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A Novel Online Insulation Fault Detection Circuit for DC Power Supply Systems

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Abstract

This paper proposes a novel online insulation fault detection circuit to overcome the shortcomings of ungrounded DC power supply system for being unable to provide high sensitivity leakage current detection. A DC power supply insulation fault detection circuit includes a leakage current detector located in each branch circuit, and a positive voltage transient compensator and a negative voltage transient compensator respectively bridging the positive terminal and negative terminal of the power supply system. The positive and negative voltage transient compensators respectively include a charge circuit to allow an energy storage circuit to be charged. When grounding insulation deterioration takes place at the positive or negative terminal of the leakage current detector, a leakage current loop is formed so that energy storage elements discharge and the leakage current detector detects current variations on the positive and negative terminals, and issue an alarm signal or control cutoff of the circuit breaking elements. The experiment result demonstrates that this novel method is able to detect 1 mA/50 kΩ insulation fault to achieve the high sensitivity detection goal.

Keywords: Insulation fault, leakage current, current sensor, DC power supply.

1. Introduction

DC power supply usually consist of batteries, chargers and electronic power converters to provide high-quality DC power source for important loads, such as DC power system for power plants, plastics and chemicals plants, steel mills, and other operations requiring stable and continuous DC power supply for control system, signal system, relay protection devices, circuit breakers and other equipment. An ungrounded system is generally used to improve DC power supply system quality. The negative electrode of DC power supply is not grounded, and maintains insulation of positive and negative bus to the ground. A single point ground fault does not affect the operation of DC power supply system. When the ground fault it is caused by two or more points, it results in short circuit of the positive and negative bus and overall DC power supply system failure.

DC power supply is usually a long-term uninterrupted power system. As the electrical devices are working in long period of time, their insulation quality tends to failure when subjected to environmental influences, climatic changes, air pollution, aging of cables and wiring, aging of insulation, failure of devices and other problems. Detecting insulation faults is difficult for DC power systems with a large branch network. The following methods are used to detect leakage current of ungrounded DC power system.

(A) Balanced bridge method:

The balanced bridge method is mainly used to detect insulation faults in DC power system. Changes in insulation resistance to ground of the positive and negative bus cause the bridge to lose balance and result in a warning signal [1]. This method can only detect the existence of a ground fault in the DC power

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supply system, and an insulation check must be performed on every branch loop before the affected branch circuit can be identified. Therefore, this method cannot achieve automatic online and real-time detection and warning of ground fault.

(B) Unbalanced bridge method:

The unbalanced bridge detection method is a modification of balanced bridge method [2]-[6]. This method is applicable for the positive and negative bus when their insulation resistance falls are equal, and can also detect the insulation resistance value of the positive and negative bus to ground. However, this method cannot identify which branch circuit has a ground fault, and so each branch circuit requires a branch leakage current detector. The positive and negative bus must be fitted with a resistor when using the unbalanced bridge method to detect the fault, reducing the insulation of the DC power system.

(C) AC signal source injection method:

The basic principle of this method is to inject a low frequency AC signal source in the positive and negative bus, and then use an AC current sensor to detect the low frequency AC current signal of the branch circuit [7]-[11]. The ground resistance can then be calculated based on the magnitude and phase angle of this current. When the measured resistance value is below the set value, this branch circuit has a ground fault. Due to micro electro mechanical devices recently using numerous anti-interference capacitors as a transient voltage compensator, this increases the capacitance in the DC power supply system and results in larger capacitance current [12]. AC signal source injection to detect ground fault point thus is ineffective for ground fault detection of a branch circuit. That is, when the ground capacitance current exceeds the leakage current value of the standard of insulation resistance, it generates a false alarm that affects the correct determination of the insulation false detection device.

(D) Portable leakage current test instrument method:

The operating principle of this method resembles that of the AC signal injection method. The portable instrument can be moved to any detection location, and its mobility simplifies the location of the ground fault point of any branch circuit. However, due to the present product having poor compatibility and low anti- interference capability on all kinds of DC power supply systems, its accuracy in ground fault detection is low and so it has not been extensively applied.

This paper proposes a novel ungrounded DC insulation fault detection device that uses capacitor group and grounds the intermediate point of the capacitor group to form a leakage current path. This allows automatic real-time detection of DC system insulation fault, and is characterized by high detection sensitivity, no need to inject AC signal source into the system.

2. Conventional Ground Fault Detection Method

Fig. 1 shows the conventional ground fault detection circuit of DC power system [13]. To improve the sensitivity of leakage current detection, the system shunt of the positive and negative bus to the ground is connected with resistance *R*. The resistance *R* should not be too small because excessively small resistance seriously reduces the insulation performance of the DC power system, and the *R* should not be too large either; otherwise, the leakage current loop will be smaller than the minimum current detection scope, preventing successful ground fault detection.

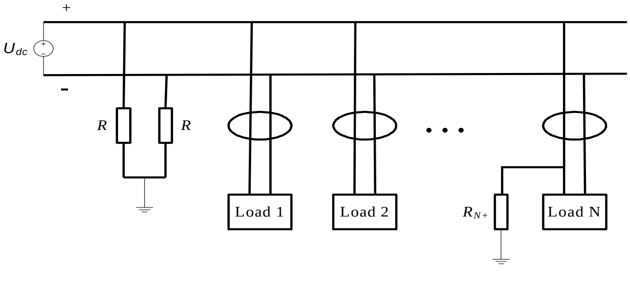


Fig. 1. The conventional ground fault detection circuit.

This paper proposes a novel online insulation fault detection circuit to overcome the shortcomings of ungrounded DC power supply system for being unable to provide high sensitivity leakage current detection. In this paper, the capacitor group is used to connect with positive and negative bus and ground the intermediate point of the capacitor group, and that each branch loop is installed with a leakage current detection device. When insulation fault occur in the system, the capacitor is able to provide a leakage current return path and discharge through the stored energy in the capacitor. This will allow the Hall effect current sensor to detect the difference of positive and negative bus current, and deliver warning signal or control the breaker to cut off the power supply.

2.1. Structure of the proposed insulation fault detection

Fig. 2 shows the proposed online insulation fault detection circuit for DC power supply. This circuit comprises two sections: capacitor grounding with the current limiting module and leakage current detection module. The former is installed on the main bus, and consists of a positive voltage transient compensator and a negative voltage transient compensator. The latter are installed on every branch, and consist of a Hall effect current sensor, voltage level regulator, filter amplifier, voltage comparator and alarm device.

The positive voltage transient compensator includes a first charge circuit, a first energy storage circuit, and a first discharge circuit. The first charge circuit includes a first diode D_{11} and R_{11} which has one end connected to the positive terminal of the power supply system and another end coupled with the first energy storage circuit in series. The first energy storage circuit has another end grounded and includes a resistor R_{12} and a first energy storage element $C1$ coupled in parallel. The first discharge circuit is coupled with the first charge circuit in parallel, and includes a first one-way discharger D_{12} and a current limiting resistor R_1 coupled in series.

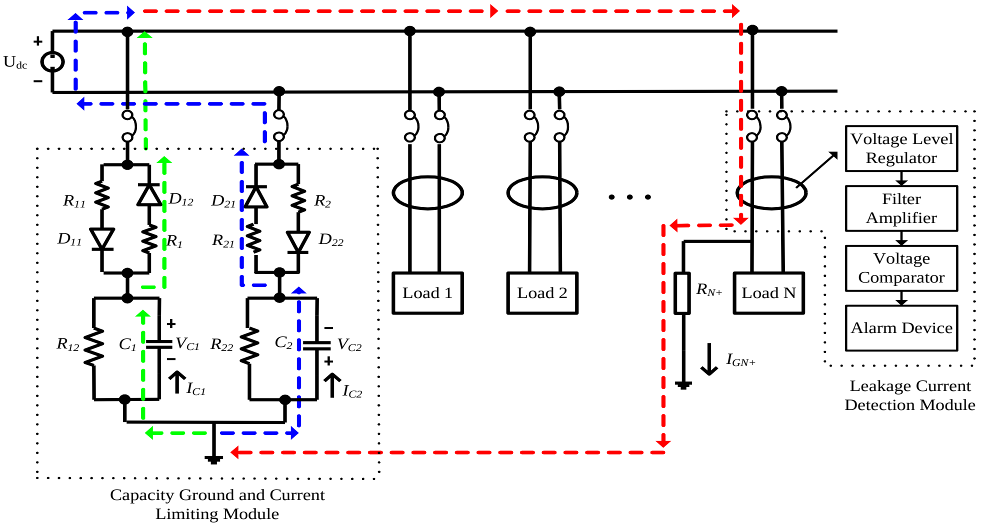


Fig. 2. The proposed insulation fault detection circuit.

The negative voltage transient compensator is includes a second charge circuit, a second energy storage circuit, and a second discharge circuit. The second charge circuit includes a diode D_{21} and R_{21} which has one end connected to the negative terminal of the power supply system and another end coupled with the second energy storage circuit in series. The second energy storage circuit has another end grounded and includes a resistor R_{22} and a second energy storage element $C2$ coupled in parallel. The second discharge circuit is coupled with the second charge circuit in parallel, and includes a second one-way discharger D_{22} and a current limiting resistor R_2 coupled in series.

The charging loop is formed by capacitors *C1* and *C2*, with the connected terminal of *C1* and *C2* being grounded. Capacitor *C1* and *C2* are charged to store the energy through diodes D_{11} and D_{21}. If insulation deterioration occurs on the positive or negative bus to ground, a return path for leakage current can form through the capacitor grounding.

In the event of an insulation fault, the capacitor is able to provide a leakage current return path and discharge via the energy stored in the capacitor. This allows the Hall effect current sensor to detect the difference between the positive and negative bus current, and deliver a warning signal or control the breaker to cut off the fault circuit to achieve high sensitivity detection. Furthermore, this detection circuit can help the operator identify whether such a loop of the DC electric network has already occurred with insulation deterioration and provide real-time warnings regarding online leakage current.

2.2. Fault current analysis

Fig. 2 shows the path of the leakage current for DC power supply. This circuit comprises two sections: capacitor grounding with the current limiting module and leakage current detection module. The former is installed on the main bus, and consists of a positive voltage transient compensator and a negative voltage transient compensator. The latter are installed on every branch, and consist of a Hall effect current sensor, voltage level regulator, filter amplifier, voltage comparator and alarm device.

Fig. 2 shows the leakage current path of the positive bus while grounding. $I_{C1}(t)$ is defined as the current flows from ground to the capacitor *C1*, $I_{C2}(t)$ is defined as the current flows from ground to the capacitor *C2*, $V_{C1}(t)$ denotes the voltage of capacitor *C1*, and $V_{C2}(t)$ denotes the voltage of capacitor *C2*.

Based on Kirchhoff's voltage law, leakage current is expressed in the following Eqn.:

$$\frac{R_{12}+R_1}{R_{12}C_1}\int_0^t I_{C1}(t)dt + I_{C1}(t)R_1 - \frac{R_{12}+R_1}{R_{12}}V_{C1}(0) + I_{GN+}(t)R_{N+} = 0 \tag{3}$$

$$\frac{1}{C_2}\int_0^t I_{C2}(t)dt + V_{C2}(0) + I_{C2}(t)R_{21} - U_{dc} + I_{GN+}(t)R_{N+} = 0 \tag{4}$$

where $V_{C1}(0)$ denotes the initial voltage of capacitor *C1*, and $V_{C2}(0)$ denotes the initial voltage of capacitor *C2*.

According to Kirchhoff's Current Law, the leakage current circuit is given by:

$$I_{GN+}(t) = I_{C1}(t) + \frac{1}{R_{12}C_1}\int I_{C1}(t)dt - \frac{V_{C1}(0)}{R_{12}} + I_{C2}(t) + \frac{1}{R_{22}C_2}\int I_{C2}(t)dt + \frac{V_{C2}(0)}{R_{22}} \tag{5}$$

$I_{C1}(t)$ and $I_{C2}(t)$ are detailed as follows:

$I_{C1}(t)$: $I_{C1}(t)$ is formed by the *C1* discharges. When insulation deterioration occur on the positive bus, the energy stored in capacitor *C1* discharges through diode D_{12} and current limiting resistor R_1. When the energy stored in capacitor *C1* gradually reduces, its voltage V_{C1} follows suit. Finally, when the steady state is reached, V_{C1} remains at a smaller voltage level and capacitor *C1* no longer releases energy, indicating interruption of the leakage current path.

$I_{C2}(t)$: The other leakage current $I_{C2}(t)$ forms from the DC power supply by ground fault resistance, charges capacitor *C2*, then flows through the diode D_{21} and R_{21}, and finally returns to the negative terminal of DC power supply. As the energy stored in capacity *C2* increases, so too does voltage V_{C2}. After this circuit reaches a steady state, V_{C2} remains higher. When insulation deterioration occurs on the positive bus, V_{C2} exceeds V_{C1}; otherwise, when insulation deteriorates on the negative bus, V_{C1} exceeds V_{C2}.

Using variables V_{C1} and V_{C2}, simultaneous Eqns. (3)-(5) are rewritten into Eqns. (6)-(8).

$$-V_{C1}(t) - R_1C_1V'_{C1}(t) - \frac{R_1}{R_{12}}V_{C1}(t) + I_{GN+}(t)R_{N+} = 0 \tag{6}$$

$$V_{C2}(t) + R_{21}C_2V'_{C2}(t) + \frac{R_{21}}{R_{22}}V_{C2}(t) - U_{dc} + I_{GN+}(t)R_{N+} = 0 \tag{7}$$

$$I_{GN+}(t) = -C_1 V'_{C1}(t) - \frac{1}{R_{12}} V_{C1}(t) + C_2 V'_{C2}(t) + \frac{1}{R_{22}} V_{C2}(t) \tag{8}$$

The above Eqns. are simplified into the state Eqns. (9) and (10).

$$\begin{aligned} V'_{C1}(t) = &-\frac{R_1R_{21} + R_1R_{N+} + R_{12}R_{21} + R_{12}R_{N+} + R_{21}R_{N+}}{(R_1R_{21} + R_1R_{N+} + R_{21}R_{N+})R_{12}C_1} V_{C1}(t) \\ &-\frac{R_{N+}}{(R_1R_{21} + R_1R_{N+} + R_{21}R_{N+})C_1} V_{C2}(t) \\ &+\frac{R_{N+}}{(R_1R_{21} + R_1R_{N+} + R_{21}R_{N+})C_1} U_{dc} \end{aligned} \tag{9}$$

$$\begin{aligned} V'_{C2}(t) = &-\frac{R_{N+}}{(R_1R_{21} + R_1R_{N+} + R_{21}R_{N+})C_2} V_{C1}(t) \\ &-\frac{R_1R_{21} + R_1R_{22} + R_1R_{N+} + R_{21}R_{N+} + R_{22}R_{N+}}{(R_1R_{21} + R_1R_{N+} + R_{21}R_{N+})R_{22}C_2} V_{C2}(t) \\ &+\frac{R_1 + R_{N+}}{(R_1R_{21} + R_1R_{N+} + R_{21}R_{N+})C_2} U_{dc} \end{aligned} \tag{10}$$

The fault resistance, capacitors *C1* and *C2*, discharge current limiting resistors R_1 and R_2, charge current limiting resistors R_{11} and R_{21}, and system voltage all are able to affect the fault current. Consequently, capacitors *C1* and *C2*, resistors R_1 and R_2, and resistors R_{11} and R_{21}, can change the fault current value and fault duration. This fault detection circuit can detect the minimum fault current 1 mA and maximum insulation fault resistance 50 kΩ.

In the event of DC power supply failure, fault detection should be as fast as possible, preferably within a few milliseconds. When the system reaches a steady state, *C1* is unable to release energy and *C2* is unable to charge. At this time, the leakage current path does not turn on. Hence, the DC insulation fault detector proposed here does not reduce the insulation level of DC power systems, and can maintain the insulation performance of the original ungrounded system.

2.3. Voltage transient compensators

When the input voltage changes, for example when it falls below a certain level or the power source fails, then unless batteries, capacitors or other energy storage devices are used, a power interruption affects normal operating load. The damage from power failure is minimized if the power failure can be detected instantaneously and the system voltage maintained using stored energy until a response can occur through data backup or power transfer.

The stored energy in the capacitor used to reduce a voltage drop can be used to calculate the capacitor size based on the minimum permissible voltage, hold up time and load size. Power flow can be set to run with constant resistance, current and power, and these can affect the capacitor designs.

If load is assumed to be constant resistance R_L, then the voltage change after power outage is indicated in Eqn. (11):

$$V_{dc}(t) = V_{dc}(t_0) \times e^{-t/R_L C} \tag{11}$$

From Eqn. (11), the capacitor *C* is obtained as:

$$C \geq -\frac{T_h}{R_L \times \ln\left(\dfrac{V_{dc\_\min}}{V_{dc}}\right)} \tag{12}$$

where T_h represents the hold up time during the power outage, V_{dc_min} is the voltage lower limit, and V_{dc} is the nominal voltage.

If the load is regarded as constant current I_L, then $V_{dc}(t)$ and C are indicated in the following two equations:

$$V_{dc}(t) = V_{dc}(t_0) - \frac{I_L \times t}{C} \tag{13}$$

$$C \geq I_L \times \frac{T_h}{V_{dc} - V_{dc\_\min}} \tag{14}$$

If the load is regarded as constant power P_L, then $V_{dc}(t)$ and C are indicated in the Eqns. (15) and (16):

$$P_L = \frac{\frac{1}{2}C(V_{dc}^2(t_0) - V_{dc}^2(t))}{t} \tag{15}$$

$$C \geq 2P_L \times \frac{T_h}{V_{dc}^2 - V_{dc\_\min}^2} \tag{16}$$

2.4. *Functional features*

The ungrounded DC insulation fault detection circuit proposed by this paper has the following functional features:

1) Online DC power insulation fault detector

2) Able to detect branch circuit ground fault

3) High detection sensitivity: insulation fault 1 mA/50 kΩ.

DC power supply systems of electric vehicles can be considered as an example. The insulation resistance of an electric vehicle is not less than 50 kΩ/100 V, which is consistent with international standards (ISO 6469, U.S. FMVSS 305/SAE J1766, European ECE R100, and Chinese GB / T 18348).

Compare with the proposed method sensitivity and conventional method sensitivity." Consider the following. (1) In the conventional method, the system shunt of the positive and negative buses to the ground is connected to resistance R. Suppose R is 200 kΩ, the grounded insulation fault resistance R_{N+} is 50 kΩ, and the DC voltage U_{dc} is 100 V; then, the ground leakage current I_{GN+} is $U_{dc}/(2\ R_{N+}+R)=0.22$ mA. (2) With respect to the proposed method, suppose that the grounded insulation fault resistance R_{N+} is 50 kΩ, the DC voltage U_{dc} is 100 V, and the initial voltages of capacitors $C1$ and $C2$ are same equal; then, the initial ground leakage current $I_{GN+}(t_0)$ is $V_{C1(0)}/R_{N+}=1$ mA. The sensitivity of the proposed method is four times that of the conventional method.

4) Voltage transient compensators

5) Does not impact the original system insulation performance

6) Cutting off the leakage current path automatically after the capacity has released its stored energy to reduce electrical corrosion incidence

7) No need to inject AC signal source

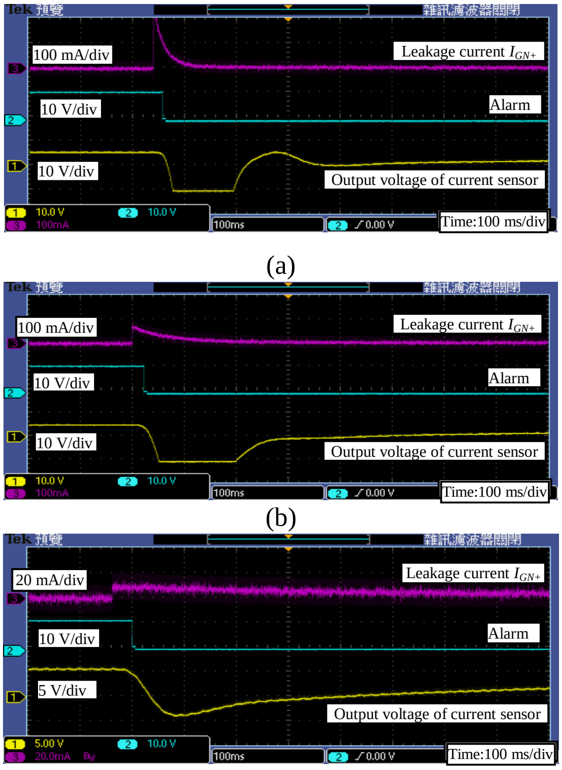
3. Experimental Results

Fig. 3 shows a prototype of the DC insulation fault detection circuit. The circuit specifications and parameters are as follows: DC voltage 100 V, branch load current 10 A, 100 uF for $C1$ and $C2$, 200 Ω both R_1 and R_2, 2 kΩ both R_{11} and R_{21}, 200~500 kΩ both R_{12} and R_{22}, and transimpedance amplifier set to ±1 V/1 mA for the leakage current detection module. Circuit breakers trip quickly when a short circuit occurs on the branch, typically in 10 ms. The positive bus of each branch is thus installed with a Schottky diode, and the positive and negative bus of the branch is connected with 2000 uF capacitors in parallel to provide sufficient transient voltage compensation to meet the branch current. Chroma 62000P of programmable DC power supply is used for the DC power source in this experiment, the value of its internal impedance is very small and the voltage regulation is 0.01 % +18 mV [14].

Fig. 3. A prototype of the DC insulation fault detection circuit.

This section simulates an insulation resistance fault of the positive bus. With the grounded insulation resistance being more than 50 kΩ, the insulation resistance is in the normal range. When the insulation resistance is lower than 50 kΩ, the system has an insulation fault. At this point, the insulation fault detection circuit activates an alarm. Five tests are conducted using different insulation resistance values: 0 Ω (direct grounding), 500 Ω, 5 kΩ, 50 kΩ and 60 kΩ to verify the circuit performance.

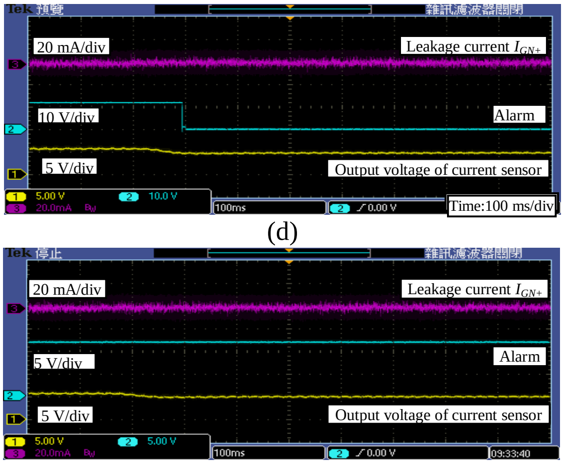
Fig. 4 shows the leakage current, alarm signal and output voltage of the current detection module for different insulation resistance faults. The voltage of the circuit alarm signal is set to 12 V under normal insulation. In the event of an insulation resistance fault, the voltage of the circuit alarm signal is 0 V. This circuit can detect the failure of 50 kΩ insulation resistance, as well as the direct grounding fault. When the insulation resistance is 0 Ω, 500 Ω, 5 kΩ and 50 kΩ, the insulation fault detection circuit delivers an alarm signal as shown in Fig. 4(a)~(d), where the alarm signal changes from 12 V to 0 V, denoting an insulation fault in the system. When the insulation resistance is 60 kΩ, the circuit does not deliver an alarm signal as shown in Fig. 4(e), where the alarm signal remains at the 12 V level, indicating that the insulation resistance of the system is normal in scope.



(a)

(b)

(c)

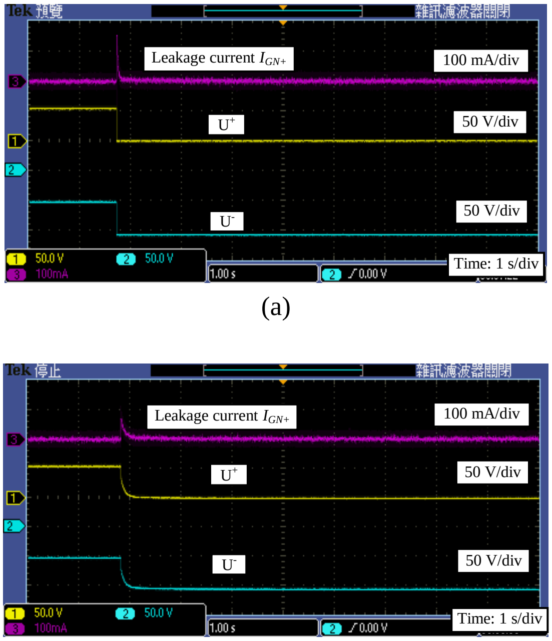


(d)

(e)

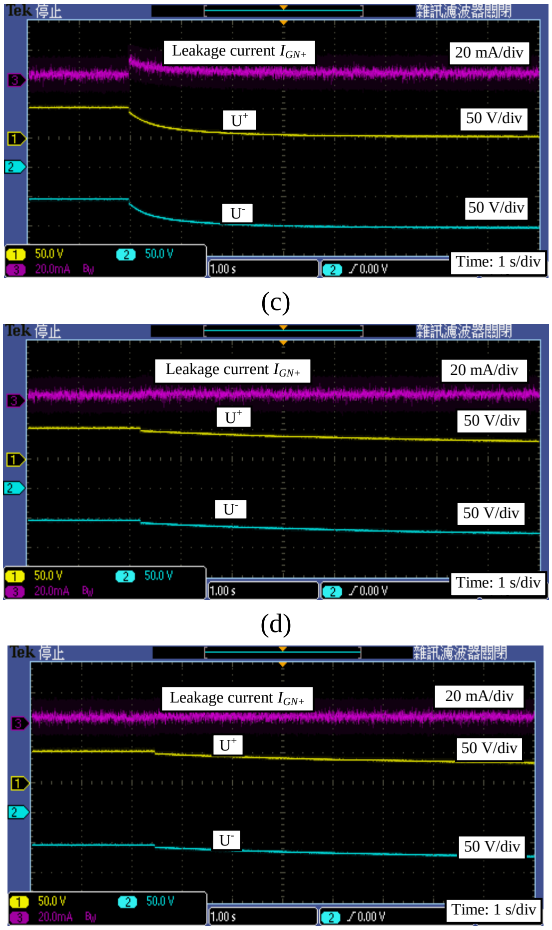
Fig. 4. The insulation resistance values are (a) 0 Ω, (b) 500 Ω, (c) 5 kΩ, (d) 50 kΩ, (e) 60 kΩ.

Fig. 5 shows the leakage current, the voltage of the positive bus to ground and the voltage of the negative bus to ground for different insulation resistance faults, where U^+ is the voltage of the positive bus to ground, U^- is the voltage of the negative bus to ground. When insulation fault occurs in the positive bus to ground, the voltage of the positive bus to ground will reduce and the voltage of the negative bus to ground will increase. The output voltage of the power supply system U_{dc} is equal to U^+ minus U^-, which keeps constant. When the system reaches a steady state, U^- remains higher, U^+ remains lower and the leakage current path does not turn on.



(a)

(b)



(c)

(d)

(e)

Fig. 5. The leakage current, the positive bus voltage and negative bus voltage for different insulation resistance (a) 0 Ω (b) 500 Ω (c) 5 kΩ (d) 50 kΩ (e) 60 kΩ.

The discharge current limiting resistors R_1 and R_2, and the charge current limiting resistors R_{11} and R_{21} are used to limit the amount of leakage current. In the event of a short circuit of positive bus to ground and leakage current of 250 mA, the leakage current declines exponentially with time. When the system reaches a steady state, the leakage current will fall to zero. At this time, the capacitor does not release its stored energy, then that is the leakage current path does not turn on. The above experimental results can verify that the insulation fault detection method proposed in this paper does not lower system insulation performance.

4. Conclusions

This paper proposes an online DC insulation fault detection circuit for high sensitivity leakage current detection. The experimental results demonstrate that the proposed method successfully achieves its goal of high sensitivity detection. Because the proposed circuit is not required to inject AC signal source in the system, it does not generate ripple voltage. The capacitors in the proposed circuit can store energy for leakage current detection, and can also be used as voltage transient compensators. Therefore, the proposed circuit can provide higher quality DC power supply. The proposed method can be applied to electric vehicles, solar photovotaic systems, energy storage systems, electric utilities, oil and gas, and process control.

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