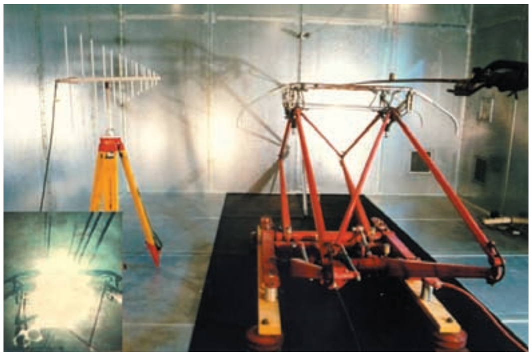

Bernardo Tellini, Massimo Macucci, Romano Giannetti, and Gabriele A. Antonacci

Line-Pantograph EMI in Railway Systems

Electromagnetic interference (EMI) in electric railway operation has become increasingly important. The components within very high-power electronics, and the circuits for treating low-level signals, comprise a complex system that must coexist and be highly reliable. Complicating this situation is the progressive integration of European railway networks that requires common standards and measurement procedures for both undesired emissions and susceptibility to electromagnetic interferences of external origin. There are also requirements for:

- interoperability of rolling stock;
- separation between the management of the network infrastructure and that of the traction equipment;
- and increased usage of wireless control and signaling.

At present, the EN50121 [1] standards are the main reference for electromagnetic compatibility in European railway systems. These standards should improve as technology and testing develops. Therefore, major sources of EMI in a railway environment need to be better understood. This study is complex because many different railway power systems exist in Europe (1.5 kV dc, 3 kV dc, 15 kV 16.7 Hz, 25 kV 50 Hz). European railways are using new control and communication systems, and electromagnetic compatibility problems should be carefully studied and solved.

Line-Pantograph Interaction

We have investigated the electromagnetic emissions from the interaction between the pantograph and the overhead contact line. Losing mechanical contact between the pantograph and the overhead wire generates an electric arc [6]. In dc systems, such as used by the Italian Railways (3 kV dc), the arc does not extinguish during normal operation and the current remains constant, maintained by the inductance of the load. A detailed model is needed to predict the contributions from the pantograph contact to electromagnetic emissions in new designs.

Experimental Setup

We started our investigation of the emissions from the pantograph and overhead line with the experimental analysis of a static setup. We wanted to understand the contributions from both the switch-on transients when the pantograph touched the contact wire and the switch-off transients when it detached. Our setup consists of a 6 m segment of Italian Railways overhead contact line, a pantograph and its pneumatic equipment, all located in a shielded room, and a resistor for load simulation, in parallel with a stray capacitance of 10 nF. The load resistor, capable of dissipating very large amounts of power, is not in the shielded room but in a separate location with appropriate ventilation. A high-voltage 4 kV dc power system (with a power capability of 5.4 MW) supplies the overhead contact line through a 39-mH inductor that simulates the inductance of the supply line. Fig. 1 illustrates the setup.

A high-speed, digital storage oscilloscope (a Tektronix TDS 680B) measured the current and voltage transients and the output of the measurement antennas. It had a maximum sampling rate of 5 Gsamples/s. We located the oscilloscope in a smaller shielded room, independent from the main measurement chamber, and connected it to a PC outside the high-voltage area via an IEEE-488 optical link.

A Tektronix P6015 voltage divider and a wide band Electro-Metrics PCL30 clamp-on current probe acquired the volt-

1094-6969/01/$10.00©2001IEEE

ages and currents. We corrected the measurements for the frequency response of the probes used.

In each experimental sequence, we raised the pantograph until it reached the overhead contact line to close the circuit. We then lowered it, which created an arc of increasing length. We turned off the arc with a fast external circuit breaker to avoid damage to the floor of the shielded room should the arc reach it when the pantograph was fully lowered.

Losing mechanical contact between the pantograph and the overhead wire generates an electric arc.

Switch-On and Switch-Off Transients

Fig. 2 shows a typical current waveform and the associated, radiated field acquired during the switch-on transient. The dc voltage was 4100 V and the load resistance was 125 Ω.

The exponential rise of the current and voltage to their steady-state value takes much longer (tens of milliseconds) than the time interval shown in our figures. The relevant transient, for EMI, lasts a few microseconds—a time span over which the 39 mH inductor can be assumed an open circuit. Two oscillations, on different timescales, occur in the current: one, strongly damped, around 1 MHz and the other, less damped, around 20 MHz. The higher frequency becomes much more significant in the electric field because of the radiation properties of the circuit.

The switch-off transient exhibits a completely different behavior. Both the current and the field values are much lower than in the switch-on transient. Fig. 3 shows the field emitted during switch-off in the same arbitrary units as the ones used for the switch-on measurement; its intensity is about 200 times lower.

Such a result should be expected considering the origin of the main electromagnetic emission. It is the consequence of the fast transient associated with the circuit switch-on event. Conversely, there is no fast transient during the switch-off event because the arc preserves the continuity of the circuit and there is no large variation in current. This is a simple, but important point [4], which has often been misunderstood in the literature. The arc has no special property from the point of view of the electromagnetic emission (except for radiation in the visible and UV spectrum due to heating); it is just a short section of the circuit.

We have studied this issue in detail with a few experimental tests on a scaled down circuit [2], [5]. We performed measurements of the radiated field, alternately shielding the arc or other parts of the circuit. Our setup is shown in Fig. 4. A 2.2 nF capacitor is charged to about 4 kV and then discharged.

We can either place or remove the covers of the boxes containing the sphere and the capacitor, thus shielding or removing the shielding from each section of the discharge circuit. We have observed that the total emission is only slightly reduced when shielding the arc, but we observed a very significant reduction when the shield covers the capacitor and most of the circuit. Fig. 5 shows experimental results for the radiated field. The top plot refers to the condition with both box covers removed and maximum emission. The middle plot shows, in the same arbitrary units, the radiated field measured when only the cover of the box containing the capacitor is in place and the box where the arc occurs is open. Finally, the bottom plot shows the situation with both boxes closed.

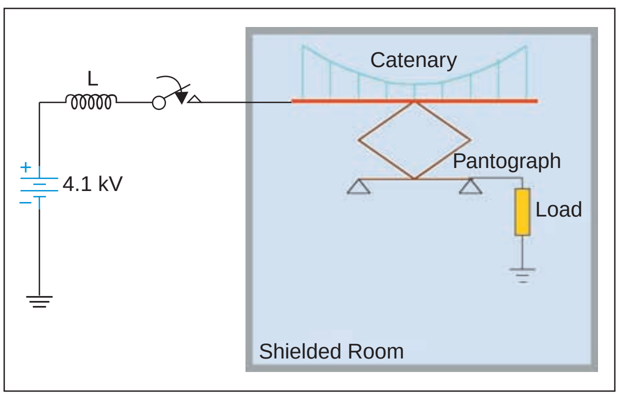

Fig. 1. The measurement setup assembled in the shielded room of the research laboratory "Sala Prove Alta Tensione" of the Italian Railways.

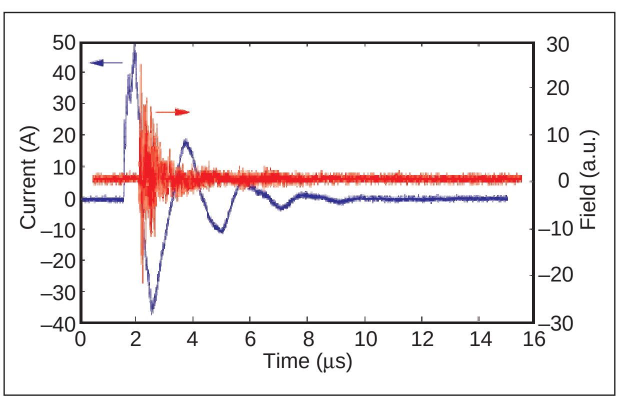

Fig. 2. A typical current waveform and the associated, radiated field acquired during the switch-on transient. The applied dc voltage was 4100 V, the load resistance was 125 Ω, and the line inductance was 39 mH.

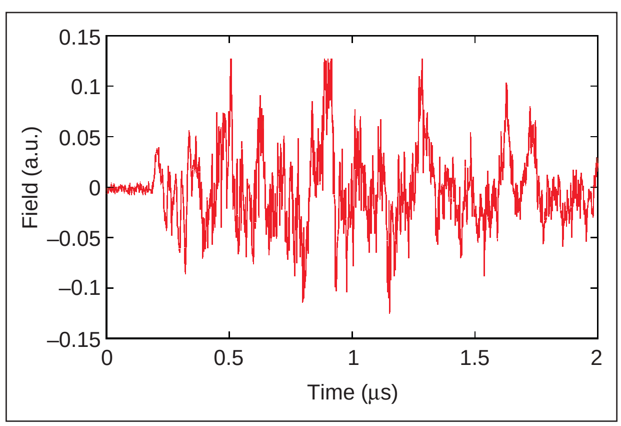

Fig. 3. The field emitted during switch-off in the same arbitrary units as the ones used for the switch-on measurement. The intensity is about 200 times lower.

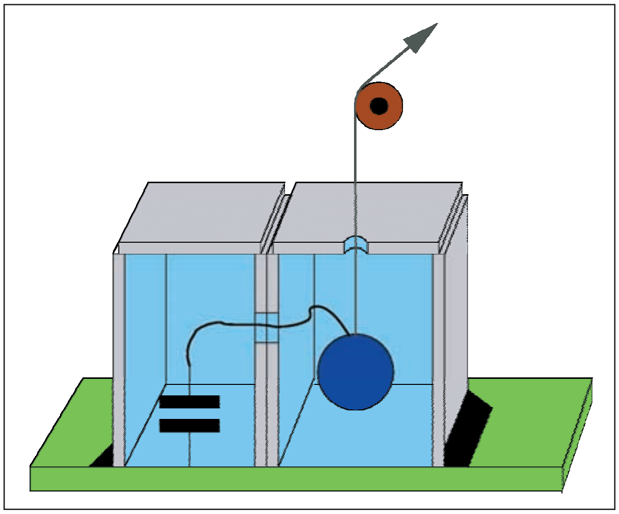

Fig. 4. A 2.2 nF capacitor charged to about 4 kV with removable leads and then discharged by lowering down a sphere that touches the ground plane.

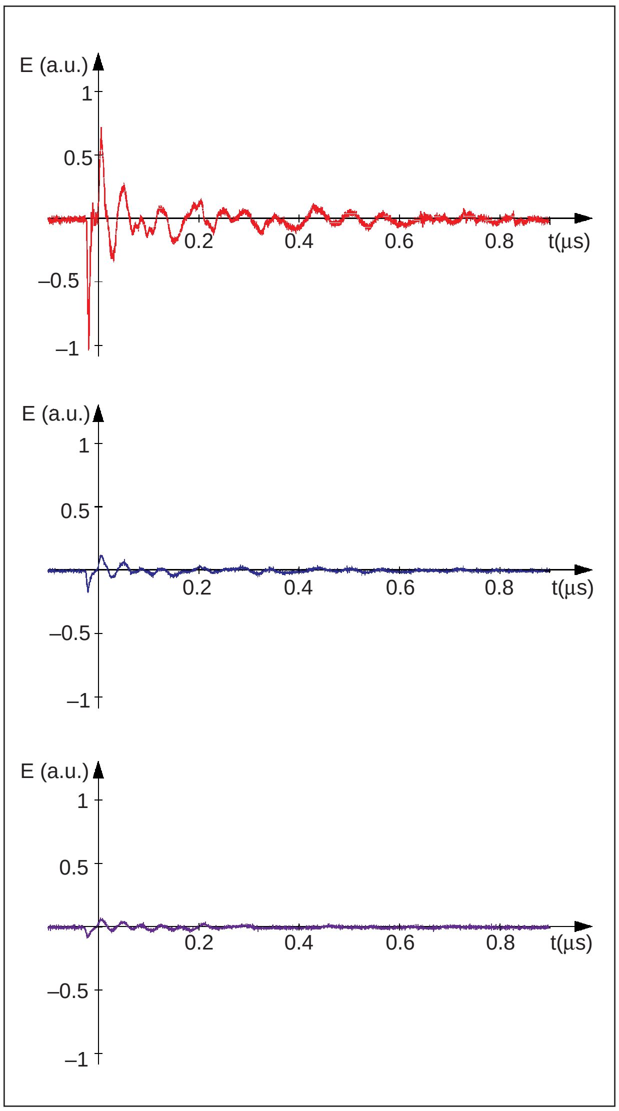

Fig. 5. Experimental results for the radiated field.

It is apparent that most of the emission is coming from the capacitor box. We can reduce the amplitude of the radiated field by 85% from the initial value, while the additional reduction from shielding the arc box is merely 8% of the initial value. Radiation is strongly dependent on the geometry of the whole circuit even in the case of a significant charge stored directly on the electrodes between which the arc takes place (with a capacitor connected directly across the spark gap), so that the current through the arc is definitely larger than that through the rest of the circuit [4]. Therefore, any model of the electromagnetic emission must account for the complete geometry of the circuit and cannot be limited to a model of the arc as a radiator.

Numerical Models

As a first step towards the development of a model for the electromagnetic transients in line-pantograph systems, we have started with a lumped-parameters model for the low-frequency component of the current transient shown in Fig. 2. We have extracted the accessible circuit parameters of the experimental setup and we have tuned the others, such as the arc resistance, to obtain a good qualitative agreement with the measured transients. Fig. 6 shows the circuit model thus derived. L is the line inductance of 39 mH. C_1, R, and L_2 are lumped representations of the circuit section between the line inductance and the pantograph (including the overhead contact line). R_a, L_a, C_a are the parameters of an additional capacitor used to validate the model. L_3 corresponds to the inductance of the pantograph structure and of the cable connecting to the load. Finally, R_{load} and C_{load} are a lumped parameter representation of the high-power resistors that make up the load.

A complete model would require a treatment with distributed parameters and a solution of the Maxwell equations taking into account the Dirichlet boundary conditions imposed by the walls of the shielded room. Such a treatment is currently in progress.

From these experiments we can already derive some useful indications. Significant electromagnetic emissions, 100 V/m or more at a distance of 1-2 m, are observed only in the case of a switch-on transient and for an extremely short time. They should not affect normal operation, at least in a dc system, because mechanical pantograph-contact wire detachments do not extinguish the arc because of the inductance of the load.

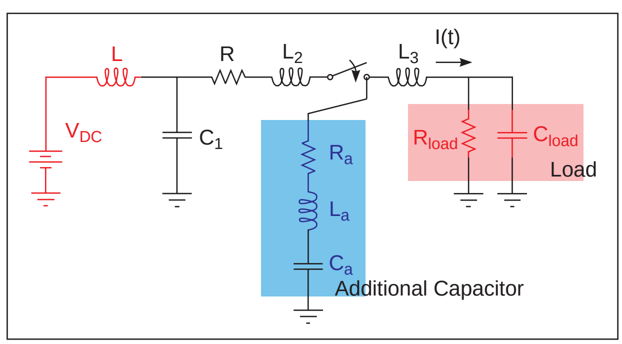

Fig. 6. The circuit model.

The results of some preliminary measurements that we have performed along the tracks of a busy railway line support this conclusion. These results are still preliminary; they have been obtained for trains moving at relatively slow speeds for which pantograph-contact wire detachments are likely to play a lesser role than at high speeds in excess of 160 km/h.

References

[1] European Pre-Standard env 50121: Railway Application. Electromagnetic compatibility, Tech. Rep., CENELEC, Bruxelles, 1996.

[2] R. Giannetti, M. Macucci, and B. Tellini, "Remarks on models for prediction of radiated fields in electrical discharge events," *Electron. Lett.*, vol. 37, no. 13, p. 817, June 2001.

[3] S. Leva, A. P. Morando, and R. E. Zich, "On the unwanted radiated fields due to the sliding contacts in a traction system," *IEICE Trans. Commun.*, vol. E83-B, p. 519, 2000.

[4] M. Mardiguian, "Comments on 'Fields radiated by electrostatic discharge'," *IEEE Trans. Electromagn. Compat.*, vol. 34, p. 62, Feb. 1992.

[5] B. Tellini and R. Giannetti, "Current measurement in electrical discharges in air gaps for conducted noise estimation," in *Proc. IEEE Instrumentation and Measurement Technology Conf.*, St. Paul, MN, 1998, p. 749.

[6] B. Tellini, M. Macucci, R. Giannetti, and G. A. Antonacci, "Conducted and radiated interference measurement in the line-pantograph system," in *Proc. 17th IMTC*, Baltimore, MD, 2000, p. 457.

Bernardo Tellini received his degree in electrical engineering in 1993 from the University of Pisa; he then obtained a doctorate degree from the same university in 1999. Since 2000, he has been Assistant Professor at the University of Pisa. His research interests include electromagnetic launchers, hysteretic material application, and electromagnetic fast transients.

Massimo Macucci received his degree in electrical engineering in 1987 from the University of Pisa. In 1990, he obtained the "Perfezionamento" (Doctorate) from the Scuola Superiore Sant'Anna di Pisa; he then obtained a Masters degree in 1991, and a Ph.D. degree in 1993 from the University of Illinois at Urbana-Champaign. Since 1992, he has been on the faculty of the Engineering Department of the University of Pisa, first as an Assistant Professor and then as an Associate Professor; he has been a Full Professor since September, 2001. His research interests include the design and simulation of novel nanoelectronic semiconductor devices, noise phenomena in electronic components, and the electromagnetic emission associated with fast electrical transients.

Romano Giannetti graduated with a degree in electrical engineering in 1989 from the University of Pisa. In 1993, he obtained a Doctorate degree from the University of Padova. From 1994 to 1998, he was an Assistant Professor at the University of Pisa; since 1998, he has been an Associate Professor at the Universidad Pontificia Comillas de Madrid. His research interests include low noise measurement systems, electro-optic sensors, biomedical instrumentation, and the electromagnetic emission associated with fast electrical transients.

Gabriele A. Antonacci graduated in electrical engineering in 1985 from the University of Pisa. He works in the Trenitalia S.p.A. Testing Department. Some of his fields include high-speed rolling stock testing, electrical research, and electromagnetic compatibility. He currently works in rolling stock electric laboratories development.