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Research on Induced Electrical Characteristics of Agricultural Machinery Operating under Ultra High Voltage AC Transmission Lines in Agricultural Areas

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ABSTRACT: In plain areas, the majority of the ultra-high voltage (UHV) transmission corridors are located in farmland. The induced voltage is generated on the metal casing of the machinery when agricultural machines are working on the ground near the transmission line. If the human body touches, transient electric shock (TES) may occur, causing displeasure and alarm to workers. Therefore, it is crucial to study the induced electrical characteristics in such scenarios. In this article, the finite element method (FEM) was employed to establish a model integrating a 1000 kV transmission line, tractor, and human body, and the induced voltage of the tractor and human body under the transmission line was calculated. Subsequently, a TES model was developed to calculate the current when an electric shock occurs. Finally, an experimental system was constructed in the area beneath the 1000 kV UHV AC line to measure the current characteristics of the human body during the TES. The results demonstrate that the induced voltage is contingent upon the position of research object and whether it is insulated from the ground. Additionally, ground conditions significantly influence the TES current induced by the voltage. Due to the electromagnetic shielding effect of the tractor's metal casing, the TES current experienced by the driver inside the machine is minimized. For ground staff, when the human body is insulated from the ground, the transient electric shock current they bear is smaller than that of the human body grounded.

1. INTRODUCTION

With the construction of UHV transmission lines in China, the electromagnetic environment issues related to these transmission lines are gaining widespread attention increasingly [1–5]. UHV system typically utilize overhead lines for energy transmission, and there are growing number of transmission corridors in agricultural areas, particularly in plain regions. When agricultural machinery operates under these transmission lines, its metal casing inevitably generates induced voltage due to the strong electromagnetic fields under the transmission lines. Operators are highly susceptible to induced or transient electric shock phenomena, leading to numerous complaints and disputes and severely constraining the harmonious development of the power grid and living environment [6]. Agricultural machinery, characterized by its large volume, generates high induced voltage under the influence of strong electromagnetic fields under transmission lines. Operators of agricultural machinery are prone to coming into contact with the metal parts of the machinery, increasing the likelihood of experiencing transient electric shock [7–9]. Therefore, it is crucial to conduct research on the induced electrical characteristics near UHV AC transmission lines in agricultural areas.

Scholars have conducted extensive research on related phenomena. Deno employed the equivalent area method to calculate the induced voltage and short-circuit current of objects under UHV transmission lines [10]. Lin et al. quantified the induced current in the human body based on the surface charge equation, constructed an equivalent circuit between people and cars, and analyzed the impulse current between cars and people [11]. Luo et al. designed dummy models for different bodies, compared the measurement results with volunteer results, and verified them. They proposed a circuit model that simulates the human body and can conduct electro-static discharge (ESD) testing in complex situations [12]. Gunatilake et al. provided experimental transient voltage and current during "micro shocks", established models in CDEGS and PSCAD/EMTDC, and compared them with experimental measurement results [13, 14]. Wang et al. conducted experiments using a metal human body model near a ± 1100 kV High Voltage Direct Current (HVDC) line, measured the induced voltage and current of the human body, and analyzed the influence of resistance and capacitance parameters on transient current [15]. Li studied various phenomena the human body may suffer from electric shock under DC transmission lines, and compared the electric field characteristics of AC and DC transmission lines [16]. Wang et al. established a calculation model for UHV AC double circuit transmission lines and simulated the induced voltage and induced current generated on the steel frame building below the line [17]. Wang et al. used Ansys modeling to calculate the potential, electric field strength, and current density

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distribution characteristics of the human body inside the UHV substation, as well as the influence of shoes on the internal electric field and current of the human body. By comparing actual measurement and theoretical calculation results, the accuracy of the proposed model was verified [18]. Cao et al. selected representative test points below 500 kV transmission lines to measure induced voltage, steady-state electric shock current, and transient electric shock current [19]. They found that the magnitude of induced electricity under transmission lines is related to factors such as air humidity and offline electric field strength. Currently, the main focus on the problem of electric shock between the human body and metal objects is on laboratory model experiments and numerical simulation research. There is relatively little research on numerical models and true-type experiments when TES occurs between human-induced voltage below actual UHV transmission lines and the metal casing of agricultural machinery. The above scenarios are widely existing problems in the electromagnetic environment of HV transmission lines in agricultural areas.

This article focused on the 1000 kV UHV double-circuit transmission line utilizing the same tower as the research object. It established a numerical simulation model of the UHV transmission line-tractor-human body and investigated the characteristics of induced voltage and current of the driver and ground staff when TES occurred. Transient shock tests were conducted to analyze the voltage and current when transient shocks occurred under different conditions, thereby verified the accuracy of the proposed model. The numerical model and experimental results presented in this article are valuable for analyzing the characteristics and variations of transient electric shocks between agricultural machinery and the human body under transmission lines in agricultural areas. Furthermore, they can provide a guidance for researching and protecting induced electricity in agricultural operations within agricultural areas.

2. ESTABLISHMENT OF SIMULATION MODEL

2.1. Simulation Model Parameters

The transmission line in question referred to the 1000 kV UHV double-circuit AC transmission line situated on the same tower in the North Henan Plain. The conductor used is 8 × LGJ630 steel core aluminum stranded wire, arranged in reverse phase sequence. The suspension height of each phase transmission line is 77.5, 56, and 32.5 meters, respectively. Considering the sag of the lines, the ground height at the lowest point of each phase conductor is 75, 53.5, and 30 m, respectively. The tractor is positioned at the lowest point of the transmission line. The induced electrical characteristics of ground staff and driver inside the cabin were studied when the tractor is positioned below the single-side conductor (P1) and at the center position of the double circuit line (P2) (as depicted in Fig. 1).

The schematic diagram of the tractor and human is depicted in Fig. 2. The height of the tractor is 3.3 m, with the cockpit seat elevation at 1.2 m. The standing height of the human is 175 cm, and the sitting position is characterized by a hip-head height of 100 cm.

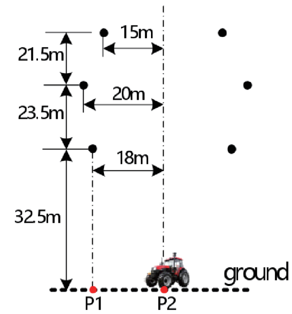

FIGURE 1. Schematic diagram of transmission line and detection point layout.

2.2. Simulation Condition

COMSOL Multiphysics was employed in the simulation research. Based on the layout and dimensions of the transmission line shown in Fig. 1, a 3D electromagnetic field frequency domain calculation model of the transmission line is established. The frequency is 50 Hz, with zero potential at ground and infinity. The phase sequence arrangement method follows the same reverse phase sequence arrangement used in the actual line. The time-domain three-phase voltage of transmission lines is as follows.

$$\begin{cases} U_a = \dfrac{\sqrt{2}U_l}{\sqrt{3}}\sin(\omega t) \\ U_b = \dfrac{\sqrt{2}U_l}{\sqrt{3}}\sin(\omega t - 120^\circ) \\ U_c = \dfrac{\sqrt{2}U_l}{\sqrt{3}}\sin(\omega t + 120^\circ) \end{cases} \tag{1}$$

where U_l is the effective value of the transmission line voltage of 1000 kV, and $\Omega = 2\pi f$ is the angular frequency. The specific parameters of the simulation model are shown in Table 1.

2.3. Human Body Equivalent Circuit Model

The study of human impedance parameters is relatively complex, and different researchers may reach different conclusions due to variations in their experimental subjects. However, under power frequency conditions, the human body is generally considered as an insensitive impedance network. Referring to the Freiberga equivalent circuit model [20], the human body modeling adopts a series-parallel structure comprising skin resistance, skin capacitance, and internal resistance of the human body, as depicted in Fig. 3.

Compared with relevant literature on human body model research, there are certain differences in the capacitance values proposed by different researchers, but these variances are approximately concentrated in the range of 100–500 pF [23–25]. In this article, referring to the experimental conclusions and recommended values of the MIL-STD-1512 standard human body model [26], the capacitance for human insulation and grounding was selected to be 200 pF and 500 pF, respectively.

According to the standard GB/T 13870.1-2008, the internal impedance of the human body from hand to foot is approxi-

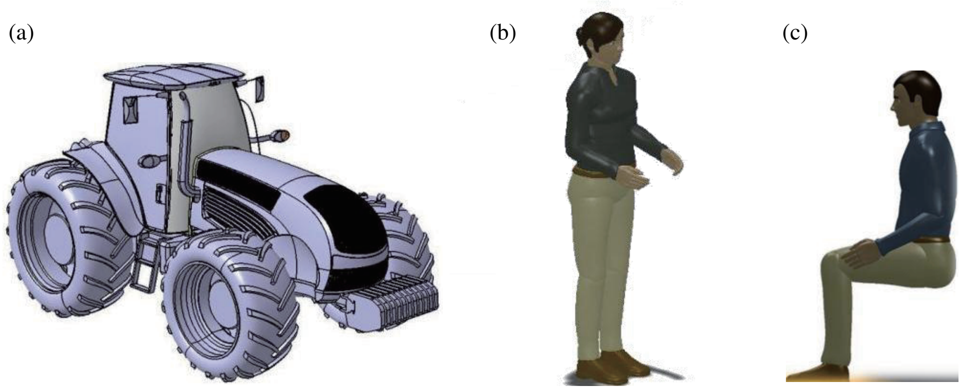

FIGURE 2. Tractor and human model diagram. (a) Tractor model, (b) standing human body, (c) human body in sitting position.

TABLE 1. Simulation model parameters.

material	Conductivity (S/m)	Relative dielectric constant
Human body	0.05	1×10^6
Wire	3.774×10^7	1
Tractor tires (rubber)	1×10^{-12}	3
Air	1×10^{-14}	1
Tractor casing (steal)	8.57×10^6	1

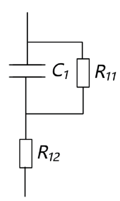

FIGURE 3. Impedance circuit of the human body.

mately 75% of the normal impedance of the human body, while from hand to foot is 50% [21, 22]. The impedance of the human body varies under different voltages, and the higher the voltage is, the lower the impedance of the human body is. For human body modeling and simulation in this article, resistance R_1 is set to 1500 Ω, and different resistance values are selected for R_2 based on the induced voltage amplitude and the ground condition of the human body..

3. SIMULATION RESULTS AND ANALYSIS

Select the lowest point of the wire, the induced voltage on the metal casing of the tractor on the ground, and the TES current when the driver or ground staff touch the tractor casing.

3.1. Induced Voltage Between the Human Body and Tractor Casing

The ground staff are subjected to insulation and grounding conditions, and the peak induced voltage of each component without transient electric shock is shown in Table 2. The waveform of induced voltage is depicted in Fig. 4.

From Table 2 and Fig. 4, it is evident that when the tractor and the person are positioned similarly beneath the transmission line, the induced voltage on the metal shell of the tractor reaches its peak. Conversely, the induced voltage experienced by ground staff, with their feet grounded, is at its lowest, falling within the safe voltage range of the power frequency. Furthermore, the induced voltages at the center of the double circuit line (point P2) surpass those beneath the single-side wire (point P1). Consequently, there is greater practical significance in studying the induced electric shock current of agricultural machinery operating on the ground at the center of the double-circuit transmission line.

3.2. Transient Impulse Current of Human Contact With Tractor Casing

This section investigates the current characteristics of transient electric shock between workers and the tractor casing when the tractor is located at P2. According to the principle of TES caused by human contact with the metal shell of the tractor, the equivalent circuit between the human body and the metal shell of the tractor is shown in Fig. 5 when transient electric shock occurs. In this circuit model, C_1 is the human capacitance, R_{11} and R_{12} represent the insulation resistance of the human skin and the internal impedance of the human body, respectively. Additionally, C_2 and R_2 represent the capacitance and resistance of the human forearm, respectively, while C_3 and R_3 are the equivalent capacitance and equivalent resistance of the tractor to the ground; R_2 is the equivalent resistance of the human body to the ground; U_1 and U_2 are the induced voltages of the tractor's metal shell and the human body, respectively. The circuit parameters are different when the transient electric shock current characteristics of drivers and ground personnel are studied with different grounding states, and the specific equivalent circuit parameters are shown in Table 3.

TABLE 2. Peak-induced voltage.

position	Research object	Peak of induced voltage (V)
P1	Driver	18572
	Ground staff (ungrounded)	9394
	Ground staff (grounded)	17
	Vehicle metal shell	25346
P2	Driver	24352
	Ground staff (grounded)	26
	Ground staff (ungrounded)	15479
	Vehicle metal shell	32124

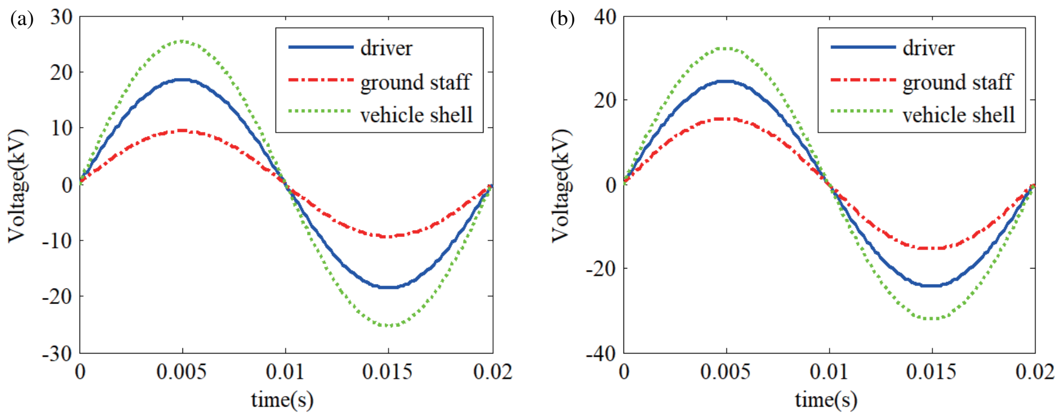

FIGURE 4. Simulated voltage waveform of the human body without discharge. (a) Induced Voltage at P1. (b) Induced Voltage at P1.

TABLE 3. Equivalent circuit parameters of TES.

Research object	C_1/pF	R_{11}/Ω	R_{12}/Ω	C_2/pF	R_2/Ω	C_3/pF	R_3/Ω	R_4/Ω
Driver	200	1500	4000	22	1250	5000	20	10000
Ground staff (ungrounded)	200	1500	4000	22	1250	5000	20	10000
Ground staff (grounded)	200	1500	4000	22	1250	5000	20	0

TABLE 4. Simulated result of TESC with human body insulation.

Research object	Simulation value of TES current
Driver	0.6
Ground staff (ungrounded)	0.95
Ground staff (grounded)	2.8

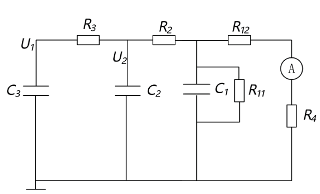

FIGURE 5. TES equivalent circuit.

Simulation results of the TES current borne by the human body are shown in Fig. 6, and the current peak is shown in Table 4.

According to the simulation results, it can be observed that when the human body is insulated from ground, the TES current reaches its maximum value within 50–80 ns. The higher the induced voltage of the human body is, the smaller the rise time of the current is, and the smaller the discharge time constant is. The TES current experienced by the driver inside the cabin is the smallest. Conversely, when the human body is grounded, the amplitude of the TES current is the largest, along with an extended discharge duration. This phenomenon can be attributed to two factors. Firstly, when the human body is grounded,

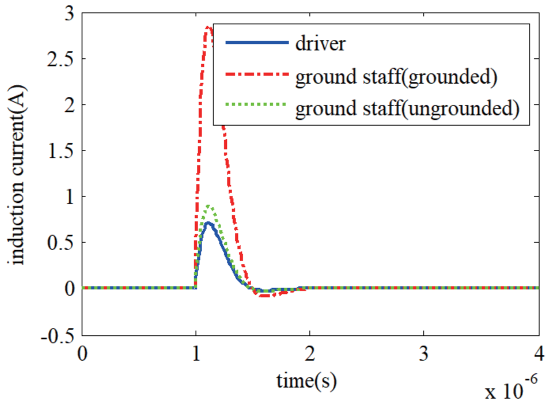

FIGURE 6. Simulated TES current in the human body.

the ground resistance is relatively small, resulting in a small impedance of the discharge circuit. Secondly, a grounded human body exhibits the highest induced voltage difference between itself and the tractor. Consequently, the rise time of the TES current is the shortest; the discharge time constant is also the minimized; and the sensation felt by the human body is the most intense.

4. EXPERIMENT AND RESULT ANALYSIS

A transient electric shock test involving a tractor and a human was conducted beneath a 1000 kV dual-circuit AC transmission line in North Henan Plain. The test aimed to simulate the scenario of a tractor operating in farmland beneath the transmission line. Measurement was taken to determine the induced voltage experienced by the tractor beneath the transmission line, as well as the TES current generated upon human contact.

4.1. Experimental Scenario and Equipment

This article selected the lowest point of a 1000 kV transmission line as the measurement area. The experimental area site is farmland post-autumn harvest, characterized by flat terrain, devoid of vegetation cover, loose soil with a moisture content not exceeding 20%, and lacking any water surface within a 1 km radius of the ground. A Dongfanghong LX2204 tractor manufactured by YTO GROUP CORPORATION is driven horizontally beneath the line, as illustrated in Fig. 7, representing the test scenario.

The equipment used in the experiment includes a high sampling rate digital oscilloscope Tek MOD3024, featuring a sampling frequency of 2.5 GS/s and an analog bandwidth of 200 MHz. The UHV differential probe was employed to collect induced voltage or clothes rack induced voltage that is insulated to the ground. Its maximum sampling bandwidth is 200 MHz, and the maximum effective value of the measurable AC voltage range is 7 kV. Customized current coils measure transient currents flowing through the human body with an accuracy of $\pm 1\%$. To mitigate the influence of external electromagnetic fields, a metal shielding box is utilized to shield the current coil. The UHV differential probe and current coil are connected to the oscilloscope through BNC coaxial cable.

4.2. Test Content

To verify the accuracy of the simulation results, this paper conducted the human body electric shock tests on the driver inside the cabin and the ground staff under two different conditions: grounded and ungrounded.

The electrode current is collected through a current transformer coil mounted on the metal rod. The induced voltage on the human body is collected using a high-voltage probe, while the TES (transient electric shock) current on the human body is collected by placing a current coil on the metal rod. The oscilloscope is configured in single pulse mode to capture the transient current waveform. During the experiment, the core of the current coil and the outer shell of the oscilloscope are grounded together.

During the electric shock experiment for ground staff, two scenarios were tested. In one scenario, they stood on epoxy resin insulation boards placed on the ground while wearing insulated boots. In the other scenario, they stood on metal boards placed on the ground with bare feet. Initially, the human hand maintains a distance of 30 cm from the tractor. Subsequently, the individual held a metal rod and gradually approached the tractor until contact was made with the outer shell, resulting in a TES. The high-voltage probe collected the induced voltage from the human body, while the current coil placed on a metal rod collected the electric shock current from the human body. The experimental measurement circuit is described in Fig. 8.

During the driver's electric shock experiment, the driver assumes a seated position inside the cabin, holding a metal rod and gradually makes contact with the metal components inside the tractor cabin. The signal acquisition system operates under the same conditions as described above.

Take the average of each experiment repeated 10 times to eliminate accidental errors. Additionally, the shock sensation experienced by the experimenter was recorded. The experiment involved three participants in the experiment, comprising two males and one female.

4.3. Comparison and Analysis of Simulation and Experimental Results

Table 5 presents the comparison between the simulated and experimental values of the effective value of induced voltage without TES. It is evident that the measured values of the ground staff induced voltage significantly deviate from the simulation values. This discrepancy can be attributed to the presence of the large tractor, which alters the distribution of electric fields near the ground, thereby reducing the induced voltage of the ground objects to some extent.

Table 6 displays the comparison between the experimental and simulated values of the current flowing through the human body when TES occurs.

According to Table 6, it is evident that when ground staff are grounded, the amplitude of the TES current that they bear is the highest, while the amplitude of the TES current borne

(a) (b)

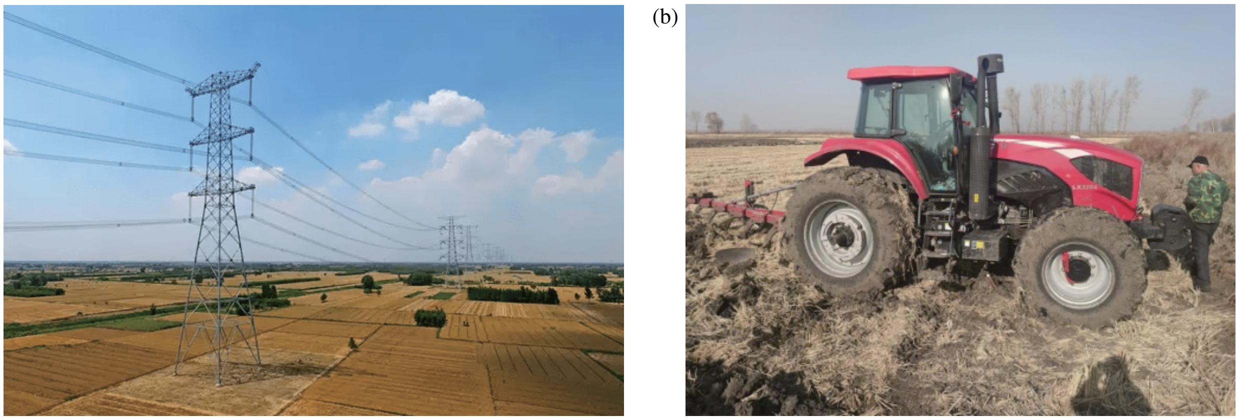

FIGURE 7. Experimental scenario. (a) Experimental area, (b) Test site.

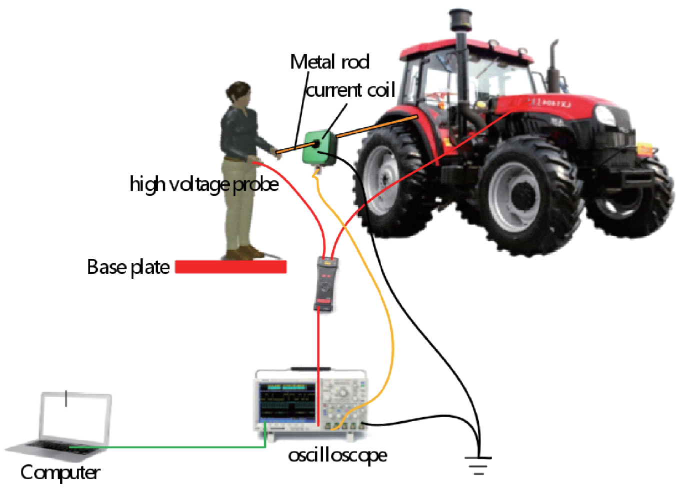

FIGURE 8. Schematic diagram of experimental circuit.

TABLE 5. Simulation and experimental results of induced voltage.

Research object	Simulation Voltage (V)	Experiment Voltage (V)	Error (%)
Driver	24352	20658	15.16
Ground staff (grounded)	26	19	26.9
Ground staff (ungrounded)	15479	13627	11.98
Vehicle metal shell	32124	32254	0.4

by the driver inside the vehicle is the lowest. This discrepancy is attributed to the shielding effect provided by the vehicle's metal shell, which protects individuals inside the cabin. The experimental values of TES currents experienced by the human body were consistently smaller than the simulation values, with a relatively large deviation. This deviation can be attributed to the simplification made in the simulation, where the soil was treated as a uniform good conductor. However, soil conductivity is highly sensitive to the factors such as water content and porosity. During a TES event, the distributed capacitance and distributed resistance within the soil serve to limit the amplitude of TES current to some extent.

From Fig. 9, it is apparent that the measured waveform of the TES current of the driver in the tractor cabin closely aligns with the simulation model. However, the actual transient process of electric shock current for ground staff with both feet grounded extents beyond the simulation results. This discrepancy arises due to the equivalent capacitance in the soil, which increases the capacitance in the electric shock discharge circuit, consequently elongating the equivalent time constant of the circuit. When ground staff are insulated from the ground, TES currents exhibit brief oscillations.

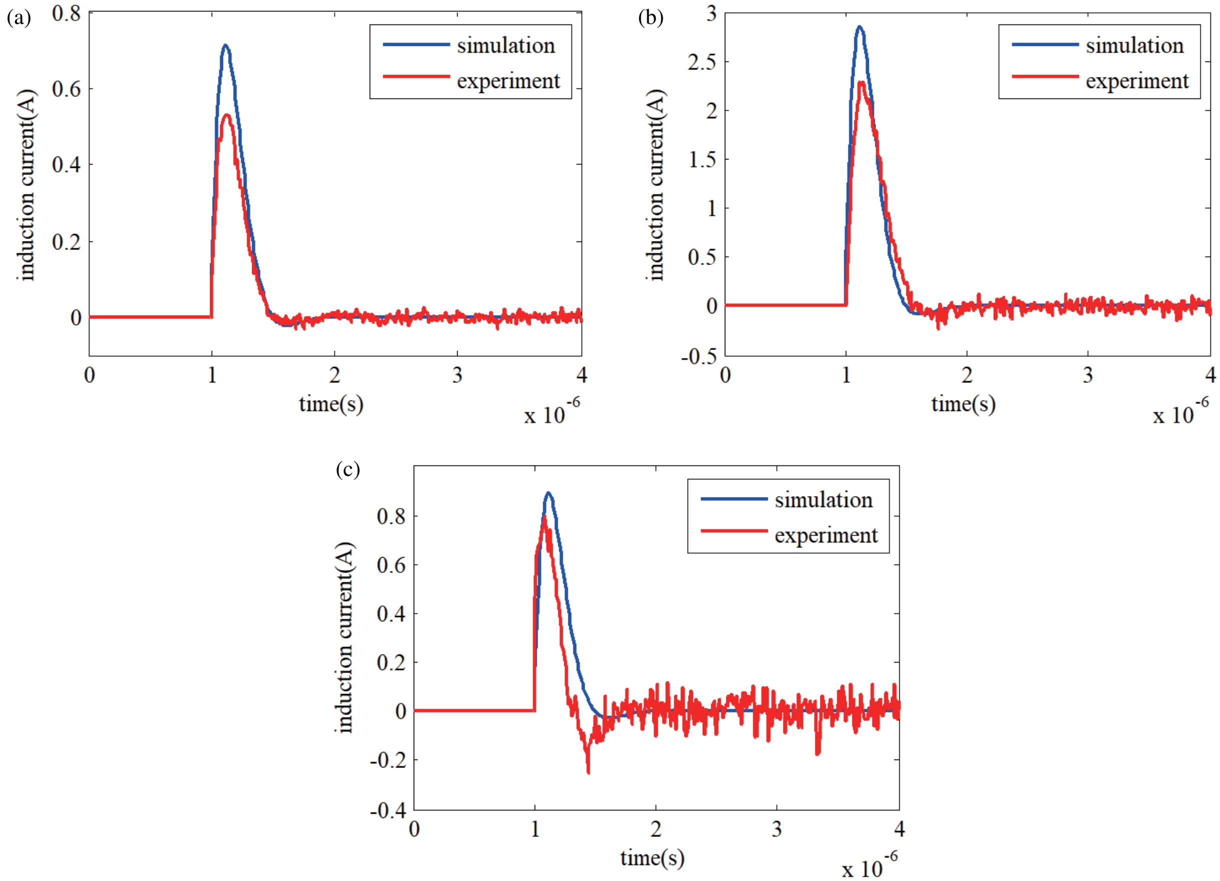

FIGURE 9. Comparison of simulation current and test current. (a) Driver, (b) Ground staff (grounded), (c) Ground staff (ungrounded).

TABLE 6. TES current flowing through the human body.

Research object	Simulation current (A)	Experiment current (A)	Error (%)
Driver	0.6	0.47	21.67
Ground staff (grounded)	2.8	2.5	10.7
Ground staff (ungrounded)	0.95	0.87	8.4

4.4. Suggestion for Induced Current Suppression

The human body's perception of induced electricity is directly related to the amplitude of induced voltage and induced current. Through numerical simulation research and experiments in this article, the following is a summary:

(1) Due to the shielding effect of the tractor's metal casing, the transient surge current experienced by the driver in the cabin is relatively small under higher induced voltage. When ground personnel are insulated from the ground, the transient impulse current upon contact with the metal casing of the tractor is much smaller than when they are grounded. For drivers of agricultural equipment, those with metal shells can significantly reduce the transient surge current experienced by operators inside the cabin. As for ground personnel, the amplitude and duration of transient surge current are related to the insulation status of ground personnel, ensuring that the good insulation of ground personnel can effectively suppress transient surge current.

(2) Serializing high impedance in the electric shock current circuit can also prevent the occurrence of induced electric shock. When it is difficult to effectively ground an insulated object, effective suppression of induced electricity can be achieved by wearing insulated gloves on the human body or brushing insulation paint on the surface of the object.

5. CONCLUSION

When induction electricity forms a discharge circuit through the human body, the amplitude of the discharge current is relatively large, causing instantaneous contraction of the human muscles and obvious local pain, leading to physical and mental discomfort. This article took the electromagnetic environment under a 1000 kV transmission line as the research object and studied the induced electrical characteristics of agricultural machinery and related personnel below the line. A numerical simulation model, which consists of a UHV transmission line, tractor, and human body, was constructed to investigate the induced voltage and the transient discharge current at transient electric shock events. Additionally, a real experimental system is constructed near the actual line, the induct voltage and transient electric shock tests are carried out. The experimental data is obtained through actual measurement. The summarized conclusion is as follows.

(1) The induced voltage experienced by agricultural machinery and the human body near the transmission line is contingent upon their proximity to the line. The closer they are to the line, the higher the induced voltage is, and consequently, the greater the transient electric shock current is. Metal shielding can effectively suppress the induced voltage and transient electric shock current.

(2) The magnitude of induced voltage and transient current is correlated to the insulation state of the human body to the ground. When the human body is grounded, its impedance is relatively low. If contact is made with the metal casing of the tractor under these conditions, it will lead to noticeable transient electric shock phenomenon, whose maximum amplitude can reach 2.2 A in this research.

(3) The simulation model proposed in this article exhibits a small discrepancy between the calculation results and experimental findings, effectively simulating the induced voltage and current of transient electric shock between the human body and metal. Through simulation and experimental research, it has been found that human perception of induced electricity is directly related to the amplitude of induced voltage and TES current. This conclusion provides a certain reference for induced current protection in high-voltage transmission corridors.

ACKNOWLEDGEMENT

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