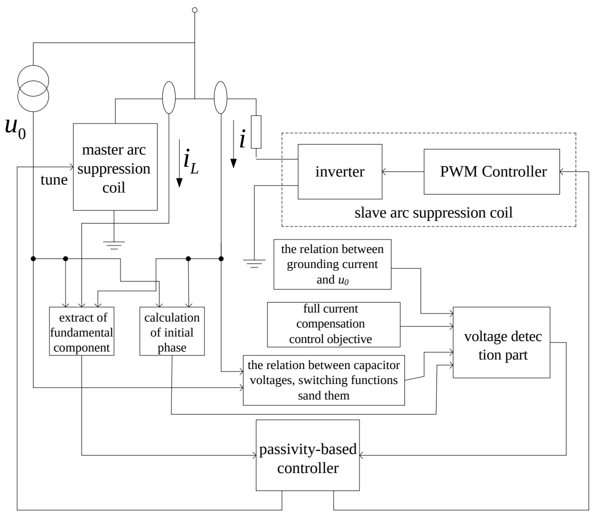


Fig.23 Control structure diagram of full current compensation arc suppression coil

The central section of the control system includes voltage detection part and passivity-based controller in full current compensation arc suppression coil. The former combined some pertinent equations and the full current compensation control objective can achieve the purpose of zero sequence voltage detection by the analysis of the zero sequence voltages and compensation currents, and the latter can output the PWM control signals and the tuning signals of master arc suppression coil through the input signal processing. Control structure diagram of full current compensation arc suppression coil is given as shown in Fig.23.

4.3 Analysis on the Performance of Full Current Compensation Arc Suppression Coil

After the design of this new device and prior to its operational use, the researches of testing and characterization are necessary. The operational characteristics of arc suppression coil are based on this system evaluations, included as follows:

(1) The inductance regulation compensation linearity of master arc suppression coil

The inductance regulation compensation linearity is characterized by the voltage-current characteristics of compensation currents. The type of ground fault is unpredictable, so the values of zero sequence voltages have a wide range. When arc grounding fault occurs, the good compensation linearity can guarantee the decrease of residual current and the validity of arc-control device.

(2) the content of the compensated residual current

The good compensation effect is closely related to the compensation effect of slave arc suppression coil and the managing and technical measure to restrain the harmonics, also the linearity of master arc suppression coil and its tuning accuracy. Full current compensation arc suppression coil is installed in order to achieve the aim of ground residual current compensation.

(3) compensation speed

When single-phase ground fault occurs, arc suppression coil must be put into operation and compensates the ground fault current quickly. The high tracking speed and dynamic output response speed are both necessary.

(4) adjustment range

The adjustment range of master arc suppression coil is characterized by adjustment depth or adjustment width commonly. Equipment capacity can be characterized by the adjustment range of slave arc suppression coil.

5. Discussion

Combining residual current compensation problem in coal mine power grid, this paper exploits new fields of the single-phase grounding fault system research. Unlike previous literatures which only focus on the research of the single-phase grounding fault system, the paper discusses the influences of harmonic source types and fault point position theoretically. Based on the measuring principle and steps of capacitive current detection, detection results and analysis are applied to discuss and compare the test results between when high resistance grounding fault occurring and when bolted grounding fault occurring. Analysis on the source of the 23rd harmonic in grounding current is identified. The study also found the model of full current compensation arc suppression coil, this device is able to make quick response to compensate the residual current. From discussions above, some valuable conclusions are drawn, which provide a theoretical reference for the control strategies and the performance development in the future.

6. Conclusion

The single-phase grounding fault system was analyzed for double harmonic sources in this paper. Then the source of the resistive and harmonic components in harmonic voltage and current was researched, and the influences of harmonic source types and fault point position on them were discussed theoretically.

Dozens of power system capacitive current were tested. As an example, grounding experimentals of XieQiao coal mine were researched, experimental results and analysis conclusion are given. According to the results of the analysis, the suggested compensation objective can’t be limited to the lower order ones of the high-order harmonic merely, and the higher ones need to be compensated by especial method similarly.

Based on the experiment conclusion of XieQiao coal mine, the proposed principle and master-slave control strategies of full current compensation arc suppression coil are calculated, the electrical properties and system evaluation of it are given.

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