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Research on key technologies of railway station codification digital twin

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Abstract. According to the requirements of railway transportation, to ensure that locomotives can receive frequency-shifted signal information through the track within the station, the track circuits must be codified. Due to the increased speed of train operations, braking has become more challenging, increasing the possibility of running a red signal compared to the present. Therefore, it is imperative to implement pre-overlay codification technology and equipment suitable for use in speed-enhanced sections. As the pre-overlay coding method must be adopted, it requires the isolation components in the interface equipment to have "fault-safe" performance. When the isolation component fails, the current or voltage introduced into the parallel track relay must not cause malfunction. Therefore, ensuring that the current and voltage of each component in the codified track meet the requirements is crucial. This research aims to establish a circuit simulation model based on MATLAB Simulink to achieve dynamic simulation of the pre-overlay ZPW-2000 codification circuit diagram of the 25Hz phase-sensitive track circuit in the electrified section. Through this model, the electrical characteristic indicators such as current, voltage, and waveform of each component on the circuit can be observed in real-time. This helps optimize the design and maintenance of the railway signal system, improving the safety and efficiency of train operations and contributing to the establishment of a digital twin model for the entire railway system's signal system.

Keywords: Codification, Circuit Simulation, Digital Twin.

1. Introduction

Digital Twins, also known as digital twin technology, is a concept that integrates various new technologies [1]. Digital twins originally originated from the concept of "virtual digital representations equivalent to physical products" proposed by Prof. Grieves in 2003 [2]. , which was then called "mirror space model" and defined as a 3D model that includes a physical product, a virtual product, and a connection between the two. In 2011, Professor Grieves explicitly applied the term "digital twin" in his book [3]. As a transcendental concept, a digital twin is a digital mapping system of one or more important and interdependent equipment systems whose core task is to solve the management problems faced by equipment throughout its life cycle using the integrated application of multidisciplinary technologies.

Digital twin technology can play an important role in the maintenance phase of rail transport systems. Through the creation of digital twin models, the state of a rail transit system can be monitored in real

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time and the system can be fault diagnosed and repaired. In addition, digital twin technology can feed field information into the digital model to simulate the effects of different maintenance programmes in order to determine the optimal maintenance programme. In each stage of the maturity of the digital twin, simulation plays an indispensable role: modelling and simulation are the core technologies of digitisation; real-time interaction is a common scenario in semi-physical simulation; and the core technology of "foreknowledge" itself is simulation. Circuit simulation technology is the key technology to realise the digital twin of rail transport.

By the end of 2022, the total mileage of China's railway operation reached 155,000 kilometres, and the related technology has been developed rapidly [4]. With the continuous speed increase of the railway, the requirements for locomotive signalling and train overspeed protection in the speed increase section are getting higher and higher. Railway as the backbone of the new era of transport power, its operational efficiency and driving safety also appear to be particularly important, the concept of locomotive signal subjectification is also more and more specific [5]. When the train is running in the automatic blocking interval, the locomotive signal can continuously receive the ground signal and uninterruptedly reproduce the display of the signal machine in front of it, and when the train enters the station, the implementation of the electric coding design of the track circuit makes the locomotive signal continuous. At present, the station code technology has been widely used in railway lines, become the "ground - car" communication technology support. With the continuous improvement of train speed, the coding technology has fixed switching, pulsation switching, superimposed frequency shift, pre-superimposed frequency shift and closed-loop, etc., the relevant coding equipment is also constantly updated, and has experienced roughly the polar frequency, AC calculations, frequency shifted three types [6,7]. Currently, two types of frequency shifted orbital circuits are in force in China, mainly the domestic 18 information frequency shifted orbital circuit and ZPW-2 000A type frequency shifted orbital circuit [8,9]. These two types of frequency shifted rail circuits have been used in China's railway transport for a long time, and the technical level is quite mature and has rich working experience.ZPW-2000A type frequency shifted rail circuit is based on the introduction of the French UM71 uninsulated frequency shifted rail circuit technology, combined with the national conditions in order to enhance the safety of the railway system related to the reliability and efficiency of the transmission of the upgrading of the localisation of the technology [10,11].

ZPW-2000 track circuit is a circuit system formed by connecting transmitter, receiver, rail and other equipments using electrical principle, the track circuit has the functions of section idle monitoring, rail integrity monitoring, and it can also transmit frequency shifting signals to the train to realise the function of vehicle-land communication, which is in line with the principle of "fault-safety" [12]. ZPW-2000 series track circuit can effectively prevent the train from venturing into and out of the signal, is to reduce driver fatigue intensity, improve transport efficiency of the technical methods, but also in high-speed railways to ensure that the operation of the safety of an important means [13].

Due to the wide range of track circuits widely laid, the environmental impact is greater, and the equipment is susceptible to external adverse effects, which leads to the occurrence of failures. As a key part of the implementation of digital twin technology for railway signals, the simulation of track circuits by using Simulink and the real-time comparison with real data are of great significance for the subsequent research and analysis as well as fault diagnosis.

2. Literature Review

ZPW-2000 track circuit is one of the indispensable key equipments in China's railway signalling system.ZPW-2000 track circuit is the railway signalling equipment which automatically completes the train occupancy status checking, and its working quality directly affects the efficiency of railway transport, and it is also an important guarantee for the safe operation of trains. Track circuit failure mode is complex, the maintenance personnel to deal with the fault time is longer, seriously affecting the order of railway transport, is the railway signals on-site maintenance of the difficult points. Exploring various intelligent diagnostic methods to shorten the fault processing time and improve the efficiency of track circuit fault maintenance is becoming a hot spot of concern [14].

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In 2019, Wang Guodong et al. based on the defects of the traditional maintenance method of the outdoor equipment of the ZPW-2000A type shifted-frequency track circuit at the present stage, designed the overall structure of the outdoor equipment fault warning system of the shifted-frequency track circuit, built a Simulink-based simulation platform of the ZPW-2000A type shifted-frequency track circuit, and carried out the Simulink simulation of the track circuit, and got the simulation waveforms of electrical parameters of outdoor equipment are obtained. At the same time, a set of real-time outdoor equipment fault monitoring system based on STM32 embedded system is established to complete the real-time monitoring and early warning of the outdoor equipment of the track circuits which are far away from the signalling area [15].

In 2021, Jiao Lu et al. carried out a research on the track circuit fault diagnosis method based on the neural network ZPW-2000R, which can quickly locate the fault location with a locating accuracy of up to 100 % even without the outdoor monitoring data when the method is used for track circuit fault diagnosis. When identifying 21 fault types, the fault diagnosis accuracy can still reach more than 90 % [16].

In 2022, Hao Bin et al. constructed a simulation model of ZPW-2000 multi-segment track circuit, simulating and analysing the sending and receiving process of frequency-shifted signals in continuous multi-segment track circuit when the track circuit is in the state of adjustment and splitting, and the change characteristics of the frequency-shifted signals in the transmission process obtained by the simulation are consistent with the actual signals, which verifies the validity and accuracy of the simulation model. The model can also simulate and analyse the change characteristics of the frequency-shifted signals in adjacent sections and their influence on the electrical isolation of the tuning area when the tuning unit has typical field faults such as lead wire detachment, capacitor failure and rail breakage, and the type and location of the fault can be inferred through the abnormal change of the signals [17].

In 2022, Bin Zhao et al. proposed to solve the problem that the transient response of the ZPW-2000A track circuit could not be calculated directly in the time domain by combining the modified nodal admittance method (MNA) with the Q-D method to analyse the transient response of the ZPW-2000A track circuit. In order to further verify the correctness of the proposed theory for analysing the transient response of the ZPW-2000A rail circuit, a hybrid model of the rail circuit is built in SIMULINK, and the simulation results are shown in Fig. 1. And the change rule of rail surface voltage affected by frequency, transmission distance and ballast resistance is further analysed [18].

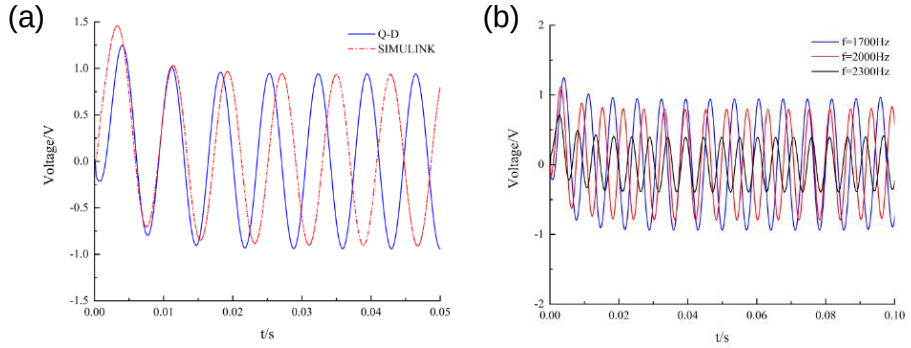

Figure 1. Transient response analysis of ZPW-2000A rail circuit (a) Simulink results and Q-D algorithm calculations; (b) transient response of rail surface voltage at different frequencies

From the current study, it can be seen that the complexity of electrified section signal circuits, including a large number of components and interconnections, increases the difficulty of design and maintenance; at the same time, traditional simulation methods cannot provide observation and analysis of the real-time electrical characteristics of the circuit components, and it is difficult to accurately simulate the dynamic behaviour of the signal circuits in electrified sections.

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3. Methods

3.1. Research Methods

Establishment of component model library: According to the names and characteristics of different components, use Simulink or Pspice to carry out digital simulation or circuit simulation, and package them independently to construct a component library suitable for ZPW-2000 electrochemical track circuits.

Realise a simulation system that can simulate the logic of relay circuits of signalling equipment, so as to realise the dynamic display of circuit states.

Develop a MATLAB Simulink model that can be used for the simulation of railway signalling circuits: connect the modules according to the circuit schematic diagram, add some logic judgement units, and use the topology to control the execution sequence of each module.

Observe and record the electrical characteristics of each component on the circuit in real time, and set up a realistic data input module to compare the real-time observation data with the realistic data to determine the possible locations of faults: Improve the efficiency of the design and maintenance of railway signalling systems.

3.2. Construction of basic component library and example analysis

There are two main ways of modelling components: the parametric modelling method and the circuit modelling method. The former is suitable for components with relatively complete functional models; the latter is suitable for constructing relatively complex and novel components or functional circuits that need to derive functional models.

Examples of the components needed for this study are analysed:

Components requiring parametric modelling method:

Transmitter ZPW.F:

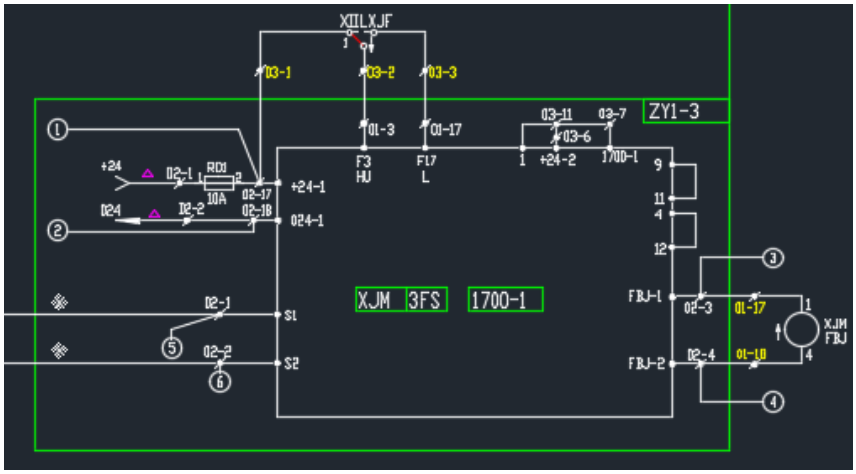

Figure 2. Transmitter electrocoderised circuit diagram

For a component where the functionality of each terminal is complete but the specific circuit diagram is unknown, consider modelling it through its principle defining feature constraints, relationships and dependencies.

Components requiring the circuit modelling method:

Adjustment Resistor Assembly ZDTR-T containing 15 RX20-T-100-1K resistors.

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Terminal to be used	1、2	2、3	1、3	3、4	3、5	2、4	1、4	1、5	2、6	1、6
Number of resistors Ω	100	200	300	400	500	600	700	800	900	1000

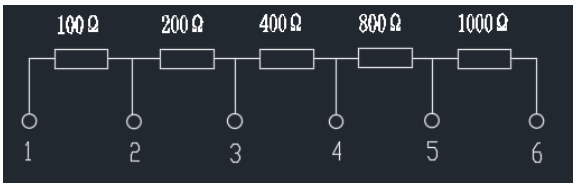

Figure 3. Adjustment resistor combination circuit diagram

3.3. Operation process and control method

A larger project is divided into a series of sub-projects, which have a logical relationship with each other; sub-projects with pre-conditions can only be carried out after the completion of their pre-projects, and sub-projects without pre-conditions can be carried out at any time. A directed graph is used to clearly reflect the relationship between them, in which the vertices represent many sub-projects, and the pointing edges indicate the relationship between the vertices, which is called Activity On Vertex network (AOV network). The premise of topological ordering is a directed acyclic graph, otherwise the ordering will be stuck in an endless loop. Therefore, the process of arranging all the vertices, i.e., sub-projects, of an AOV net that does not have loops in such a way that each vertex conforms to the backward and forward relationships is called topological sorting.

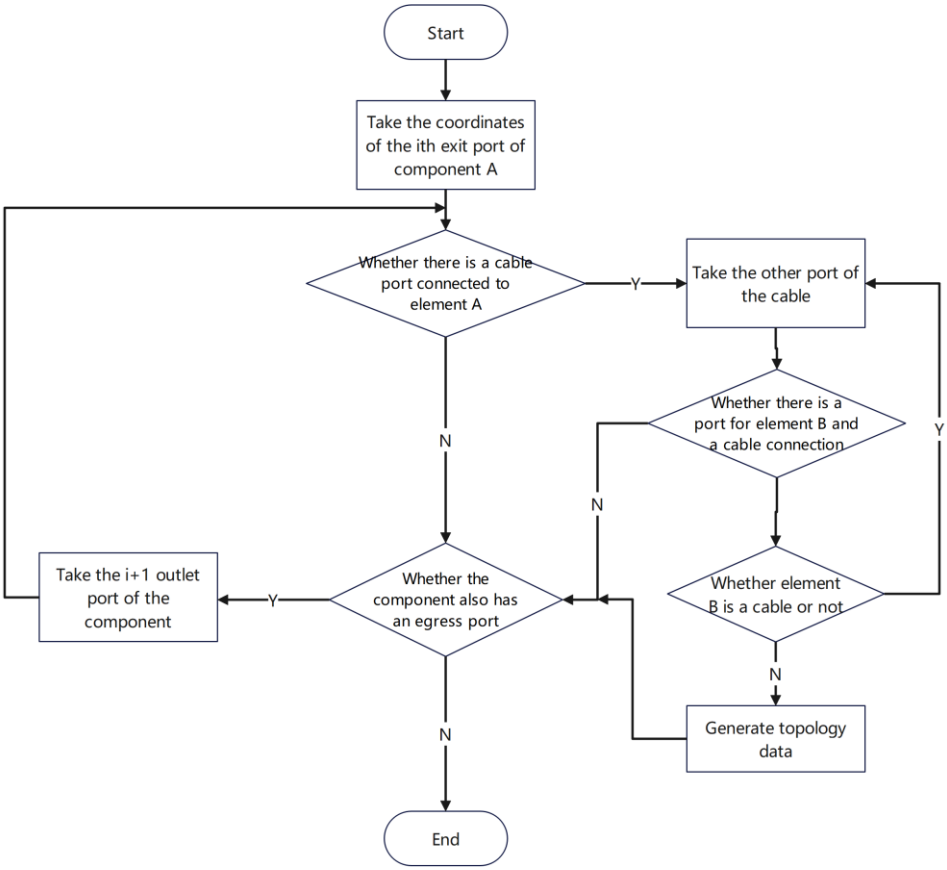

Figure 4. Execution flowchart

The topological sorting algorithm constitutes elements including vertices (i.e., sub-projects) as well as the access degree of the vertices, i.e., the number of vertices in the vertex preorder and postorder, and

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there are two most commonly used methods for its implementation: breadth-first traversal (BFS, Breadth First Search) algorithm and depth-first traversal (DFS, Depth First Search) algorithm.

The topological sorting algorithm is implemented in Matlab, which requires some modifications and improvements to the algorithm, mainly two points: firstly, it is necessary to choose a suitable data structure in Matlab to store the information of the directed acyclic graph, and secondly, the implementation of the algorithm needs to be modified and improved according to the storage structure in order to improve the performance of the algorithm.

3.4. Modelling approach

Simulink is a visual simulation tool in MATLAB. Simulink is a modular graph environment for multi-domain simulation as well as model-based design. It supports system design, simulation, automatic code generation, and continuous testing and verification of embedded systems. SPICE (Simulation Program with Integrated Circuit Emphasis) software for analogue circuit simulation was developed in 1972 by the University of California, Berkeley's computer-aided design group using the FORTR AN language, and is mainly used for computer-aided design of large-scale integrated circuits. PSpice's speciality is the simulation of circuit topology, Simulink's speciality is the simulation of the control system, through the two joint simulation can complement each other.

Specific implementation steps:

For the CAD form of coded circuit diagrams, first of all, the overall circuit diagram is split into a sub-projects, in Simulink for their respective packaging and simulation, which need to simulate the circuit simulation of the part of the use of pspice to draw and simulate, and then use the SLPS interface will be imported into the simulink. pspice SLPS Interface is an interface tool provided by Mathworks that links PSpice to the MATLAB modelling tool and also to the Simulink system simulator. Finally, the topology is used to arrange all the vertices, i.e., sub-projects, of the AOV net without loopbacks in an order where each vertex conforms to the before-and-after relationship. The order of execution between the sub-projects is ensured.

4. Conclusion

ZPW-2000 uninsulated track circuit is one of the important equipments of railway signalling system, which has the functions of detecting train occupancy, integrity checking and transmitting travelling information to the train, etc. It is widely used in railway engineering.ZPW-2000 track circuit has the characteristics of complex structure, and the operation in harsh environment is prone to failure and affect the safety and transport efficiency. Track circuit simulation design is an important part of the implementation of digital twin technology for rail transport, and is also an important means of fault analysis, which can provide technical support for the reliable operation of trains. Based on the simulation of the electrocoderised track circuit, simulating the circuit situation when various trains enter, the current voltage and waveform of each component can be detected, and a series of circuits can be tested, which greatly reduces the time spent on modifying circuit prototypes or building circuit prototypes. Observing the values of each component in the simulation environment and comparing them in real time with the values detected in reality, accurate and complex circuit analysis is carried out, which facilitates the maintenance of the entire track circuit.

5. Discussion

The purpose of modelling rail circuits is to analyse the causes of faults, to validate the correctness of the simulated fault data, and to provide corresponding rail circuit data for the intelligent diagnostic model, which can support the research of big data analysis and artificial intelligence, and realise the establishment of a digital twin model of the rail transit system. Although, the project has collected the relevant data of rail circuit equipment, however, there is a large uncertainty in the occurrence of rail circuit faults, the time, location, and specific equipment components are random, it is difficult to find out the data recorded when the fault occurs from the system, and it has certain limitations.

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