Development of traction system models for real-time simulation

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Abstract

Many factors are affecting the broader adoption of electrified railway systems. One such factor is the concern for global climate change, of which the exhaustive fumes of internal combustion engines is a critical contributing factor. Thus, the pressure is growing in the railway applications that the usage of internal combustion engines should be eliminated eventually. Meanwhile, a substantial portion of the applications is already in use, mostly underground railways such as urban metros. Furthermore, the speed of urbanization spurs the faster spread of the electrified mass transportation systems.

Consequently, the need for testing and evaluation in an electric traction system has been growing. In this paper, one such approach, real-time simulation and its application towards testing and evaluation of electric traction systems, is presented. Its application in a congested marshaling yard circumstance is given to probe the usefulness of the proposed concept.

Keywords- Electrified railway system; tractive force source; real-time simulation

1 INTRODUCTION

Electrification of railway systems has been making progress since the first locomotive with electric motors run on a railway track more than 100 years ago. Such progress is not exclusively observed in urban settings such as subway systems. The ever-increasing desire for the speed of travel, both for passengers and freights, is pushing the need for the electrification to a higher level. One such example is the linear Chuo Shinkansen in Japan[1]. The target speed of the project is to be around 800km/h, eventually. Such a high speed is in the same range as the commercial airliners. However, the ability of the transportation in the same amount of time (e.g., per hour) and the level of comfort (e.g., accessibility to the metro area) is far superior to the service by airliners.

Meanwhile, the consciousness of the environment in the transportation sector is putting more weight on railway transportation. The subsequent result of such unfolding of the circumstances is further electrification of the system. This paper presents a way to address the need for the testing and evaluation of the electrified railway system. The focus of the proposed idea is regarding the real-time modeling and simulation of traction systems. The electrified traction systems are mostly run by the combination of a motor drive system and a traction motor. As a starting point, this paper presents a real-time simulation model of such a combination in a detailed modeling level. Then, the advantage and drawbacks of the approach are discussed. Then, an average model approach is introduced and explained. One advantage coming from the approach is the necessary amount of computational burden. It is substantially smaller than the first approach; thus, the approach allows more comprehensive coverage of the railway system within a given amount of dedicated computational hardware for real-time simulation. The usefulness of the approach is presented by a realistic real-time simulation case, where a congested marshaling yard is modeled and simulated with a large number of trains (29 in total) running in real-time. The paper finishes with a set of concluding remarks.

2 TRACTION SYSTEM MODELING AND SIMULATION

Most of the modern electrified traction systems are utilizing the development of power electronics systems. In a typical AC fed electrified railway system application, a traction car, either one of the motor cars in an EMU or an electric locomotive, receives the necessary electricity from an overhead single-phase line. Then, the incoming electricity goes through a main on-board transformer, and then it goes through a 4-Q converter. The 4-Q converter usually feeds an intermediary DC stage in the traction system. Finally, the combination of a 3-phase induction machine and a drive system would generate the necessary tractive force following the given order. Or if the order is in the reverse direction, i.e., braking, the combination can extract the kinetic energy of the train and send it back to the AC feeder. Such a mode of operation is usually called regenerative braking. Mode sophisticated control would be desired in real applications once such control of the traction control is adhesion control, which would regulate the slip and slide of the traction system wheels on a rail.

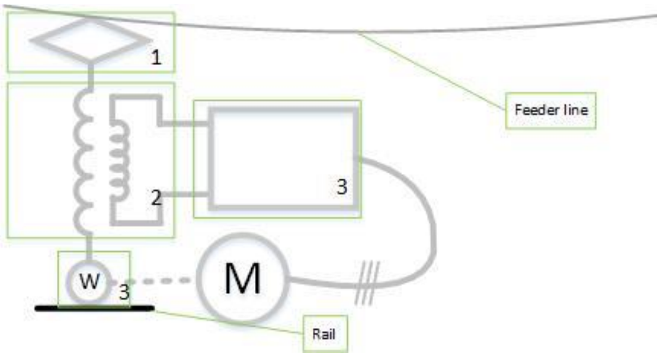

Figure 1 An electric traction system configuration

Figure 1 shows the structure of a traction system. The box labeled as ‘1’ in Figure 1 shows the pantograph. It connects the electrical system in the motor car to the feeder line, enabling the electrical system either to exert the tractive effort or to return the returning energy from braking to the AC feeder system. The box labeled as ‘2’ in Figure 1 shows the main transformer of the motor car. It brings down the feeder AC voltage to a lower voltage level suitable for the power conversion system on board. The box labelled as ‘3’ in Figure 1 presents the on-board power conversion system. It includes the AC-DC power conversion system, usually referred to as a 4-Q converter system and a motor drive system. The drive system takes in the DC electricity produced by the 4-Q converter system, then uses it to generate AC electricity with the necessary frequency and magnitude. Then, the circle with letter ‘M’ in Figure 1 is a representation of a traction motor. Its role is to turn the electrical energy into mechanical energy. When the train decelerates, the motor begins to act as a generator, transforming the kinetic energy stored in the moving mass of the train into electrical energy (Regenerative braking).

Figure 2 shows a detailed simulation model of the primary electrical circuit. The model was made using a commercially available real-time digital simulator[2]. The model describes a configuration so-called as ‘1C4M’, meaning that a single motor drive runs a set of 4 induction motors.

The detailed implementation includes a FOC (Field Oriented Control) based motor control modeling. The modeling is from an indirect vector control method of induction motors[3]. The critical element of the algorithm is the estimation of the slip speed. The following equation, (1), shows how the slip speed is calculated, assuming that the control is in the good grip of the q-axis flux control, making it effectively zero.

$$\varpi_s - \varpi_r = \varpi_{sl} = -\frac{R_r \cdot i_{qr}^e}{\lambda_{dr}^e} \tag{1}$$

In equation (1), the rotor current, ‘ i_{qr}^e ,’ is difficult to measure in a real system. Therefore, the rotor current component can be replaced with stator current component, coming from the following equation, (2).

$$\lambda_{qr}^e = 0 = L_r i_{qr}^e + L_m i_{qs}^e \tag{2}$$

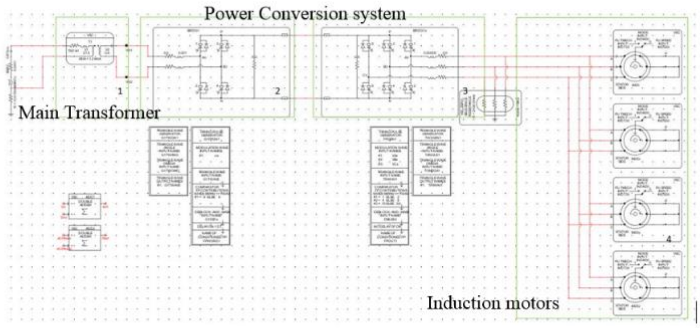

Figure 2 A detailed simulation model of the main electrical circuit

Such configuration, described in Figure 2, became popular because it fits with a popular physical configuration of a motor car. A motor car, especially in a metro train design, is usually equipped with two bogies. Each bogie can house two propulsion motors inside. Then, the total number of motors in the motor car becomes 4, two per bogie, and two bogies per motor car. A single set of power conversion systems is placed underneath the floor of the car. The space available for the installation is between the underneath of the floor and the rail; thus, it restricts the size of the equipment to be placed there. However, the modern drive system and transformer design are compact enough to make it possible to be placed in a tight space. The equipment set underneath the floor includes the main transformer, a 4-Q converter, and the motor drive system, etc. One purpose of the design is to make a motor car a self-sufficient system. In other words, the motor car can be standalone with no other function from another car in the same train set. Such a design offers a higher level of flexibility in configuring a train set.

While the advantage of this detailed approach presented in Figure 2 is the higher fidelity in the simulation result, the drawback is the amount of calculation load. In order to keep up with the strict real-time requirement, the calculation machinery should complete the calculation of the real-time simulation in a fixed size of time step with no exception. As a result, a substantial amount of computational hardware becomes necessary for a representation of a small simulation scope. Therefore, when the scope of simulation becomes extended in terms of the number of train sets or the extent of the railway system or both, more generalized representation of the system becomes necessary.

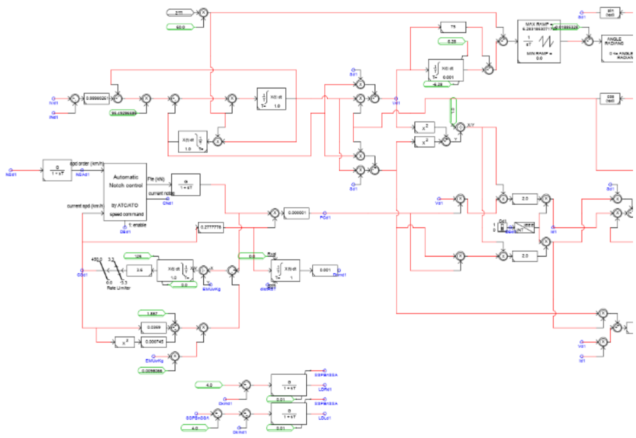

Figure 3 A generalized simulation model of the main circuit

Figure 3 shows a generalized simulation model of the main electrical circuit. The model captures the behavior of the system in terms of lower bandwidth, i.e., slower dynamics. While the high-speed dynamics such as harmonics characteristics cannot be produced from the simulation model, the computational burden becomes significantly reduced, allowing more train models can be fit into a given amount of computational hardware for the necessary real-time simulation. The generalization becomes mandatory if the required simulation is a congested marshaling yard in a railway system. Figure 4 shows a congested marshaling yard simulation case. The simulation case includes 29 train sets. Each train set is modeled and simulated in the way depicted in Figure 3. The AC feeder system of the simulation case is composed of a set of Scott transformer, which describes the feeding substation. Then, multiple sets of Autotransformers (AT) are included in the case, attempting to capture the same features of a real AC railway system. Then, the line models are based on a variable-length PI section model, which enables the modeling and simulation of moving trains. The speed of each train is controlled by a central commanding post, which would be equivalent to an automatic train operation (ATO) system in a real system. The commanding post receives the speed command of each train through a communication interface. Therefore, if necessary, a real ATO can be interfaced with the real-time simulation. Such interconnection would allow testing and evaluation of various operating scenarios in real-time without causing any real or unexpected disruption in a real system.

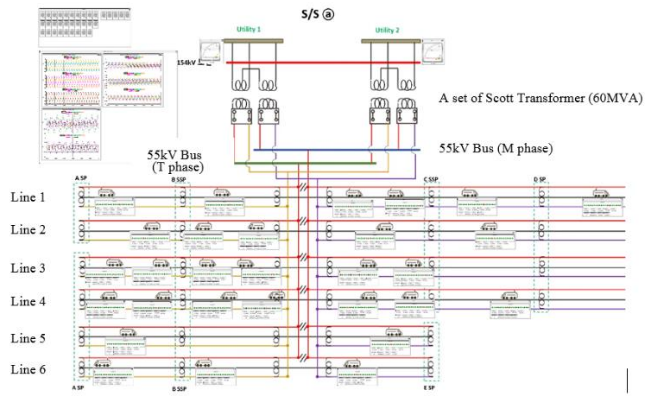

Figure 4 A congested marshaling yard

3 TEST RESULT

A train operation timetable was implemented as a simple text file. The schedule of each train from the time table was read and transmitted from a MATLAB[4] environment. The following figure, Figure 5, presents the simple time table in a text file format used in the simulation.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	0	0	70
115	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	0	0	70	70
120	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	0	0	70	70	70
125	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	0	70	70	70	70
130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	70	70	70	70
135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	70	70	60
140	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	70	70	60	50
145	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	70	70	60	50	40
150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	70	60	50	40	30
155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	60	50	40	30	20
160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	50	40	30	20	10
165	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	40	30	20	10	0
170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30	20	10	0	0
175	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	10	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0

Figure 5 A time table text file

Each column represents the sequence of the speed order to be given to a train in the simulation case. The top line shows the train ID, while the leftmost column shows the sequence of time. Then, the information is sent, carrying the necessary data to the simulation model, running in real-time through TCP socket communication. Such a configuration attempts to capture a realistic railway system operating system. Figure 6 shows a simple simulation result. The simulation presents the speed order, current speed, force, notch position, and the position of each train. The simulation case runs in strict real-time. Such realtimeness of the simulation covered the entire range of the real-time requirement, from the low end at the traction system representation to the high level of the time table and its subsequent planned train operation time table (i.e., diagram) evaluation.

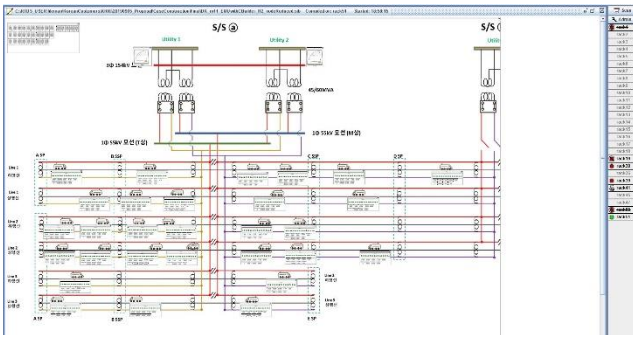

Figure 6 Simulation running in real-time

5 CONCLUSION

Real-time modeling and simulation of an electrified railway system were introduced and explained. The necessary models for the railway system were built and incorporated into the simulation. The holistic view provided by the coverage from the real-time simulation would enable the more accurate representation of the railway system.

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