COMPUTER SIMULATION OF TRANSIT POWER SYSTEMS

J G Yu, A M M Khan, K Loring

Cegelec Projects Limited

SYNOPSIS The Cegelec Multi Train Simulator (MTS) is a suite of computer programs, which are used to assist the design of d.c. railway power supply systems. At Cegelec Projects Limited (CPL), the MTS has been used extensively in the engineering of large projects such as the Manchester Metrolink, Ankara Metro and the Jubilee Line Extension. This paper describes the applications of the MTS in engineering and the most recent developments on the simulator which have been driven by such applications.

1. INTRODUCTION

Computer simulation techniques for railway power supply systems have been well established over the last two decades [1,3,8]. The techniques have been widely used to study all aspects of railway operations and designs. Some examples are: studies of energy savings by the introduction of new traction drive technology [2], system optimisation for new and existing transit railways [6,9], system earthing strategy and its effects on rail potential and stray current [4,5,10], the effects of voltage controlled rectifiers with various output characteristics can also be modelled. Virtually all elements that affect the system can be included in the simulation and all necessary data can be obtained from the simulation results [8].

An important aspect of any computer programming is that of validation. The Cegelec MTS having been developed over a period of some two decades has been validated using a combination of different methods. As the program is modular in construction, each module can be checked and validated individually. Initially, the program was validated against manual calculations, and latterly against an actual operational railway which provided excellent correlation with the simulation results [9]. Therefore, methods of validation include manual calculations, running of test or previously validated programs or sub-routines, comparison with actual results or as in the case of the a.c. load flow module against a propriety software package.

Briefly the input data for the simulation is:

- track profiles including gradients, curvatures, speed limits, substation/track parallel hut locations, passenger station locations.
- train characteristics, train headways, regeneration flag, coasting flag.
- electrical power network parameters including convertor regulation characteristics, electrical conductor resistances, system earthing arrangements.

The output results include:

- train minimum voltage,
- system receptivity with regeneratively braking trains,
- train speed and journey times,
- electrical plant load cycles for all plant within the system, including transformers and convertors, track feeder cables, d.c. conductors, a.c. cables.
- d.c and a.c. network voltage regulation,
- harmonic currents in all a.c. cables, harmonic voltages at all a.c. buses, total voltage distortion at the given point(s) of common coupling,
- rail potential and stray currents, including the performance of rail potential control devices.

Both numerical summaries and graphical outputs are made available from the simulation. Details of how the MTS output results are organised are contained in [8]. Figure 1 shows a typical graphical output from the simulation for train performances (distance based). Figure 2 shows a typical substation rectifier load cycle from the simulation (time based).

In line with modern technological developments in power electronics and computers, railways have undergone significant changes since the first simulator emerged. Traction drives have changed from camshaft controlled d.c. motors to chopper controlled d.c. motors, and then to inverter controlled a.c. motors involving modern power electronic devices. Railway signalling is gradually changing from fixed block to moving blocks to permit higher train densities. On the power supply side, there is a greater awareness of the requirements for improving power quality control, including the effects of harmonic generation by rectifier equipment, touch voltage and stray current control, and so on.

All these requirements call for enhancements to the MTS to ensure that the simulation tool remains an effective means of determining the overall performance of the railway electrical system.

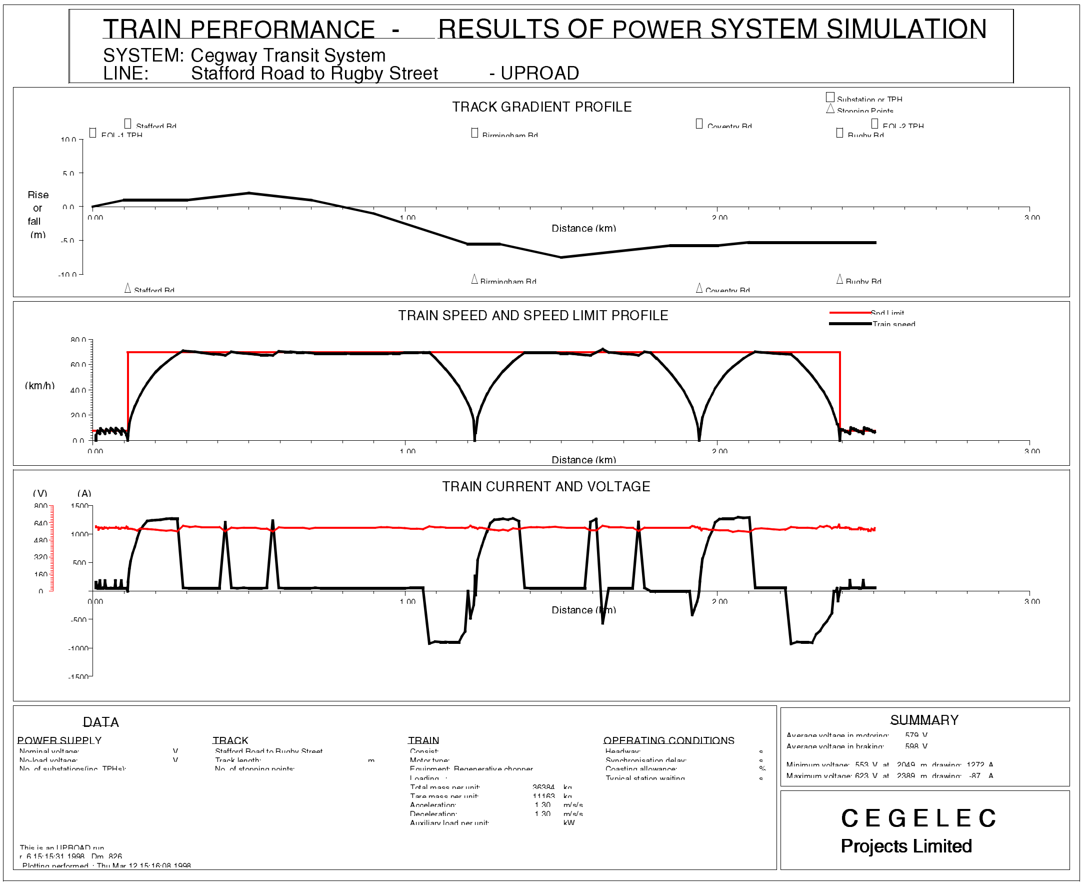

Figure 1. Typical Train Performance Output

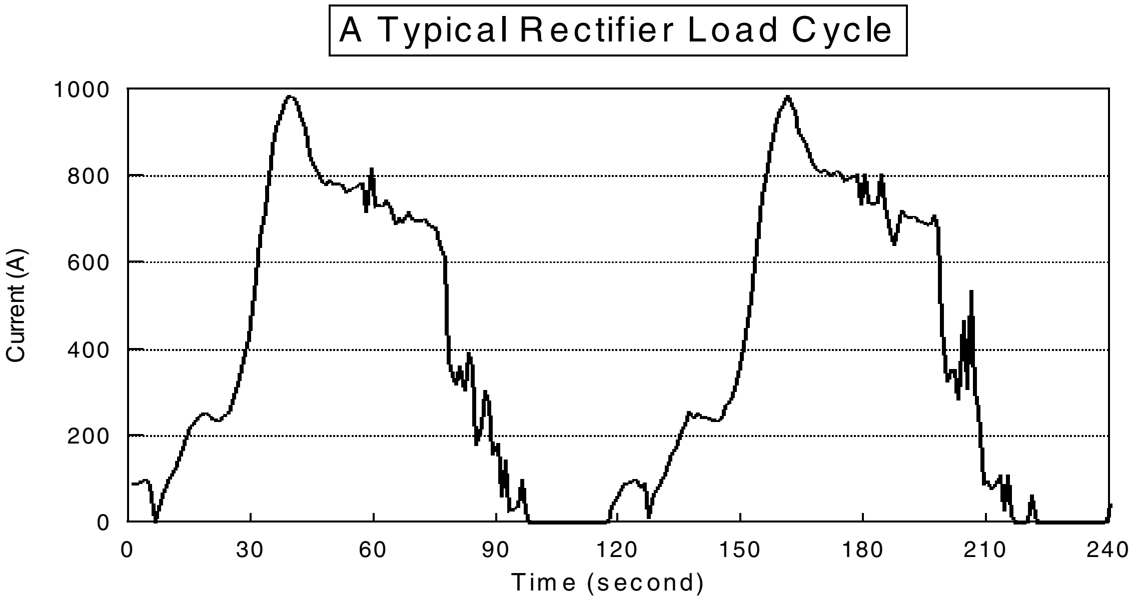

Figure 2. Typical Substation Rectifier Load Cycle

2. TRACTION MOTOR MODELS

Over many years, d.c. motors have been the work horses for electric traction due to their desirable characteristics. Traditionally d.c. motors were controlled by rheostats and latterly by Gate Turn Off (GTO) choppers. Consequently, when the MTS was first developed, only d.c. motors were modelled [2,3].

With the rapid advancement in power electronic technology, the use of a.c. motors has become normal practice due to their many advantages over the d.c. motor, such as lighter weight for the same ratings and reduced maintenance. Power conditioning equipment is provided to achieve acceptable power system characteristics. Power electronic devices range from thyristor switches, GTO thyristor switches with the latest being Insulated Gate Bipolar Transistors (IGBT).

It is apparent that the d.c. motor modelling techniques in the MTS had to be expanded to enable the modelling of a.c. motors. This was first prompted by the studies for the Skytrain project in Vancouver, where linear induction motors (LIM) are used for traction drives. This was followed by the studies for the Jubilee Line Extension project [9]. In the tendering stages for the project, both d.c. and a.c. traction motors were required to be considered, a.c. motors being ultimately selected by the end user.

Due to the life span of traction equipment being quite long, the operational practices in railways result in mixed fleets of trains being used while the d.c. motors are gradually phased out. Therefore, the MTS modelling capability was enhanced to address both d.c. and a.c. motors. This is achieved by making the motor modelling programs “off line” from the MTS. Each type of motor is modelled individually, whilst a common output data structure is maintained. The outputs of these models are organised into four tables, namely

- tractive efforts vs. speed in motoring (at different d.c. voltages);
- d.c. line current vs. speed in motoring (at different d.c. voltages);
- braking efforts vs. speed in braking (at different d.c. voltages);
- d.c. line current vs. speed in braking (at different d.c. voltages);

The motor data is then read by the MTS as input data. Therefore, as far as the MTS is concerned, it does not matter whether the traction motor is d.c. or a.c., all the MTS recognises is the output characteristics. The structure of the motor data organisation is shown in Figure 3.

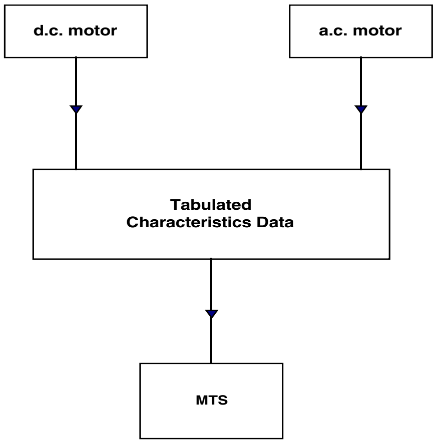

Figure 3. Interface between Motor Modelling Programs and the MTS

The MTS is further improved by reading different motor data for different track sections. The generalisation of the motor modelling approach makes it possible to study such syetems as required. For example, the motor characteristics are different in tunnel sections from open track sections. This is the case for most of London Underground’s lines.

A different example is that of the Skytrain system of Vancouver mentioned above. While most track sections use solid back iron as the reaction rail for the linear motor, some sections use laminated iron to achieve higher output for the motor. Consequently, the motor characteristics change as the train travels along the track.

3. INTERACTIVE A.C. AND D.C. LOAD FLOWS

Usually, the d.c. traction system is studied in isolation from the a.c. power supply network by assuming that the convertors are supplied at nominal voltages. Proprietary software packages are available for a.c. network load flows, which solve load flows at a given steady state load condition. This is usually done by assigning a notional load figure at traction substations (e.g. The rms currents at the substations over a simulated load cycle derived from a d.c. system simulator) and other load centres. This approach is illustrated in Figure 4(a).

There are two major reservations of this approach. One concerns the voltage regulation on both the d.c. and a.c. sides. The results obtained could be optimistic, which is undesirable in the design of the power system. The other concern is that of cable ratings on the a.c. side, as some software packages only produce indicative cable loading.

The modern practice in railway system design requires that the power supply contractor be responsible for both the d.c. power supply and the a.c. power distribution network feeding the railway. Therefore, in terms of system design, both sides of the convertor should be treated as an integral system.

This demands that the simulator should have the capability of studying both d.c. and a.c. networks interactively. Subsequently a new version of the CPL MTS was developed (SIM60), which combines the solutions of d.c. and a.c. networks interactively. This is illustrated in Figure 4(b). As a result, more accurate results are obtained on both a.c. and d.c. sides.

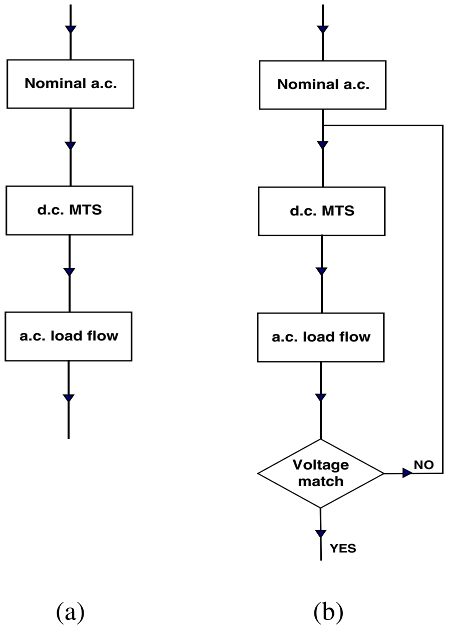

Figure 4. D.C and A.C. Load Flows
(a) Decoupled load flows (b) Coupled load flows

The d.c. traction system loading model is started with a.c. input voltage assumed to correspond to no load rectifier voltage. The traction substation current and voltage calculated by the d.c. model is then passed to the a.c. system load flow routine to apply equivalent P and Q loads. The per unit (pu) a.c. voltage as calculated by the load flow program is then applied to modify the rectifier d.c. side voltage. The d.c. loading is calculated again and the process is iterated until the pu a.c. voltage and the d.c. model calculated voltage lies within the specified tolerance limit (typically at 1 Volt). Auxiliary station and other loads can be assigned to the a.c. busbars independently.

The a.c. load flow algorithm uses a fast decoupled method as described in [11]. This gives very fast iteration time and convergence is good for all types of transmission and distribution network.

The a.c. network data preparation can be in a physical format such that bus couplers and switches can be represented as zero impedance links in the base network. This allows rapid studies of line outages and busbar re-configurations. A pre-processor routine condenses the physical busbar model to the traditional node-branch model. This pre-processor also identifies islands and allows the load flow of each “island” to be carried out one at a time in a loop. Up to a maximum of 10 electrical island can be processed, provided that there is generation and load in each island. Tap changers fitted to both distribution and convertor transformers are also modelled. Additionally, shunt elements such as cable stray capacitances and installed filters are modelled when required.

Input data error checking and convergence problems are reported as the program is executing. The inclusion of a.c. network solutions at each time frame slightly increases the execution time. For example for the Jubilee Line Extension simulation of 600 time frames (600 seconds), the computer time without the ac network model is 2m 37s on a HP715 workstation. This is increased to 3m 10s when the ac network is included (with 1200 a.c./d.c. power network solutions as 2 a.c. islands are involved). The number of iterations required for a.c./d.c. convergence is mostly 1 or 2, with only a few time frames requiring more than 5 iterations. The a.c. network for this study was split into two islands, having a total of 56 busbars and 47 branches.

A summary result file for the a.c. network is constructed at the end of the simulation and contains data such as minimum, maximum, mean and rms values for currents and voltages. The voltages at each busbar and currents in each branch for each time frame are deposited into separate files for plotting/printing by additional post processing programs.

4. HARMONIC FLOWS IN A.C. NETWORK

A separate module was developed to solve the harmonic flows in the a.c. power network. This module is “off line” from the main simulator as a post processing program. This is because the harmonics do not have a substantial effect on the power frequency load flows.

The harmonic load flow solution is a deterministic non-iterative problem. The harmonic current injections are calculated as a function of traction loading [12]. The a.c. network reactance and susceptance are assumed to be directly proportional to the harmonic order. The a.c. resistance is assumed to remain constant at all harmonics if skin effect is not specified. Otherwise the skin effect factor is applied for the given harmonics. Infeeds and generation are modelled as a shunt reactances representing the fault MVA. The effect of auxiliary loads at the traction substations can optionally be included.

As fault level calculation is necessary to determine the system reactance looking from each of the traction substation, the fault levels at all a.c. busbars are output separately to a file.

Input data error checking and solution problems are reported as the program is executing. As matrix inversion is the only major cpu intensive task in this program, the impedance matrix for a given harmonic order and a given island is solved once and all time frames for that harmonic are processed before solving the next harmonic.

As for computer time, the simulation for the Jubilee Line Extension project as mentioned above, is taken as an example. The simulation included 10 orders of harmonics. For solutions at each of the 600 time frames, a total of 12000 load flows in two electrical islands was performed in 55.18 seconds on the HP715 computer. This equates to an average load flow solution time of 4.6 ms.

5. D.C. NETWORKS WITH BRANCHES AND LOOPS

Usually a railway line is a double track, "straight" line. As the system expands, one or more branches may be added to the existing line (the mainline). A loop may be present at the end of the line or other locations. The combinations of such features are endless.

Due to the nature of the d.c. system, the mainline and the branches and loops are usually connected electrically. Therefore, the whole system should be treated as an integral entity. The simulation should reflect all factors in the system.

The CPL MTS is capable of solving such networks (SIM70). The configurations that can be studied are illustrated in Figure 5. If a given network is the combination of these features, it can still be dealt with by the simulator with sensible application.

The principle as applied to main line only loop equation formation [3] is applied for branch/loop line modelling. It has been found that with an efficient loop numbering technique, the expansion of bandwidth can be effectively limited. Choleskey decomposition can then be applied to solve the equations as before.

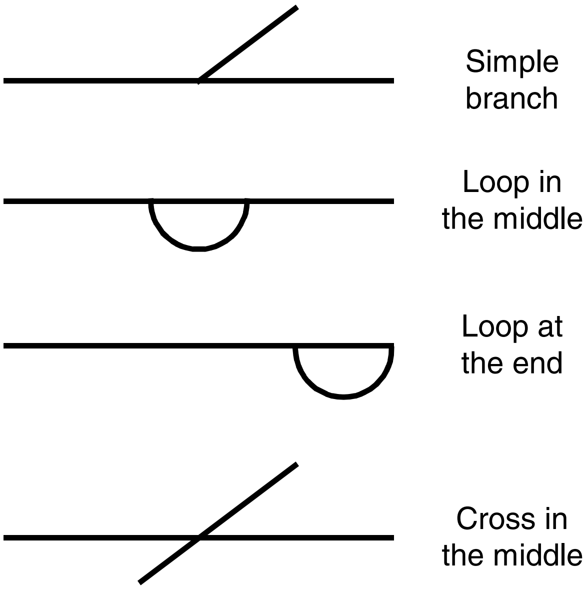

Figure 5. Track configurations that can be studied

6. EARTHING STRATEGIES

Due to economic considerations, most d.c. railways use the running rails as the traction current return conductor. The disadvantages associated with such an arrangement are those of rail potential and stray current problems:

- Rail potentials rises or falls above certain thresholds and may be hazardous in the forms of touch and/or step voltages.
- Stray current may cause or accelerate electrochemical corrosion to metallic structures in the vicinity of the system.

The control of rail potential and stray current is an important aspect of all d.c. railway system design. There are many measures that have been adopted in the attempt to mitigate the harmful effects of the two problems. Among them the choice of earthing strategies within the d.c. system has a profound influence on both rail potential and stray current control. The tasks of controlling both rail potential and stray current are conflicting, therefore a balance has to be struck between the two. This calls for a comprehensive study before a final strategy can be determined. Subsequently a computer program was developed to simulate the performances of systems against defined criterion, namely maximum rail potential, total stray current and gross leakage charge [4,5,10]. With this program, different earthing strategies can be studied for a given system before a final decision is made. The earthing schemes include

- totally floating earth (with no intentional connection between the rail and earth)
- directly connected earth
- diode earth
- floating earth with Rail Potential Control Devices (RPCD earth)

In the case of RPCD earth, the studies can be used to optimise the device settings (voltage, current and time). A detailed description of this capability is contained in [10].

7. CONCLUSION

Over the years, the CPL MTS has proven to be an essential tool in the design optimisation of d.c. railway power supply systems. The rapid advancement in technological developments, particularly in power electronics and computers, demands that the MTS be maintained up to date.

This paper has described the development of the CPL MTS in the areas of traction drives, coupled a.c. and d.c. load flows, harmonic flows, track configurations with branches and loops, earthing strategies and rail potential, stray current control, etc, all of which have been driven by practical applications. There is no doubt that further developments of this suite of programs is a continuous theme, which will be determined by tracking the technological advancements in all areas of d.c. railways. This will enable CPL to continue to design and optimise d.c. traction power systems with confidence.

8. ACKNOWLEDGEMENT

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