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ACCURATE TRACK MODELING FOR SKIN EFFECT ON DC RAILWAYS

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Abstract: - A technique for simulation of transient skin effect of the dc railway system is described in this paper. For time-domain simulation the classic calculation of skin effect based on frequency domain is not suitable. The aim of this paper is to build up a time-domain calculation process which can be realized in MATLAB/ Simulink. Results are applied to the calculation of frequency voltage signal and compared with skin effect impedance of frequency for the investigation of the step series algorithm. Accurate simulation of the transient skin effect produces precise modeling of the remote fault current. This is important for the dc railway protection to develop techniques for discriminating remote short circuit currents from locomotive starting currents.

Keywords: Bessel function, circular cylinder conductor, dc railway, MATLAB/ Simulink, skin effect, step series, time domain.

I. INTRODUCTION

In modern dc traction system, because of the emergence of long block trains and the increase in traffic density, it is becoming increasingly difficult to distinguish between the starting currents of locomotive and the current occurred by a remote distance fault, particularly a high resistance fault.

These faults must be detected to prevent them from being a potential cause of tunnel fires . The magnitude of the remote fault current can be less than the starting current of the trains. For this reason, dc feeder relays are required to use techniques other than the current magnitude to judge fault conditions. A traditional dc feeder relay uses current rising rate and current increment algorithms to differentiate between train starting currents and remote fault currents, which sometimes has disoperation due to the high resistance remote short-circuit fault and other scenarios. Published work has presented methods with this problem: use the new logic of the di/dt protection algorithm to improve the relay's reliability, and use the wavelet transform to detect the time constant of remote short-circuit current and train starting current. In new algorithm research and development, accurate track modeling for fault current plays the key character.

II. LITERATURE SURVEY

The key technique of the calculation of remote short-circuit current is the calculation of skin effect. Thus, lots of research has been done on this technique. A typical solution, which is widely accepted, is to use the equivalent circular cylinder conductor of the rail. In the circular cylinder conductor skin effect calculation, it is first calculated by Tuohy *et al.* who use Carslaw *et al.*'s solution of the heat-flow equation to solve the transient skin effect calculation However, this solution is based on a step of electric-field intensity applied to the surface of a cylinder. In practical calculation, it is normal to know the voltage of the conductor, not the electric-field intensity.

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Thus, it is cannot directly be used in transient calculation. Brown *etal.* use the frequency model to solve the Bessel function and turns the conductor's impedance into frequency domain .This impedance model can be calculated with power circuit, and the result's inverse Fourier transform is the time-domain solution. This approximation is frequently error-prone, especially for complex time variations associated with power inverters, converters, etc. For these power applications, time-domain analyses are required. Silvester uses the modal network to simulate the skin effect characteristics. This method is easy to realize but still has an error which cannot be ignored. Hill *et al.* use the infinite element method to analyze the skin effect characteristic of rail. Wang *et al.* [uses a subdivision of conductors to evaluate the frequency-dependent impedance of the third rail. Giacoletto uses the inverse Laplace transform with series expansion. The method changes the frequency-domain result into time domain accurately, but cannot realize real-time calculations. This paper, however, gives the authors the idea to take full use of series expansion to realize real-time calculation.

The paper provides a simple simulation method of the short circuit current's skin effect based on MATLAB/Simulink. This paper describes the use of a computer-based system capable of providing an accurate current/time profile for remote distance faults, using the step series calculation technique. This paper also concludes with a comparison of practically measured results, results of calculation based on frequency domain, and the results of this new method.

III. SIMULATION OF THE DC RAILWAY SYSTEM

The dc railway system uses the dc transformer and rectifier to supply dc power to the train through the third rail and running rails. The system is complex, as it includes a power-electronic converter, rail, electrical motor, controlling system, and mechanical system. The MATLAB/Simulink provides a promising simulation tool for modeling a system, since it allows not only the analysis of an electrical circuit but also its interactions with mechanical, thermal, control, and other systems. Considering the factors that affect the shortcircuit voltage, this paper uses a detailed substation model on MATLAB/Simulink which can obtain the accurate characteristics of the output voltage. However, the rail system cannot directly model with the latest MATLAB/Simulink's standard power system block (PSB). Thus, it is necessary to model with S-Function, which allows users to build the model by designed functions. The equivalent circular cylinder conductor model lets researchers use circular cylinder conductor calculation results in transient rail current calculation. The real-time simulation can be realized with RTDS or MATLAB/Simulink to test the algorithm of the dc feeder relay and calculate the setting value of relay, as Fig. 1's model structure.

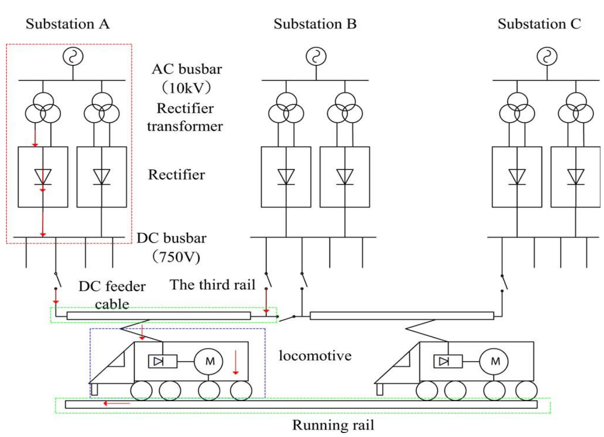


Fig. 1.Structure of the dc railway power-supply system.

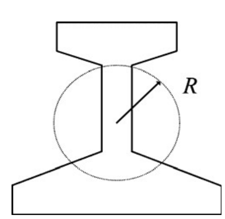


Fig. 2. Equivalent circular cylinder conductor of the rail.

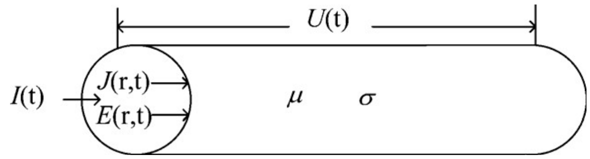


Fig. 3. Model of the unit circular cylinder conductor

A typical transient skin effect calculation of the circular cylinder conductor is the dc railway short-circuit current calculation. the equivalent circular cylinder conductor of the rail with the same perimeter, which is shown in Fig. 2

$$R = \frac{P}{2\pi} \qquad (1)$$

Where
P = Perimeter of the rail;
R = Equivalent radius of the rail.

IV. THEORETICAL CONSIDERATIONS

A. Basic Function

An analysis of skin effects normally starts with Maxwell's equations. Maxwell's equations for a circular cylinder conductor can be reduced as 2

$$\nabla^2 J = \mu\sigma \frac{\partial J}{\partial t} \qquad (2)$$

Where

- μ= permeability;
- $\sigma =$ conductivity;
- U(t) = voltage of the unit circular cylinder conductor;
- I(t) = current of the unit circular cylinder conductor; current density;
- J(t) = electric-field intensity.

In a cylindrical conductor model as in Fig. 3, this is simply the partial differential equation

$$\frac{\partial^2 J}{\partial r^2} + \frac{1}{r}\frac{\partial J}{\partial r} = \mu\sigma \frac{\partial J}{\partial t} \qquad (3)$$

.
This is a typical Bessel function, the solution of which need to consider the boundary condition. Carslaw *et al.* use series to define the boundary condition: the surface temperature of the conductor is stable. Tuohy *et al.* also define the boundary condition as: a step of the electric-field intensity applied to the surface of a cylinder conductor [9]. The solution is

$$J(r,t) = J_s\left\{1 - 2\sum_{n=1}^{n} \frac{J_0(x_n r)}{\alpha_n J_1(x_n)}\, e^{-x^2{}_n t/\mu\sigma}\right\} \qquad (4)$$

Where
$J_0 =$ Bessel functions of the first kind of order zero;
$J_1 =$ Bessel functions of the first kind of order one;
x_n = roots of the equation

Thus, the current of conductor is

$$I(t) = \pi R^2 J_s - 4\pi R^2 J_s \sum_{n=1}^{\infty} \frac{1}{(x_n)^2} e^{-x^2 t/\mu\sigma R^2} \quad (5)$$

Where

R = radius of the circular cylinder conductor.

This solution only suits, but cannot suit. Also, it only describes the relation of the electric-field intensity and current density. Due to this phenomenon, the paper discussed is transient; the electric-field intensity is not equal to the conductor's voltage. Thus, the relation of voltage and electric field intensity needs to be discussed.

B. Step Voltage Signal and Current Response

Consider another scenario: a step of current density applied to the cylinder conductor. Obviously, this is also an ideal scenario, because, in practice, it is not possible to have an extreme step signal. But for algorithm research and numerical calculation, it is meaningful. This also means that the angular frequency is also infinity. According to the definition of skin effect, when angular frequency is infinity, the inside current density can be considered as infinitesimal.

$$I_{t=0} = 0 \quad (6)$$

Thus, at this time, t= ∞ the voltage of the conductor can be calculated by; the depth is infinitesimal; thus, the conductor current can be considered infinitesimal. In numerical calculation, the current can be defined as

$$I_{t=0} = \pi R^2 J_s \quad (7)$$

When of the step voltage signal, according to, the inside current density can be considered as equal to . Thus, at this time, the voltage of the conductor can also be calculated by, which is the same as the time t=0. The result is

The 0 and scenarios are the boundary conditions.

This phenomenon can also be described as the step of voltage applied to the conductor.

$$U = R_{int} I + L_{int} \frac{dI}{dt} \quad (8)$$

C. Step Series Method

This paper uses a step series method to realize the numerical calculation of the skin effect. Since the analysis of the relation of the step voltage and current response, there are two conclusions: the magnitudes of step voltage and current response have direct proportion; and the current response only has a relation with the voltage, which can also be tested in the frequency domain. Fig. 5 shows the step series method. In the practical engineering field, the voltage signal normally gets into the process system by sampling.

This method builds the relationship with voltage and current response. Thus it makes easier to calculate the transient skin effect current and can be realized in MATLAB/Simulink.

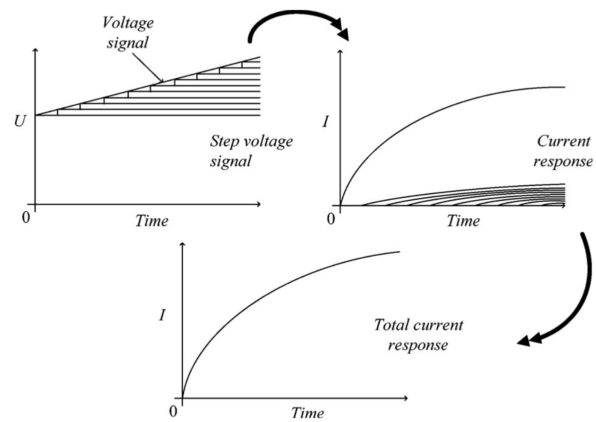


Fig. 4. Examples of the step series method.

V. CALCULATION OF FREQUENCY CURRENT

This paper presents a comprehensive analysis of the transient skin effect calculation of the circular cylinder conductor based on time domain, which is dominated by the series voltage signal. This paper uses a stable ac voltage signal to test this method and compares the simulation results with d c railway test results. The skin effect impedance of frequency is derived from Maxwell's equations.

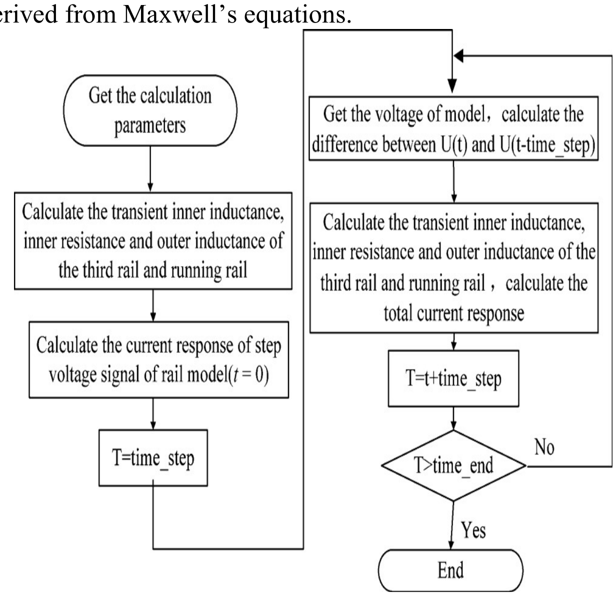


Fig 5: Flowchart of the S-function model.

The variation of different frequencies of the 1V ac voltage source is calculated to produce transient current responses. It can be found that at low frequencies, the results show some difference. Calculating with high frequency, the result shows that the results are almost the same. Therefore, it may imply that the frequency calculation is more suited for high frequency. It is possible to prove the correctness of this transient calculation in the algorithm. However, the strict and direct test still needs to be designed to prove the correctness.

VI. SIMULATION AND EXPERIMENTAL RESULTS

To study the remote short-circuit faults in the dc railway power-supply system with the substation model and locomotive model, a comprehensive MATLAB/Simulink model of the rail skin effect model has been presented in this paper. A new calculation method of skin effect on time domain has been presented and simulated and could be tested with the frequency model. With the factor that voltage signal could be constructed by a series step voltage signal, it is possible to calculate the current response with the series current response of step voltage signal. By comparing and investigating the stable frequency responses with the calculation of the series step ac voltage signal and impedance in frequency domain, the results of each frequency have been given. The results of the model have been compared with the recorded data and good agreement has been obtained over time. It also proved that the proposed tubular conductor model can provide satisfactory results.

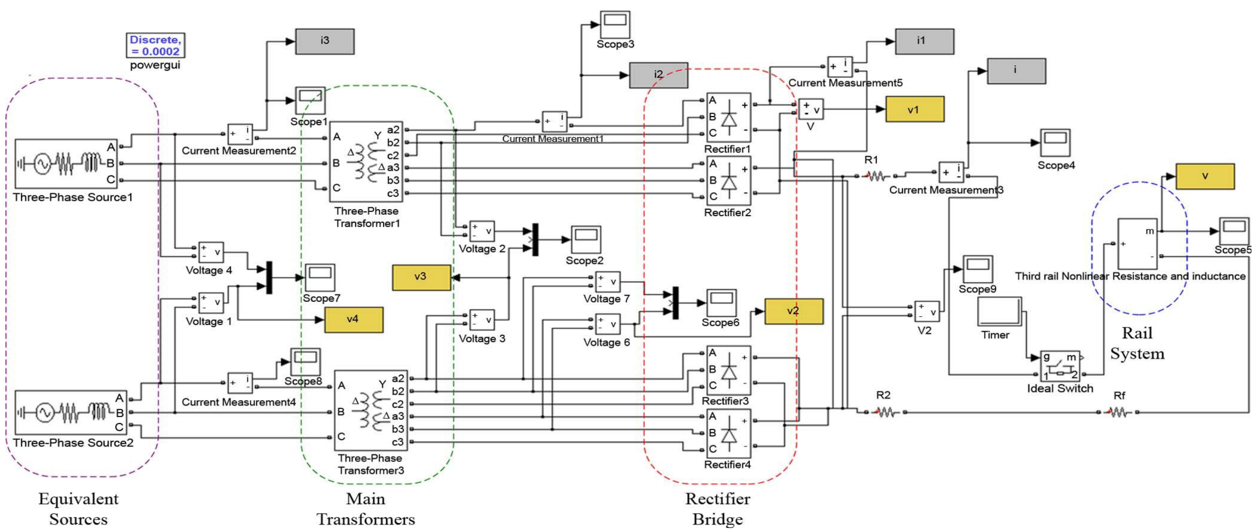


Fig. 6. Complete Simulink model of the remote short circuit

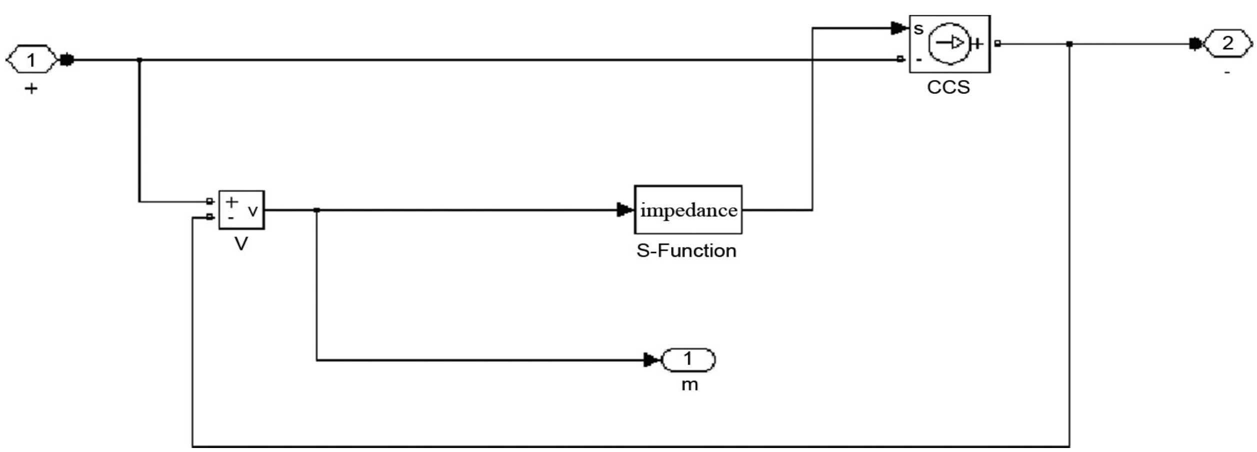
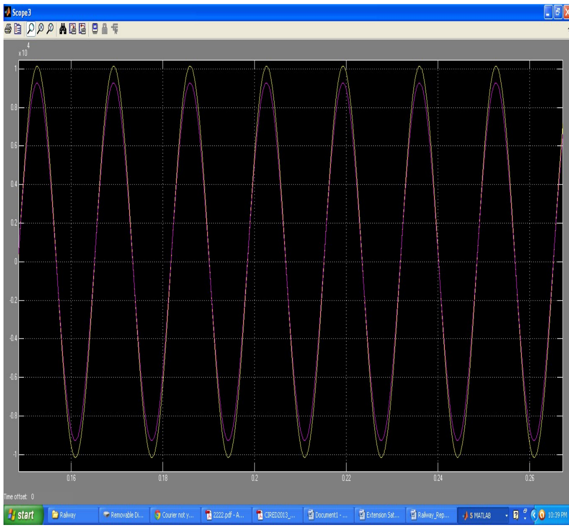


Fig. 7. Model of the S-function control current source.



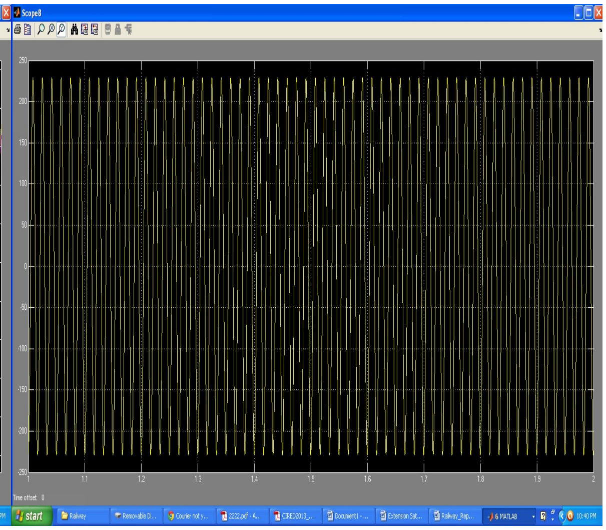
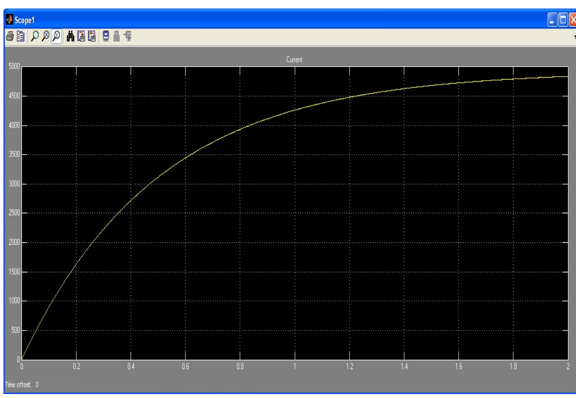


Fig 8. Input Voltage

Fig 9.Input current



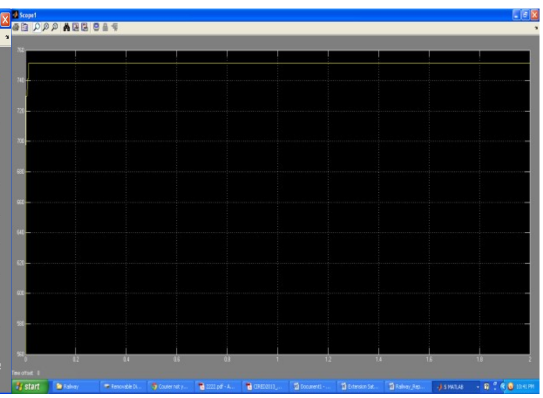


Fig 10: Short Circuit Current

Fig 11. Rectifier output Voltage

VII. CONCLUSION

This paper presents an integrated MATLAB/Simulink simulation model of short-circuit fault which could be used to extend previous skin-effect studies. This simulation can be easily rebuilt according to the different substation construction and track parameter. However, this paper ignores the arc, hysteresis, and stray currents and other factors that may require careful tuning of the parameters by trial and error to allow the model to fit the test current curve better. Our future work is therefore to develop a more comprehensive method for optimally determining the transient parameters and consider the situation when the train is running.

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