Volume 1
1st Quarter 2012

# ieee electromagnetic compatibility magazine


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Transportation Systems EMC
page 74

EMC SOCIETY

IEEE

# Rail Transit EMI-EMC

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***Abstract***—Rail transit systems around the world benefit from increasingly sophisticated systems for electric propulsion, auxiliary power, control, and signaling. Applying these systems cost-effectively requires interoperability standards and testing procedures that guarantee EMC. This paper surveys the sources of EMI in rail transit from propulsion and auxiliary power systems, and the potential disruption of track signaling and train control systems that can result. U.S. and European standards for design and testing of rail transit system equipment are reviewed. Standards and test procedures for radiated interference in rail transit systems are reviewed, and EMI/EMC challenges are noted.

## 1. Introduction

Beginning in the late 1970's, the availability of high-power semiconductor thyristors led to the development of solid-state propulsion controllers for rail transit cars operating on DC power. These power controllers were essentially large switched mode power supplies using switching frequencies of 200 to 500 Hz. Not surprisingly, they generated audio frequency EMI from the fundamental switching frequency through the audio spectrum. Subsequent semiconductor developments led to the introduction of solid-state DC-AC converters for both propulsion and auxiliary power for heavy- and light-rail urban transit systems and to AC- DC-AC converters for commuter rail systems using high voltage AC power. To develop tools for anticipating, reducing and measuring power system EMI and to insure EMC with automatic train control and signaling systems, the U.S. Department of Transportation rail transit EMI/EMC program was born. The program formed a group known as EMI-TWG, with representatives from rail transit propulsion suppliers and signaling suppliers, transit agencies, consultants, and government engineers. The EMI-TWG created technical frameworks, analytic data, test procedures, and emission limits which continue in broad use today.

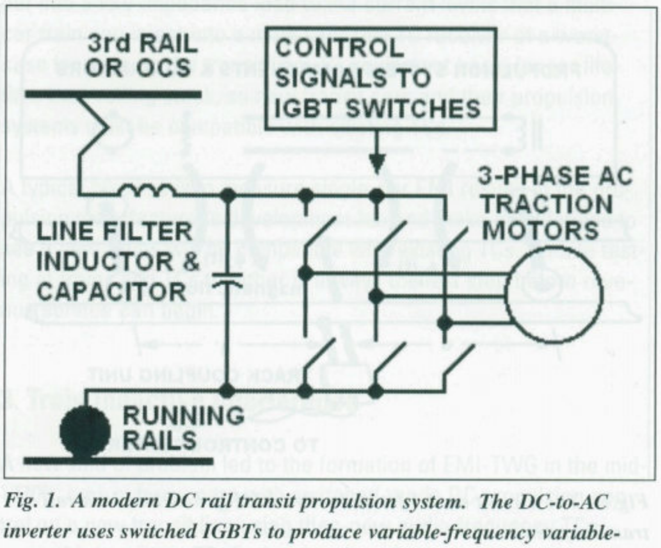


*Fig. 1. A modern DC rail transit propulsion system. The DC-to-AC inverter uses switched IGBTs to produce variable-frequency variable-voltage 3-phase AC currents that drive induction propulsion motors.*

This paper outlines EMI characteristics of rail transit propulsion systems, and describes the U.S. and European standards for emissions and susceptibilities as well as test procedures to assure compatibility of propulsion and signaling systems, both on the equipment level, and for trains and rail systems taken as a whole.

For equipment EMC, the rail transit industry makes broad use of the US Federal Communication Commission Part 15 limits for equipment conducted and radiated emissions. Increasingly, the rail transit industry is using the set of Euronorm standards such as [1] to provide a compatible set of emission and immunity limits and test standards for equipment of all types.

For trains and rail transit systems, the rail transit industry considers three modes of rail transit EMI – conductive, inductive and radiated. The transit industry evaluates conductive and radiated EMI as in most applications, as EMI currents carried by conductors and as EMI fields present in space. Inductive EMI is described in a way more unique to rail transit operations. It arises from very short range inductive coupling of source conductors that carry EMI current to target conductors connected to rail transit signaling apparatus. These three modes are considered below.

## 2. Train Conductive Interference

Fig. 1 shows the operating principle of modern DC powered rail transit propulsion systems. The Insulated Gate Bipolar Transistors (IGBTs) are switched on and off in patterns that approximate variable-frequency variable-voltage 3-phase current waveforms to drive the AC induction motors. The pulsed current flow produces harmonic EMI currents in the overhead contact system (OCS) or third rail. These currents include strong harmonics of the instantaneous frequency of the 3-phase motor current, which

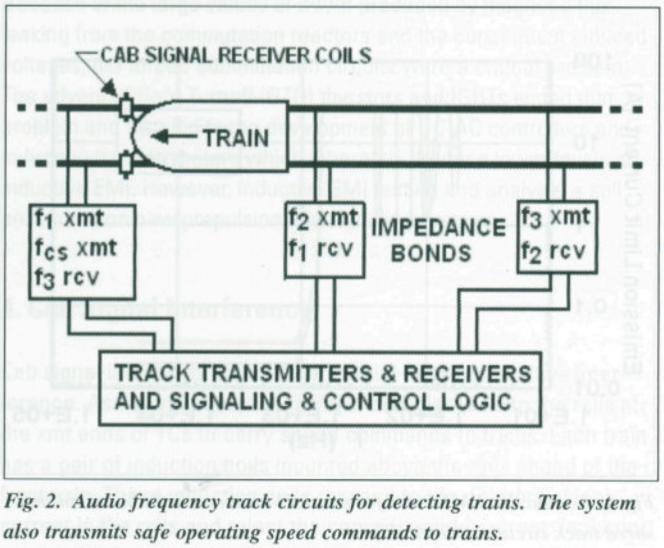


*Fig. 2. Audio frequency track circuits for detecting trains. The system also transmits safe operating speed commands to trains.*

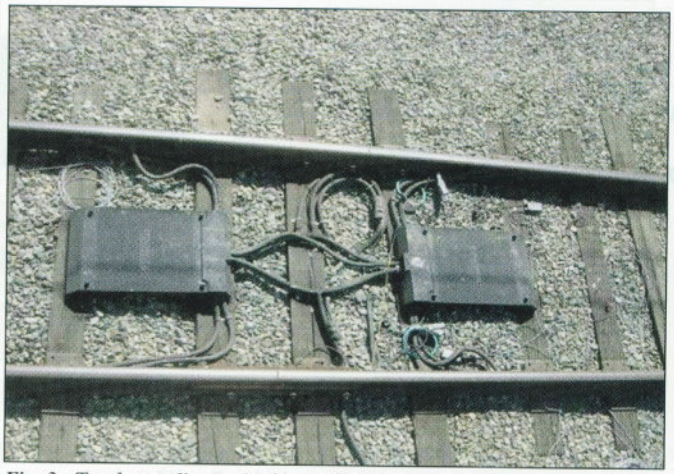

*Fig. 3. Track coupling units for audio frequency track circuits.*

sweep with changes in motor speed. These currents are train conductive EMI.

The LC line filter attenuates the harmonic EMI current flowing to the DC traction power supply. Railcar size and weight considerations limit the values of L and C and and how much the harmonic EMI current can be attenuated.

The asymmetrical location of the third rail in heavy-rail DC-powered rapid transit systems leads to a differential or circulating-loop component of all harmonic currents flowing in the running rails. Even in OCS systems, coupling between the various conductors in a 2-track right-of-way causes differential harmonic EMI current flow. These differential EMI currents can disrupt the signal systems that control the movement and speed of trains.

Modern rail transit systems typically employ audio frequency track circuits (TC) to detect the presence of trains at specific locations on a track. The TCs vary in length from 100 to 5000 ft. Fig. 2 shows a track using continuously welded rails with several TCs. A current at audio frequency f1 is injected at the transmit (xmt) end of TC1 by a coupling transformer called an "impedance bond". The current is often modulated by frequency, code, or amplitude. A pair of impedance bonds is shown in Fig. 3. If the current is

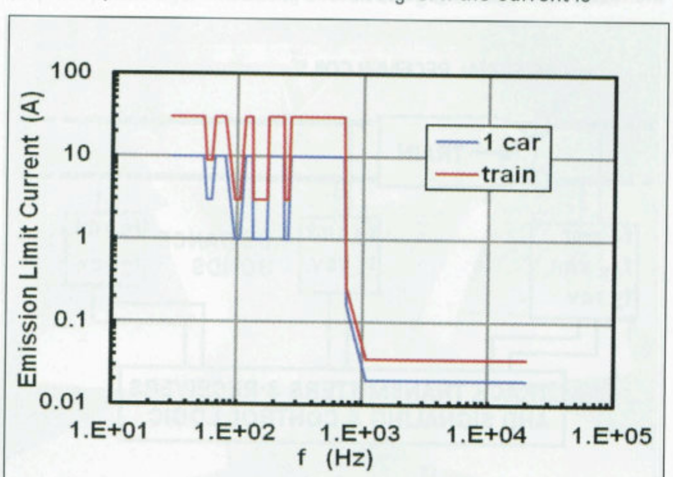


*Fig.4. Conductive EMI limits for one LRV and one train based on measured track circuit susceptibility.*

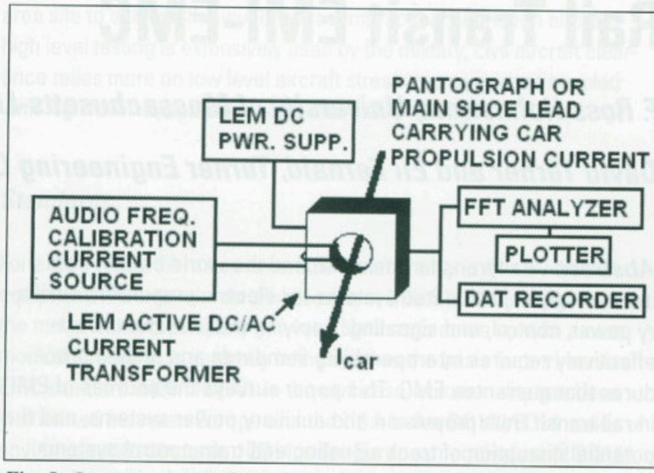


*Fig. 5. Instrumentation for recording conductive EMI from a single rail transit car.*

received at the receiver (rcv) end, then no train is present in TC1. If a train is present in TC1, the xmt current will be shunted by the train axles and wheels and will not make it to the rcv end. Information on train presence along the length of an entire track is used to determine safe operating speeds of trains in TCs along the track. Impedance bonds are tuned to have high impedance at the frequencies at which they transmit and receive signals and low impedance at other frequencies.

The track signal system typically uses a pattern of three or four TC signal frequencies along each track. In addition, TC transmitters circulate modulated cab signal (CS) currents at unique frequencies to send speed commands to each train. These CS currents are sensed by inductive pickup coils ahead of each train's leading axle. CS speed commands may be encoded as a frequency modulated code, as a pulse rate, or as a frequency pair.

Propulsion system conductive EMI can potentially cause two modes of track circuit failure. An EMI current at the TC rcv end could be interpreted as a valid TC current and falsely indicate the absence of a train, causing a "false clear" (FC) or "wrong-side" failure. Alternatively, the EMI current could swamp the rcv so it cannot detect the actual presence of the TC signal, causing a "false occupancy" (FO) or "right-side" failure.

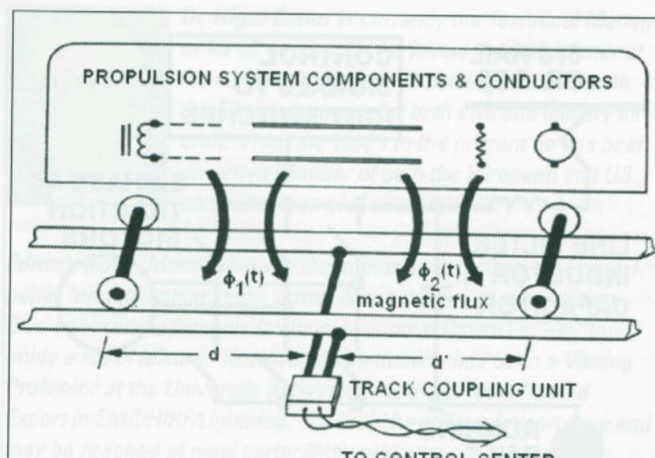


*Fig.6. The circuit model for inductive EMI generation in a rail transit system.*

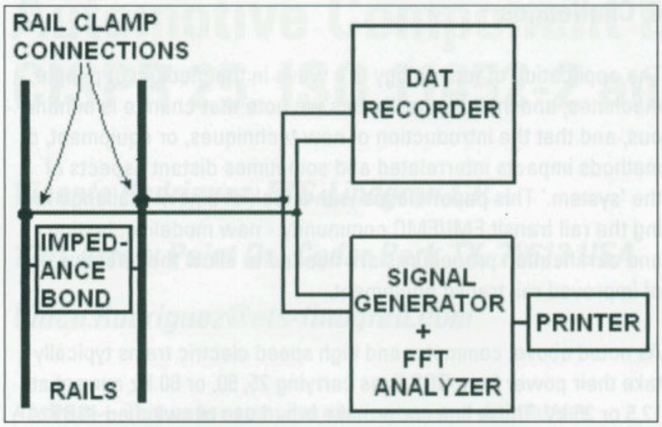


*Fig.7. Inductive emission measurement setup.*

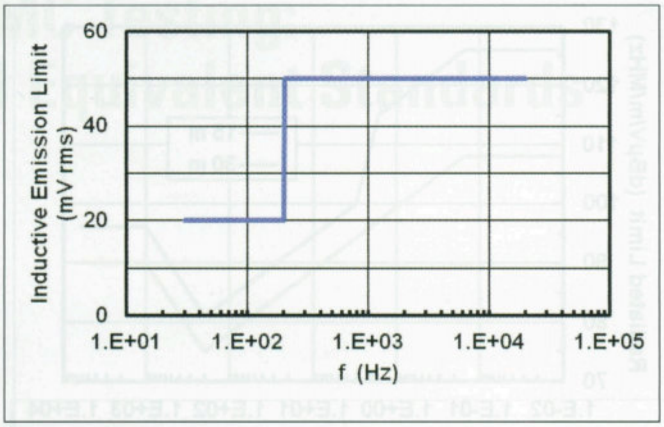


*Fig.8. Inductive emission limit for a light rail transit line.*

FC failures obviously can lead to disaster. Fortunately, the use of TC signal correlation and comparison techniques to discriminate between actual received TC signals and EMI dramatically mitigate this hazard.

FO failures cause service delays and disruptions, and also increase the liklihood of an accident. If a manual mode is used when the signal system has a high FO failure rate, automatic protections are no longer available, and operating staff may not fully recognize the potential for hazards and the necessary limitations to maintain safety.

To guard against these EMI hazards to rail transit signal systems, the EMI-TWG developed suggested test procedures for measuring conductive EMI current levels produced by rail transit cars and trains and for measuring the susceptibility of track circuit receivers to EMI [1]. These standards, developed as transit systems began using switched-mode DC propulsion power supplies and DC traction motors, have been broadly adapted for application to DC-AC converters powering AC traction motors.

Fig. 4 shows conductive emission limit curves resulting from susceptibility tests performed on audio frequency TC equipment. Fig. 5 shows the instrumentation setup for recording conductive EMI currents produced by a single rail car under test.

To ensure compatibility on the train – signal system level, circuit and signal analysis extrapolates the EMI current levels of a single car into a low-impedance load to the current levels that a multi-car train can inject into a most sensitive TC receiver at a worst-case location on the transit line. TC equipment has a longer lifetime than rolling stock, so new transit cars and their propulsion systems must be compatible with existing TCs.

A typical process is to measure single-car EMI results in the propulsion manufacturer's development lab and make calculations to see if new trains will be compatible with existing TCs. On-site testing of trains and TCs together is always the last step before revenue service can begin.

## 3. Train Inductive Interference

A new kind of problem led to the formation of EMI-TWG in the mid-1970's: new subway cars with switched-mode DC propulsion control on a new transit line using then-new audio frequency TCs caused intermittent FCs in the signal system.

EMI-TWG eventually solved the problem. The switched-mode propulsion power controllers incorporated solenoid-type inductors. Pulsed components of magnetic flux emanating from the solenoids induced pulsed voltage in the conducting loops immediately under a car formed by the car's axles, rails and TC leads, shown in Fig. 6.

Understanding the roots of this problem led directly to changes in the design and mounting of inductors in similar propulsion systems, changes in the design of TC systems, and development of test procedures for assessing TC inductive EMI susceptibility and emission levels [2].

Fig. 7 shows an inductive EMI test setup over which a powered rail transit car will accelerate many times from an array of starting points to assure that worst case EMI levels are observed and recorded. Fig. 8 shows the inductive emission limit curve for a light rail transit line.

The 1970s switched-mode propulsion power controllers that caused the initial inductive EMI problem used silicon controlled rectifier thyristors that were easy to turn on, but only could return to their off-state when the instantaneous current was zero. Therefore the controllers used "forced-commutation" circuits – LC loops with resonant frequencies in the 10 kHz range – and these loops were pulsed to produce a large-amplitude short-duration reverse-current pulse to the main thyristor which would drive its total current to zero so that it could be turned off.

Because of the large values of $d\Phi/dt$ produced by magnetic flux leaking from the commutation reactors and the consequent induced voltages, the forced commutation circuits were a critical problem. The advent of Gate Turnoff (GTO) thyrstors and IGBTs ended that problem and also led to the development of DC-AC controllers and induction traction motors which inherently produce lower levels of inductive EMI. However, inductive EMI testing and analysis is still performed on new propulsion and signaling systems.

## 4. Cab Signal Interference

Cab signal interference (CSI) is a special case of inductive interference. As noted above, CS currents are injected into the rails at the xmt ends of TCs to carry speed commands to trains. Each train has a pair of induction coils mounted above the rails ahead of the front axle. These induction coils respond to the differential loop current in the rails and reject the common mode current. In theory, conductive interference arising from propulsion-caused EMI loop

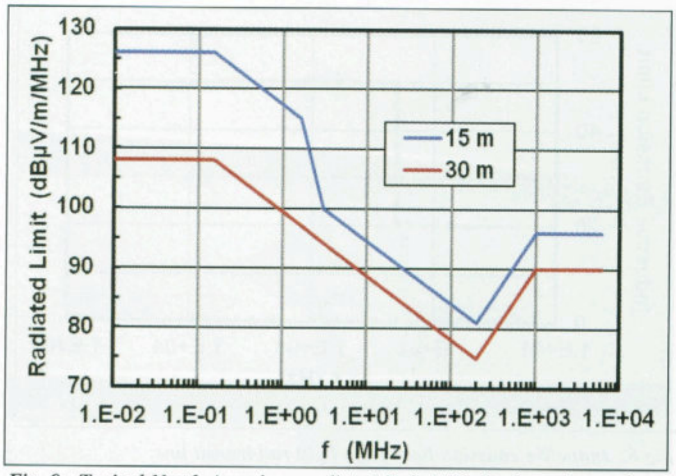


*Fig. 9. Typical North American radiated E-field limits for rail transit trains measured at distances of 15 and 30 meters from the track.*

currents in the rails could interfere with correct reception of the ATC command signals. In practice, this isn't as big a problem as the one caused by harmonic components of magnetic flux arising from the motor leads and motor casing of a rail car's front motor passing directly along the axes of the pickup coils.

CSI can interrupt speed signal reception, which will cause a train to slow or stop; and it also can potentially cause reception of a wrong higher speed command, which is an immediate hazard.

A CSI limit applies to a specific train, and is determined by the onboard CS antennas and receiver and by the typical and worst-case CS levels in the track. Typically, the limit is a graph showing CS receiver sensitivity levels vs. frequency. The graph will be based on CSI testing conducted under controlled conditions in the rail car maintenance facility.

## 5. Radiated Interference

Radiated interference from rail transit vehicles can interfere with communication systems belonging to neighbors and to a transit system itself. EMI-TWG developed the standard for testing U.S. rail transit systems for radiated EMI [3]. Related standards are [4]-[7].

Figure 9 shows two typical North American radiated EMI limit curves, for EM fields measured at distances of 15 m and 30 m from the track. The standard calls for measuring both horizontally and vertically polarized fields.

Another consideration is power-frequency magnetic fields. Commuter and high speed rail systems use AC traction power, e.g., 12.5 or 25 kV at 25, 50, or 60 Hz. Magnetic fields from OCS and rail currents can potentially affect people with implanted electronic devices such as pacemakers. For power frequency magnetic field exposure, IEEE Standard C95.6 specifies a maximum permissible exposure (MPE) level of 9 G (0.9 mT) for the general public. However, other sources, such as one pacemaker manufacturer, recommend a maximum exposure of 1 G (0.1 mT) or less for people with implanted devices. This issue is of special interest to one of the authors of this paper, who has an implanted pacemaker. Note that an AC-powered commuter rail car at a location midway between the running rails and an OCS at 4 m elevation carrying 1 kA the magnetic field strength is 2 G.

## 6. Challenges

The application of technology is a wave in the medium of people, machines, and institutions. By this we note that change is continuous, and that the introduction of new techniques, or equipment, or methods impacts interrelated and sometimes distant aspects of the 'system.' This paper closes with a look at a new challenge facing the rail transit EMI/EMC community - new modeling, testing and certification procedures are needed to allow the effective use of improved rail transit equipment.

As noted above, commuter and high speed electric trains typically take their power from OCS lines carrying 25, 50, or 60 Hz current at 12.5 or 25 kV. These lines now make broad use of switched-IGBT rectifiers for converting input AC power to DC so that the DC power can then be inverted back to variable-voltage variable-frequency AC power to drive induction traction motors. The rectifier IGBTs are controlled to produce a near-unity power factor load to the power transmission system, which power utility companies strongly prefer over earlier GTO and thyristor systems which are rich in low order harmonics. Increasingly, power utility companies demand compliance with IEEE Std 519 [8] to control power frequency harmonics.

The IGBTs typically switch on and off approximately 20 times per power frequency cycle, and EMI currents are produced in clusters of odd harmonics of the power frequency around even multiples of the switching frequency. These strong clusters span the audio frequency band. Two key questions arise about these harmonic currents.

First, the amplitude and locations of these clusters interfere with the operation of many audio frequency TCs, including those in broad use across the US for grade crossing protection on electric railways. If the clusters interfere with the operation of enough TC frequencies, rail line designers won't have enough choices to cover all the required locations.

Second, the end-to-end length of many commuter rail lines is longer than a wavelength at a typically expected 20 kHz harmonic frequency, and standing wave phenomena have been predicted. The main train power transformers may have resonances due to interwinding capacitance at frequencies in the 5 to 25 kHz range. And it is uncertain what resonance properties power company high voltage distribution transformers have. High frequency transit EMI currents appear new to them. And so, to be continued. . . **EMC**

## References


[1] EN 50121-3-2:2006, Railway applications. Electromagnetic compatibility. Rolling stock. Apparatus

[2] UMTA-MA-06-0153-85-6, Conductive Interference in Rapid Transit Signaling Systems, Volume II: Suggested Test Procedures.

[3] UMTA-MA-06-0153-85-8, Inductive Interference in Rapid Transit Signaling Systems, Volume II: Suggested Test Procedures.

[4] UMTA-MA-06-0153-85-11, Radiated Interference in Rapid Transit Signaling Systems, Volume II: Suggested Test Procedures.

[5] EN 50121-2, Railway applications - Electromagnetic compatibility Part 2: Emission of the whole railway system to the outside world.

[6] IEEE Std C95.6, Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0 - 3 kHz.

[7] Mil-Std-417, Requirements For The Control Of Electromagnetic Interference Characteristics Of Subsystems And Equipment.

[8] IEEE 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems


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## President's Final Report

Concluding her last meeting as EMC Society President, Francesca Maradei thanked everyone for attending and contributing to the Board meeting. See provided an overview of the Society's accomplishments over the past two years. Despite the economic slump and global recession, the Society has managed to remain strong and focused on its primary objectives. Membership has remained stable with some 4,000 members, of which half reside outside the US. After a three year effort, the EMC Society completed the development and approved the Strategic Plan (SP). Symposium locations have been selected five years out, through 2016, with one symposium being located outside the US in Dresden Germany (the first time since 2003). A new approval process has been initiated for providing EMC-S technical co-sponsorship to symposia. In the last two years, the Society has welcomed six new chapters worldwide: Syracuse and Pikes Peak in IEEE Regions 1-7; Nigeria and Serbia/Montenegro in IEEE Region 8; Shanghai and Chengdu in IEEE Region 10. There are 77 chapters to date. The EMC-S unanimously approved the implementation of a special Standards travel grant that was received from a donor to support travel to actively participate in Standards committee meetings. The EMC-S successfully completed the periodic five-year Society review on behalf of the TAB Society Review Committee (SRC). As a result, several of the Society's best practices will be shared with other Societies. Due to the popularity of TC-11 on Nanotechnology, the *IEEE Transactions on EMC* scheduled a special issue on "Applications of Nanotechnology in Electromagnetic Compatibility (nano-EMC)". The IEEE has approved the transition of the Newsletter to an EMC Magazine that will be launched in January 2012. The Magazine will be included in the IEEE Xplore digital library and indexed in the official Journal Citation Report. Other highlights included in the report address global outreach and increasing internationalization of the Board membership.

*Francesca Maradei congratulated the incoming Board members for 2012-2014, including (from left) Fred Heather, Colin Brench of Amphenol High Speed Interconnect and Mark Montrose.*

## Adjournment

The meeting adjourned at 5:15 pm.
Submitted by:
Janet O'Neil
Secretary, EMC Society Board of Directors **EMC**

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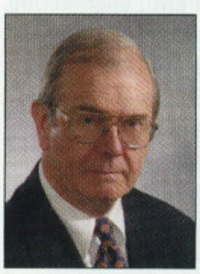
## Biographies



***Dr. F. Ross Holmstrom*** *is a leading US authority on electromagnetic interference and compatibility (EMI/EMC) in transit applications, with more than 36 years of experience and leadership. He is a Professor Emeritus of Electrical Engineering at the University of Massachusetts - Lowell. He performs research and development on electronics and electromagnetics applications in rail transit operations and safety, sponsored by FTA and the Federal Railroad Administration. His research areas include EMI, intelligent highways, signal processing and analysis for automatic train controls systems. Dr. Holmstrom also served as a staff member of the US Department of Transportation's Transportation Systems Center, conducting and advising on government programs in electronic aspects of ground transportation.*

***David Turner*** *manages development, integration, and certification of advanced safety-critical train control, communication, propulsion, energy, and information systems for high-tech rail transportation applications. He has broad experience with transportation electromagnetic compatibility (EMC) methods and programs; high-tech and safety-critical software development and hardware structured design practices; and transportation reliability, maintainability, and safety (RAMS) programs and techniques. His projects include trains and systems for mainline and commuter railroads, rail transit, and driverless peoplemovers. He is President of Turner Engineering Corporation.*

***Eli Fernald*** *is a senior electronics, software, and system engineer with extensive experience in rail transit equipment and system engineering, electromagnetic compatibility engineering, safety assessment for rail transit signal systems and railcars, and rail transit energy improvement projects, for signals, trains, and communications, including for New York City Transit, Metro North, Philadelphia SEPTA, and Denver Eagle P3. He is also adept at high-performance electronic integrated circuit design, embedded and web software development, instrumentation hardware and software, design and integration of communications circuits and equipment, and use of computer modeling tools for complex design and verification projects. He is a Principal Engineer at Turner Engineering Corporation.*