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Study on Selective Leakage Protection System of Mine High Voltage Grid Based on Harmonic Phase Comparison

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Abstract: As for the wide application of arc suppression coil to the grounding in neutral point of mine high voltage grid, grid leakage fault rules and harmonic characteristics of the neutral point grounding system through arc suppression coil are analyzed, the selective leakage protection program “zero-sequence voltage starts, fifth harmonics of grid zero-sequence voltage and zero-sequence current are extracted for phase comparison” is proposed, and corresponding fifth harmonic extraction circuit and power direction discrimination circuit are designed. The experimental results show that the protective principle applies not only to the neutral point insulated power supply system, but also to the power supply system in which neutral point passes arc suppression coil, which can solve selective leakage protection problems under different neutral grounding ways, improving the reliability of selective leakage and guaranteeing the stability of the action value.

Keywords: high-voltage grid, selective leakage protection, the fifth harmonic phase comparison, zero-sequence voltage

1. Introduction

Mine high-voltage power supply system belongs to a small current grounding operation mode, usually composed of three levels of substations: ground substation, underground central substation and mining area substation. These three substations shall be fitted with selective leakage protection system. By now, there are various protection principles such as additional DC detection method, zero-sequence current method, zero-sequence voltage method, zero-sequence current power direction method, etc., all of which play a positive role in the security of electricity supply in the mine high-voltage grid to different degrees. However, due to the limitations of technological levels in relevant fields such as power electronics technology and microelectronics technology, as well as the lack of knowledge about the laws governing the operation of the underground high-voltage grid, these leakage protection systems in the past were not reliable with high false positive rate. In addition, with the increasing consumption of coal production, supply way of the underground power supply system and technical requirements for power supply system are changing. Currently, more than half of the mines beyond the single-phase ground current limit can reach the current over 30A, up to 70A; so great ground current makes intermittent arc not able to be extinguished automatically, resulted in dangerous arcing ground overvoltage, which makes the single-phase ground fault expanded to two-phase ground short-circuit fault. Meanwhile, the existence of arc also increases the danger of gas and coal seam explosion. Therefore, measures must be taken to restrict the single-phase ground current. According to electricity regulations, it is recommended to use arc suppression coil to compensate in order to reduce the ground capacitive current, which is the exact method adopted in most mines currently. Although the tandem connection of arc suppression coil at the neutral point in the grid can reduce single-phase ground current, it leads to the change in the grounding way of the neutral point, which causes great impact on detection principle of original leakage system, and even destroys the protection principle of original selective leakage, making it ineffective. Most integrated protection systems that have been finalized and produced are only suitable for the insulation system at neutral point. After the installation of the arc suppression coil at the grid neutral point, the single-phase ground fault current may be smaller than that of the non-fault line, and the phase is identical with the non-fault sub-circuit in overcompensation, so that these zero-sequence current and zero sequence power directional protection systems cannot meet the selectivity requirements. Therefore, the invention and development of selective leakage protection system, especially suitable for underground high-voltage power supply system, is urgent, which has great significance for improving the underground safety, supply reliability and continuity of coal mine.

The power-leakage malfunction characteristics of mine high voltage grid in various run modes are studied through experiments, and on the basis, “zero-sequence voltage starts, take comparisons of harmonic waves extracted five times from zero sequence voltage and zero sequence current” to complete the selective leakage protection, to adapt to the eigenvalues of different leakage malfunction under coal mine under different neutral grounding modes.

2. System leakage malfunction characteristics of high voltage grid neutral point by Petersen coil grounding

Compensation principle of high voltage grid neutral point being grounded through arc suppression coil is shown in Figure 1, in which L is the arc suppression coil that compensates single-phase ground capacitor current. When a ground fault occurs, the inductor current and the capacitor current are of opposite directions, counteracting each other, so that the ground current is reduced[1].

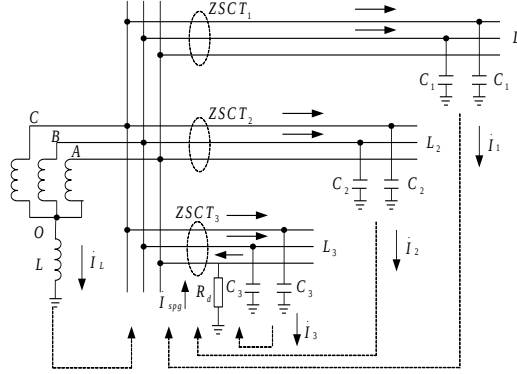


Fig.1. Distribution diagram of fault currents in neutral point grounded system through arc suppression coil

When there is no ground current, the potential neutral point $U_0=0$, and the current $I_L=0$ in inductance. When A-phase is ground connected, the zero-sequence voltage U_0 appears in the neutral point, there is a reactive current flowing through the inductor to the ground, of which the value is

$$I_L = U_0 / j\omega L = -j\omega U_0 / \omega L \quad (1)$$

Where the ground current is

$$I'_{jd} = I_L + I_1 + I_2 + I_3 = jU_0(3\omega C_\Sigma - 1/\omega L) \quad (2)$$

If the inductance value L is appropriate to make $(3\omega C_\Sigma - 1/\omega L) = 0$, the ground current at this time $I'_{jd} = 0$, called complete compensation; when L value is too large, making $I_L < I_{jd}$, the inductor current is not enough to counteract all the ground capacitor current, so that the total ground current is capacitive, called under-compensation. Conversely, when the L value is too small, $I_L > I_{jd}$, the ground current is inductive, called over-compensation[2].

In the absence of automatic compensation track, arc suppression coil can only be adjusted by segments. Therefore, it is impossible to form a complete compensation with the grid distribution capacitance. To avoid the dangerous overvoltage of series resonance caused by complete compensation (under compensation also has this possibility, as it may be close to complete compensation while cutting down subcircuits by the grid opening), the actual grid arc suppression coils are all in the state of overcompensation[3].

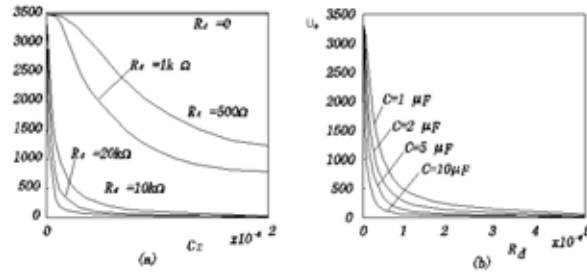
The zero-sequence impedance of grid (when there is arc suppression coil compensation) is

$$Z_0 = 1 / \left(\frac{1}{3} j\omega L + j\omega C_\Sigma \right) \quad (3)$$

Zero-sequence voltage effective value is

$$Z_0 = \frac{U_A}{\sqrt{1 + R_d^2(3\omega C_\Sigma - 1/\omega L)}} \quad (4)$$

The change curves of U^0 with R^d and C^Σ when $P = 10\%$ are depicted according to Equation 6, as shown in Figure 2 (a) and (b). The figure shows, there are similar variation rule for two operation modes of zero-sequence voltage of neutral point. Zero-sequence voltage will not be reduced because of the introduction of arc suppression coil, but increased[4].



(a) Changing curve of with capacitance in different leakage resistance

(b) Changing curve of with grounded resistance in different distribution capacitances

Fig. 2. Zero-sequence voltage in neural point grounded system through arc suppression coil

3. Selective leakage protection principle based on harmonic comparison phase of five times

3.1. Protection system performance of different grounding ways

From the analysis of fault characteristics above, the fault characteristics in leakage under different grounding ways are different, so the performance of selective leakage protection system must be adapted. As isolated power supply system of neutral point holds aforementioned three characteristics, the sizes and the directions of current can be distinguished between the fault line and the non-fault line, and therefore available zero-sequence current type and power direction type protections can both meet the selectivity requirements. For the grounding system by arc suppression coil, the single-phase ground fault current may be smaller than that in the non-fault subcircuit due to the compensation and the direction changes with the compensation state, so protection principles of current zero-sequence current type and power direction type cannot meet the selectivity requirements[5].

In order to be simultaneously adapted to the requirements of various neutral point operation modes for selective leakage power, the principle of harmonic phase comparison is proposed in this paper, which is to use the relationship between the high-order harmonic components of zero-sequence voltage and zero-sequence current in leakage to meet leakage selectivity requirements. Arc suppression coil grounding system is taken as an example to in the following[6].

In the grid that transformer neutral point grounded through arc suppression coil, the inductor current in arc suppression coil mainly compensates the fundamental component of capacitor current. As the inductance of inductor and the capacitance of capacitor change with current frequency, the fundamental angular frequency is supposed as ω , the relationship between the inductance and capacitance of the fundamental harmonic incomplete compensation is $1/\omega L = 3\omega C_\Sigma$, however, the relationship between the inductance and capacitance of the harmonic for five times is $1/5\omega L \neq 3(5\omega)C_\Sigma$, from which it can be seen that the inductance is 5 times of the fundamental harmonic component for five times, while the capacitance is 1/5 of the fundamental harmonic component. The capacitive current through fault branch in single-phase ground for the fifth harmonic is

$$I_{C\Sigma(5)} = j3(5\omega)U_{ZS5}C_\Sigma \quad (5)$$

where U_{ZS5} is five equivalent zero-sequence voltage. The de resonance degree P of arc suppression coil in unsaturation and overcompensation is supposed to be 10%, and then it can be obtained that $1/\omega L = 3.3\omega C_\Sigma$.

The inductor current of harmonic through fault branch for five times

$$I_{L5} = \frac{U_{ZS5}}{5\omega l} = j \frac{3.3}{5} U_{ZS5} \omega C_z \quad (6)$$

From Equation 5 and 6, it can be obtained that which indicates the capacitive current of the fifth harmonic is 23 times of inductor current, from which it can be seen the fifth harmonic component cannot be compensated, and the remained fifth harmonic capacitive current is

$$\frac{I_{CZ(5)}}{I_{L5}} = \frac{j3(5\omega)U_{ZS5}C_z}{j(3.3/5)U_{ZS5}\omega C_z} \approx 23 \quad (7)$$

According to the above analysis, the fifth harmonic capacitive current cannot be compensated either in the complete compensation, under-compensation or over-compensation. When a ground fault occurs in the power grid, the distribution rules are the same as those of the fundamental current in the power grid where neutral points are insulated from ground. Actually, as arc suppression coil itself may saturate, $I_{L(5)}$ may be bigger, but still far from the fifth harmonic capacitive current compensation, which is the theoretical basis of selective leakage protection “zero-sequence voltage fundamental start, the fifth harmonic phase comparison” presented in this paper.

3.2. Harmonic characteristics of high-voltage grid

Harmonic type selective leakage protection can work in the most basic condition that there must be harmonic currents and voltages in the grid, and actually the grid is also able to meet this requirement[7].

High-order harmonics exist in the grid, mainly because the magnetic induction strength in air gap between stator and rotor cannot be distributed exactly in accordance with sinusoid, resulting in that the induced electromotive force in generator windings cannot be strictly sinusoidal, which contains a certain number of harmonic components. Furthermore, the core of the transformer is non-linear inductance element, and even though the voltage applied across the coil is the sine wave with fixed frequency, due to the magnetic saturation of the iron core, the excitation current of the transformer also includes a high-order harmonic component. These high-order harmonic currents flow through the motor winding and line impedance, creating a high-order harmonic voltage, and obviously harmonics are inherent phenomena in the grid, among which the third and the fifth harmonics components are larger. Due to the impact of the transformer connection group by the third harmonic, and also because of the same direction, there is no third harmonic voltage among phases, while the fifth harmonic is not affected by this. When leakage fault occurs, the fifth harmonic component of zero-sequence voltage and zero-sequence current in grid also has three characteristics summarized before, so it can be extracted as the protective testing physical quantity which means to form harmonic leakage protection.

The content of the fifth harmonic of the grid is only about 1 to 2% of the fundamental harmonic, and the zero-sequence voltage in the fifth-order harmonic component is somewhat larger, but substantially does not exceed 2% of the fundamental one.

Therefore, although there are five harmonics in grid, the number is small and the amplitude stability is poor, so that the harmonic signal is easily interfered with other components, and thus the accuracy and robustness of the proposed signal processing circuit should be faced with more stringent requirements. This is one of the main reasons that the application principles of harmonic detection are limited. So far, the protection based on harmonic detection is to use computer for sequential processing line selection of all physical quantities fed, only for the ground substation.

3.3. Identification of selective leakage protection principle in high-voltage grid

The above discussion shows that the fifth harmonic component distribution in the grid of zero sequence voltage and zero sequence current when leakage fault occurs can be utilized to realize selective leakage protection, but nothing to do with the neutral point wiring way. Further study for harmonic characteristics shows that, the fifth harmonic component phase stabilities of both zero-sequence voltage and zero-sequence current are better, but the fluctuation magnitude is great, so judgment for fault branch by the magnitude value must lower the reliability of protection.

In addition, the steady-state characteristics of zero-sequence voltage magnitude are not affected by neutral point wiring (except for neutral grounding grid), and its stability is much better than that of the fifth harmonic component. From the above analysis, however, at the same ground resistance, zero-sequence voltage is subject to significant change with different capacitance distribution of grid. Through comprehensive consideration, zero-sequence voltage fundamental harmonic is applied as the start signal of leakage protection in the design; meanwhile the fifth harmonic phases are compared the zero-sequence voltage and zero-sequence current extracted by hardware circuit; when the zero-sequence voltage exceeds the setting value, the software is started to test the comparison results to determine whether it is a fault branch. In order to meet the requirements of different power grids, the zero-sequence voltage setpoint are made multi-speed adjustable, which can be selected according to the grid size, so that can guarantee the stability of the system operation values.

4. Hardware design of harmonic selective leakage protection system

Harmonic phase comparison selective leakage protection system is used to extract the fifth harmonic of zero-sequence voltage and zero sequence current as well as the grounding fault in the grid of hardware phase comparison insulated against neutral point or the grounding grid of neutral point arc passing suppression coil for selective leakage protection.

4.1. Selective Leakage System Design

System selective leakage is started by fundamental start of zero-sequence voltage, and completed by extracting the fifth harmonic of zero-sequence voltage and zero-sequence current in grid to take phase comparison. The hardware circuit diagram is shown in Figure 3.

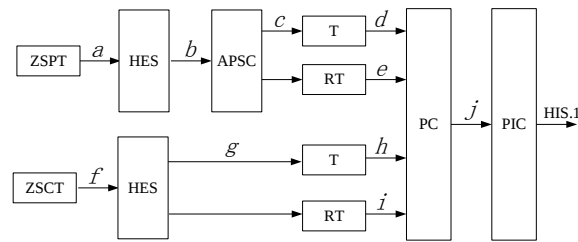


Fig.3. Hardware of selective leakage protection

Where ZSPT is Zero Sequence Potential Transformer; ZSCT is Zero Sequence Current Transformer; HES is Harmonics Extracting Schematic; T is Transformation; RT is Reverse Transformation; PC is Phase Comparison; PIC is Photoelectric-Insulation Circuit.

Seen from Figure 3, the hardware circuit of the unit is mainly composed by three parts, the zero-sequence voltage circuit, zero-sequence current circuit and a phase comparator circuit. Zero-sequence voltage circuit is composed by extraction circuit, phase circuit, waveform conversion circuit and optical coupling circuit of the fifth harmonic of the zero-sequence voltage. Its function is to extract the fifth harmonic component of the zero-sequence voltage in single-phase ground fault, and conduct appropriate phase shift and waveform transformation, to be compared with the output signal of zero-sequence current circuit by phase.

Zero-sequence current circuit is composed by extraction circuit, waveform conversion circuit and optical coupling circuit of the fifth harmonic of zero sequence current. Its function is to extract the fifth harmonic component from zero sequence current signals in the zero-sequence current transformer and take amplification and waveform transformation to be compared with the output signal of zero-sequence voltage circuit by phase.

The phase comparison circuit adopts CPLD device EPM240T100C5N to form logic gate circuit to conduct pulse comparisons of positively and negatively changing signals output through zero-sequence voltage circuit and zero-sequence current circuit, and the output signal is connected to the high-speed input port side, in order to determine whether this branch has single-phase ground fault.

4.2. Work principles of selective leakage system

It can be seen from the protection principle above, when single-phase ground fault occurs in the grid, the zero-sequence voltage is $100/3.14V$, zero sequence fifth harmonic current phase flowing through the fault branch lags behind in the zero-sequence fifth harmonic voltage phase by 90° . Therefore, in hardware design, zero-sequence voltage values collected by AC sampling are firstly applied, and if U_0 value collected by the computer system is less than the reference voltage, it is processed according to the non-leakage case; if U_0 value collected is greater than the reference voltage, the computer system continues to detect HIS.1 frequency at signal high-speed input to determine whether there is leakage.

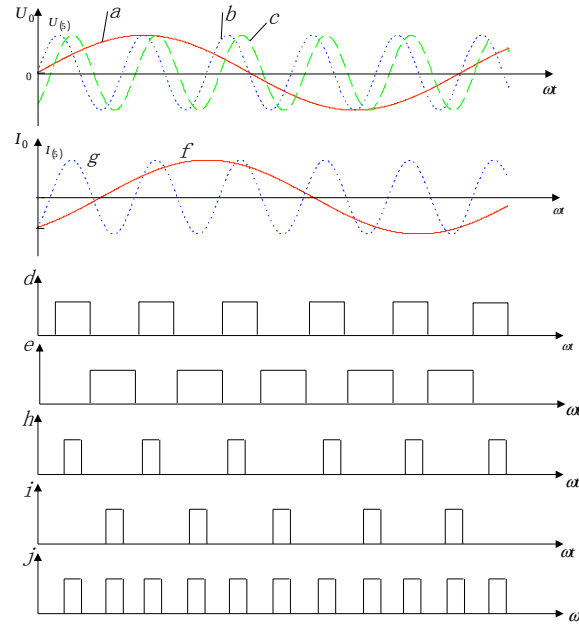


Fig.4. The waveform of each point in selective leakage protection unit

The waveform of each point in selective leakage protection unit is shown in Figure 4.

In hardware system, phase discrimination is based on the fifth harmonic U_{ZS5} of zero-sequence voltage phase after shift as reference; if U_{ZS5} and I_{ZS5} are of the same phase, this branch is judged to have leakage; CPU sends a control signal, leading to breaker tripping to lockout the circuit, otherwise it is the leakage of other branches, and CPU keeps this branch running.

The fifth harmonic signal is obtained by five times extraction of harmonic by zero-sequence voltage (the phase angle exceeds zero-sequence current fifth harmonic signal by 90°), and square wave signal with a period of 4ms is obtained after the processing of phase shifting circuit and waveform conversion circuit; the waveforms in processing procedure are as shown in a, b, c, d and e in Fig. 4. Zero-sequence current reaches the pulse sequence with a period of 4ms through the fifth harmonic extraction circuit, waveform conversion circuit, as shown in f, g, h and i in Fig. 4. In order to improve the reliability of judgment and operating speed, the positive and negative half-wave output signals of zero-sequence voltage and zero-sequence current fifth harmonic are extracted for phase-pairwise comparisons. When a fault occurs, after the transformation and the negative conversion circuit respectively, they are in the same phase, and phase comparison circuit output is a positive pulse with a period of 2ms, as shown at point 5j in the figure; when the grid is normal, the phases are opposite respectively, and point j outputs low and flat signal. Computer system eventually completes the selective leakage protection by determining the pulse width.

4.3. Realization of selective hardware circuit

4.3.1. Fifth harmonic extraction circuit

There are two requirements for the fifth harmonic extraction circuit from system: the first one is to ensure sufficient gain of the fifth harmonic signal, and the second one is sufficient attenuation for other frequency components. Requirements in performance make this part of the circuit more complex, of which the composition is shown in Figure 5:

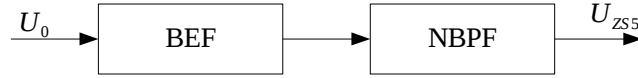


Fig.5. Schematic diagram of harmonics extraction circuit

where BEE is Band Elimination Filter; NBPF is Narrow Band-Pass Filter.

The center frequency band-stop filter is 50HZ, for suppressing the fundamental ingredients of 50HZ, with double T bandstop active filters, as shown in Figure 6, and the quality factor Q_{of} the circuit can be adjusted while the notch frequency is unchanged. Q value of the circuit can be changed from about 0.3 to 50 by adjusting R_4 . When the wiper of R_4 is at low potential, the obtained Q value is minimum. The notch depth and frequency are controlled by the six elements of double-T network and the maximum Q value of the six basic double-T elements (C_1 , C_2 , C_3 , R_1 , R_2 and R_4) is approximately 0.3. U_1 and U_2 provide bootstrap feedback for double-T grounding, so that the maximum of Q value reaches 50.

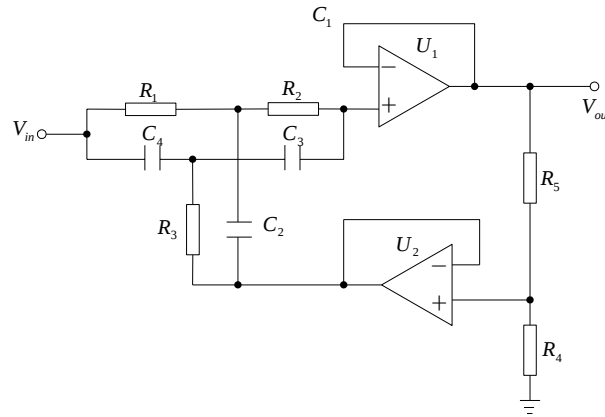


Fig.6. Circuit of double T band-stop filter

The center frequency of narrow-band pass filter is 250HZ, which allows the fifth harmonic frequency component to pass while inhibits the other frequency components. Four-order biquadratic bandpass active filter is used in the system as shown in Figure 8, of which the circuit is characterized by Biquadratic circuit needs more components than any other band-pass filter, but it has very good adjustment performance as a circuit applied widely. Moreover, Q value that biquadratic bandpass filter can achieve is more than 100, and has good stability, easy to get high-order Chebyshev response by cascade several stages.

Adjustment process of biquadratic bandpass filter is very simple, with the gain adjusted by varying R_1 , and Q by changing R_2 , while changing R_3 influences the center frequency.

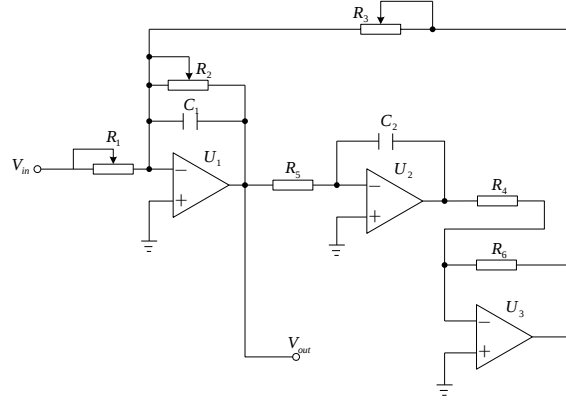


Fig.7. Circuit of biquadratic band pass filter

4.3.2. Fifth harmonic extraction circuit

In the leakage fault state, zero-sequence voltage exceeds zero-sequence current by 90° . In selective leakage protection system, zero-sequence voltage phase is generally shifted, and RC phase shift circuit is applied. This circuit, although simple in form, the cost is low, with the narrow scope of phase shift, so multi-section RC circuit must be connected in series to increase the phase shift angle; in addition there are also shortcomings such as serious reduction and adjustment inconvenience. An active-passive RC phase shift circuit is proposed in the system in place of passive RC circuit to conduct the shift of the zero-sequence voltage signal, and the active phase shifter circuit is shown in Fig. 8.

The input resistance and feedback resistance are R_1 , capacitor C_1 , and potentiometer PM_1 are phase shifting elements, and OP is for operational amplifier in the figure.

The use of phase shift circuit can make zero-sequence voltage phase shift backward by 90° , with the same phase as zero-sequence current, preparing for later phase comparator circuit.

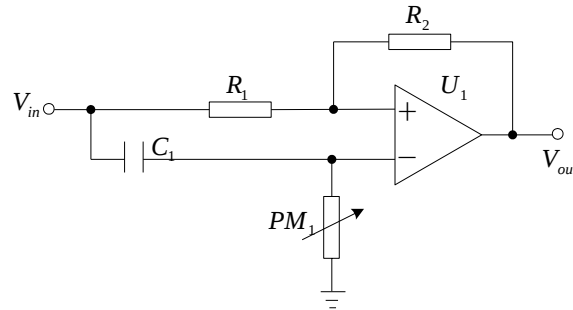


Fig.8. Circuit of active phase shifter

4.3.3. Wave transforming circuit

Wave transforming circuit provides phase comparison waveforms directly for the phase comparator circuit, which also enhances the fault tolerance of the phase comparison. The waveform conversion circuit of zero-sequence voltage channel outputs square wave while zero-sequence current channel outputs narrow pulse.

The entire circuit is composed by two parts, forward transform and inverse transform, with the same signal processing of positive and negative half waves, which includes three links primary comparison, integration and secondary comparison, and the width of the narrow pulse can be adjusted by changing comparative level of comparator circuit.

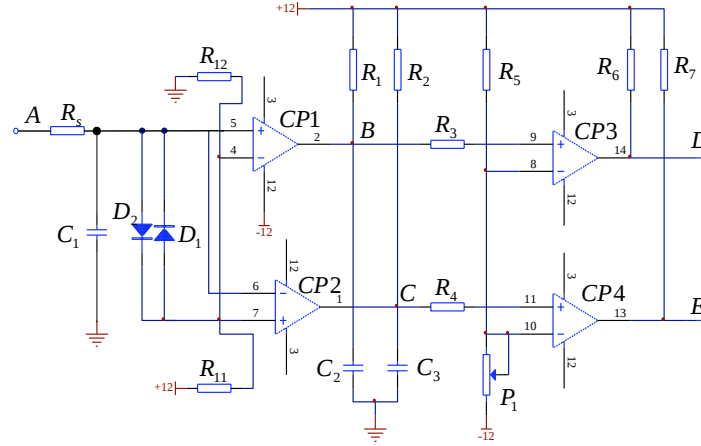


Fig.9. Wave transforming circuit

In order to maintain the correctness of phase comparison while the phase of zero-sequence current I_0 changes within a certain range, waveform I_0 needs to be transformed. Under the premise of ensuring the waveform width can be reliably detected by the CPU, narrower square wave signal reflecting the zero-sequence current phase at phase circuit input means larger scope of the changes in the timeline, and then zero sequence current signal phase requirements can be relaxed. This paper presents an integrated analog comparator to constitute waveform conversion circuit, of which the principle circuit is shown in Figure 9.

The entire circuit is composed by three parts—the primary, the integral and the secondary comparisons. The comparator CP1 is non-inverting input form, while CP2 is the inverting input form, to conduct zero-crossing comparison respectively between positive and negative half-cycle signals. As a capacitive load of converted signal, capacitive C1 has purification effect at the same time. R5 is current limiting resistor; anti-parallel diodes D1 and D2 protect the comparator by limiting large signal; R1 and R2 are pull-up resistors; C1 and C2 are integrating capacitors, which convert square wave output from the two comparators into sawtooth wave, and the output sawtooth waves are coupled respectively by resistors R3 and R4 to the secondary comparison unit composed by CP3 and CP4, to be compared with reference level V_{ref} , of which the waveform of each point is shown in Figure 10.

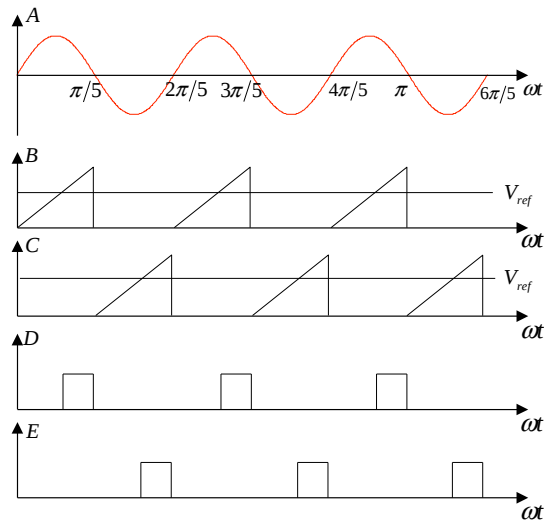
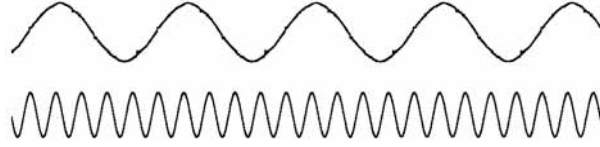


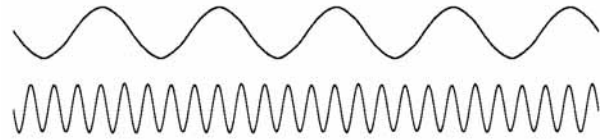
Fig.10. Wave transforming circuit

5. Experiment of leakage protection system

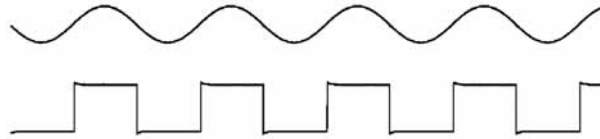
Analog AC voltage is connected to the terminal block of zero-sequence voltage and zero-sequence current in protection system, oscilloscope is used to observe and record the waveforms at different points of Figure 3 at the normal state and fault state, and the waveform are as follows.



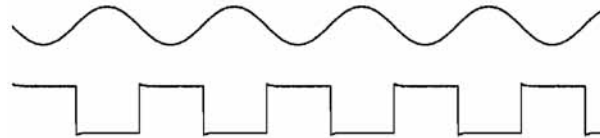
Zero-sequence voltage wave of point a and zero-sequence voltage fifth harmonic component wave of point b



Zero-sequence voltage wave of point f and zero-sequence voltage fifth harmonic component wave of point g



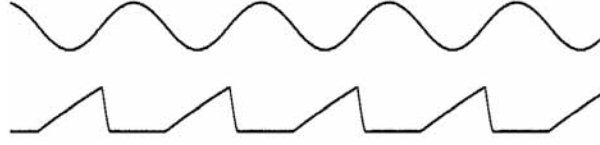
Zero-sequence voltage fifth harmonic component wave of point c and the wave of point d after positive conversion



Zero-sequence voltage fifth harmonic component wave of point c and the wave of point e after positive conversion



Zero-sequence voltage fifth harmonic component wave of point g and the wave of point h after positive conversion



Zero-sequence voltage fifth harmonic component wave of point g and the wave of point i after positive conversion

In the test of leakage protection, digital phase shifter is used to simulate zero-sequence voltage and zero-sequence current signals. Because the zero-sequence current transformer itself has a current/voltage converter, voltage signals can be directly used to simulate zero-sequence current signal. In this system, the setting value of zero-sequence voltage is 10V, and the setting value after conversion of zero-sequence current is 100mV, of which the test circuit is shown in Figure 11, adjusting the adjustable resistor on the digital phase shifter can change the phase between U_0 and U_1 .

where PS is Phase Shifter and SPS is Synthetic Protection System.

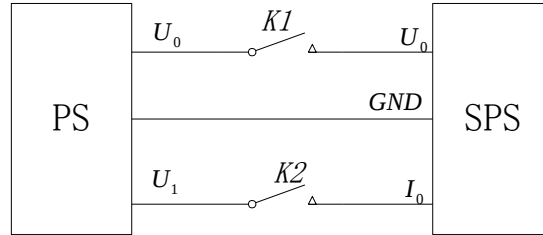


Fig.11. Test circuit for leakage protection

The size of the analog voltage U_0 is adjusted and meanwhile the phases of analog voltage U_0 and U_1 are adjusted; when U_0 reaches the setting value, and the phase of which exceeds that of U_1 by 90° , the protection system is operated, with the LCD display showing “leakage fault!”, and the corresponding indicator is lighted. Through the observation with an oscilloscope, waveform shown in Figure 12 is obtained.



Fig.12. Wave of HSI.1 when leakage fault occurs

The phase shifter is adjusted so that the phase of U_1 exceeds that of U_0 by 90° , namely simulating the phase relationship between zero-sequence current and zero sequence voltage under normal circumstances; the protection system is not operated at this time, and the waveform shows low level by the observation with an oscilloscope.

6. Conclusions

Grid leakage fault rules and harmonic characteristics of the neutral point grounding system through arc suppression coil are analyzed, the selective leakage protection program “zero-sequence voltage starts, fifth harmonics of grid zero-sequence voltage and zero-sequence current are extracted for phase comparison” is proposed, and corresponding fifth harmonic extraction circuit and power direction discrimination circuit are designed. The experimental results show that the protective principle applies not only to the neutral point insulated power supply system, but also to the power supply system in which neutral point passes arc suppression coil, which can be a good solution to selective leakage protection issues under different neutral grounding ways, improving the reliability of selective leakage to ensure the stability of the action value, with a certain application value.

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