Residual Current Detection Prototype and Simulation Method in Low Voltage DC System

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ABSTRACT With the rapid development of dc system, the residual current in dc system has become an urgent problem to be solved. However, the type B residual current devices (RCD) for ac systems could not be directly used in dc systems. In the dc system, the voltage fluctuation generated by the rectifier and the system circulating net currents generated by the line with different positive and negative parameters would interfere with the detection of RCD. In this paper, the residual current experimental platform was built firstly. Then the residual current detection prototype was developed and its operating characteristics were tested. The impedance model of human body was built for different electric shock conditions secondly. Thirdly, the influence of system factors on circulating net currents and the detection of residual current was analyzed. Finally, the configurations of RCD in dc system were proposed finally, protecting human body from electric shock and preventing electric fire accident threats.

INDEX TERMS Dc residual current, LVDC, detection algorithm, magnetic modulation model, simulation.

I. INTRODUCTION

In recent years, renewable energy has made great progress. The energy industry has become a strong driving force for the development of dc system by changing from fossil energy to clean energy. Compared with ac power distribution system, dc power distribution system has the advantages of reduced complexity and low power loss[1]. However, the research on dc distribution protection technology is still in its infancy, which hinders the development of dc system. Among of them, the residual current threatens the safe and reliable operation of LVDC system, and has become a research hotspot.

Residual current refers to the current vector sum of each phase line in the system circuit which is not zero. Residual current could cause fire, electric shock and other hazards, which has become a key problem in dc distribution system. Insulation aging of wires and electrical equipment, excessive load on distribution lines and reduced insulation level of wires in wet conditions all lead to residual current. Some fault currents are small, usually hundreds of milliampere or even dozens of milliampere. Common overload protection and short-circuit protection measures cannot effectively protect such faults. Meanwhile, the ac residual current caused by distributed capacitance and rectifier could interfere with the detection of the dc RCD[2]. There have been several standards for RCDs used in ac systems[3][4]. However, none of them could be applied to dc systems to detect dc residual current. In 2017, the international electrotechnical commission formulated IEC TS 63053, an international standard for dc residual current detection of electrical appliances[5].

There are some related studies in order to find and improve some problems of existing RCD. Theoretical analysis and experiments are presented. Several mechanisms which could influence the tripping sensitivity of RCDs were validated, and their dominant conditions were identified[6][7]. The influence of harmonics on the operating characteristics of RCD device was analyzed, and some solutions were given to eliminate these effects[8][9]. Some studies analyzed the operation characteristics of RCD under different conditions and gave the optimization method[10]-[12]. A smart Residual Current Circuit Breaker with Overcurrent protection was presented. The device was fully automated and had adjustable settings to ensure safety while allowing increased flexibility to better match users' needs[13]. In order to detect the residual current in the dc system efficiently, improved dc component methods were
presented and different dc residual current sensors based on the magnetic modulation were designed[14]-[16][25]. Generally, hundreds of milliamperes dc residual current is fatal to humans and could cause electric fire. Many scholars have carried out research on electric shock in LVDC system. The biological electric shock experimental platform was built to collect the voltage and current data of electric shock. Then the electric shock simulation model was established according to the data fitting of multiple groups[17]. The contact voltages of indirect electric shock in TT, IT and TN systems are simulated and the results show that the RCD is needed for protection in TT and TN systems[18]-[20]. The break time of RCD under different voltage levels and grounding modes are researched in LVDC[21]. Ground faults in LVDC are researched and results show that it is difficult for the converter to limit and break the current circuit under certain fault currents and paths[22]. The PSCAD simulation model of unipolar low voltage DC TN system is researched and analyzed for its phase fault and ground fault. The results show that the contact voltage is only half of the dc bus voltage when the indirect shock occurs, which may cause the operation rejection of RCD[23]. The representative electric shock simulation models of TN, TT and IT systems were established. And the characteristics of residual current caused by direct and indirect electric shock in different grounding modes were researched[29].

This paper solves the detection and protection of low-voltage DC residual current from the design of RCD prototype and configuration of RCD, as shown in Figure 1. In this paper, for residual current detection prototype design, a magnetic modulation detection simulation model of dc residual current based on MATLAB platform is proposed. And experiments of different types residual current are carried out in the dc resistive system. The experimental results show that the proposed model and detection algorithms are effective. For configuration of RCD, the current effects on human beings are also researched. And the human body impedance model applicable to a variety of situations is proposed. The influence of system factors on the circulating net currents is analyzed. Finally, according to the analysis of experiment and simulation, combined with the actual situation of low-voltage dc system, the configuration principle of residual current protector in low-voltage dc system is summarized.

II. RESIDUAL CURRENT EXPERIMENT

A. EXPERIMENTAL PLATFORM AND METHOD

According to the standard IEC/TS 63053[5], it is necessary to detect the residual current of the type such as steady increase of residual current and sudden residual current. At present, most of the dc systems are from ac system through rectifier, such as dc charging pile, dc municipal street lamp, etc. At the same time, due to the increasingly use of power electronic load of the dc side, there is a risk that the residual current in the ac form is connected into the dc system. Therefore, according to the standard IEC/TR 60755[24], the typical ac residual current is tested.

Shown in Figure 2, the residual current experimental system is composed of the main circuit and the residual current circuit. The total power supply capacity of the platform is 10 KVA, and three-phase 380 V power supply is used. The main circuit consists of ac source, dc source and dc feedback load. The current in the main circuit is 10 A to 150 A adjustable. The residual current circuit consists of rheostat and residual current simulator. The sudden residual current of 10 mA to 10 A can be adjusted by rheostat R1. The residual current simulator could be programmed by computer to simulate the sudden appearance of residual current, the steady increase of residual current, the sinusoidal residual current, etc., according to the standard[3]-[5]. It can be loaded in the positive and negative circuit respectively, and the simulated residual current is adjustable from 0 to 10 A. The RCD is placed in the main circuit and its magnetic core is traversed by two wires of the main circuit. HIOKI CT6863 current sensor and HIOKI CT9557 current sensor are used to measure the current of main circuit and residual current circuit separately. And the demodulation current is measured by HIOKI CT9557. HIOKI 9666 voltage probe is used to measure the voltage of main circuit. All data are recorded at a sampling frequency of 1 MHz in the Yokogawa DL850E memory recorder. This experimental platform can be used to carry out many kinds of residual current experiments under various working conditions, and realize the development, debugging and testing of residual current detection module in complex environment.
The switches and air circuit breakers are used to change the operation state of the whole system. In order to simulate a positive sudden residual current, QF1, QF3, QF4, QF5, and QF6 need to be closed first. Secondly, switch B and C need to be closed. To simulate a negative sudden residual current, switch A and D need to be closed rather than switch B and C. The value of residual current is determined by the voltage of the dc source and the resistance value of the rheostat.

In order to simulate a steady increase of residual current or the sinusoidal residual current, QF1, QF2, QF3, QF4, and QF5 need to be closed first. Secondly, switch A and C (or switch B and D) need to be closed. The value, polarity and type of residual current is determined by the residual current simulator.

B. RESIDUAL CURRENT DETECTION METHOD

Magnetic modulation is a method of residual current measurement using the non-linear of ferromagnetic materials[26].

In addition to the magnetic modulation method, the traditional residual current detection methods include electromagnetic current transformer detection method, Hall detection method and giant reluctance detection method. The selection of detection method is discussed from the following four aspects:

1) Detect bandwidth. In order to achieve the protection of personal shock and electrical fire protection, the dc and frequency up to 1kHz residual current should be accurately detected. Compared with the above four detection methods, the electromagnetic current transformer detection method can not accurately detect the DC residual current;

2) Detection accuracy. The structure of open-loop Hall detection method and giant reluctance detection method is relatively simple, but the detection accuracy is low. Closed-loop Hall detection method and giant reluctance detection method have higher detection accuracy, but their structure design is complex and their power consumption is high. Due to the magnetic core air-gap magnetic leakage effect of hall detection method and giant reluctance detection method, the detection accuracy is not as high as that of magnetic modulation detection method.

3) Response speed. According to relevant standards, the residual current action protector should operate within 40 ms under the most stringent conditions. Therefore, the faster the response speed of detection method, the better. The electromagnetic current transformer uses Faraday's law of electromagnetic induction to directly induce the residual current in the secondary coil, which has a fast response speed. The open-loop Hall detection method and the giant reluctance detection method directly amplify and output the signal of the sensing element, and also have a fast response speed. In order to make the magnetic core in zero flux state, the closed-loop Hall detection method and giant reluctance detection method have slow response speed due to the influence of magnetic hysteresis. The magnetic modulated detection method can accelerate the response speed by increasing the excitation current and voltage frequency.

4) Temperature drift and zero drift. The residual current action protector is usually installed in the switch cabinet, where the electromagnetic environment around it is complicated, and the working environment temperature varies greatly. Therefore, the residual current detection method is required to have good electromagnetic compatibility, small temperature drift and zero drift. Hall type detection method and giant reluctance detection method have large temperature drifts. The magnetic modulated detection method has a small temperature drift. The magnetic core working point of electromagnetic current transformer is easily affected by the dc component, and its zero drift is large. The closed-loop Hall detection method and giant reluctance detection method have smaller zero drift than the open-loop detection method. Magnetic modulation detection method because of the excitation current, excitation voltage, its zero drift is smaller.

To sum up, the magnetic modulation method has the advantages of simpler structure, lower cost, smaller detection error, sufficient detection bandwidth, higher detection accuracy and faster response speed. There is no air gap in the magnetic core and it is less affected by temperature. So it could accurately measure dc and ac residual current in low voltage DC system. The comparison of several mainstream residual current detection methods is shown in TABLE I. The dc RCD is mainly composed of modulation module, demodulation module and microcontroller unit (MCU), as shown in Figure 3.

| Detection method                              | Method type | Residual current detection type | Detection bandwidth | Detection accuracy | Response speed | Temperature drift & zero drift | Cost          |
|-----------------------------------------------|-------------|---------------------------------|---------------------|-------------------|---------------|-------------------------------|---------------|
| electromagnetic current transformer detection method | open-loop   | ac                              | 10Hz~20kHz          | a bit high        | fast          | a bit small temperature drift, a bit large drift | quite low     |
| Hall detection method                         | open-loop   | ac, dc                          | 0~200kHz            | a bit low         | a bit fast    | a bit large temperature drift, a bit low    | low           |
The excitation module outputs positive and negative pulse voltage and can make the magnetic core in a fully saturated state. Due to the inductance effect of the coils, the voltage of the operational amplifier reverse input end lags behind that of the output end. When the residual current is zero, the variation of excitation voltage and excitation current is shown in Figure 5.

![Figure 5](image-url)

**FIGURE 5.** Variation of excitation voltage and excitation current[25].

In the region I, the voltage at the positive and negative terminals of the op amp is $U_{R_1} < U_{R_2}$, the operating point is in the negative voltage positive saturation region (that is, the voltage is in the negative voltage and the magnetic core is in the positive saturation state, and so on), and the excitation current decreases sharply from the positive maximum current $I_{H1}$ until the core exits the positive saturation region. In region II, the operating point is located in the negative voltage linear region, and the excitation current gradually decreases until it enters the negative saturation region. In the region III, the operating point is located in the negative voltage negative saturation region, and the excitation current decreases sharply until the minimum negative current $-I_{H1}$ is reached, the voltage at the positive and negative terminals of the op amp changes to $U_{R_1} > U_{R_2}$, and the excitation voltage changes from negative to positive. In the region IV, the working point is located in the positive voltage negative saturation region, and the excitation current increases sharply from negative to positive.

The excitation module is generally composed of a magnetic core, an operational amplifier, a resistor, a coil, etc., which is generally a single magnetic core structure. As shown in Figure 4, a typical structure of the voltage type magnetically modulation module is presented. The coil is not only the excitation coil, but also the detection coil. The transformer usually applies materials with high initial permeability and low coercive force as its magnetic core, such as permalloy, amorphous alloy, nanocrystalline alloys and so on. Its performance is directly related to the detection range and accuracy.

![Figure 4](image-url)

**FIGURE 4.** Modulation principle of dc RCD.

The modulation module is generally composed of a magnetic core, an operational amplifier, a resistor, a coil, etc., which is generally a single magnetic core structure. As shown in Figure 4, a typical structure of the voltage type magnetically modulation module is presented. The coil is not only the excitation coil, but also the detection coil. The transformer usually applies materials with high initial permeability and low coercive force as its magnetic core, such as permalloy, amorphous alloy, nanocrystalline alloys and so on. Its performance is directly related to the detection range and accuracy.

![Figure 3](image-url)

**FIGURE 3.** Schematic diagram of dc RCD.
minimum current \( I_{th} \) until the core exits the negative saturation region. In the region V, the operating point is in the positive voltage linear region, and the excitation current begins to increase gradually until it enters the positive saturation region. In the region VI, the operating point is located in the positive voltage positive saturation region, and the excitation current increases sharply until it reaches the maximum positive current \( I_{th} \), the voltage at the positive and negative terminals of the op amp changes to the state before the start of the region I. The excitation voltage and excitation current repeat the above variation to modulate the residual current.

When there is no residual current in the circuit, a regular square wave is output in the coil. When the residual current in the circuit is not zero, the excitation current no longer oscillates on both sides of zero and has a certain offset, and its output wave will contain both the residual current and the excitation square wave, which is the modulated current.

In order to obtain the measured residual current from the modulated current, a demodulation module is required. Demodulation is the process of decoupling the residual current signal from the excitation current. According to Shannon Law, the excitation current frequency should be more than two times of the measured residual current frequency. Therefore, the low pass filter could be used as a decoupling module.

### C. THE TEST OF THE RESIDUAL CURRENT DETECTION PROTOTYPE

In the previous work, we have designed the magnetic modulation RCD, developed a prototype based on it, and then tested it on the experimental platform described in section A. The test is based on the Standard IEC/TS 63053[5], which specifies the operating time of non-delay dc residual current protector for low voltage DC system in different types and sizes of residual current. We have also tested some residual current types of the engineering prototype developed by a manufacturer, and the results are displayed together. The \( I_{th} \) of the engineering prototype is 80 mA.

The residual current detection prototype is tested for detection error, and the results are shown in Figure 6. In the range of 300 mA, the relative error is kept within 3\%, and when the residual current is greater than 100 mA, the detection error is kept within 2\%. The typical test results of dc rated residual operating current of 80 mA, 300 mA and ac rated residual operating current of 30 mA are shown in Figure 7. In fact, at least five tests have been carried out for each operating characteristic test item under each working condition, and the results of multiple tests are averaged, which are shown in TABLE II. To sum up, the operating characteristics of the prototype meet the requirements of relevant standards, and it can detect AC/DC residual current quickly and accurately.

Test results of operating characteristics of engineering prototype are shown in Figure 8. The Waveform of operating characteristics of engineering prototype is shown in Figure 9. The engineering prototype operates within 75 ms, meeting the Standards’ requirements of DC-RCD breaking time when the residual current of 80 mA, 160 mA and 240 mA suddenly appears. It can detect residual current quickly and accurately.
is 140 mA and ac safety threshold is 40 mA. Therefore, dc has better security than ac.

However, in addition to the current size and current duration, there are many factors that affect the physiological effects of human current, such as contact voltage, current frequency, current path, environmental conditions, human state, etc.

1) Contact voltage. With the increase of contact voltage, the total impedance of human body will gradually decrease. This leads to the further increase of current flowing through the human body at higher voltage level, which will cause greater harm to human body;

2) Current frequency. Although the total impedance of human body will decrease with the increase of current frequency and the influence of skin capacitance, the physiological effect of current will also decrease;

3) Current path. The probability of ventricular fibrillation caused by the same current is different in different current paths. For example, the probability of ventricular fibrillation caused by 200mA current flowing from foot to foot is lower than that by hand to foot;

4) Environmental conditions. The environmental conditions will affect the total impedance of human body, and then affect the electric current. Under the conditions of drying, water wetting and saltwater wetting, the total impedance of human body decreases in turn, the current flowing through the body increases in turn, and the harm to human body is also greater;

5) Human state. The health status of human body is closely related to the effect of human current. People with unhealthy heart may have lower ventricular fibrillation current threshold. The impedance of different human body varies with the different constitution.

In order to analyze the current effect of direct and indirect shocks on human body more accurately, it is necessary to establish the impedance model of human body.

### B. HUMAN BODY IMPEDANCE MODEL

The impedance model of human body could be regarded as a multi-component model composed of resistors and capacitors in series and parallel. The total impedance of human body $Z_T$ is composed of skin impedance and internal impedance[28].

Human body impedance $Z_T$ of dry conditions, large contact surface area and current path from one hand to the other hand is available in IEC 60479. Dry conditions refer to dry skin in normal indoor environment. Large contact area refers to the whole hand contact conductive surface. Therefore, the expressions of human ac and dc impedance could be obtained:

$$Z_T = a \cdot e^{bi} + c \cdot e^{di}$$

where $a$, $b$, $c$, $d$ are the fitting parameters under different conditions. Under the above conditions, the obtained expressions are as follows[29]:

### III. HUMAN BODY IMPEDANCE MODEL

#### A. CURRENT EFFECTS ON HUMAN BEINGS

After a large number of experiments and the analysis of electric shock accidents that have occurred, the physiological effects of ac and dc current has been published in the standard IEC 60479 (Effects of current on human beings and livestock)[27]. Generally speaking, the physiological effect of dc on human beings is weaker than that of ac with the same magnitude. The dc safety threshold...
The simulation model of low voltage DC system with two power supplies is shown in Figure 10. The system is bipolar connection and TN grounding, which is powered by source I and source II. The simulation parameters of the system are shown in the TABLE III. When the cross-sectional area of copper line is 25 mm², the resistance of each line could be calculated at 20°C:

\[ R_w = \rho \frac{L}{S} \]  

(4)

\[ \rho = \rho_{20} \left[ 1 + \alpha \left( T - 20 \right) \right] \]  

(5)

where \( R_w \) is resistance of the line, \( \rho \) is the resistivity of copper, \( L \) is the line length, \( S \) is the cross-sectional area of the line, \( \rho_{20} \) is the resistivity of copper at 20°C, which is about 0.0175 Ω·mm²/m. \( T \) is temperature, \( \alpha \) is temperature coefficient of copper resistivity, about 0.004. The line resistances are as follows, \( R_{11} = R_{1M} = R_{1} = 0.14 \ \Omega \), \( R_{22} = R_{2M} = R_{2} = 0.28 \ \Omega \), \( R_{33} = R_{3M} = R_{3} = 0.42 \ \Omega \) and \( R_{44} = R_{4M} = R_{4} = 0.56 \ \Omega \). The simulation results with these conditions show that the current sum of each loop is zero, \( i_{L1} = i_{L2} = i_{L3} = i_{L4} = 0 \). Because of load balancing, the current of neutral line M is zero, and the circulating net current is zero.

If the resistance of load \( L_1 \) is reduced from 15 Ω to 7.5 Ω, the current in neutral line M is no longer zero. The current in loop 1 is as follows, \( I_{R1L} = 36.73 \ \text{A}, I_{R1M} = -18.74 \ \text{A}, I_{R1M} = -17.99 \ \text{A} \). Although the sum of the current in each loop is still zero, there is no circulating net currents in the system. Due to the imbalance of line current, the line temperature would also change, leading to the change of line resistance.

IV. CIRCULATING NET CURRENTS SIMULATION IN LVDC

A. CIRCULATING NET CURRENT SIMULATION MODEL

In order to increase the capacity of the power supply system and improve the reliability and stability of the power supply, the network multi terminal power supply will be used in the low voltage DC system. However, on the one hand, due to the changes of power supply voltage and line parameters, the circulating net current, i.e. false residual current, will be generated in the line; On the other hand, most of the dc current is rectified by ac, and the output voltage of the system power supply has ripple, which will also produce false residual current in the system. These false residual currents may cause the maloperation of residual current operated protector and cause the protection failure. Therefore, it is of great significance to build a low-voltage dc mesh multi terminal power supply simulation system and study the possible false residual current, so as to optimize the configuration of residual current operated protectors, so as to provide more effective protection for faults caused by residual current in different systems.

The simulation model of low voltage DC system with two power supplies is shown in Figure 10. The system is bipolar connection and TN grounding, which is powered by source I and source II. The simulation parameters of the system are shown in the TABLE III. When the cross-sectional area of copper line is 25 mm², the resistance of each line could be calculated at 20°C:

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**TABLE III. SIMULATION PARAMETERS OF CIRCULATING NET CURRENTS**

| Parameters                     | Initial Value |
|--------------------------------|---------------|
| Temperature                    | 20°C          |
| Power supply voltage           | ±375 V        |
| Distance from source I to load | 200 m         |

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B. THE SIMULATION RESULTS

In this section, the effects of line temperature and source voltage change on the net circulating current are discussed by using the simulation model.

When the temperature of the loop 1 positive line and the loop 4 of negative line change, the line resistances also change. The sum of currents in each loop are shown in Figure 11. The results of loop 3 and loop 1 are the same, and the results of loop 4 and loop 2 are the same, so they are not repeated in the drawing. With the increase and decrease of temperature, the absolute value of current sum in each loop increases, and negative current means that the current direction is opposite. When the temperature of one line changes ±12°C, the current sum reaches 90.1 mA. When the temperature of both lines changes, the maximum current sum can reach 206.5 mA, which exceeds the residual current operating threshold of 80 mA. It can be seen that when the line impedance changes due to temperature or other reasons, the circulating net current will be generated in the system, which may lead to RCD misoperation.

When the positive voltage of the source I and the negative voltage of the source II change, the current sum of loop 1 and loop 2 is as shown in Figure 12. For the same reason as before, the results of loop 3 and loop 4 are not repeated. With the change of voltage, the absolute value of current sum in each loop increases. When any source voltage changes by 2%, the sum of current can reach 123.3 mA. When both source voltages change, the sum of current can reach 1294.4 mA. These circulating net currents may interfere with the normal operation of the system.

The above simulation results show that in the low-voltage dc mesh multi terminal power supply system, the changes of line temperature rise and power supply voltage will produce circulating net current in the loop, and cause interference to the detection and protection of residual current. Therefore, more requirements are put forward for the configuration and design of RCD in this kind of system.

V. CONFIGURATION OF RCD IN LVDC

Based on the simulation of human impedance models and electrical shock accidents in different systems in section III and the simulation of circulating net current in section IV, some guidelines for configuration of RCD in LVDC are obtained.

The main function of RCD is to accurately detect the residual current and then prevent personal electric shock and electric fire. According to the standard IEC TS 63053...
When the dc residual current protector is connected, all the live conductors in the main circuit should be connected. For unipolar system, both L+ and L- should be connected. For bipolar system, L+, L- and neutral M should be connected. It should be noted that PE line can not be connected, otherwise the dc residual current protector may refuse to operate in case of fault, resulting in protection failure.

In TN and TT systems, residual current operated protector can protect the lower end from direct electric shock. For the indirect electric shock accident in TN system, because of the large fault current of the system, the over-current protection of the system will be triggered. The residual current operated protector can be used as the backup of the over-current protection to disconnect the corresponding lines in time. In TT system, the fault current is difficult to trigger the over-current protection, so the residual current action protector is needed as the main protection to disconnect the fault circuit in time. In IT system, when a direct or indirect electric shock accident occurs at a point, the fault current is very small, and there is no harm to human body, so the system operates normally. For the direct electric shock accident of two-point fault, the fault circuit may not pass through the line connected by the dc residual current protector, so the dc residual current protector cannot operate correctly, and the fault current is difficult to trigger the over-current protection at this time. For this kind of fault, it can only be protected by insulation detection device. For the direct electric shock accident with two-point fault, it is also difficult to use the dc residual current protector for protection, but at this time, the system fault current has a large rise, which may trigger the over-current protection. Therefore, for IT system, insulation monitoring devices (IMD) should be used as the main protection.

In the low voltage DC system with multi-power supply, the circulating net currents may cause the misoperation of the RCD. The previous results in section IV B have shown that current sum and current direction of the two sources supplying the same load are the same. Therefore, when the RCDs have the communication function, the central monitoring system (CMS) could be used to comprehensively judge the detection value at the power supply at both ends, so as to determine whether there is a real residual current in the system or a circulating net current. Taking the system's loop 1 in Figure 10 as an example, RCDs are installed on the power side of each loop, with the same number as the loop number, and one CMS can communicate with four RCDs. The flow chart of the CMS's detection method is shown in Figure 14. When \( i_{\Delta 1} \) is not zero, CMS obtains \( i_{\Delta 3} \) at the same time. If \( i_{\Delta 1} = i_{\Delta 3} \), it is judged as circulating net current and the system will continue to operate; Otherwise, it is judged as residual current, CMS will send a command to RCD1 to cut off the loop 1.

### TABLE IV.

THE CUT-OFF TIME STANDARD VALUE WHEN THE DC RESIDUAL OPERATING CURRENT IS EQUAL TO THE FOLLOWING VALUE[5]

| \( \Delta t \) | 2\( \Delta t \) | 3\( \Delta t \) | 1A, 2A, 5A, 10A | 20A, 50A, 100A |
|--------------|--------------|--------------|-----------------|-----------------|
| 0.3s         | 0.15s        | 0.04s        | 0.4s            |

**FIGURE 13.** Comparison of breaking time curve and human current effect curve of personal electric shock protection.

The hierarchical protection of dc residual current protector should meet the selective cooperation between upper and lower levels. Generally, the superior is delay type, which is configured in the distribution circuit for the protection of electrical fire and grounding fault. The lower level is non-delay type, which is configured in the terminal circuit for personal electric shock protection. Delay type is only applicable to RCDs with \( i_{\Delta t} > 0.08 \) A. The minimum non-driving time of the upper dc residual current protector should be greater than the maximum breaking time of the lower dc residual current protector.

(General requirements for residual current operated protective devices for dc systems), the standard values of \( I_{\Delta n} \) were 0.08 A, 0.3 A, 0.6 A and 1 A, and thresholds for electric shock and electric fire protection are 80 mA and 300 mA, respectively[5]. The operation time of non-delay dc RCD used in low voltage DC system is stipulated, as shown in TABLE IV. For personal electric shock protection, set \( I_{\Delta n} = 0.08 \) A. Compare the breaking time curve of dc residual current operated protector with the current effect curve of human body, as shown in Figure 13. It can be seen that most of the breaking time curves are on the left side of dc human body current effect curve c, and they intersect at about 500mA and 40ms. This means that when the human body is shocked and the shock current is less than 500 mA, the dc residual current operated protector with \( I_{\Delta n} = 0.08 \) A can protect human body from ventricular fibrillation and protect their lives. When the human shock current exceeds 500 mA, the dc residual current action protector can also disconnect the circuit within 40ms to avoid more serious injury to the human body. For the protection of electrical fire, \( I_{\Delta n} \) could be set at 0.3 A.
FIGURE 14. Flow chart of CMS’s detection method.

VI. CONCLUSION

In this paper, a residual current detection method based on magnetic modulation is proposed. A prototype is made by using the principle, and the residual current tripping experiment is carried out to verify the effectiveness of the method. Then the human body current effects of ac and dc are analyzed, and the human body impedance model is built based on the literature data. According to the actual situation of dc system, the influence of line temperature rise, power supply voltage and other factors on the detection of circulating net current and residual current is analyzed. Finally, according to the results of prototype experiment and simulation, the configuration principle of residual current protector in low voltage DC system is summarized.

In this paper, the detection and protection of dc residual current is studied from design and configuration method of dc-RCD. The experimental and simulation results show the effectiveness of the proposed method.

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