METHOD AND DEVICE FOR REDUCING TRANSIENT RISK OF HUMAN ELECTRIC SHOCK WITHOUT POWER INTERRUPTION

Field of the Invention

The present invention relates to the technical fields of electrical safety and intelligent power distribution, and particularly to a method and device for reducing transient risk of human electric shock without power interruption.

Background to the Invention

In the operation and maintenance of low-voltage distribution networks, personal electric shock accidents are the primary risk threatening electrical safety. For a long time, the electric shock protection system of power distribution systems has mainly relied on passive cutoff mechanisms, with the most typical application being residual current operated protectors. Its standard working process includes monitoring the residual current of the circuit through a current transformer, and once the current value exceeds the human safety threshold, the protection device immediately triggers the tripping mechanism to physically disconnect the power switch, thereby blocking the electric shock circuit.

However, traditional technologies mostly use circuit breakers to cut off the power supply, which must be powered off and have dead zones, resulting in power supply interruption and inability to suppress transient impacts.

Statement of Invention

To make up for the above deficiencies, the present invention provides a method and device for reducing transient risk of human electric shock without power interruption, aiming at solving the problems of traditional technologies that mostly use circuit breakers to cut off the power supply, which must be powered off and have dead zones, resulting in power supply interruption and inability to suppress transient impacts.

In a first aspect, the present invention provides the following technical solution: a method for reducing transient risk of human electric shock without power interruption includes the following steps:

S1, collecting a ground voltage and zero-sequence current of an alternating current (AC) power supply circuit in real time, and calculating a ground admittance value representing an impedance characteristic of the circuit;

S2, when a change rate of the ground admittance value exceeds a preset threshold and the zero-sequence current and the ground voltage show a resistive phase characteristic, locking a power grid voltage vector at a moment of electric shock;

S3, solving a modulation voltage reference command based on the power grid voltage vector, where a phase of the modulation voltage reference command is opposite to that of the power grid voltage vector, and an amplitude is equal to an instantaneous value of the power grid voltage vector minus a preset residual voltage value;

S4, converting the modulation voltage reference command into a driving current and feeding the driving current into a primary winding of a magnetic coupling modulator, and establishing a controlled alternating magnetic flux inside a magnetic core; and

S5, using a power supply conductor passing through the magnetic core as a secondary side to induce a physical modulation electromotive force, which is series-superimposed with an original power grid voltage vector in the power supply circuit, to cause a ground potential at a human contact point to be equal to the preset residual voltage value.

By adopting the above technical solution, a reverse electromotive force is injected through magnetic coupling to clamp the electric shock potential to a safe value, thereby improving the problems of traditional technologies that mostly use circuit breakers to cut off the power supply, which must be powered off and have dead zones, resulting in power supply interruption and inability to suppress transient impacts.

Preferably, the calculating a ground admittance value includes:

synchronously acquiring an instantaneous ground voltage value and instantaneous zero-sequence current value of the power supply conductor through a high-frequency sampling unit;

extracting fundamental wave components of the instantaneous ground voltage value and the instantaneous zero-sequence current value; and

dividing the fundamental wave component of the instantaneous zero-sequence current value by the fundamental wave component of the instantaneous ground voltage value to obtain a real-time ground admittance value.

Preferably, the locking a power grid voltage vector at a moment of electric shock includes:

calculating a derivative of the ground admittance value within a sliding window;

when an absolute value of the derivative is greater than a set threshold, calculating a phase angle between a zero-sequence current vector and a ground voltage vector; and

when the phase angle is in a resistive interval, generating an electric shock triggering signal and storing power grid voltage vector data at a current moment.

Preferably, the solving a modulation voltage reference command based on the power grid voltage vector includes:

reading an amplitude and phase of the locked power grid voltage vector;

subtracting the preset residual voltage value from an amplitude of the power grid voltage vector to obtain a cancellation voltage amplitude; and

constructing a waveform with an opposite phase to the power grid voltage vector and the cancellation voltage amplitude as the modulation voltage reference command.

Preferably, the determining the preset residual voltage value includes:

acquiring a minimum detection current threshold of a human electric shock circuit and a human impedance model value; and

calculating a product of the minimum detection current threshold and the human impedance model value, and setting the product as the preset residual voltage value.

Preferably, the converting the modulation voltage reference command into a driving current and feeding the driving current into a primary winding of a magnetic coupling modulator include:

inputting the modulation voltage reference command into an inverter control unit to perform sinusoidal pulse width modulation operation and generate a switch control signal;

using the switch control signal to drive power switching tubes in a full-bridge inverter circuit to turn on or off, and converting direct current (DC) power into AC driving current; and

transmitting the AC driving current to the primary winding of the magnetic coupling modulator.

Preferably, the using a power supply conductor passing through the magnetic core as a secondary side to induce a physical modulation electromotive force includes:

using the AC driving current flowing through the primary winding to excite an alternating magnetic flux in an annular nanocrystalline magnetic core;

using the power supply conductor passing through a window of the annular nanocrystalline magnetic core as a single-turn secondary winding to cut the alternating magnetic flux; and

generating an induced electromotive force corresponding to the modulation voltage reference command at two ends of the power supply conductor.

Preferably, when the power supply circuit is a three-phase four-wire system, S5 further includes:

passing three-phase live wires and a neutral wire through a magnetic core window of the same magnetic coupling modulator simultaneously;

driving the magnetic coupling modulator to establish a zero-sequence magnetic flux in the magnetic core; and

inducing zero-sequence electromotive forces with the same amplitude and phase on the three-phase live wires and the neutral wire simultaneously, and superimposing the zero-sequence electromotive forces into a ground potential of each phase conductor.

Preferably, S5 further includes a backup protection step:

starting a timer to record a continuous injection time of the physical modulation electromotive force;

when the continuous injection time reaches a preset time limit, detecting the ground admittance value of the power supply circuit; and

if the ground admittance value still indicates a human access state, outputting a trip signal to drive a mechanical circuit breaker to disconnect the power supply circuit.

In a second aspect, the present invention provides the following technical solution: a device for reducing transient risk of human electric shock without power interruption includes the following modules:

a detection module for collecting a ground voltage and zero-sequence current of an AC power supply circuit in real time, and calculating a ground admittance value representing an impedance characteristic of the circuit;

a contact identification module for, when a change rate of the ground admittance value exceeds a preset threshold and the zero-sequence current and the ground voltage show a resistive phase characteristic, locking a power grid voltage vector at a moment of electric shock;

a control module for solving a modulation voltage reference command based on the power grid voltage vector, where a phase of the modulation voltage reference command is opposite to that of the power grid voltage vector, and an amplitude is equal to an instantaneous value of the power grid voltage vector minus a preset residual voltage value;

a power electronic drive module for converting the modulation voltage reference command into a driving current and feeding the driving current into a primary winding of a magnetic coupling modulator, and establishing a controlled alternating magnetic flux inside a magnetic core; and

a magnetic coupling modulation module for using a power supply conductor passing through the magnetic core as a secondary side to induce a physical modulation electromotive force, which is series-superimposed with an original power grid voltage vector in the power supply circuit, to cause a ground potential at a human contact point to be equal to the preset residual voltage value.

The present invention has the following beneficial effects:

1. In the present invention, a reverse electromotive force is injected through magnetic

coupling to clamp the electric shock potential to a safe value, thereby improving the problems of traditional technologies that mostly use circuit breakers to cut off the power supply, which must be powered off and have dead zones, resulting in power supply interruption and inability to suppress transient impacts.

2. In the present invention, the voltage is locked through the admittance change rate combined with the resistive phase to accurately identify the transient electric shock, thereby improving the problems of traditional technologies that mostly use a single leakage current criterion, which ignores capacitive interference and causes misjudgment or refusal to operate.

3. In the present invention, the isolated regulation of strong electricity by weak electricity is realized through the magnetically coupled induced electromotive force, thereby improving the problems of traditional technologies that mostly use direct series connection of devices, which lack electrical isolation and cause high system voltage resistance risks.

Brief Description of the Drawings

FIG. 1 is a flow chart of a method for reducing transient risk of human electric shock without power interruption provided by the present invention;

FIG. 2 is a detailed flow chart of electric shock identification and locking of the method for reducing transient risk of human electric shock without power interruption provided by the present invention;

FIG. 3 is a flow chart of modulation control and magnetic flux establishment of the method for reducing transient risk of human electric shock without power interruption provided by the present invention;

FIG. 4 is a flow chart of backup protection logic of the method for reducing transient risk of human electric shock without power interruption provided by the present invention; and

FIG. 5 is a system architecture diagram of a device for reducing transient risk of human electric shock without power interruption provided by the present invention.

Detailed Description

Technical solutions in examples of the present invention will be described clearly and completely in the following with reference to the attached drawings. Obviously, all the described examples are only some, rather than all examples of the present invention. Based on the examples in the present invention, all other examples obtained by those of ordinary skill in the art without creative efforts belong to the scope of protection of the present invention.

The present invention provides a method for reducing transient risk of human electric shock without power interruption, as shown in FIGS. 1-5, including the following steps:

In S1, a ground voltage and a zero-sequence current of an AC power supply circuit are collected in real time, and a ground admittance value representing an impedance characteristic of the circuit is calculated.

Further, the ground admittance value being calculated includes:

synchronously acquiring an instantaneous ground voltage value and instantaneous zero-sequence current value of the power supply conductor through a high-frequency sampling unit;

extracting fundamental wave components of the instantaneous ground voltage value and the instantaneous zero-sequence current value; and

dividing the fundamental wave component of the instantaneous zero-sequence current value by the fundamental wave component of the instantaneous ground voltage value to obtain a real-time ground admittance value.

Specifically, this step is executed by the detection module to establish a quantitative representation of the insulation state of the power supply circuit.

The detection module uses a high-frequency sampling unit to synchronously collect output signals of the voltage transformer and current transformer, acquiring the instantaneous ground voltage value and instantaneous zero-sequence current value of the power supply circuit. The processor performs digital filtering on the collected data to filter out high-order harmonics and extract the power frequency fundamental wave component, ensuring that the calculated data only reflects the power frequency impedance characteristic.

Based on the extracted fundamental wave component, the real-time ground admittance value is calculated according to the following formula:

$$\mathrm{Y(t)} = \frac{\mathrm{I_{0\_fund}(t)}}{\mathrm{U_{g\_fund}(t)}}$$

where $\mathrm{Y(t)}$ is a real-time ground admittance value at time t; $\mathrm{I_{0\_fund}(t)}$ is an instantaneous value of a fundamental wave component of a zero-sequence current; and $\mathrm{U_{g\_fund}(t)}$ is an instantaneous value of a fundamental wave component of a ground voltage.

During normal operation, the line presents high impedance to the ground, and $\mathrm{Y(t)}$ approaches zero; when an electric shock occurs to a human body, the access of human body resistance causes a sudden drop in the circuit impedance, $\mathrm{I_{0\_fund}(t)}$ increases while $\mathrm{U_{g\_fund}(t)}$ remains stable, leading to a step mutation of $\mathrm{Y(t)}$. The admittance value can shield the interference of voltage fluctuation and be directly used as the input data of S2 to determine electric shock.

In S2, when a change rate of the ground admittance value exceeds a preset threshold and the zero-sequence current and the ground voltage show a resistive phase characteristic, a power grid voltage vector is locked at a moment of electric shock.

Further, the power grid voltage vector being locked at a moment of electric shock includes:

calculating a derivative of the ground admittance value within a sliding window;

when an absolute value of the derivative is greater than a set threshold, calculating a phase angle between a zero-sequence current vector and a ground voltage vector; and

when the phase angle is in a resistive interval, generating an electric shock triggering signal and storing power grid voltage vector data at a current moment.

Specifically, this step executes the logical judgment of electric shock characteristics, with the input being the real-time ground admittance value and the output being the trigger signal and locked voltage.

Discrete differentiation is performed on the real-time ground admittance value sequence using a sliding window to calculate the time change rate: $D_Y(k) = \frac{Y(k)-Y(k-N)}{N \cdot T_s}$; where $D_Y(k)$ is the admittance change rate at the k-th sampling moment; $Y(k)$ is the ground admittance value at the current sampling moment; $Y(k-N)$ is the ground admittance value at the sampling point N points before the current moment; T_s is the system sampling period; N is the number of sampling points included in the sliding window.

The system presets a mutation threshold λ_{th}. When $|D_Y(k)|$ exceeds the preset threshold λ_{th}, the phase criterion is activated. The phase angle θ between the zero-sequence current vector I_0 and the ground voltage vector U_g is calculated: $\theta = \angle I_0 - \angle U_g$; where θ is the phase angle; $\angle I_0$ is the phase angle of the fundamental wave vector of the zero-sequence current; $\angle U_g$ is the phase angle of the fundamental wave vector of the ground voltage.

If θ is within the resistive interval $[-\delta, +\delta]$ centered at θ, a human electric shock is confirmed. The system immediately generates a trigger signal and solidifies the power grid voltage vector U_{lock} at the current moment as the subsequent control reference.

In S3, a modulation voltage reference command is solved based on the power grid voltage vector, where a phase of the modulation voltage reference command is opposite to that of the power grid voltage vector, and an amplitude is equal to an instantaneous value of the power grid voltage vector minus a preset residual voltage value.

Further, the modulation voltage reference command being solved based on the power grid voltage vector includes:

reading an amplitude and phase of the locked power grid voltage vector;

subtracting the preset residual voltage value from an amplitude of the power grid voltage vector to obtain a cancellation voltage amplitude; and

constructing a waveform with an opposite phase to the power grid voltage vector and the cancellation voltage amplitude as the modulation voltage reference command.

The preset residual voltage value being determined includes:

acquiring a minimum detection current threshold of a human electric shock circuit and a human impedance model value; and

calculating a product of the minimum detection current threshold and the human impedance model value, and setting the product as the preset residual voltage value.

Specifically, this step is executed by the control module to generate a reverse cancellation control command based on the locked power grid voltage vector.

First, determine the safe voltage bottom line, and calculate the preset residual voltage value to maintain the minimum detection current of the electric shock circuit and prevent misjudgment of electric shock release. The calculation formula is: $V_{\mathrm{resid}} = I_{\min} \cdot |Z_h|$; where V_{resid} is the preset residual voltage value; $I_{\min}$ is the minimum detection current threshold; $|Z_h|$ is the modulus value of the human impedance model.

A reverse cancellation waveform is constructed based on the power grid voltage vector. The target cancellation amplitude is set as the power grid amplitude minus the preset residual voltage value. The time-domain function of the modulation voltage reference command is:

$$u_{\mathrm{ref}}^{*}(t) = -(U_m - V_{\mathrm{resid}})\sin(\omega t + \phi)$$

where $u_{\mathrm{ref}}^{*}(t)$is the modulation voltage reference command output at time t; U_m is the amplitude of the locked power grid voltage vector; V_{resid} is the preset residual voltage value; ω is the power grid fundamental wave angular frequency; ϕ is the initial phase of the power grid voltage vector.

The calculated $u_{\mathrm{ref}}^{*}(t)$ is directly transmitted to the power electronic drive module as a digital control signal, aiming to drive the hardware to force the ground potential of the human body to be clamped to the V_{resid} level.

In S4, the modulation voltage reference command is converted into a driving current and fed into a primary winding of a magnetic coupling modulator, and a controlled alternating magnetic flux is established inside a magnetic core.

Further, the modulation voltage reference command being converted into a driving current and fed into a primary winding of a magnetic coupling modulator include:

inputting the modulation voltage reference command into an inverter control unit to perform sinusoidal pulse width modulation operation and generate a switch control signal;

using the switch control signal to drive power switching tubes in a full-bridge inverter circuit to turn on or off, and converting DC power into AC driving current; and

transmitting the AC driving current to the primary winding of the magnetic coupling modulator.

Specifically, this step is executed by the power electronic drive module to realize energy conversion from digital control commands to physical magnetic fields.

The inverter control unit receives the modulation voltage reference command and generates a sinusoidal pulse width modulation signal by comparing with a high-frequency carrier. The full-bridge inverter circuit responds to the signal, driving the power switching tubes to turn on and off in sequence, chopping the constant DC bus voltage into a controlled AC driving current. The relationship between the output current and the pulse width modulation voltage is: $\mathrm{i_{dr}(t)} \approx \frac{1}{\mathrm{L}} \int \mathrm{u_{pwm}(t)dt}$; where $\mathrm{i_{dr}(t)}$ is the instantaneous value of the AC driving current output to the primary winding; L is the equivalent inductance value of the primary winding; $\mathrm{u_{pwm}(t)}$ is the pulse width modulation voltage waveform output by the full-bridge inverter circuit.

The AC driving current is injected into the primary winding of the magnetic coupling modulator, and an alternating magnetic flux is established inside the magnetic core according to Ampère's circuital law. The magnetic flux is calculated as: $\Phi(\mathrm{t}) = \frac{\mathrm{N_p} \cdot \mathrm{i_{dr}(t)}}{\mathrm{R_m}}$; where $\Phi(\mathrm{t})$ is the controlled alternating magnetic flux established inside the magnetic core; $\mathrm{N_p}$ is the number of turns of the primary winding; $\mathrm{R_m}$ is the equivalent magnetic resistance of the magnetic circuit.

This process realizes electrical isolation and energy transfer between the primary weak current control side and the secondary strong current circuit through the magnetic coupling structure, and the established alternating magnetic flux $\Phi(\mathrm{t})$ is the physical carrier for the subsequent induced electromotive force.

In S5, a power supply conductor passing through the magnetic core is used as a secondary side to induce a physical modulation electromotive force, which is series-superimposed with an original power grid voltage vector in the power supply circuit, to cause a ground potential at a human contact point to be equal to the preset residual voltage value.

Further, the power supply conductor passing through the magnetic core being used as a secondary side to induce a physical modulation electromotive force includes:

using the AC driving current flowing through the primary winding to excite an alternating magnetic flux in an annular nanocrystalline magnetic core;

using the power supply conductor passing through a window of the annular nanocrystalline magnetic core as a single-turn secondary winding to cut the alternating magnetic flux; and

generating an induced electromotive force corresponding to the modulation voltage reference command at two ends of the power supply conductor.

When the power supply circuit is a three-phase four-wire system, S5 further includes:

passing three-phase live wires and a neutral wire through a magnetic core window of the same magnetic coupling modulator simultaneously;

driving the magnetic coupling modulator to establish a zero-sequence magnetic flux in the magnetic core; and

inducing zero-sequence electromotive forces with the same amplitude and phase on the three-phase live wires and the neutral wire simultaneously, and superimposing the zero-sequence electromotive forces into a ground potential of each phase conductor.

S5 further includes a backup protection step:

starting a timer to record a continuous injection time of the physical modulation electromotive force;

when the continuous injection time reaches a preset time limit, detecting the ground admittance value of the power supply circuit; and

if the ground admittance value still indicates a human access state, outputting a trip signal to drive a mechanical circuit breaker to disconnect the power supply circuit.

Specifically, this step is executed collaboratively by the magnetic coupling modulation module and the safety protection logic, aiming to realize dynamic reconstruction and multiple protection of physical potential.

The input AC driving current flows through the primary winding, exciting an alternating magnetic flux $\mathrm{e_{inj}(t)}$ inside the annular nanocrystalline magnetic core. The power supply conductor passing through the magnetic core window is used as a single-turn secondary winding to cut the magnetic field lines. According to Faraday's law of electromagnetic induction, a physical modulation electromotive force $\Phi(\mathrm{t})$ is generated at both ends of the power supply conductor, calculated as:

$$\mathrm{e_{inj}(t)} = -\frac{\mathrm{d}\Phi(\mathrm{t})}{\mathrm{dt}}$$

where $\mathrm{e_{inj}(t)}$ is the instantaneous value of the induced electromotive force; $\Phi(\mathrm{t})$ is the instantaneous value of the magnetic flux. This electromotive force is series-superimposed with the original power grid voltage vector $\mathrm{U_s}$ in the power supply circuit, forcing the ground potential $\mathrm{u_h(t)}$ at the human contact point to satisfy:

$$\mathrm{u_h(t)} = \mathrm{u_s(t)} + \mathrm{e_{inj}(t)} \approx \mathrm{V_{resid}}$$

where $\mathrm{V_{resid}}$ is a preset residual voltage value.

In a three-phase four-wire system, the three-phase live wires and the neutral wire pass through the same magnetic core. The magnetic core establishes a zero-sequence magnetic flux, and zero-sequence electromotive forces with the same amplitude and phase are induced on the four wires simultaneously. This electromotive force acts as a common-mode component to reduce the ground voltage of each phase, but cancels each other out in the calculation of the phase-to-phase voltage, maintaining the line voltage on the load side unchanged.

The system starts a timer to monitor the continuous injection time $\mathrm{t_{inj}}$ of the voltage. If $\mathrm{t_{inj}}$ exceeds the preset time limit $\mathrm{T_{lim}}$ and the real-time ground admittance value still shows a human access state, a trip signal is output to drive the mechanical circuit breaker to act and physically cut off the circuit.

Finally, it is to be explained that the above is only the preferred embodiment of the present invention, and it is not used to limit the present invention. Although the present invention is described in detail with reference to the foregoing embodiments, a person skilled in the art may still make modifications to the technical solutions described in the foregoing embodiments or make equivalent replacements to some technical features thereof. Any modification, equivalent replacement, or improvement made without departing from the spirit and principle of the present invention fall within the protection scope of the present invention.