Invited Paper

Modelling and simulation of electric railway traction, track signalling and power systems

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Abstract

Research at the University of Bath on modelling and simulation of electric traction systems has led to the derivation of an accurate electric circuit model of rail track and traction line. This paper describes the application of that model for the simulation of systems in which the track is the transmission medium. The studies include track signalling system operation, DC and AC traction power line voltage regulation and the prediction of electromagnetic interference between traction power, drives and signalling systems.

1 Introduction

Simulation of railway traction systems is necessary to optimise and verify designs in the planning stage, to assist the adjustment of systems during installation and to adapt and further develop existing designs for new situations. To simulate traction power, signalling and propulsion subsystems as electrical circuits, appropriate track and traction line models are required. Work at the University of Bath has resulted in the derivation of accurate, frequency-dependent track models, which this paper will review in connection with the simulation of traction power and track signalling systems.

A specific difficulty in setting up an electric circuit model of a traction system is in defining the equivalent electric component values of the track and traction line impedance and admittance. The track is laid over and is in contact with the weakly conducting earth, and its impedance is frequency and current dependent from the skin effect in the rails and ground. Moreover, its admittance is highly environmentally dependent. Most prior work in track simulation has relied on simplifications to obtain the track transfer function for specific applications which have been concerned mainly with single-frequency excitation using equivalent single-phase transmission line parameters. This paper describes the application of a comprehensive track simulation model, the development of which has been reviewed in reference [1], to the solution of problems in railway traction and signalling. The applications considered include track signalling operation, power line voltage regulation in both DC and AC
systems including the modelling of rail voltages, and the prediction of electromagnetic interference between traction power, drives and track signalling systems.

2 Coupled track transmission line model

The complete rail track and traction line system consists of the running rails, power rails or catenaries, auxiliary conductors and signalling cables laid parallel to the track. A suitable electrical circuit representation must be able to model the current and voltage distribution in all these conductors. As the track is a distributed electrical circuit, it may be modelled as an earth-return transmission line with distributed self and mutual impedance and admittance (Fig. 1).

In the model, the distance-dependent phase voltage and line current vectors are related by the system impedance and admittance matrices through the coupled transmission line equations. The mutual impedances and self admittances are referred to remote ground which is physically inaccessible.

The data necessary to utilise the track model is both frequency and current dependent in the case of impedance, and frequency dependent in the case of admittance, because of the variation of the conductivity, permeability and permittivity of the various track components. Work at the University of Bath has led to the derivation of values for this data by practical measurement, finite-element modelling (FEM) and theoretical modelling. An example of a data set is given in Fig. 2, which was obtained by FEM using a ground conductivity of 0.077 S/m.

3 Track circuit modelling

A railway track circuit is a failsafe detector used to locate the position of vehicles within a section of track (Fig. 3). A signal transmitter is connected across the rails at one end of the section with a detector at the other end. The receiver de-energises when short circuited by the leading train axle, indicating the presence of a train. If the train is approaching the transmitter, transmission of data for cab signalling and ATC is also possible.

In the design of track circuits, it is necessary to choose the operating
Figure 2: Phase impedance and admittance of single track with catenary
(1: catenary; 2, 3: running rails)

Figure 3: Vehicle detection and data transmission using track circuits

length, carrier & modulation frequencies and the topology of the termination area for target resolution, train shunt sensitivity and broken rail detection performances, given specific variations in track impedance and admittance. Simulation based on a differential-mode transmission line circuit model of the track can be used for the initial setting up and adjustment of track circuits, but the full coupled-line track model is necessary for investigations of asymmetric conditions including broken rail effects and electromagnetic interference.

Research at the University of Bath has considered many problems
concerned with track circuits, such as the frequency characteristics of termination areas [2], use of circuit simulation packages for design of audio track circuits [3], and the simulation of parametric effects in the tuned area using a coupled-line track model [4, 5]. The value of the Bath track model for track circuit simulation relates to the structure of the model in separating the effects of the self and mutual impedances and admittances as well as defining their frequency dependency. Present work is aimed at quantifying the effects of current dependency in the track self impedance which is due to saturation and hysteresis effects in the rail iron.

4 Traction power system modelling

4.1 DC traction power system simulation
DC traction power supply is the most advantageous for metrorail and urban transportation systems. The standard voltages are 750 V DC third rail and 1.5 kV DC overhead. 3 kV DC was formerly used as the standard main line system in the 1920s and 1930s, but is used now only for existing system extensions.

The problems in the design of DC traction power systems solved by simulation are to select the substation spacing and rating for the specified train service to satisfy constraints on permissible catenary or third rail voltage, to maintain rail voltage and earth current below specified levels and to optimise energy flow including power from regenerating vehicles. Whereas static “freeze-frame” pictures can identify particular effects such as worst-case power flow, dynamic simulation, modelling the motion of many trains, can be used to evaluate average conditions over a complete traffic cycle. Simulation in the millisecond timescale is necessary to determine the effects of electromagnetic interference from power-electronic controlled substations and traction drives on sensitive signalling and communications circuits.
The DC traction system simulation model shown in Fig. 4 is of a double-track light rail system with a track branch. Research at the University of Bath has developed effective solution algorithms to invert the nodal conductance matrix for this circuit [6, 7]. The simulation objectives are to determine the train & rail voltage and the rectifier substation feeding conditions to satisfy the design constraints. The value of the Bath track model in this context is that the determined rail voltage is critically dependent on the value of the track conductance, which has been the subject of extensive investigations via the ground conductivity [1]. Simulation results have been obtained using design data pertinent to the new generation of street-running light rail systems manufactured by companies in Europe, North America and Japan.

Further work on DC traction power supply systems at Bath includes the modelling of traction fault currents, as described in references [8, 9].

4.2 AC traction power system simulation
AC traction power supply is used on heavy freight and high speed railways. The standard system is 25 kV at 50/60 Hz although previously established low frequency systems at 16.7 or 25 Hz are in use in Central Europe and North America. Simulation is necessary to assist system design including achievement of the substation rating and spacing necessary to satisfy voltage regulation constraints, and determination of the effects of catenary high-voltage faults on step and touch voltages on the rails and other track components.

There are several implementations of AC electrification which include the use of booster transformers or autotransformers. Fig. 5 shows a model of an autotransformer electrified railway. 50 kV is applied between the catenary and return feeder to allow increased substation spacing, greater transmission efficiency and reduced interference to communications systems. Simulation models of this system have been implemented at Bath in order to predict voltage regulation effects [10, 11]. The Bath track model enables the line self impedances and inter-line mutual impedances at the power frequency to be evaluated for use as model data, in addition to harmonic impedances for the determination of higher harmonic resonant conditions in the overhead line.

![Figure 5: AC traction autotransformer-fed power system simulation model](image-url)
5 Modelling interference between power and signalling systems

Electromagnetic interference from traction power systems and power-electronic controlled traction drives appears as noise and can cause in-band interference in the signalling and communications systems. Reference [12], for example, describes some possible interactions between 3 kV DC and 25 kV, 50 Hz traction systems. To produce realistic models of interference, the inclusion of frequency-dependent track data within the simulation models is required. At Bath, research in interference simulation has taken two directions, corresponding to finite-element modelling (FEM) and circuit simulation.

5.1 Crosstalk between parallel tracks
Crosstalk occurs when stray electromagnetic fields from one circuit pass through the conductors of an adjacent circuit. The evaluation of crosstalk effects is difficult in traction systems due to nonlinearity in the track component material properties. Although research using the FEM at Bath has been directed mainly at evaluating values for the track impedances and admittances from their known material properties and the track structure, the FEM has also been used to evaluate crosstalk. Fig. 6 gives an example result from one of the Bath models [13]. Currents flowing in the third rail traction power circuit on the right track generate fields which induce crosstalk voltages in the running rails of the left track, which may include the receiver of a track signalling circuit operating at a frequency corresponding to harmonics produced by the transmitter track. The FEM model will produce values for the inter-track coupling and hence help assess the likelihood of crosstalk.

![Figure 6: Field plot of crosstalk to adjacent track from third rail traction current](image)

5.2 Modal domain modelling
Circuit simulation using commercial packages designed for power systems represent transmission lines using a modal domain transformation [14]. This technique has been applied at Bath to model single-frequency interference from chopper traction [15]. Further work has led to a technique for evaluation of the modal characteristics of rail track [16].

To illustrate the problems of using technique, Fig. 7 shows the modal impedance and admittance for overhead catenary electrified track obtained using the phase data of Fig. 2. To apply the method in harmonic studies, models which are accurate over the entire frequency range of interest are required. This is the subject of current work at Bath.
5.3 Harmonic interference models in the time domain
An alternative approach to model the frequency-dependent behaviour of rail track is to set up component-based models of the phase impedance and admittance that can be used directly in time-domain circuit simulation. This current work is being carried out in association with Università degli Studi di Genova.

6 Concluding remarks
The simulation of railway traction systems is a systems task which must deal with traction power transmission, track signalling and electromagnetic interference. The key to accurate modelling is the representation of the rail track itself, for which sophisticated models have been produced at Bath. Current work will further develop the models to include current dependent effects in track impedance and frequency dependent modal and time domain track models.

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8 References
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