Power Quality Study of a Commuter Train System

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Abstract

The proliferation of non-linear loads resulting from new technologies has increased the levels of harmonics in power systems, and traction systems represent large nonlinear loads. This paper presents results of a simulation of the harmonic distortion related to Mass Transit Railway system. Stochastic studies of the train loading and headway were included in a Monte Carlo EMTP simulation of the supply network, and comparisons were made with field measurements. Summaries of the parameters affecting the harmonic performance of the traction system and estimates of the most predominant harmonics in network are also presented and recommendations are made for the improvement of the power quality.

Introduction

The increasing presence of solid-state power electronic equipment has led to a significant increase in power system harmonics in recent years. Since traction systems represent large nonlinear loads on the power system, more and more concern about the power harmonics generated from these systems has been raised. To estimate the effects of harmonics in the system simulation and measurement were done so as to identify the worst case in the network. Train operation and electrical system are the main parameters influencing the harmonic performance. Those harmonic currents cause voltage harmonic distortion which pollutes the electricity supply source.

In this paper a stochastic method is presented which incorporates the statistical nature of the train schedule with the traction system in order to predict the harmonic distortion in the electrical supply network. The percentage harmonic content and the total harmonic distortion (THD) of current are predicted by means of EMTP simulation, where the passenger flow, train control, train net weight, and train schedule are considered.

System Description

The system studied in this paper is represents part of a network between two stations of a typical commuter railway. The electric company supplies power at 33kV from two 50MVA transformers. Multi-winding transformers with 7.5 degree phase shifts step down the voltage to 586V AC and supply the 24-pulse rectifiers to produce 1500 DC after rectification. The catenaries then distribute the power to every train on the railway. The schematic diagram of the AC/DC interface is shown in Figure 1.

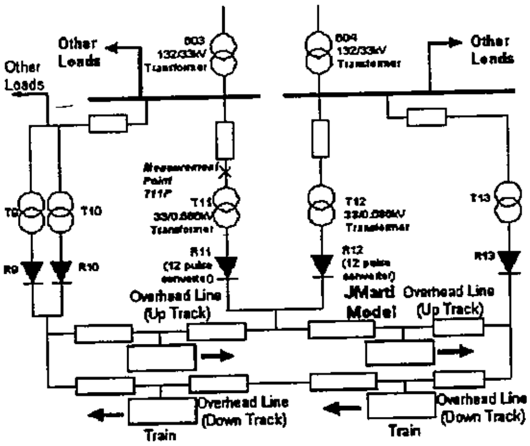

Figure 1 Schematic diagram of the network

The passenger train consists of 3 motor units and 1 non-motor unit. Each motor unit also consists of 2 cars with 4 dc motors in series. The voltage input of the motors is controlled by choppers with a frequency of 260Hz and the chopper frequencies for these two cars are interlaced.

Classification of train pattern

For the normal train pattern, there are three modes to describe the train movement: acceleration mode, coasting mode and deceleration mode. For each of these modes the train drive has different characteristics. In the acceleration mode, the train motors properly switch to motoring mode – the incoming switches of train motors are closed and the chopper switches of the motors are controlled by the signal of the motor controller. After the acceleration mode of the train, the train runs at a targeted velocity and the train switches into coasting mode. In this situation, the incoming switches of train motors open such that no power flows into and out of the train motor to the overhead line. The train decelerates by regenerative braking before the safety deceleration distance form the next station. The incoming switches close again and the motor regenerates the current back to the overhead line [1].

In the simulation only the acceleration mode is considered since during the coasting mode the contactors are open and no current flows. During deceleration the regenerative current from the train motor is absorbed either by other trains or by a regenerative braking resistor (the regenerative currents cannot feed back to the ac source owing to the blocking of substation rectifiers). Additionally, it is assumed that all voltage sources from electric supply company are constant and free of harmonics.

Train Schedule

The train schedules of both up track and down track with train time interval are considered in the simulation in order to calculate the multi-train schedule.

The typical train schedules for the rush hour are then plotted in Figure 2.

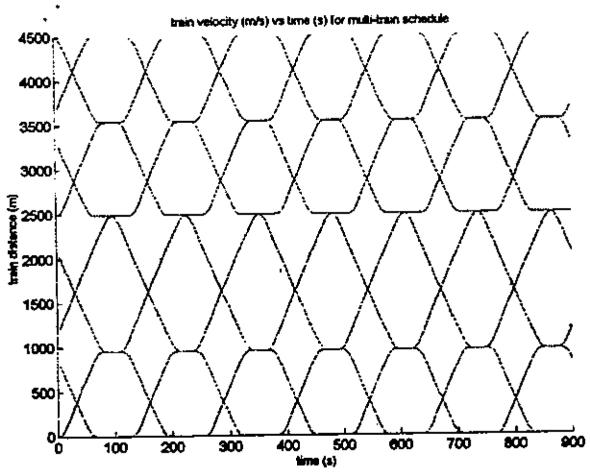

Figure 2 Multi-train schedule including up track and down track - schedule for rush hour

Assumptions

In normal daytime only passenger trains are operated on the local railway. The harmonic performance of these passenger trains depends on several parameters: the amount of passenger load on trains, the net weight of trains, and the velocity and location of trains on the railway. According to the data provided, the train weight is constant while the velocity and location of trains are scheduled with a certain pattern in the normal situation. Furthermore, the number of passengers on trains is an undetermined variable, so the trains are actually random fluctuating loads from the viewpoint of the power system. In this study, mean values are used of the number of passengers on trains and the velocity and acceleration profiles of trains in different tracks are in accordance with the predetermined train schedule on the given rail.

The deviations of train schedule causing train delay are considered although there is a lack of statistical information of this aspect available. Sampling site measurements for checking the time accuracy were carried out. From this measurement, the mean and standard deviation of train delay are 0 second and 3 seconds, respectively.

Other loads of trains such as lighting, air conditioning and control systems are also considered in the simulation. In the region of this simulation, all platforms of the stations are designed as open type, which is natural ventilation design without air conditioning systems. The measurement date was in the summer and owing to the hot weather a large amount of conditioned air from the trains is exhausted when trains stop at a platform and opens the slide doors. Therefore, 95% of the total operating loads for lighting, air conditioning and control systems are assumed.

Unbalanced voltages between three phases and that between different sources were accounted for in the simulation [2]. Since the voltage unbalance leads to the current uncharacteristic harmonics and load flow shift, the Monte Carlo Method for source voltages was applied in accordance with the probability density function from the measurements.

Modeling

The modeling of power network has already described. However, EMTP can only simulate one case at a time. For the traction system, some undetermined parameters cannot be defined directly in EMTP. Therefore, Matlab was incorporated with EMTP to run the simulations. Figure 3 shows the flow chart of the simulation.

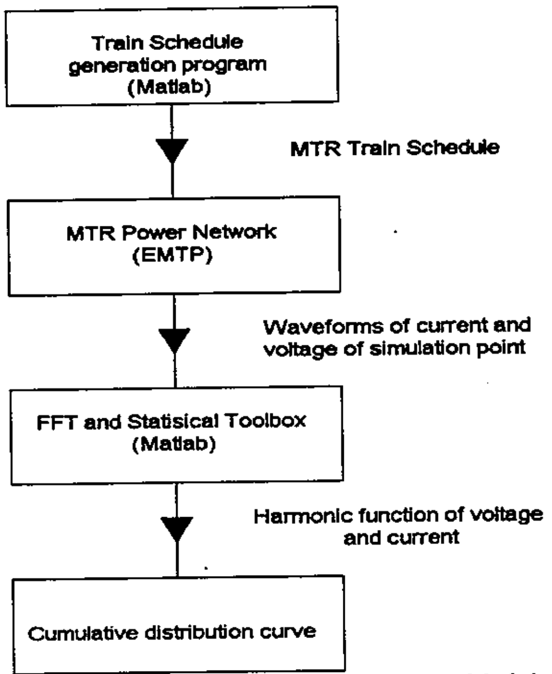

Figure 3 Simulation model procedures – Matlab & EMTP application

Matlab generated the train schedule for the EMTP simulation according to typical train information. This Matlab train schedule was imported into the EMTP simulation and the EMTP simulated the targeted voltage and current waveforms. Those waveforms then transferred to Matlab again and Fast Fourier Transform and the statistical toolbox were used to create cumulative distribution curves, which were used to analyse the harmonics.

Simulation and Measurement

In this study, the stochastic behaviour of the harmonic distortion under different train scheduling and passenger loadings was determined both by simulation and measurement [3]. The measurements were performed during rush hours, and both the voltage and current harmonics on the ac feeders were measured a data-logging instrument, the Reliable Power Recorder (RPM). A stochastic model was created in the EMTP environment where models of the converters, motors, overhead lines and the rails were developed.

A case in rush hour is discussed. Only fundamental, 11th, 13th, 23rd and 25th orders of current harmonics at point T11A were plotted in Figure 1 since those harmonic orders are significant in this power system because 12-pulse rectifiers are applied in this network. Occurrence probability curves in rush hour period were used to present the harmonic situations.

Findings

The harmonic levels, both the individual levels as well as the THD determined by simulation compared reasonably well with measured data. Furthermore, the levels were found to be within the tolerable levels specified in IEEE 519 [4].

Rush hour simulation results

Figures 4, 5, 6, 7 and 8 are occurrence probability curves of fundamental, 11th, 13th, 23rd and 25th orders of current harmonics at point T11PA in rush hour.

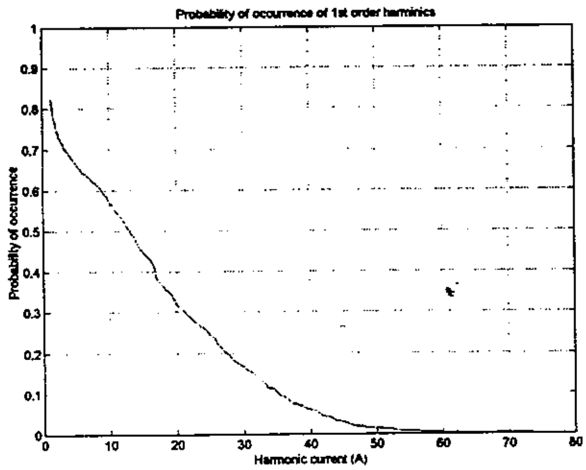

Figure 4: 1st order harmonic current at T11PA (Simulation)

Figures 9 and 10 are total demand distortion and total harmonic distortion curves of current harmonics at point T11PA in rush hour.

The ratio of the short current I_{sc} (31.5kA) to the maximum fundamental current I_L (80A) at the point T11PA is 350 for the simulation point T11PA. Therefore, the TDD in the IEEE standard is 15%. To compare the simulated total demand distortion (TDD) to the standard, the probabilities of TDD exceeding the limit are 0.50% for rush hour. From the total harmonic distortion (THD), the points with high THD concentrate on the region of low current. Although some situations with high THD occur, the magnitudes of harmonic currents are smaller than the maximum harmonic currents with the low THD.

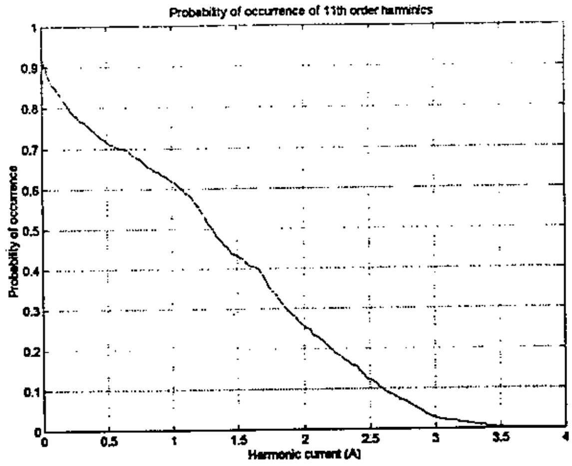

Figure 5: 11th order harmonic current at T11PA (Simulation)

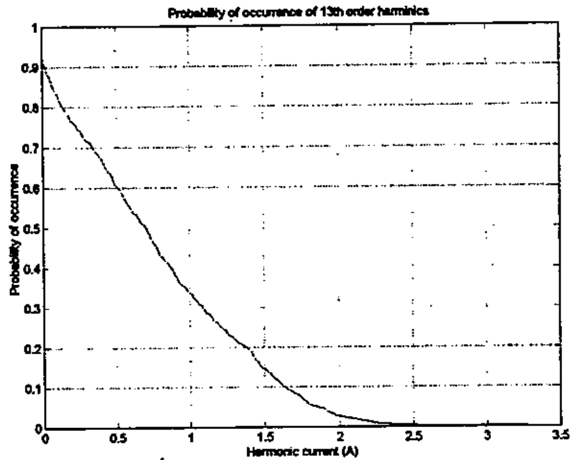

Figure 6: 13th order harmonic current at T11PA (Simulation)

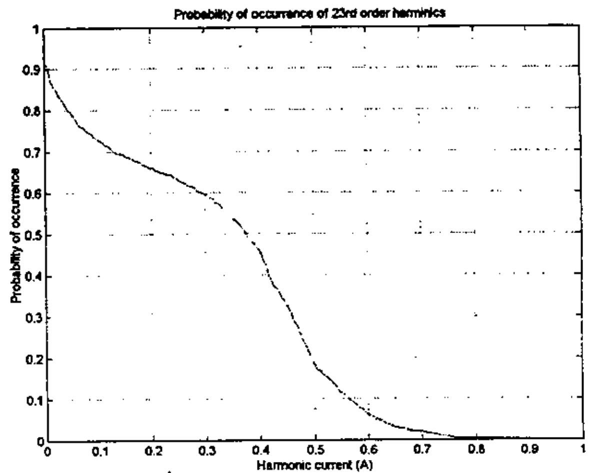

Figure 7: 23rd order harmonic current at T11PA (Simulation)

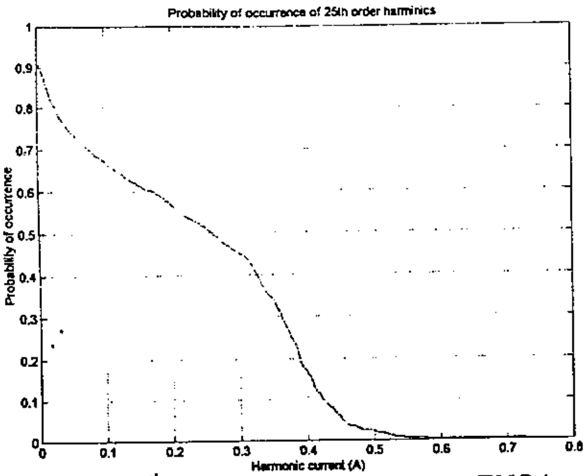

Figure 8: 25th order harmonic current at T11PA (Simulation)

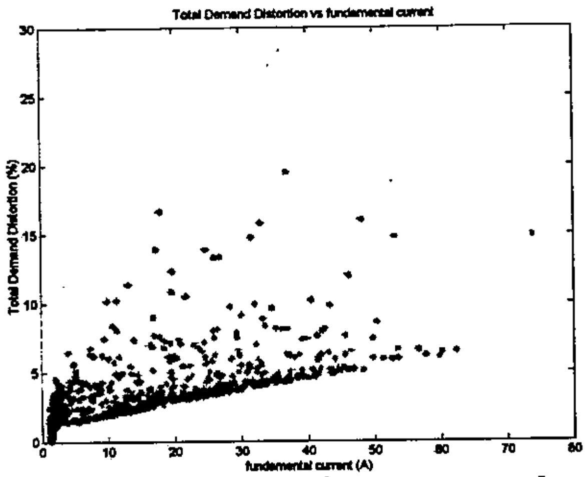

Figure 9: Total Demand Distortion vs I_1 (Simulation)

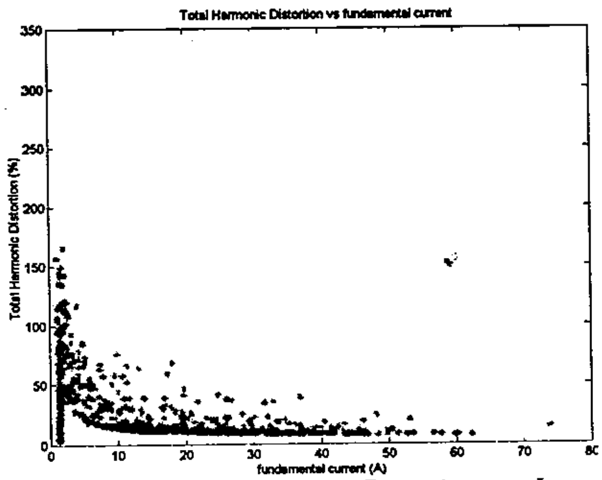

Figure 10: Total Harmonic Distortion vs I_1 (Simulation)

From the above figures, the harmonic characteristics with the probability of occurrence can be summarised. Harmonic current covering 50% probability of occurrence ($I_{50\%}$), that covering 90% probability of occurrence ($I_{90\%}$), that covering 95% probability of occurrence ($I_{95\%}$) and that covering all probability of occurrence ($I_{100\%}$) are considered. $I_{50\%}$, $I_{90\%}$, $I_{95\%}$ and $I_{100\%}$ in rush hour are shown in following Tables 1.

Harmonic order	*$I_{50\%}$ (A)*	*$I_{95\%}$ (A)*	*$I_{95\%}$ (A)*	*$I_{100\%}$ (A)*
1	13	35	42	73
11	1.3	2.6	2.8	3.8
13	0.7	1.6	1.8	3.2
23	0.38	0.56	0.61	0.94
25	0.25	0.42	0.45	0.75

Table 1: Table $I_{50\%}$, $I_{90\%}$, $I_{95\%}$ and $I_{100\%}$ in rush hour (Simulation)

Site Measurement Results

Figures 11, 12, 13, 14 and 15 are occurrence probability curves of fundamental, 11th, 13th, 23rd and 25th orders of current harmonics at measurement point T11PA in rush hours.

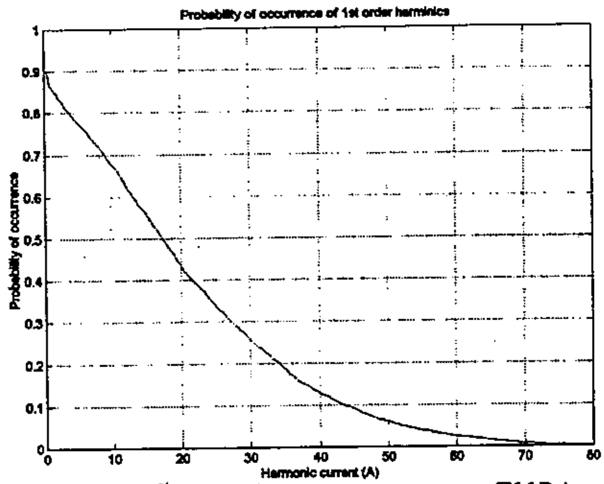

Figure 11: 1st order harmonic current at T11PA (Measurement)

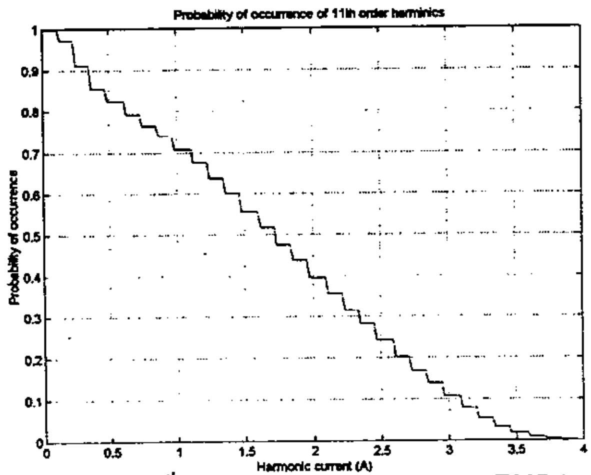

Figure 12: 11th order harmonic current at T11PA (Measurement)

Figures 16 and 17 are total demand distortion and total harmonic distortion curves of current harmonics at measurement of T11PA in rush hour.

From the curves, the harmonic characteristics with the probability of occurrence with $I_{50\%}$, $I_{90\%}$, $I_{95\%}$ and $I_{100\%}$ for both cases can be summarized in the Table 2.

From the curves and tables, $I_{100\%}$ is much larger than $I_{95\%}$. However, the probability of harmonic current between $I_{95\%}$ and $I_{100\%}$ is around 5% of occurrence. This is similar to the simulation result.

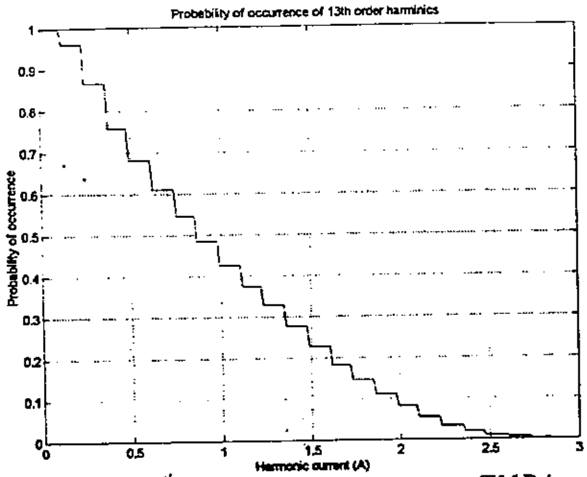

Figure 13: 13th order harmonic current at T11PA (Measurement)

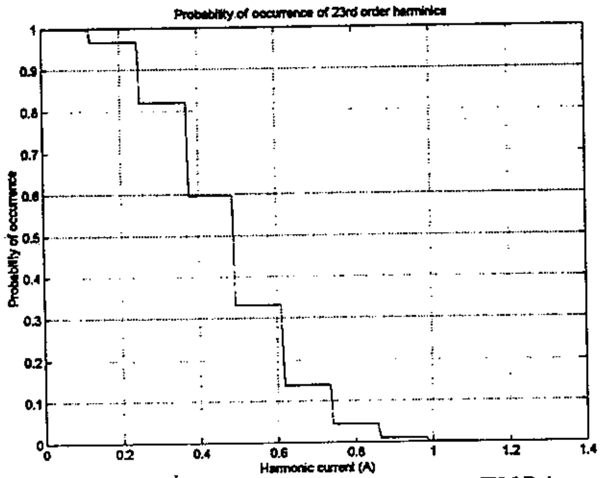

Figure 14: 23rd order harmonic current at T11PA (Measurement)

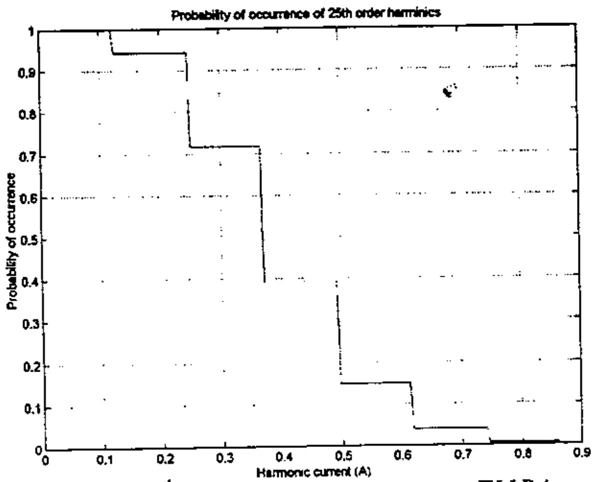

Figure 15: 25th order harmonic current at T11PA (Measurement)

Harmonic order	*$I_{50\%}$ (A)*	*$I_{90\%}$ (A)*	*$I_{95\%}$ (A)*	*$I_{100\%}$ (A)*
1	18	42	52	80
11	1.7	2.9	3.2	4.0
13	0.8	2.0	2.2	2.8
23	0.49	0.56	0.60	1.1
25	0.38	0.62	0.68	0.85

Table 2: $I_{50\%}$, $I_{90\%}$, $I_{95\%}$ and $I_{100\%}$ in rush hour (Measurement)

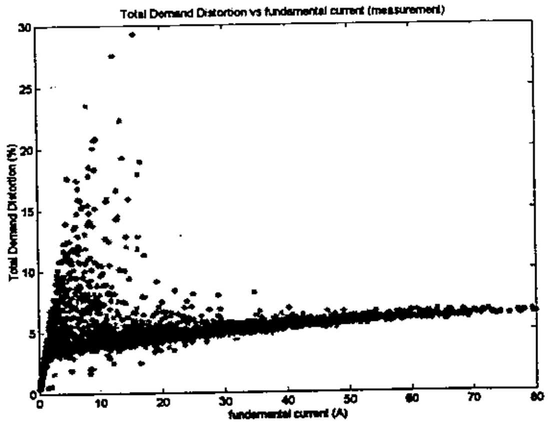

Figure 16: Total Demand Distortion vs I_1 (Measurement)

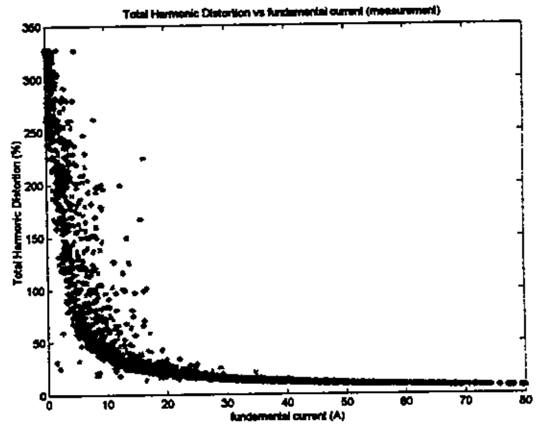

Figure 17: Total Harmonic Distortion vs I_1 (Measurement)

Conclusions

This paper presented a study of the voltage and current distortions in an electrical distribution system feeding a DC traction system. The study involved both field measurements and computer simulation.

The electrical load presented by a train is stochastic in nature, and depends on factors such as train schedule, passenger loading, air conditioning, lighting, etc. A statistical analysis was performed, and this involved determining the probability density functions of the loading variations. The statistical data was incorporated into the computer simulation, and the results compared well with the measured results.

From the results of the simulations and measurements, the harmonic phenomena were acceptable in accordance with the IEEE 519 standard [4]. Therefore, no extra harmonic filter is recommended to be installed for the treatment. If the MTR would like to optimise the harmonic situation, rearrangement of train schedule is one of the most cost-effective methods. From the simulations for the MTR network, the harmonic currents increase when the loading currents increase. Therefore, to prevent large currents in the harmonics, the accelerations among all trains at the same time in train schedule should be prevented.

References

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3. IEC Std.1000-4-7 1991 Part 4 "Testing and Measurement Techniques".
4. IEEE 519-1992 standards - IEEE recommended practices and requirements for harmonic control in electrical power systems.