A Comprehensive Computer Simulation Model of a Railway Locomotive

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Summary: A complete electrical system computer simulation of the Queensland Rail class 3100/3200 locomotive has been completed. The Simulink simulation software package which has been utilised offers an easy to use graphical user interface which readily allows the manipulation of system variables during the run time. The simulation model has been calibrated and validated against measured results made on a locomotive in normal revenue gaining service. A simulation model is a valuable tool for the investigation of fault conditions. In this paper the models value is illustrated by its application in gaining a better understanding of the effects of harmonic currents on transformer and power factor correction system performance.

1.0 INTRODUCTION

Over the past three years the Centre for Railway Engineering (CRE) has been developing a comprehensive computer simulation model of a 3100/3200 Class locomotive. Included in the model is a detailed representation of the electrical power system with six DC traction motors, traction transformer and power factor correction system.

The SIMULINK software simulation package has been used as the modelling platform, [1]. SIMULINK is a dynamic systems analysis package capable of simulating mechanical and control systems. Using the Dynamic Node Technique, developed at the CRE, it is also possible to easily simulate power electronic circuits in the same platform, [2]. All electrical components including multiwinding transformers, thyristor converters, smoothing reactors and traction motors may be modelled.

The purpose of the computer model is to allow engineers the opportunity to study locomotive characteristics and performance at a detailed level away from the track. To ensure that the simulation is capable of giving credible results comparison with actual measurements and subsequent fine tuning of the model was necessary. The measurements were obtained from a sophisticated data acquisition system placed on board a locomotive.

The simulator has been successfully used in an investigation into overheating of the electrostatic screens in the traction transformer, [3]. In this instance the system was simulated in various operating modes to determine the worst case heating conditions. The information gathered from the simulation was subsequently validated by actual measurements. This allowed the investigators to gain a more thorough understanding of the heating mechanism and to formulate strategies for its minimisation.

This paper presents the completed simulation model, describes the validation process and how it may be applied to provide real technical solutions to difficult problems.

2.0 MODELLING TECHNIQUE

The basic functional blocks of the individual subsystems are developed initially and are interconnected to form the full system model. Each system element is modelled based on its specifications and nature. For example, the converter consists of power semiconductor devices and passive components. The approach used is to model semiconductor devices as voltage casual, that is the current is a time dependent function of the voltage. Examination of a circuit reveals that the circuit contains parasitic capacitance which can be regarded as being lumped at the circuit nodes. The node voltage is directly related to the accumulated charge. Capacitive nodes are used as interface blocks between devices. Nodes simply sum all the device currents applied to the left of the block and integrate to obtain the nodal voltage at the right side of the block as shown in figure 1. The device inject or extract current from the nodes in response to voltage differentials between different nodes as illustrated in figure 2. Because of the integral nature of the node, an additional advantage is that algebraic loops are avoided. All circuit element functional blocks can be divided into two categories, controlled devices and uncontrolled or

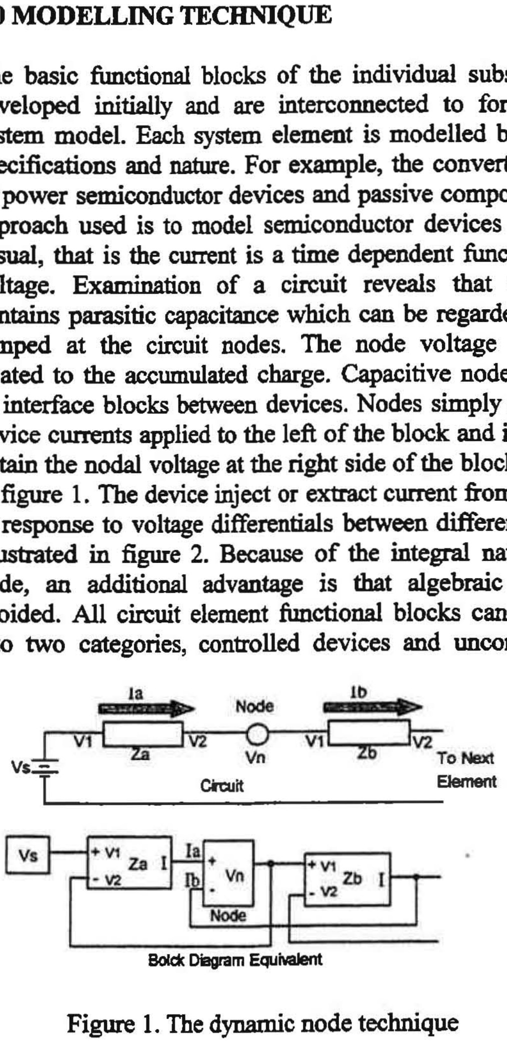

Figure 1. The dynamic node technique

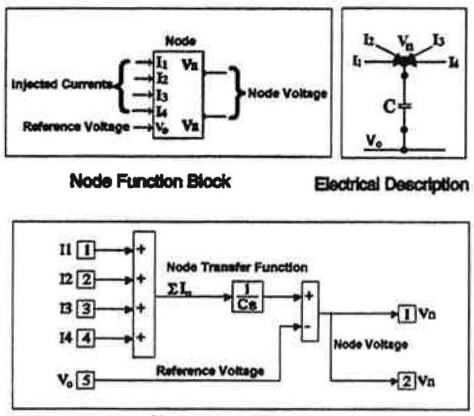

Figure 2. Simulink representation of the node

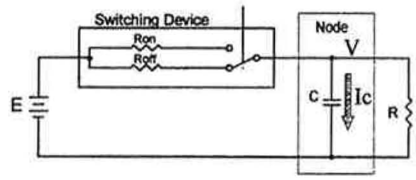

Figure 3. Power electronic switch modelling

passive devices. Figure 3 shows the general approach to switch modelling that has been employed. Characteristics such as diode reverse recovery, forward threshold voltage, forward resistance, thyristor latching and holding current have been incorporated to this model. Other standard electrical circuit elements such as inductor, capacitor and resistor have also been modelled. The dc motor model consists of mechanical shaft dynamics expressed with moment of inertia, rotational resistance and load torque in addition to its electrical parameters.

3.0 LOCOMOTIVE SYSTEM DESCRIPTION

Throughout the world, different electrification systems for electric locomotives are in operation today, [4]. In this paper, a 3100/3200 Class locomotive which operates from 25kV, 50Hz ac supply having compound dc traction motors and phase controlled thyristor converters has been considered for simulation. The locomotive power circuit is shown in figure 4. ac voltage from the 25kV overhead line is reduced to the required voltage of the power converters using a transformer. The two series connected power converters convert ac voltage from the transformer secondary to a controlled dc voltage. The input side low power factor due to the phase angle control of the converters is improved by switching in and out, four power factor correction capacitor banks depending on the reactive power level. An additional inductor in the traction motor armature circuit limits the ripple current. The armature and field control systems are cascaded up to the speed at which both bridge rectifiers are in full conduction, the field current is maintained constant. Above this speed the armature current can no longer be manipulated by the armature circuit. Instead the controlling signal is diverted to the field control system initiating a reduction in field current as the speed increases. The overall control system still acts to maintain the armature current and hence tractive effort constant.

4.0 LOCOMOTIVE MODELLING

A mathematical model of the whole system has been developed using the 'SIMULINK' simulation package as shown in figure 5. This model is a more detail version of that presented in a previous paper, [5]. In the electrical subsystem, a main transformer, two phase controlled converters for traction motor armature circuit, field excitation control, power factor correction modules and traction motors are included.

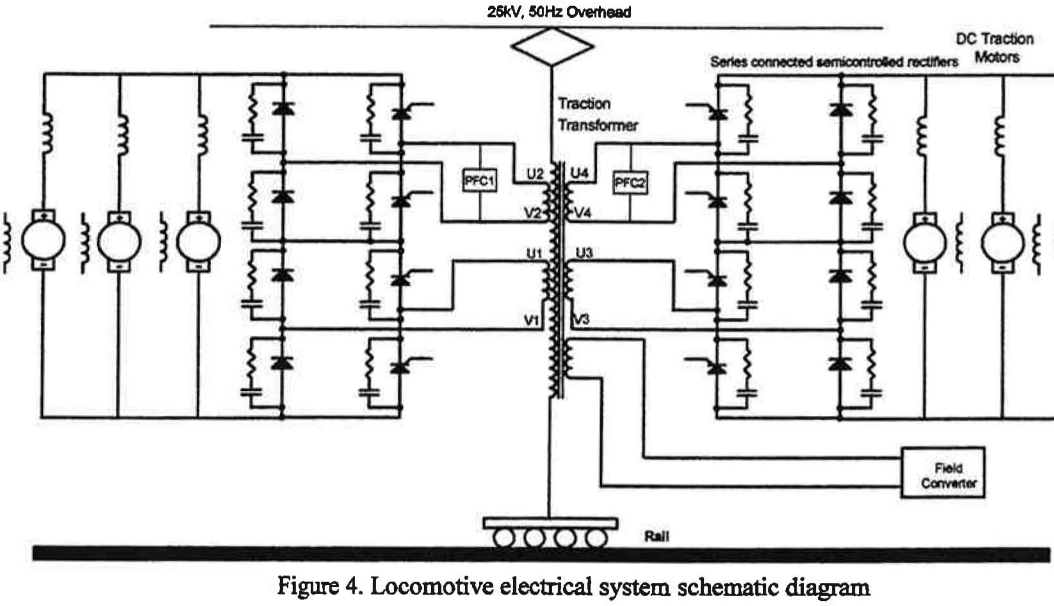

Figure 4. Locomotive electrical system schematic diagram

4.1 TRACTION MOTOR MODEL

The traction motors utilise both a series and a separate field. The Simulink model of the traction motor is shown in figure 6. The separate field transfer function considers the resistance and inductance of the winding and determines the field current. The armature current also contributes to the total excitation. The proportion is controlled by the factors K_f and K_s. The total magnetising force of the excitation system will give rise to a field flux, however the relationship between magnetising force and flux is non-linear due to saturation effects. The non-linearity may be modeled by built in saturation and dead-band blocks. The armature current is determined from the difference between the applied voltage and the motor back EMF passed through the armature transfer function which takes into account armature resistance and leakage inductance. The product of the armature current with the total field flux gives the electrical torque which once subtracted from the load torque gives the torque available for acceleration of the machine shaft. The machine shaft is modelled by a rotational inertia and loss element. The speed is the output of the shaft transfer function. The model has voltage input and current output and therefore conforms to the dynamic node techniques requirements.

4.2 THE TRACTION TRANSFORMER MODEL

The traction transformer has five main windings plus two auxiliary windings. For the purpose of this study it was only necessary to model the primary winding and the four secondary traction windings. Because of the multi-winding structure a simple transformer model as may be used in a two winding situation is not adequate in this circumstance. Instead the mutual coupling between all windings must be considered. This is most conveniently handled in Simulink using matrix algebra.

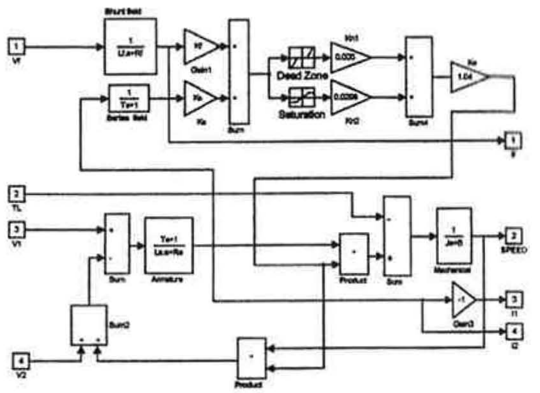

Figure 6. Traction motor model

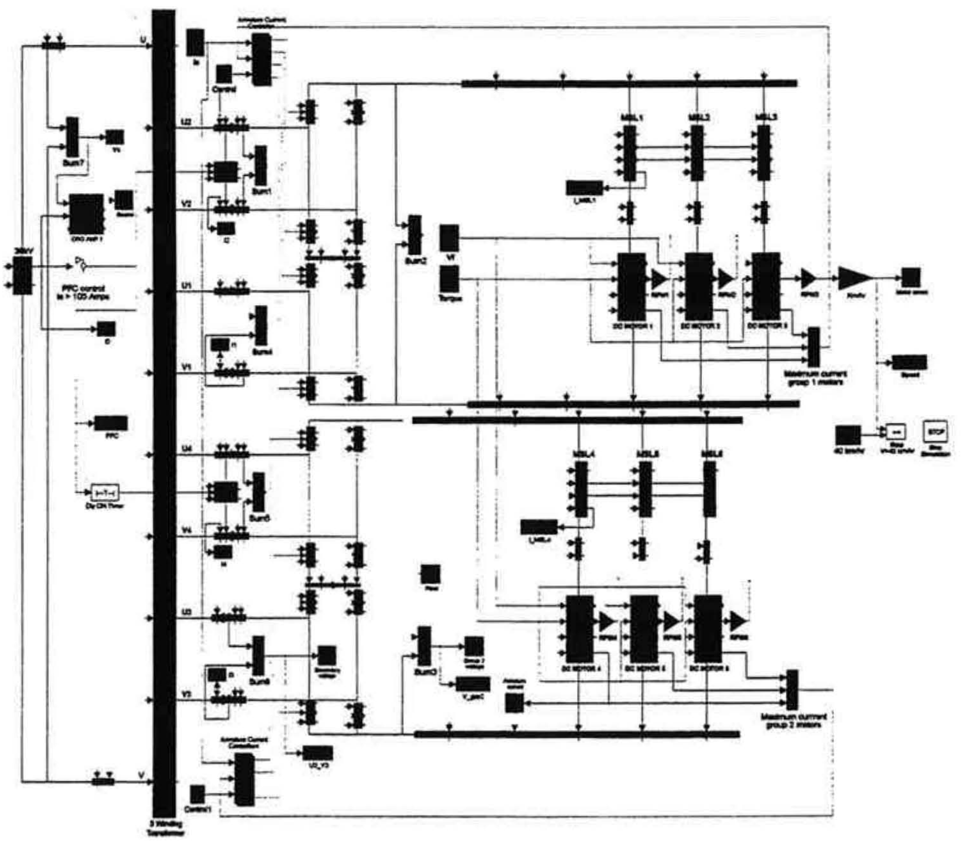

Figure 5. Simulink model of the locomotive traction drive electrical system as it appears on the PC screen

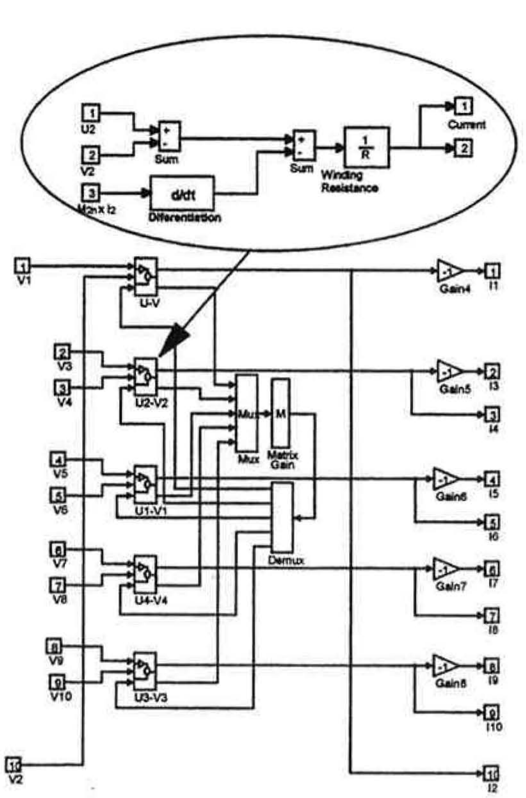

Figure 7. Traction transformer model

The transformer model is described in figure 7. It is based on a matrix model of the mutual coupling between each winding according to the following equation:

$$\vec{E} = [M] \times \frac{d\vec{I}}{dt} \qquad (1)$$

Where the vector 'I' contains the winding currents and the vector 'E' contains the winding back EMF's all referred to the low voltage secondary side. The square matrix 'M' contains the mutual and self inductances for all windings. In its expanded form for a five winding transformer the equation becomes :

$$\begin{bmatrix} E'_{(u-v)} \\ E_{(u1-v1)} \\ E_{(u2-v2)} \\ E_{(u3-v3)} \\ E_{(u4-v4)} \end{bmatrix} = \begin{bmatrix} L_{11} & M_{12} & M_{13} & M_{14} & M_{15} \\ M_{21} & L_{22} & M_{23} & M_{24} & M_{25} \\ M_{31} & M_{32} & L_{33} & M_{34} & M_{35} \\ M_{41} & M_{42} & M_{43} & L_{44} & M_{45} \\ M_{51} & M_{52} & M_{53} & M_{54} & L_{55} \end{bmatrix} \cdot \begin{bmatrix} \dot{I}'_{(u-v)} \\ I_{(u1-v1)} \\ I_{(u2-v2)} \\ I_{(u3-v3)} \\ I_{(u4-v4)} \end{bmatrix} \qquad (2)$$

The mutual and self inductance matrix elements were determined through open and circuit tests on each winding combination. The back EMF's are determined from the sum of the derivitives of the currents in each winding multiplied by their respective mutual coupling. The back EMF is subtracted from the voltage supplied to the terminals and becomes the voltage drop across the winding resistance, from which the current may be determined. The model structure is consistent with the dynamic node technique in that it is voltage causal.

4.3 CONVERTER MODEL

The converter thyristors and diodes are modeled by considering them as a two valued switched resistance. In the on state the switch resistance is very low an in the off state the resistance may be made arbitrarily high. In the case of the thyristor the switch state is controlled by the trigger pulse and the device current. The diodes state is controlled by the direction of current flow alone. Resistance plus capacitance snubbers are incorporated as an integral part of the thyristors and diodes to provide damping of the transformer leakage inductances during switching. These are both necessary for the simulation and are a requirement in actual practice. In addition the actual converter system utilises RC snubbers across each of the secondary traction windings, these have also been incorporated in the simulation model.

The bridge rectifiers are arranged in two groups each with two bridges. The primary bridge is fired to initially up to firing angle approaching 180° to produce a DC output voltage necessary to reach a locomotive speed of approximately 18km/hr. At this point the secondary bridges commence firing with the firing angle being advanced as the speed rises reaching maximum at the rated speed of 40km/hr.

4.4 THE POWER FACTOR CORRECTION SYSTEM

The power factor correction system consists of two banks of capacitors each of 4104μF connected across each of the two secondary traction windings associated with the secondary bridge rectifiers as illustrated in figure 8. A series inductor with a nominal value of 0.24mH is incorporated to control the commutation of the thyristors and diodes. Additionally a series resistance of nominal value 0.02Ω is used to provide damping for the LC circuit thus formed. The system is activated by a pair of back to back thyristors once the line current conditions necessitate.

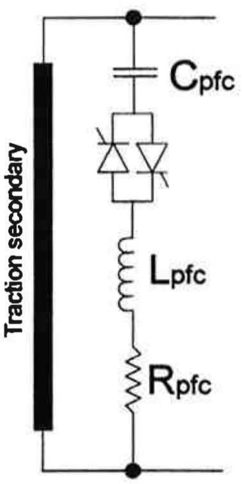

Figure 8. PFC circuit

4.5 CONTROL SYSTEM MODEL

The control system uses a typical approach for this class of locomotive. Essentially it is configured to produce the tractive effort-speed curves for each notch setting as specified by the manufacturer. Basically there are three loops which are active in control of the traction motor as illustrated in figure 9. A current control loop, power control loop and a voltage control loop. The current control loop is in operation up until speeds at which the locomotive reaches its rated power after which the power controller becomes effective. This status continues up until the rated speed and hence the maximum armature voltage is reached. After this point the armature voltage is controlled at its rated value. Further speed increases are obtained by field weakening. The simulink package allows with little effort the application of complex control systems as illustrated in this instance.

5.0 VALIDATION OF MODEL RESULTS

Another project which was running concurrently with the investigation into harmonic levels in the traction system was a sophisticated instrumentation system for measuring parameters relative to DC traction motor performance in relation to brush and commutator wear. This instrumentation system was extended to measure all the transformer currents and voltages plus the power factor correction circuit currents for both groups. The measured results were then used to validate the model. Figure 10,13 and 15 shows the simulated transformer traction winding currents, PFC currents , primary current and voltage and the DC traction motor current and voltage. These should be compared against the measured waveforms of figures

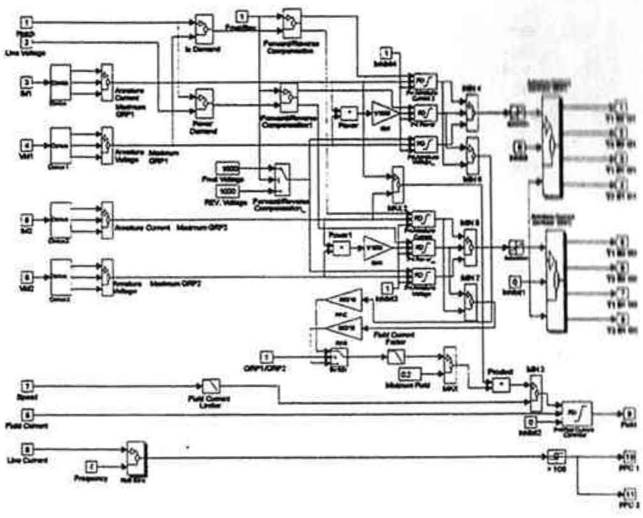

Figure 9. Simulink Sub-model of the control locomotive control system

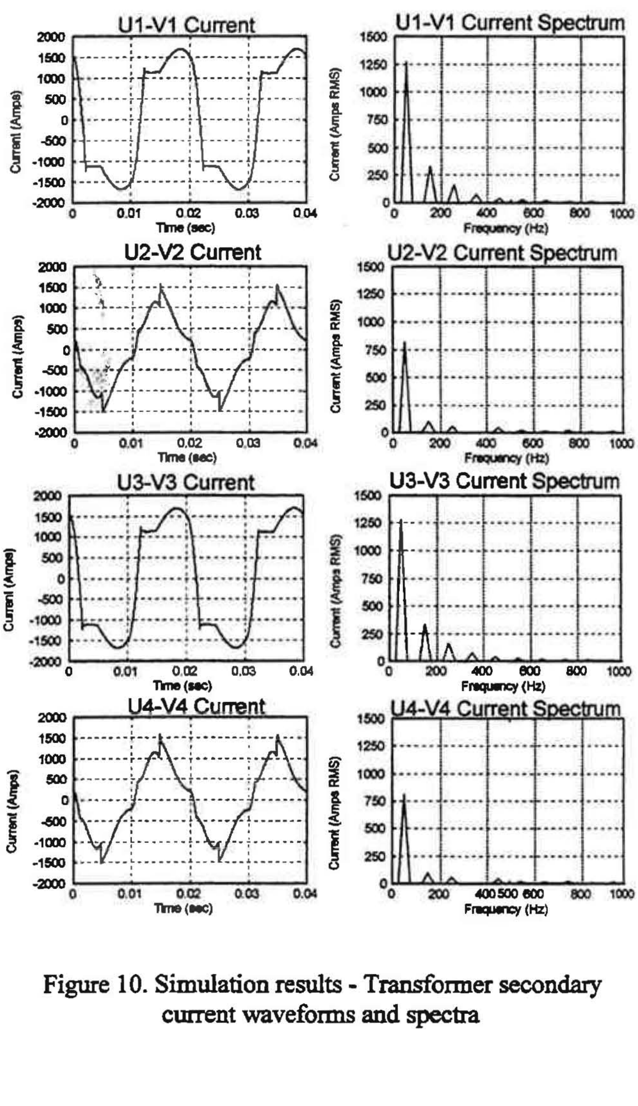

Figure 10. Simulation results - Transformer secondary current waveforms and spectra

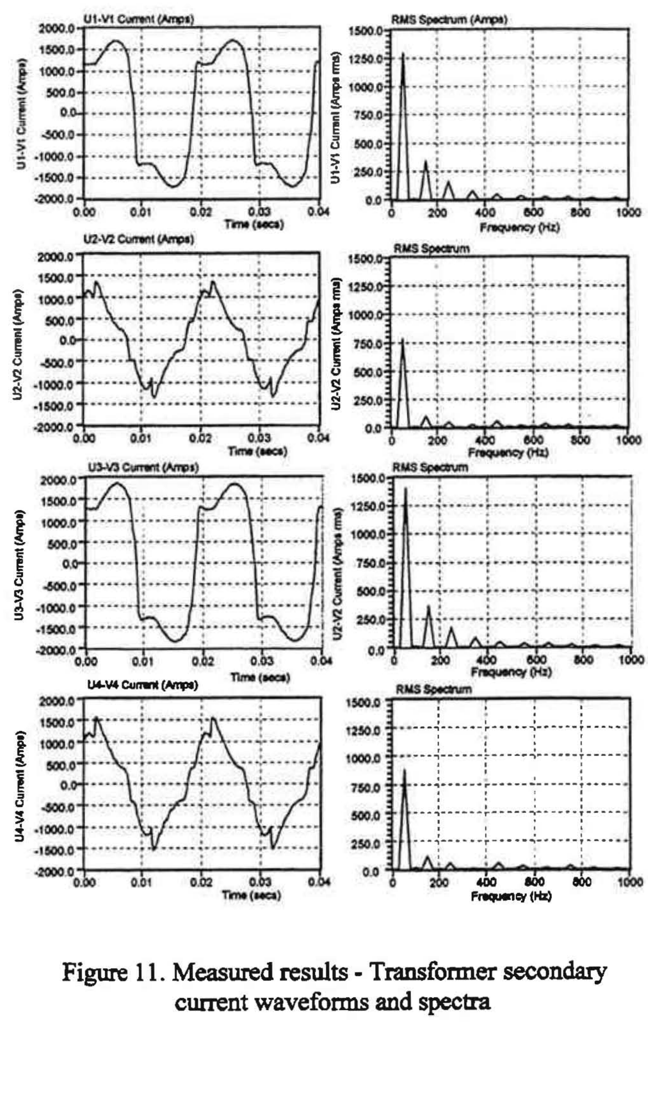

Figure 11. Measured results - Transformer secondary current waveforms and spectra

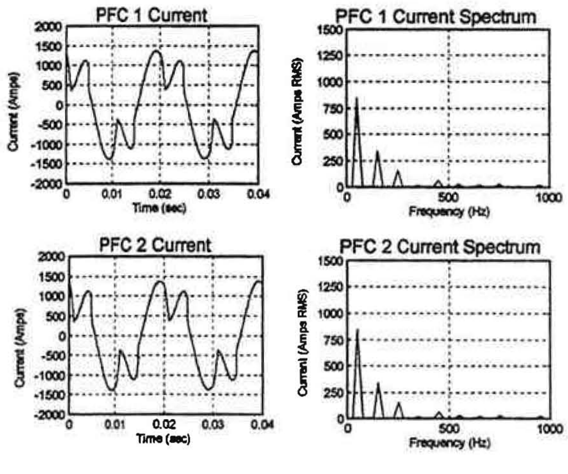

Figure 12. Simulation results - PFC circuit currents and spectra

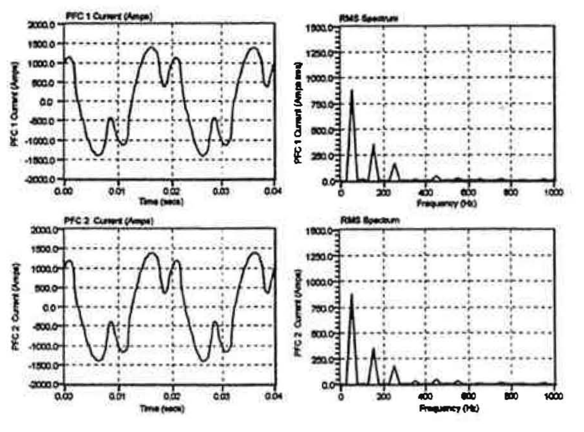

Figure 13. Measured results - PFC circuit currents and spectra

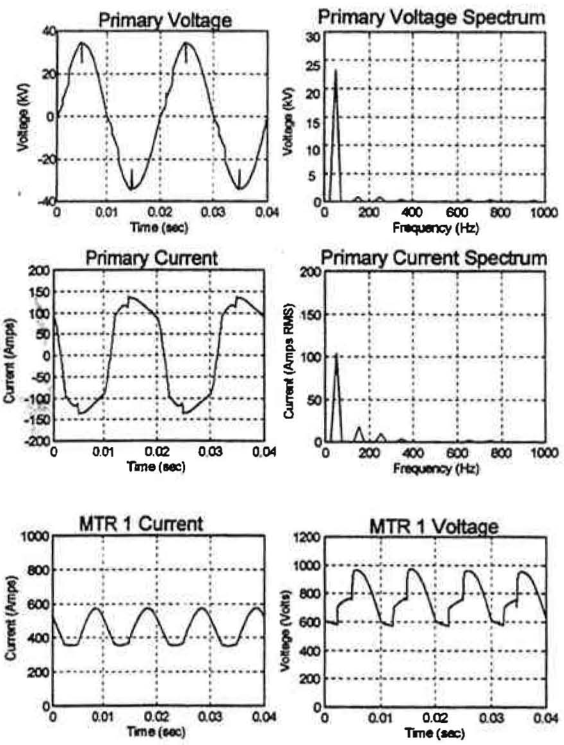

Figure 14. Simulation results - Transformer primary voltage and primary current waveforms and spectra plus motor current and voltage

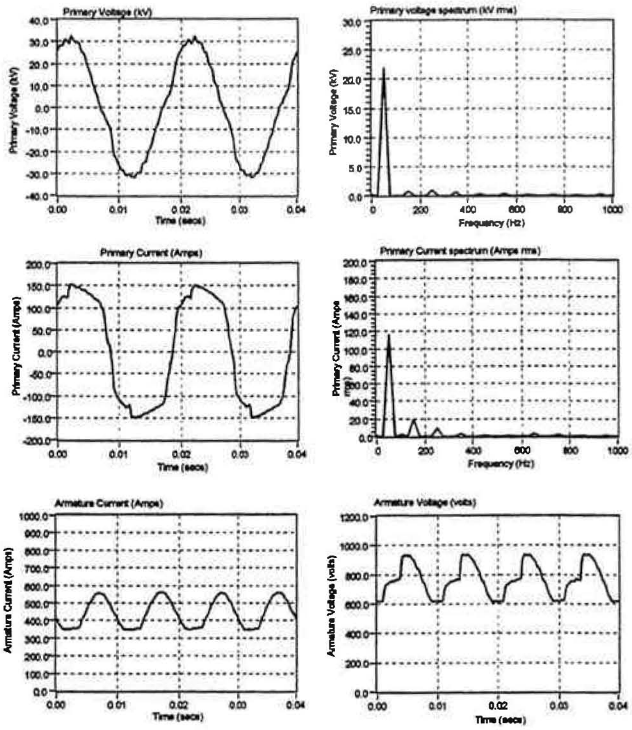

Figure 15. Measured results - Transformer primary voltage and primary current waveforms and spectra plus motor current and voltage

11,13 and 15. Additionally the spectrum of the transformer waveforms has been calculated for both the simulated and measured results.

For this particular case the following conditions applied:

Locomotive speed - 32 km/hr
Armature current - 460 amps
Field current - 537 amps
Armature voltage - 764 volts
Line impedance - 5.85+15.65**j**
Supply voltage - 24.5Kv

One difference between the simulated and measured results is that the group 1 and group 2 transformer currents are slightly different in magnitude. For example the measured RMS value of the group 1 secondary 1 (U1-V1) current is 1295 amps whereas for group 2 secondary 1 (U3-V3) it is 1406 amps.

The simulation shows a value of 1280 amps for both windings. The bias between group 1 and group 2 which is measured is introduced by the control system to account for the weight distribution on the bogies during acceleration. This bias was not implemented in the simulation. Also the simulated RMS currents are on average 5% lower than the measured counterparts. The actual reason for this is not known, however it could be due to losses and non-linearities which have not been correctly modelled. It is believed that overall simulation results match measured results to within 10% over a wide range of operating conditions. Further refinement of the system component models will undoubtedly increase its accuracy. None the less the simulation model in its present status represents arguably the best tool available for engineering investigations into electrical system problems for this locomotive.

6.0 SYSTEM HARMONIC STUDY

The simulation model is at present being used to determine the harmonic levels in the PFC system and traction transformer under various operation conditions. This study has been prompted by overheating problems that have been experienced in both the transformer electrostatic screens and the PFC system. The overheating is thought to be due to excessive 3rd harmonic level in the system. The 3rd harmonic level is a function of PFC component values, transformer characteristics, line impedance, system voltage, locomotive speed, control system operating mode and the presence of other locomotives in the same section of overhead line. Only a simulation is able to produce accurate results rapidly in a complex system such as a railway locomotive.

7.0 FUTURE DEVELOPMENTS

The simulation model in the future will be used to study the harmonic current stresses on the individual components of the locomotive under normal and abnormal operating conditions. Influences such as the electrical interaction between locomotives on the same overhead line section will be studied

8.0 CONCLUSION

A comprehensive simulation model of a locomotive traction drive system has been successfully simulated and the results compared against measured values. Good agreement with measurements has been achieved. The simulation model is being used to establish the levels of harmonic currents in the traction system over a wide range of operating conditions.

9.0 ACKNOWLEDGEMENTS

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