Research on High-voltage Leakage Monitoring of Electric Tractor Based on Insulation Resistance Model

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Abstract. Electric tractor is more environmentally friendly and more efficient than traditional tractor, which has become a hot spot in the field of Agricultural Engineering in China. In order to monitor the leakage phenomenon of lead-acid battery device, this paper takes the 25 horsepower electric tractor as the research object, takes the high-voltage monitoring leakage model of electric vehicle established by the overall insulation resistance model as reference, establishes the overall insulation resistance model of battery and DC brushless motor system to monitor the overall insulation resistance of battery and motor working system to ground. Firstly, the theoretical analysis is carried out to clarify the insulation resistance measurement principle. Secondly, the measurement results are observed by changing the insulation parameters and auxiliary measurement resistance value. Finally, the measurement principle diagram is built by using the Simulink simulation environment of MATLAB simulation software. The model is simulated by setting reasonable parameters. The measurement error is obtained by comparing the operation results with the theoretical values. According to the simulation results, the measurement error of asymmetric insulation resistance of motor side to ground is smaller than that of symmetrical insulation resistance of motor side to ground, and the smaller the auxiliary resistance value is, the smaller the measurement error is.

1. Introduction

Traditional tractors mostly use internal combustion engines as power, which not only pollutes the environment, but also has low efficiency, whilst electric tractors powered by motors not only save energy and protect the environment, alleviate the problem of primary energy depletion, but also have high efficiency [1,2]. At present, the research of electric tractors has become a research hotspot in the field of agricultural engineering [3]. The electric tractor can be divided into four parts, the battery part, the motor part, the transmission part and the driving wheel part [4]. As an important part of power supply and power conversion, this article focuses on the battery and motor parts as the research object.

Lead-acid batteries are widely used and studied by various electric vehicles in various countries due to the comprehensive factors such as cheap price, abundant material sources, high specific power, mature technology and manufacturing process, and high resource recovery rate [5]. Leakage is a
common problem for lead-acid battery devices [6], so it is necessary to monitor the insulation resistance of the lead-acid battery to ground in real time to avoid leakage. The brushless DC motor has the advantages of small size, large output and high efficiency, and is widely used in electric vehicles as its power unit [7, 8]. As the power supply equipment, the insulation parameters of the cable should be monitored online in real time to ensure the normal operation of the motor.

In this paper, the 25-horsepower electric tractor is taken as the research object, and the electric vehicle high-voltage monitoring leakage model [9] established by the overall insulation resistance model is taken as the reference to establish the overall ground insulation resistance model of the battery and the DC brushless motor system, and monitor the overall ground insulation resistance of the battery and the motor working system. 240V is selected as its input voltage, the Simulink simulation of MATLAB is used to model, and the auxiliary measuring resistance is paralleled on both sides of the positive pole of the battery [10], the incorporation time is set, the influence of the change of the auxiliary measuring resistance and the change of the insulation resistance to the ground on the model measurement is studied.

2. Modeling of insulation resistance of battery motor to ground

2.1. Measurement of insulation resistance of lead-acid battery to ground

When the motor drive circuit does not work, you only need to consider the measurement of the insulation resistance of the lead-acid battery to the ground. The measurement principle is shown in Fig. 1 [11].

\[ R_p = \frac{2V_{in}(V_2' - V_2)}{(V_{in} - V_2)(V_{in} - 3V_2') + V_2V_2'}R \]  \hspace{1cm} (1) \\
\[ R_n = \frac{V_{in}(V_2' - V_2)}{V_2(V_{in} - 2V_2')}R \]  \hspace{1cm} (2)

Where Vin is the input voltage, and V2 and V2' are voltage values measured after the switch is turned on and off, respectively.
2.2. Principle of DC brushless motor drive
When the motor drive circuit works, the brushless DC motor works. According to its driving principle and different conduction sequences, a combination of different motor power supply cables' insulation resistance to ground is obtained. The driving circuit principle is shown in Fig.2 [12,13].

![Fig 2. Schematic diagram of the motor drive circuit](image)

The conduction sequence of the switch tube is VQ1VQ2, VQ2VQ3, VQ3VQ4, VQ4VQ5, Q5VQ6, VQ6VQ1. According to the conduction sequence of the switch tube, the parallel connection of different insulation resistances to the ground can be obtained, and the different situations are given in the following table 1.

2.3. Modeling of integral insulation resistance
Considering the interaction between the battery and the motor system, a DC brushless motor system is added to the battery model to establish a combined overall insulation resistance model, as shown in Fig.3. Since the model is DC power supply, in each conduction sequence, the DC current is added on both sides of the capacitor, so the influence of the distributed capacitance on the ground is not considered.

![Fig 3. Model of overall insulation resistance](image)

Considering the conduction sequence of the switches in the driving circuit, the input voltage is equivalently transformed. The equivalent circuit is shown in Fig.4, and the voltage at the middle point...
is $V_0$, the resistance is $R_p$ and the positive voltage are $V_p$ and $V_n$ and there is an equal relationship between the voltages:

$$V_p = V_0 + \frac{V_m}{2}$$

(3)

$$V_n = V_0 - \frac{V_m}{2}$$

(4)

In (3) and (4), $V_p$ and $V_n$ are the positive voltage of resistance $R_p$ and $R_n$ respectively.

![Insulation resistance model considering driving circuit](image)

**Fig 4.** Insulation resistance model considering driving circuit

The change of $R_x$ and $R_y$ with the conduction state is shown in Table 1. According to the conduction sequence, the six conduction states are respectively marked as 1-6.

| resistance | 1 | 2 | 3 | 4 | 5 | 6 |
|------------|---|---|---|---|---|---|
| $R_x$      | $R_A$ | $R_B$ | $R_B$ | $R_C$ | $R_C$ | $R_A$ |
| $R_y$      | $R_C$ | $R_C$ | $R_A$ | $R_A$ | $R_B$ | $R_B$ |

**Table 1.** Changes of $R_x$ and $R_y$ with the conduction state

2.4. *Static measurement of overall insulation resistance*

When the motor is not working, manually turn on a switch in the drive circuit, and its equivalent circuit is shown in Fig.5.
According to Kirchhoff’s current law and the set parameter values, calculate the resistance value of $R_p$ and $R_x$ in parallel, where $R_p$ is calculated by formula (1), $R_x$ is selected according to the relationship between the conduction of switch tube in Table 1 and the insulation resistance to ground.

2.5. **Overall dynamic measurement of insulation resistance**

First, the insulation resistance value of the three phases of the motor side is set to the ground as $R$, and use the Kirchhoff’s law of current to get:

$$\frac{V_p}{R_p} + \frac{V_p}{R} + \frac{V_n}{R_n} + \frac{V_n}{R} = 0$$  \hspace{1cm} (5)

Substituting (3) and (4) into (5), we can get:

$$V_o = \frac{V_p \left( \frac{1}{2} \frac{1}{R_n} - \frac{1}{R_p} \right)}{1 + \frac{1}{R_p} + 2 \frac{1}{R}}$$ \hspace{1cm} (6)

Considering (3) and express the result with conductance, we can get:

$$V_p = \frac{V(G_p + G)}{G_p + G_n + 2G}$$ \hspace{1cm} (7)

$$K_p = \frac{V_p}{V} = \frac{G_n + G}{G_p + G_n + 2G}$$ \hspace{1cm} (8)

Considering adding auxiliary measurement resistance, we can get:
Together with (8) and (9), the equivalent insulation resistance formula can be obtained:

\[
K'_p = \frac{G_s + G}{G_p + G_n + 2G + G_0}
\]  \hspace{1cm} (9)

It can be seen from (10) that the auxiliary measurement resistance incorporation time is set, and \( K_p \) before and after the parallel connection is obtained through measurement, and then the equivalent insulation resistance can be obtained according to the value of \( R_0 \).

\[
R_e = \frac{1}{G_p + G_n + 2G} = \frac{K_p - K'_p}{K'_p} R_0
\]  \hspace{1cm} (10)

3. Matlab simulation of the overall insulation resistance model to ground

This paper uses Matlab software for simulation, and the built circuit is shown in Fig. 6.

![Matlab simulation of the overall insulation resistance model](image)

**Fig 6.** Matlab simulation of the overall insulation resistance model

First, the auxiliary measurement resistance value is set to 100kΩ, \( R_p \) to 100kΩ, \( R_n \) to 300kΩ, and the insulation resistance to ground on the motor side is set to 200kΩ; secondly, voltage measuring elements on the input voltage side and both sides of the resistance \( R_p \) is set, and the \( K_p \) value before and after parallel connection of the auxiliary resistance is calculated; finally, it is connected to the oscilloscope for display through the digital filter [14,15]. In this paper, the simulation time is 2s, and the auxiliary resistance is incorporated in 1s. The \( K_p \) value before and after parallel connection is as shown in Fig.7.
Fig 7. $K_p$ value changes before and after $R_0$ parallel connection

It can be seen from Figure 7 that the $K_p$ value before parallel connection is 0.37, the $K_p$ value after parallel connection is 0.28, and $R_0$ is 100kΩ. The calculated equivalent insulation resistance value is 32.142kΩ, which is relatively close to the theoretical value of 35.294kΩ. By changing the resistance value of auxiliary measurement resistance, the change of measurement error is shown in Table 2.

Table 2. Variation of measurement error with AUXILIARY RESISTANCE value under symmetrical condition

| $R_0$  | Measured value | Error  |
|--------|----------------|--------|
| 110kΩ  | 30.724kΩ       | 12.95% |
| 100kΩ  | 32.142kΩ       | 8.9%   |
| 90kΩ   | 31.091kΩ       | 11.9%  |
| 80kΩ   | 31.698kΩ       | 10.2%  |
| 70kΩ   | 31.569kΩ       | 11.8%  |

It can be seen from Table 2 that when the value of the auxiliary resistance $R_0$ is changed from 100kΩ to both sides, the errors are significantly increased. Considering the case where the three-phase insulation resistance is asymmetric, the three insulation resistances are set to 100kΩ, 200kΩ, and 300kΩ respectively, and then the value of $R_0$ is continuously changed. The measurement error changes are as shown in Table 3. The theoretical resistance value at this time is 28.57kΩ.

Table 3. Variation of asymmetry measurement error with auxiliary resistance value

| $R_0$  | Measured value | Error  |
|--------|----------------|--------|
| 100kΩ  | 26.67kΩ        | 6.65%  |
| 90kΩ   | 27.93kΩ        | 4.13%  |
| 80kΩ   | 28.27kΩ        | 1.05%  |
| 70kΩ   | 28.56kΩ        | 0.04%  |

It can be seen from Table 3 that when the resistance on the motor side is asymmetric, the measurement error can be reduced by decreasing the value of the auxiliary resistance.

4. Conclusions

In this paper, the high-voltage monitoring of the electric tractor is carried out by establishing the overall insulation resistance model of the lead-acid battery and the motor system, and the auxiliary measurement
resistance is added in the DC input measurement. Based on the theoretical analysis, according to the auxiliary resistance value and the ratio \( K_p \) between the voltage at both ends of the positive insulation resistance \( R_p \) of the battery and the input voltage before and after parallel connection, the overall insulation resistance value to the ground is calculated. At last, the simulation test is carried out by Matlab software, and the following conclusions are obtained:

1. The model can better reflect the overall insulation level of lead-acid battery and motor system to the ground;
2. When the insulation resistance of the motor to the ground is asymmetric, the error can be reduced by decreasing the value of the auxiliary resistance \( R_0 \).

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