EMC COMMISSIONING & SAFETY CERTIFICATION OF AC RAIL TRANSIT VEHICLES -- U.S. EXPERIENCE

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INTRODUCTION

For the past several years, rail transit vehicles employing ac traction have been operating in revenue service in the U.S. In addition to demonstrating the performance and maintenance improvements inherent in ac traction, these vehicles have been operating safely and compatibly with existing fleets and conventional infrastructure. These applications include heavy rail, light rail, commuter rail, and passenger/freight mainline railroad operations. Most of these applications are on existing systems with very conventional traction power and signalling, not new start-ups. Also, during this time period, as a precursor to its High Speed Train Project, Amtrak has operated the Swedish X2000 and German ICE trainsets in an extensive revenue service demonstration on its Northeast Corridor route between New York and Washington. This route uses 25 Hz 11 KV traction supply and conventional signalling with relay-based track circuits in the 90 Hz-100 Hz frequency range.

BACKGROUND

In 1979, to address major signalling system compatibility problems during commissioning of early dc chopper controlled vehicles, the author, while with the U.S. Department of Transportation, founded and chaired the Rail Transit EMI/EMC Technical Working Group (TWC) composed of propulsion & signalling suppliers (Frasco et al (1)). The TWG, working with rail transit operators, developed standardized methods of analysis and testing to quantify and resolve these specific dc chopper problems as well as address future issues of rail transit vehicle electromagnetic compatibility (EMC). In 1980, under the auspices of the U.S. Department of Transportation, a draft recommended practice was developed by the TWG for use by the U.S. rail transit community (U.S. DOT UMTA/TSC (2)).

The underlying methodology of the recommended practice is based on sound system engineering principles. This allowed critical interfaces to be defined between vehicle electrical power and signalling subsystems in a very basic way. With this approach, vehicle and signalling subsystem technical innovation and design could proceed basically unconstrained as long as proper consideration was given to EMC criteria at the defined interface--e.g. emission or susceptibility levels, input impedances. These criteria could be easily factored into subsytem design, then verified by laboratory and field testing at the subsystem and system level. The details of this methodology are presented in Frasco et al (3).

The draft recommended practice was successfully applied to resolve the existing dc chopper problems which motivated its development. Of equal importance, it provided both propulsion and signalling design engineers with the necessary tools to design compatible systems for future applications. The methodology was successfully applied to both new transit system start-ups and existing systems with a wide range of existing vehicles and power & signalling infrastructure. It soon became an adhoc standard. Beginning in 1985, following several successful applications and an extensive validation program, the methodology was formally published. In particular, the volumes of suggested test procedures are routinely referenced in U.S. rail transit vehicle EMI/EMC specifications (U.S. DOT UMTA/TSC 4,5,6)).

AC VEHICLE EMI/EMC METHODOLOGY

With the introduction of ac rail vehicles in the U.S., the same EMI/EMC methodology could be applied. Of course, new analyses of an ac vehicle as EMI interference source had to be developed by the propulsion system designer, but the interface equivalent circuit modelling of vehicle, traction supply network, and signalling system remained unchanged. The suggested test procudures for measurement of emissions and susceptibility were also generally applicable. Therefore, for example, once the ac vehicle interface equivalent circuit parameters were determined--successively by analysis, simulation, and testing--an existing dc chopper vehicle system application of the methodology could be easily updated to apply to ac vehicle applications.

Figures 1 and 2 present a graphical representation of the basic methodology with examples of system/ subsystem models, interfaces, and standardized tests. Figure 1 shows the equivalent electrical circuits for the vehicle as an inductive emission source and a track circuit receiver connected rail-to-rail. The parameter Zs accounts for the impedance of the under-vehicle rail-axle-rail loop. The voltage Voc is the equivalent open-circuit induced voltage

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appearing rail-to-rail. IEXX, ISXX, and OCO1A denote standardized tests for measuring emissions and susceptibility circuit parameters of these equivalent circuits in the labortory and in the field. Figure 3 is an example of a limit curve for maximum allowable rail-to-rail voltage levels, undervehicle, for a rail transit system with relay-based (low frequency) and audio frequency (AF) electronic track circuit signalling.

Figure 2 shows a block diagrm of the conductive interference model. CEXX, CSXX, and OCO1A denote the standardized tests for measuring circuit parameters. Figure 4 is an example of limit curve, to be applied to CEXX test measurement results, for maximum allowable harmonic emission current at line supply input (dc third-rail/catenary) for relay-based and AF track circuit applications. Figure 5 is an example of an ac catenary traction supply conducted emission limit curve for a similar conventional power & signalling infrastructure of relay-based and AF track circuits, where an effort has been made to distinguish between allowable levels of even and odd harmonics of the traction suppl;y, and swept harmonic emissions of the ac vehicle traction inverter. Finally, it should be noted that CSXX, ISXX standard test procedures concentrated on AF signalling circuits for dc chopper applications. Although some exposure exists for low frequency relay-based circuits from dc chopper swept frequency or pulse-skipping operation at low power, compatibility with ac vehicle operation is a major concern where the motor fundamental frequency continuously sweeps through this signalling frequency band. To address this issue, the TWG developed conducted susceptibility test procedures for relay-based track circuits. Under the auspices of the U.S. DOT, these procedures were applied to the testing of a wide variety of such track circuits to determine representative susceptibility levels, frequency selectivity, and time response (U.S. DOT UMTA/TSC (7)).

As part of the overall EMI/EMC methodology, radiated EMI suggested test procedures were initially developed to assess potential interference with radio communication systems of both the rail operator and the surrounding community--primarily voice radio and commercial broadcast services, although the entire frequency range from 100 Khz to 1 Ghz is scrutinized. To date, EMC compliance in this area for dc chopper and ac drives has been exceptional. However, with the introduction of higher frequency IGBT power switching devices and radio communication-based signalling (RCBS) systems on the horizon, increased EMC diligence is this area will become increasingly important. In response to these concerns, the measurement frequency range for vehicle radiated EMI testing has been extended from 1 Ghz to 3 Ghz by the author in a number of recent applications to cover the RCBS 2.4 Ghz spread-spectrum frequency band in the U.S.. To assess potential RCBS compatible operation, measurements of vehicle pulse/transient broadband noise shall be performed. As a benchmark, an emission limit of 60 dbuV/m/MHz, 2400 Mhz to 2483.5 Mhz, measured both at 3 meters from the track centerline and at a typical RCBS receive antenna location on the vehicle (Note: This field intensity level corresponds to a received level of approximately - 85 dbm, 1 Mhz bandwidth, 0 db receive antenna gain).

Application & Evaluation of Methodology

A number of ac vehicle applications have successfully entered revenue service in U.S. during the past several years. Table I lists many of these, including signalling infrastructure characteristics, and updates a similar list the author prepared just a few years ago (Frasco (8)). The system engineering process used in each case extends throughout the vehicle development and commissioning life cycle.

Limits established by this process on harmonic emissions and susceptibility, calculated and measured in the early stages of application design, power lab testing, and on the test track, have been found to be ultimately consistent with predicted and measured levels as observed during on-property in-circuit signalling system measurements. This exhaustive validation of the process and of the specifics of vehicle, network, and signalling subsystem modelling has provided a high degree of confidence in achieving EMC under extreme worst-case conditions.

It is difficult if not impossible to achieve the simultaneous combination of all worst-case conditions during field testing - e.g. maximum train consist emissions, worst-case coupling with fault conditions. Therefore, actual limits are established based on calculated worst-case conditions plus an additional safety margin (6 db). It should be noted that despite the above argument, during initial development of the EMI/EMC methodology, several unsuccesful attempts were made to measure safety margin empirically through tape recording and interference amplification and playback through signalling circuits. More recently, this approach, called the “Margin Relay” approach was again attempted at the NYCTA during EMC on-property testing of R110A/B ac trainsets. In the author’s opinion, on witnessing these tests, it was clearly demonstrated that this approach is not a reliable indication of vehicle/consist worst-case EMC performance--it is easily corrupted by vehicle and wayside transient conditions, amplifier filter characteristics, etc.

TABLE I - AC Vehicles in Revenue Service in United States

Vehicles	*Signalling Infrastructure*
Heavy Rail	
SEPTA/Philadelphia Norristown High Speed line	100 Hz Relay-based with Cab Signalling
SEPTA/Philadelphia Market Frankford Line	60 Hz Relay-based (Single Rail) Future: Audio Frequency with Cab Signalling, 60 Hz Interlockings
WMATA/Washington, DC All Lines	Audio Frequency with Cab Signalling, 60 Hz Interlockings
MBTA/Boston Red Line	Audio Frequency with Cab Signalling, 60 Hz Interlockings
NYCTA/New York City - R110A/B NT Trains (2)	25 Hz, 60 Hz Relay Based (Single, Double Rail)
MTA/Los Angeles Red Line	Audio Frequency with Cab Signalling, 60 Hz Interlockings
NJT/New Jersey - Arrow III EMU Trains on Amtrak NEC AC Catenary	90Hz-100Hz, 200Hz-250Hz Relay-based with Cab Signalling 500Hz-20,000Hz Audio Frequency Overlays
Light Rail	
MTA/Baltimore	100 Hz Relay-based, Audio Frequency Overlays
DART/Dallas	100 Hz Relay-based, Audio Frequency Overlays
Tri-Met/Portland IGBT AC Traction	100 Hz Relay-based, Audio Frequency Overlays
MBTA/Boston IGBT AC Traction	25Hz, 60Hz, 100Hz Relay-based (Single, Double Rail)
MTA/Los Angeles Green Line/Blue Line	100 Hz Relay-based and Audio Frequency with Cab Signalling, Audio Frequency Overlays
Locomotives	
United States Freight Railroads: Diesel Electric AC	60Hz-100Hz Relay-based, Audio Frequency Overlays
MTA/New York Metro North - Third Rail/Diesel Electric Dual-Mode (Two Suppliers)	90Hz-100Hz, 200Hz-210Hz Relay-based with Cab Signalling (Single, Double Rail), 500Hz-20,000Hz Audio Frequency Overlays
MTA/New York Long Island Railroad - Third Rail/Diesel Electric Dual-Mode (One Supplier)	25Hz, 90Hz-100Hz Relay-based with Cab Signalling, 500Hz-20,000Hz Audio Frequency Overlays
High Speed Trains	
Amtrak/Northeast Corridor - X2000, ICE High Speed Train Set - Six Month Revenue Demonstation	90Hz-250Hz Relay-based with Cab Signalling (Single, Double Rail), 500Hz-20,000Hz Audio Frequency Overlays

While much more complex EMC models exist, simple and effective parameterized models have been developed and validated. They yield results that are quite accurate in practice. They are very easy to use and to understand by both design engineers and transit operating staff. The models require simple calculations and provide continual "sanity checks" of predicted and measured results throughout development and testing. Figure 6 and 7 show examples of these models.

GENERAL EMI/EMC CONSIDERATIONS - U.S. EXPERIENCE

Based on U.S. Experience, the following EMC issues and concerns should be noted:

- Cab Signal Interference
- Undervehicle Inductive Emissions
- Vehicle Input Impedance
- EMI Monitoring/Limit Checking

It is interesting to note that vehicle inductive emissions, the source of the orginal dc chopper signalling compatibility problems in the U.S. almost 20 years ago, is still a major concern.

Cab signal interference induced from ac traction motor cabling in proximity to vehicle cab signal antenna coils has been observed in several railraod and metro applications. The problem is most pronounced with power frequency cab signalling such as 100 Hz, but significant interference levels have been observed well into audio frequency range. The problem for the most part has been resolved by re-orienting motor cables--in extreme cases with very low level cab signalling, special antenna coils or active noise cancelling circuits are available if necessary. Based on these potential high interference levels, re-evaluation of cab signal receiver speed code detection algorithms is underway to minimize susceptibility to this “new” swept harmonic noise source.

Undercar inductive emissions from a variety of potential sources is still a major concern. Constant diligence and scrutiny of vehicle detailed design is required. In a recent application, interference from an ac traction motor “slotted” to fit mechanically into a truck assembly inductively coupled into the nearby axle-wheel-rail loop producing an induced rail-to-rail voltage of more than ten times the audio frequency signalling circuit pick-up voltage. In another recent ac catenary locomotive application, the main transformer has been located under the locomotive with major potential EMC consequences.

With the increasing number of vehicles with solid-state propulsion (dc chopper or ac) and auxiliary power systems, specification and control of vehicle input impedance is becoming a major concern. Vehicle input impedance at traction power supply and critical signalling frequencies can have significant impact on harmonic levels at these frequencies. In solid-state applications, the vehicle input impedance is determined primarily by the propulsion and auxiliary line filters. Care must be taken to avoid filter resonances at critical system frequencies--including resonance with third-rail and catenary impedances. In the U.S., the author has recommended that miminum vehicle input impedance should be 1 milli-henry inductive at these critical frequencies.

Finally, EMI monitoring and limit checking is an important EMC consideration in U.S. A number of ac vehicle applications are presently in revenue service using monitoring systems and are under evaluation. Also, a number of further developments and refininements including line filter integrity checking, etc. are ongoing in this area for both locomotive/power car and electric MU applications to address improvements in performance and impact on vehicle operational reliability. The subject warrants its own paper, but it is certainly clear that EMI monitoring is only a tool and not the total answer in addressing ac vehicle EMC concerns. As can be seen from past U.S. experience reported above, vehicle inductive emissions have been an elusive and major safety concern--an area EMI monitoring doesn’t address.

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REFERENCES

1. Frasco L. A., Gagnon R., and Holmstrom F. R., April 1980, “Choppers Affect Operation of AF Track Circuits”, Railway Gazette International

2. U.S. DOT UMTA/TSC, July 1980, “Draft Recommended Practice Rail Transit Intra-System Electromagnetic Compatibility Vehicular Electrical Power and Track Circuit Signalling Subsystems”

3. Frasco L. A., and Holmstrom F. R., November 1981, “EMC Consequences of Power Electronics Applied to Rail Transit”, IEE International Conference on Railways in the Electronic Age, London, UK

4. U.S. DOT UMTA/TSC, May 1987, “Conducted Interference in Rapid Transit Signalling Systems, Vol II: Suggested Test Procedures”, U.S. Department of Transportaion, UMTA-MA-06-0153-85-6

5. U.S. DOT UMTA/TSC, March 1987, “Inductive Interference in Rapid Transit Signalling Systems, Vol II: Suggested Test Procedures”, U.S. Department of Transportation, UMTA-MA-06-0153-85-8

6. U.S. DOT UMTA/TSC, June 1987, “Radiated Interference in Rapid Transit Systems, Vol II: Suggested Test Procedures”, U.S. Department of Transportation, UMTA-MA-06-0153-85-11

7. U.S. DOT UMTA/TSC, February 1986, “Labor-atory and Field Testing of NYCTA Power Frequency Track Circuits”, U.S. Department of Transportation, Urban Mass Transportation Administration, Washington, DC, UMTA-MA-06-0153-85-12

8. Frasco L. A., June 1993, “Report on AC Traction Operating Experience - EMI/EMC Considerations”, APTA 1993 Rapid Transit Conference, Miami, FL

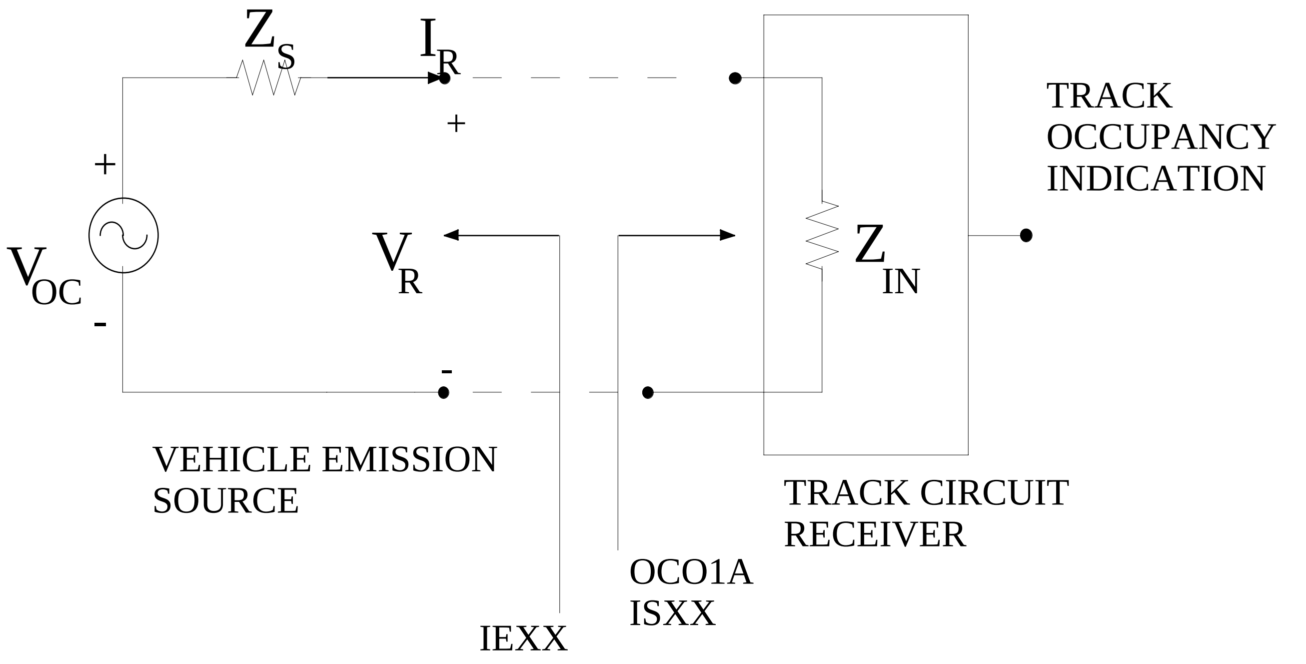


Figure 1: Inductive Interference Circuit

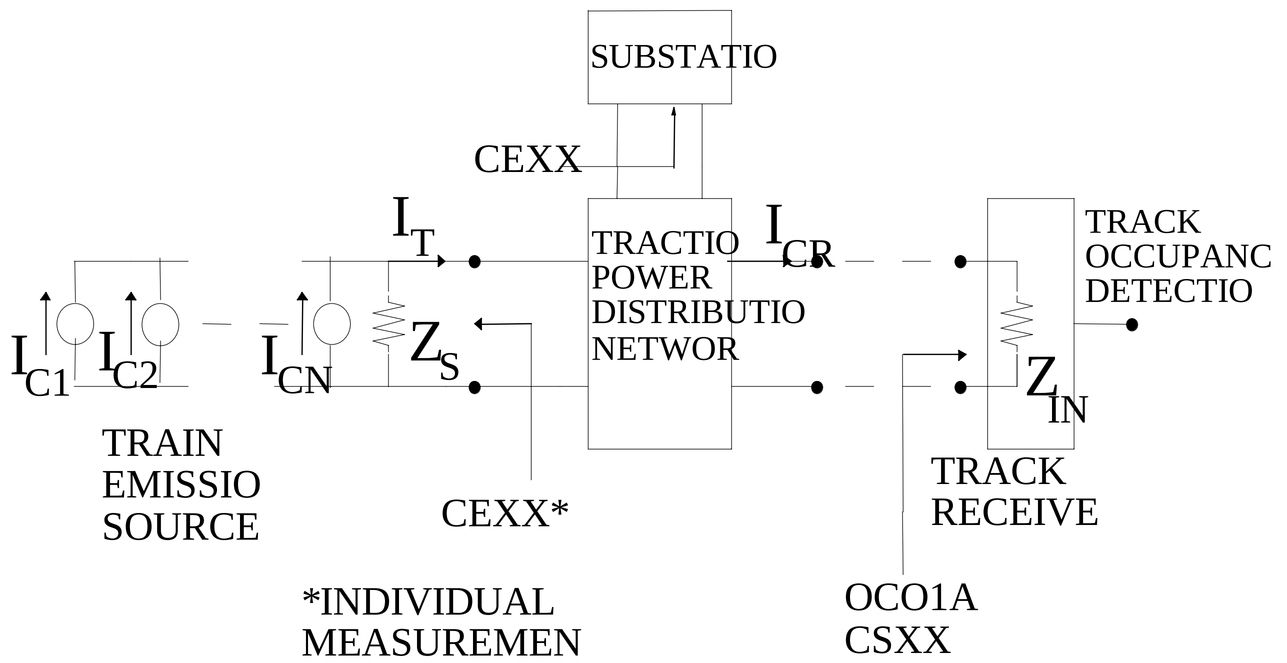


Figure 2: Conducted Interference Equivalent Network

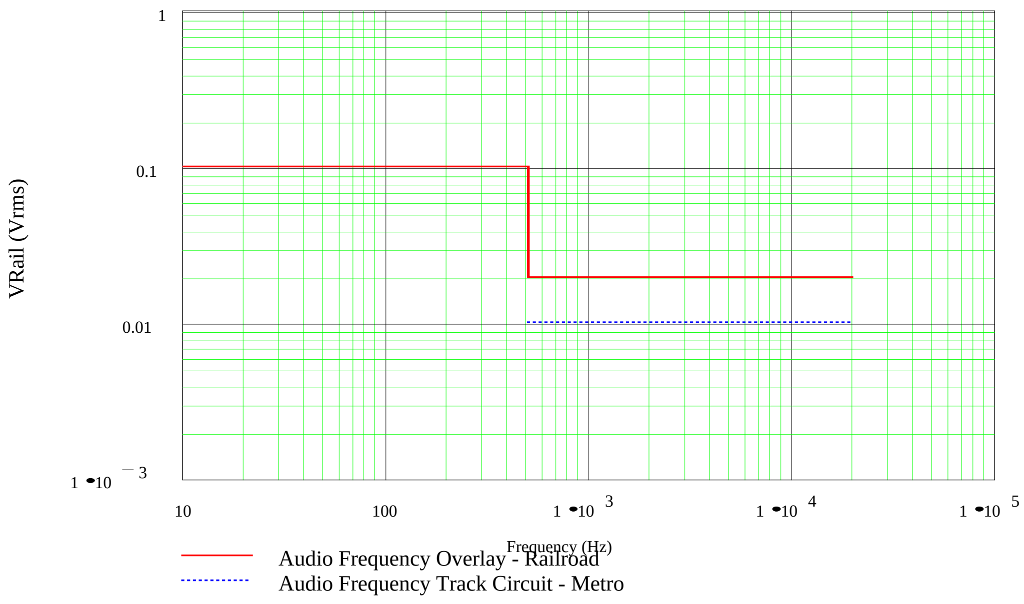


Figure 3: Maximum Allowable Rail-to-Rail Voltage, Under Vehicle

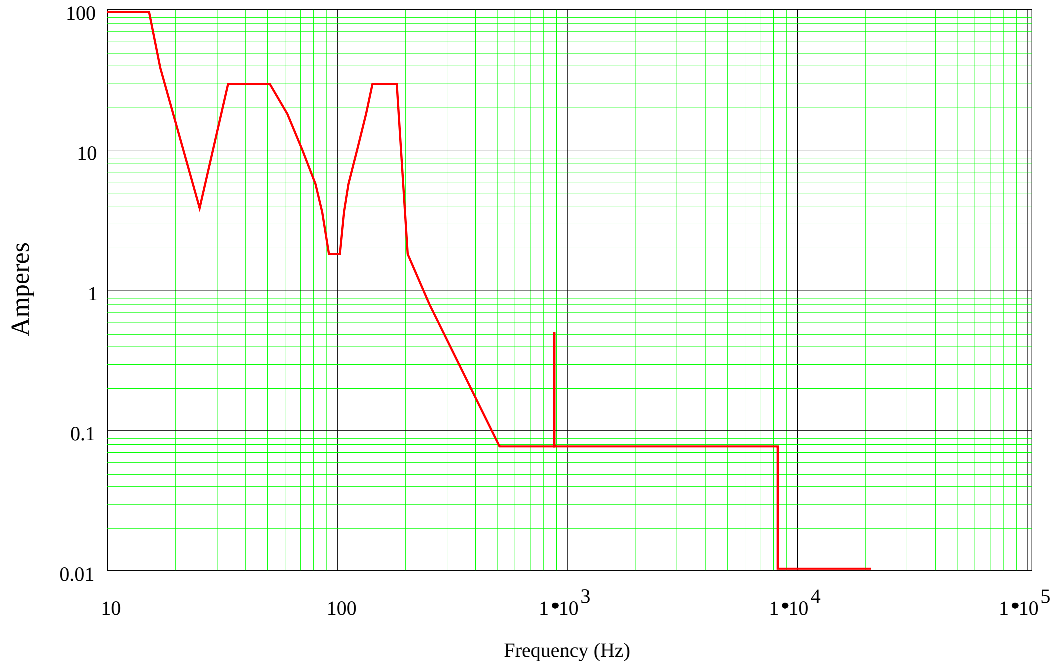
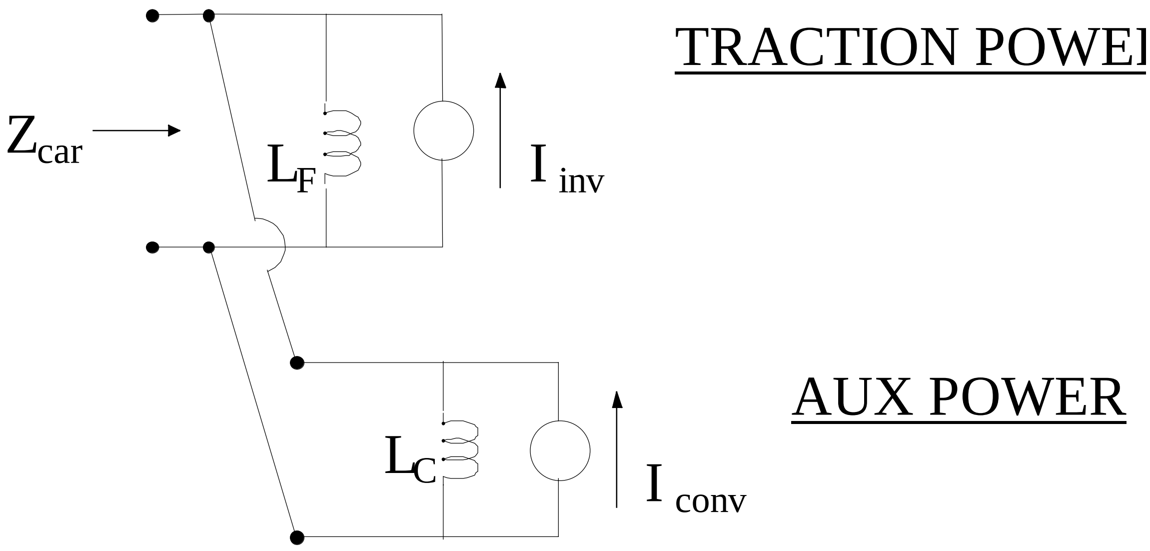
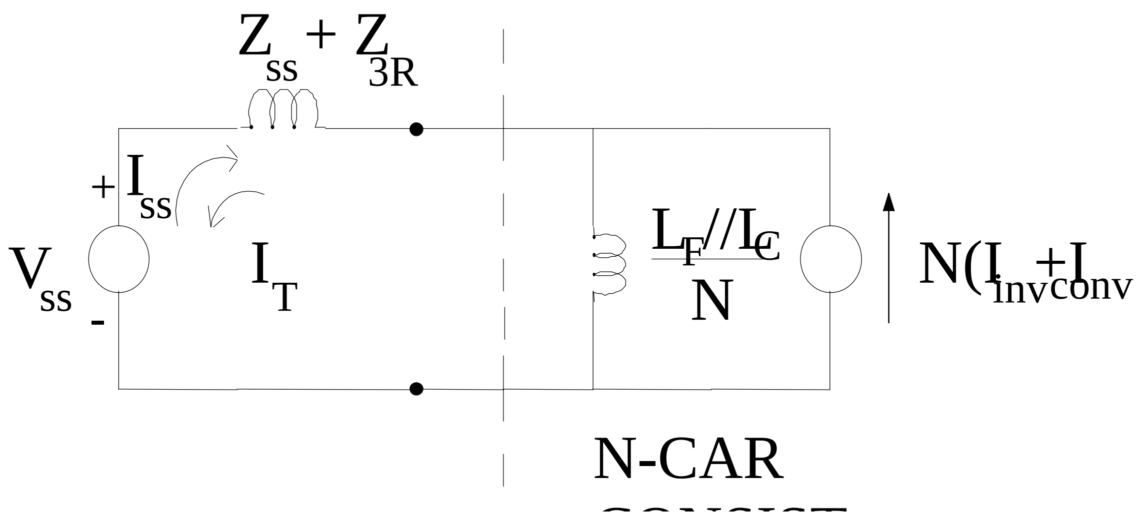


Figure 4: Maximum Allowable Harmonic Emission Current At Line Supply Input (Train Consist)

Figure 5: AC Catenary Conducted Emissions Harmonic Current Limit (Train Consist)

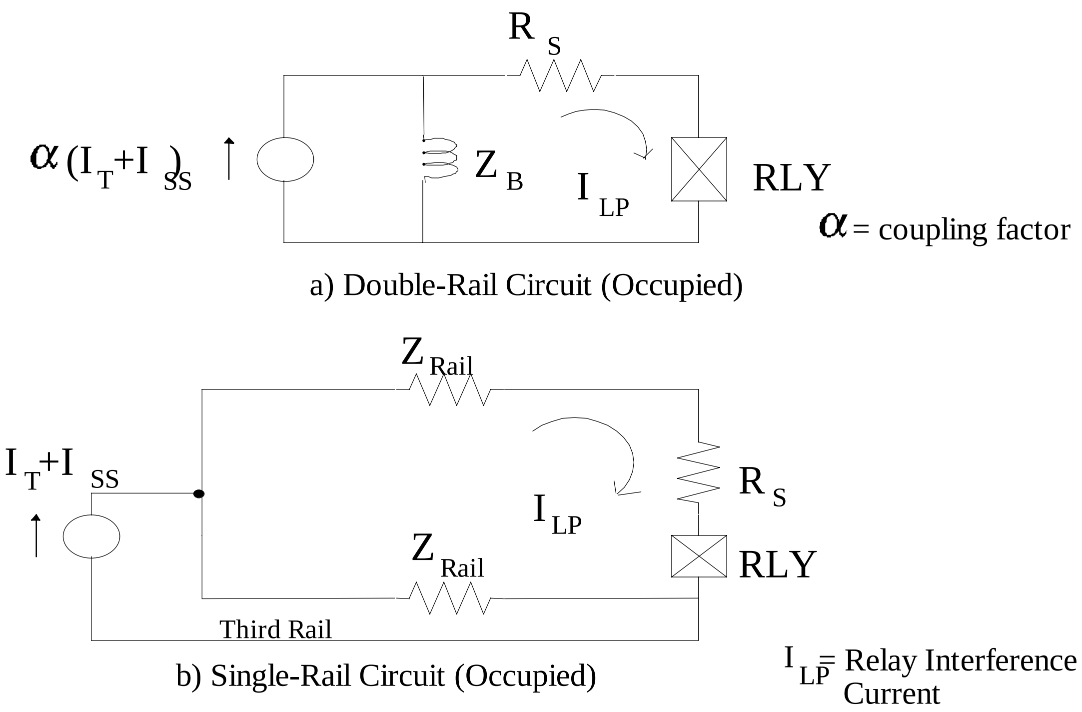


a) Single Car Model



b) Train

Figure 6: Sample Vehicle/Electrical Network Model



a) Double-Rail Circuit (Occupied)

b) Single-Rail Circuit (Occupied)

Figure 7: Sample Signalling Models