Multi-conductor Train Simulations for Electrification Systems

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Abstract— Railway Operators and Infrastructure Owners are required to design the railway to specific international and national technical and safety performance standards. These standards and codes of practice provide the basis for company ‘Codes of Practice’ which detail the design methodology, application and system installation. Atkins and the University of Birmingham have developed the Multi Train Simulator (MTS) to model both A.C./D.C. railway electrification infrastructures. This paper describes the development of A.C. railway electrification infrastructure based on multi-conductor model for MTS. The modelling of A.C. railway networks covers all types of A.C. feeding arrangements, including rail return system, classic booster transformer system and autotransformer system. The modelling of multi-conductors in A.C. power network separately instead of lumping together enables more accurate calculations of induced voltage, EMC analysis, and positive & negative energy consumptions and losses calculation, etc.

Keywords— Electrification, Train Simulator, Design, Multi-conductor model.

I. INTRODUCTION

Electrified railways have many advantages, such as lower capital and maintenance cost of locomotives, reduced environmental pollution, and capacity. A.C. electrification systems however need to additionally address EMC, induced voltage and power system losses [3,4,5,6,7 & 8]. Multi train simulators for electrified railways are now required to additionally focus on these issues. However, train simulators Vision Oslo, and others, often fail in addressing such problems. Therefore, it is now necessary to develop simulators to be more accurate in modelling the behaviour of the electrical traction power network against service schedules. The accurate model for the MTS has been developed on the basis of a multi-conductor model which allows modelling the multi-conductors in an A.C. power network, to be modelled separately rather than the traditional method where are lumped together.

Atkins and the University of Birmingham have developed the Multi Train Simulator (MTS) to model both A.C./D.C. railway electrification infrastructures. This Knowledge Transfer Partnership (KTP) project has looked at innovative ways that will address the requirements to comply with electrical safety, EMC standards and the need to ensure that new designs take into account carbon critical design.

During the period of the KTP, the McNaulty Report (May 2011) identified ‘the efficiency gap’. The study concluded that ‘cost savings, when added to the savings planned from Network Rail in Control Periods 4&5 needs to have the potential to close the 30% efficiency gap by 2018/19, with further savings beyond those dates’. To this end the MTS has been designed to be able to accurately model the energy usage and loss in the electrification system.

In this paper, various A.C. feeding arrangements are described and modelled based on a multi-conductor model. This paper introduces object oriented design in terms of modelling requirements. This methodology enables various complex railway electrification infrastructure and trains to be easily constructed and modelled.

II. A.C. TRACTION FEEDING ARRANGEMENT

A.C. railway electrification requires a connection to the 3-phases of the National Grid. The length of feeding section may vary depending on the types of feeding arrangement applied. There are three types of A.C. traction feeding arrangements applied in the UK: classic rail-return system, classic booster transformer (BT) system, and auto-transformer (AT) system. This multi train simulator is able to model all these systems or hybrid systems where there are interfaces.

A. Classic System Configuration

Classic Supply Grid Connection: The supply points (132kV/25kV) for the railway electrification system are normally provided at intervals of between 40-60 km. The grid at 132kV is transformed to 25kV. Feeder station, intermediate track sectioning cabin and mid-point track sectioning cabin are required to control the distribution of the supply to the overhead line equipment.

Classic Rail-Return System: A rail return system is a simple 25kV feeding system with feeding currents travelling through overhead lines (OHL) and returning directly through contacted running rails, and return conductors (RC) if installed. Typically, rails are bonded every 300 metres, and tracks and RCs are bonded every 600 metres [3].

Classic Booster Transformer system: The rail return system will allow 40% of the traction current to return via earth this is liable to cause an excessive amount of electromagnetic interference in adjacent communications circuits. The return current is therefore constrained to flow in the return conductor by booster transformers (current transformers) which have their primary connected in series with the 25 kV line and their secondary connected in series with the return conductors and the rail return. These booster transformers are positioned at approximately 3.2 km intervals, one booster is required for each 25 kV overhead track feed. This arrangement serves to reduce the level of interference in telecommunication and communication copper line side circuits.
B. AT System Configuration

Autotransformer distribution is increasingly used for A.C. railway electrification to take advantage of 50 kV power transmission while being able to utilise standard 25 kV traction equipment. The Auto Transformer system is based on a double wound transformer with one primary 400kV and two 25kV secondary windings connected in series; one connected to the contact wire and the other to the auxiliary feeder wire. The train is supplied between the contact wire (+25kV) and rail. Auto transformers (25kV 0 -25kV) spaced at (5 or 10km) are used to transform 25kV current to 50kV. The current in the traction unit (25kV) is therefore twice the current in the 50kV distribution.

The Classic Booster Transformer system is different from the Autotransformer arrangements in that the booster transformer is only energised when a train is in section. The autotransformer is energised whenever the supply is available and is independent of train position. In practice most of the train current is supplied from the two adjacent autotransformers.

The main advantage of the autotransformer system over the booster transformer system is that the voltage drop is less meaning that the auto-transformer is capable of supplying more power with less system losses, providing there is a train in section. Auto Transformers are energised permanently and therefore the losses increase when there is a reduced train time table.

III. A.C. ELECTRIFIED RAILWAY NETWORK MODELLING

Multi-conductor modelling of 25kV electrification includes the overhead line conductors, the return current and earth system. The modelling uses self-impedances (internal and external) and mutual inductance between all conductors to determine the current flowing in each ‘branch’ conductor and the voltage on each ‘node’ within the network.

The 25kV supply transformer is set to limit the no load voltage and the short circuit fault level to 6 or 12kA. When the trains are in operation the current that flows in the overhead and return current system would be dependant on the train service frequency, train electrical demand, power factor and the impedance of the electrification system.

A. Modelling the conductors and Carson Pollaczek Equations

The characteristic value of the circuit impedance/km has been modelled using the known equations for separation of conductors and the Carson Pollaczek formulae as detailed in the ITUI Vol II [5, 6]. The impedance matrix is assembled by including the self and mutual values for the discrete lengths for each section of the electrification overhead line equipment and return conductor system.

The self impedance increases with an increase in earth resistivity or a decrease in the conductor radius. The resistance component is independent of the resistivity of the earth.

B. Modelling the Earthing and Bonding

The effects of the earth return system are included in this simulator as the current can choose to flow at a depth determined by the resistivity of the ground.

On rail return systems, the two running rails for double rail return are designated as the 'traction current return rails'. The traction current return rails are bonded together and to the adjacent overhead line structures. A track-to-track bond connects both tracks at set intervals [3], to form an earthed return current system that is less than 1 ohm.

This simulator has been designed with the inclusion of aerial earth wires, buried earth wires, return conductors, return current screening conductors, mutual screening conductors, rail bonds and track to track bonding. The number of rail cross bonds can be varied to suit the specific arrangements of earthing and bonding.

C. Induction Effects

The induction effect is related to the frequency and magnitude of the disturbing current flowing in the overhead line, earth/return conductors and the running rails. This will normally be a maximum when the inducing currents are flowing in the catenary conductors nearest to the lineside cable, with parallel feeding of the overhead line.

IV. OBJECT ORIENTATED DESIGN A.C. RAILWAY MODELLING DESIGN

The A.C. railway has been modelled and developed into standalone software via object oriented design. In the object oriented design, the whole A.C. electrified railway has been treated as one system which is able to be broken down into series of subsystems and components as shown in Figure 1, in terms of the concept of object oriented design. Trains moving on the infrastructure are dynamic components in the system.

The A.C. electrified railway infrastructure is a complex system the supply and distribution requires the following electrical components:

- Grid supply transformers can be further broken down into conductors and voltage source:
  - Classic 132kV/25kV Supply Transformer;
  - Double Wound Supply Transformer:
    - Symmetric feeding 400kV/50kV;
    - Asymmetric feeding.
  - Earth mats a resistive conductors of which one side is always connected to earth;
  - Neutral earthing reactors.

The 25kV distribution systems include the following components:

- A.C. tracks: consisting of AC Links to represent current section of track layout;
- A.C. Links: consisting of connectors and track blocks, and each AC link to represent a link between two points (connectors). Each track block is sliced into numbers of track segments by conductor bonding, such as rail-to-rail bond, cross bond. Each track segment can be further broken down into conductors e.g. for modelling OHL, return conductors, earth wires and rail and rail leakages (a resistive conductor of which one side is always connected to earth).
- Booster Transformers (BTs): are modelled as a mutually
coupled conductors;
- Auto Transformers (ATs): are modelled as mutually coupled conductors;

After this top-down approach, the whole system is broken down into subsystems and components that consist of conductors and voltage sources, as it can also be treated as a A.C. circuit for each moment of trains running in the network. The A.C. circuit is finally turned into a single matrix equation for circuit analysis.

V. FUNDAMENTAL MODELLING ELEMENTS

As mentioned earlier, the conductor and voltage source become the fundamental elements, which need to be modelled first and then used to compose components and then to subsystems and finally to the overall system in the hierarchy.

A. Conductor

A conductor in A.C. circuit is modelled as an impedance element with two terminals and a complex number to represent its resistance and reactance, as shown below.

\[ Y_i \cdot V_i^L - V_i^R - I_i = 0 \]  

(1)

The only constraint of this conductor model is the self admittance \( Y_i \), and its variables are the terminal voltages \( V_i^L, V_i^R \) and the current \( I_i \) through the conductor \( i \).

If there are \( m \) conductors in parallel in an A.C. circuit, the mutual coupling between conductors can be modelled as:

\[ V_i^L - V_i^R = Zd_i - \sum_{j=0}^{m} M_{i,j} \cdot I_j = 0, i,j = 1,2,3, ..., m \]  

(2)

where \( M_{i,j} \) is the mutual impedance of conductor \( i \) and \( j \); \( I_i \) and \( I_j \) are the current through the conductor \( i \) and \( j \) respectively; \( V_i^L \) and \( V_i^R \) are the terminal voltages of conductor \( i \) with self impedance \( Z_i \).

B. Voltage Source

A constant voltage source in A.C. circuit provides constant voltage with two terminals to power elements in the circuit. It can be modelled as:

\[ V_s^L - V_s^R = V_s \]  

(3)
where \( V^L \) and \( V^R \) are the terminal voltages of voltage source providing constant voltages \( V \). In this model, the current through voltage source is also a variable, which will be used in Node-Voltage method for circuit analysis.

VI. NODE-VOLTAGE METHOD

As Node-Voltage method is applicable to both planar and non-planar circuits, it is very suitable for complex A.C. circuit analysis. In this method, the sum of \( m \) branch currents joint at a node is equal to zero, which gives:

\[
\sum_{i=0}^{m} I_i = 0
\]

where \( I_i \) is a branch current joint at a node. Then, in terms of equations above, A.C. circuit can be easily turned into a single matrix equation, which is defined as:

\[
\begin{bmatrix}
Y_1 & -Y_1 & -1 \\
Y_2 & -Y_2 & -1 \\
\vdots & \vdots & \vdots \\
Y_m & -Y_m & -1 \\
1 & -1 & -Z_1 & -M_{1,2} & -1 \\
1 & 1 & -M_{2,1} & -Z_2 & \vdots \\
1 & 1 & \vdots & \vdots & \vdots \\
1 & 1 & \vdots & \vdots & \vdots \\
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
\vdots \\
V_m \\
I_1 \\
I_2 \\
\vdots \\
I_m \\
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

where \( Y_1, Y_2, ..., Y_m \) are admittances of conductors in A.C. circuit; \( M_{1,2}, M_{2,1}, \) are mutual impedances between two conductors; \( Z_1, Z_2, ..., Z_m \) are self impedances of conductors in A.C. circuit; \( V_1, V_2, ..., V_m \) are variables for voltages of nodes that circuit elements link to; \( I_1, I_2, ..., I_m \) are variables for currents through circuit elements; \( V \) is a voltage of constant voltage source.

The solution of the equation above can be realised by the LU (Low and Upper Triangular Matrix) decomposition and matrix reduction technique.

VII. OBJECT ORIENTATED DESIGN

In the object oriented design, elements in the hierarchy shown in Figure 1, such as AC track, track segment, are identified as objects, however they are named as blocks which sound more appropriate. The blocks are built in terms of sub-blocks, which are internally or externally linked together to build the whole AC electrified network.

Detailed block design for components in AC electrification systems are shown in Figure 2. Each block works out its own equations contributing to the single matrix equation as shown above. For example, equations of a power link as shown in Figure 2 will consist of equations of conductors.

The simulator is designed for supporting Classic Feeding Arrangements and Auto Transformer feeding arrangements. Figures 3,4&5 show how these blocks are connected to model these feeding arrangements.

Two track (rail return) arrangement, as shown in Figure 3, this can be simplified into series connected blocks. A Neutral Section Block (NS) is required to separate feeding sections. Powerlink (PL) blocks, including the overhead line conductors and rails, where connected in parallel are mutual coupled together. Power link blocks are needed for connecting the Neutral Section (NS) and Feeding Point (FP). Termination (T) block is used to simulate the continual section of the track.

For two track Classic Arrangement with booster
transformers and return conductors are shown in Figure 4. The booster transformers (BT) as blocks are added into the power network. In this case, Powerlink (PL) blocks are required to include return conductors.

For two AT feeding arrangement are shown in Figure 5, Auto Transformer (AT) as blocks are connected to the power network through ATC interface block, which can simulate ATs connected either in parallel or independently. Powerlink (PL) blocks, including the overhead line conductors, auto feeder wire (AFW), and rails, where connected in parallel are mutual coupled together. Powerlink Blocks and ATFP are required to connect together the Auto Transformer Grid Site and Feeder Station (DS) to the +25kV and -25kV overhead lines.

The benefits of this modelling design can be summarised as follows:

- Blocks can be composed with other blocks and or fundamental elements.
- Blocks can work out their own energy consumptions and losses in terms of composed elements.
- Blocks can manage the connections of their own composed elements.
- Existing blocks can be easily be utilised in other blocks.
- New blocks can easily be designed and introduced into an existing system.

VIII. MULTI-TRAIN SIMULATOR

This simulator had been developed in Visual C++ and C# for Windows platforms. It has a graphical user interface for input data (in development) and output display, and a combination of robust iteration processors as a core of the simulation, as shown in Figure 6.

A. Simulation data input

The simulation input data includes railway network and topography, signalling network, AC electrification network, train operational timetable, train data including train length, traction data etc. All the input data are maintained in XML files in a clear and consistent manner.

B. Iteration processors (Figure 6)

For each time interval, the demanded tractive effort of each train in the network is calculated in terms of railway network, track gradient and curvature, signalling and operational timetable. The dynamic electrification load flow calculations work out achieved tractive effort for each train based on the system voltage of the electrification network. This is achieved by the electrification network iterating to find the maximum tractive effect on the basis of location, speed, and operational mode of trains.

The train movement calculation then updates the status of trains, including location and speed that will be used for the next time interval. The overall process will be repeated until the simulation terminates.

The train movement is required to assess whether the tractive effort required is positive motoring, or negative regenerating.

C. Simulation output

The outputs of simulation are either displayed on graphical user interface or stored in Excel or XML files. The data is organised in following formats:

1) Train Electrical Operation:
   This includes run-time information of each train against timetable, which includes position, speed, voltage, train current, instantaneous power, and operating mode.

2) Substation Electrical Output:
   This includes positive and negative busbar voltages, output voltage, current, and instantaneous power.

3) Individual Electrification Conductors:
   Instantaneous currents.

4) Power System Components (transformers):
   Instantaneous currents.

5) Data for rail potentials
   The rail potential along the line for every second. This information is used to analyse rail and touch potentials against timetable.

   Post Processing Calculation

6) Induced Voltage Calculation
   The individual conductor currents are used to calculate the induced voltage to a lineside ‘victim’ cable. This is based on a specific length and position of the ‘victim’ cable. The induction calculation is based on moving the cable throughout the model length (km) for each step of the time table; the maximum induced voltage over the model length can then be calculated.

7) Electrical Energy Consumption
   The power system currents, associated with the Grid Supply Points are used to calculate the overall system energy consumption.
8) Electrical Energy Power Losses
The individual conductor currents and power system currents are used to calculate the overall energy losses of conductors, grid transformers, booster transformers and autotransformers.

9) Magnetic fields produced by the conductors.

MTS has subsequently been validated against Vision Oslo on a simulation of the West Coast Main Line between Wolverton and Rugby.

The results from both methods are compared in details at the level of branch currents, nodal voltages and mutual impedances between conductors. Since both models are earth return systems it was noted that the behaviour of rail potential was a good way of determining the accuracy of the models.

X. Project Works
MTS has been used to accurately determine the induced voltage in lineside cables. This is possible as the model determines the currents in individual conductors. Additionally MTS is being used to compare energy consumption for various electrification arrangements, including classic, autotransformer and other European operated systems.

XI. Conclusion
This paper describes the development of MTS, focusing on A.C. electrification network calculation using a multi-conductor modelling rather than a lumped analysis.

MTS has been developed into standalone software by using C++ and C#. The MTS has been designed to be able to accurately model behaviours of currents and voltages, the energy consumption and losses in the electrification system.

This enables a more accurate calculation of the system behaviour particularly induced voltage, EMC analysis, and positive & negative energy consumptions and network losses, etc.

The software developed from this work currently has been applied in practice for induced voltage calculations and energy consumption analysis.

This work has been graded as an A ‘outstanding’ KTP project by the Technology Strategy Board (TSB).

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References

Abbreviations
AC Alternating Current
AFW Auto Feeder Wire
AT Auto Transformer
ATC Auto Transformer connector
ATFP Auto Feeding Point
BT Booster Transformer
DC Direct Current
DS Direct Feeding Substation
LU (Low and Upper Triangular Matrix)
MTS Multi Train Simulator
OHL Overhead Line
RC Return Conductor