Pantograph-Catenary Arc Detection Technique
based on Conducted Effects Measurement on Railway Supply System

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Abstract

This paper focuses on the electric circuit model of the railway supply system and locomotive to analyze the conducted effects of arc events at the sliding contact. The characterization of the arc voltage waveform is backed up by an intense preliminary laboratory activity. The comparison between simulated and measured pantograph voltage and current shows which electric parameters are relevant to identify the characteristic dynamic responses of the system, to use as electric signature of arc events.

Keywords: Arc discharge, Electric arc, Power Quality, Rail transportation system

1. Introduction

The technical activities here described are part of the European research project 16ENG04 MyRailS, devoted to the development of the metrological infrastructure to underpin the efficiency of the railway infrastructure. One of the new keyword related to the efficiency in railway systems is the Power Quality (PQ) at the pantograph. Definitions and metrics of PQ suitable for a direct current railway system have been only preliminarily considered [1,2,3]. The contact quality between the overhead-line and the pantograph is a key point in the definition of PQ; waveform distortion related to electric arc events can significantly pollute the line voltage spectrum [4]. A device installed on-board trains, able to detect the arc events, can monitor continuously and in real-time the pantograph contact quality [5]. Such a monitoring system, if extensively used, can contribute to diagnose both contact line and pantograph conditions, as well as to correlate with PQ phenomena and their characterization. The proposed technical approach to detect arcing phenomena exploits the low-frequency conducted effects caused by an arc event, occurring between the Overhead line (OHL) and pantograph. Voltage and current transducers connected to the train pantograph and a suitable algorithm able to recognize the arc conducted effects can represent such monitoring system. The final objective is to foster predictive maintenance based on a continuous monitoring of the arc events, which degrade the overhead contacts and thus decrease the energy efficiency of the whole railway systems, without the need of additional specific measuring devices and so without additional costs.

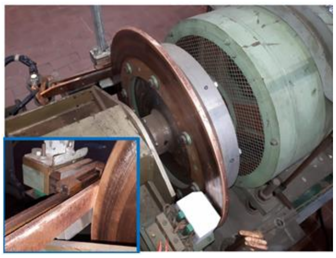
Modeling accurately and thoroughly all the phenomena involved in the arc event at the sliding contact is quite a complex task [6,7]. The arc, to sustain itself, absorbs electrical energy from the railway system; as a consequence, it is commonly modeled by a non-linear resistance whose value depends on the flowing current, material and dynamics of the electrodes, surrounding electromagnetic and environmental conditions. By applying the substitution method, a pulsed voltage generator v_{arc} between the OHL and the pantograph shoe can replace the non-linear resistance. This generator actually absorbs energy, emulating the energy dissipation that occurs in the plasma.

The analysis of the time behavior of measured transient arc voltages allows identifying the characteristics of the voltage generator v_{arc} that with a circuit model of the railway supply and locomotive allows the comprehension and analysis of the effects of arcing events conducted along the OHL.

2. Experimental campaign on arc voltage in sliding contact

2.1 Laboratory setup for arc generation

The experimental setup employed in this work was arranged at INRIM in the 90s for a research project devoted to the analysis of the electromagnetic field at high frequency emitted by the arcs generated between two sliding contacts [6].
The elements of the sliding contact, namely OHL and pantograph, are emulated by the profile of a 60 cm diameter copper disk, coupled with the shaft of a DC motor and a real pantograph sliding element. The pantograph is kept against the copper disk edge by means of a weight that, thanks to a leverage system, provides the correct contact pressure. Moreover, a crank connecting-rod system moved by a compressed air actuator, which allows an alternative horizontal translation of the pantograph, simulates the zig-zag arrangement due to staggering of the real OHL (see Fig.1 a). Different speeds of the locomotive sliding contact are obtained by varying the motor rotational speed.
The sliding contact is supplied at an almost constant DC voltage. The electrical current flows from the positive pole of the supply system to the rotating disk through a brush system and then, through the sliding contact, to the pantograph, which is connected to the negative pole of the supply. A series connected 156 μH inductor (resistance of 3.59 mΩ) is used to sustain the arc at the sliding contact (see Fig.2). With the leverage system it is possible to reduce the contact pressure of the pantograph against the copper disk until it is completely detached and arc injection begins. Then, distance may be further increased at the point that the arc quenches. An example of arc evolution is shown in Fig. 1(b).
Different supply conditions and rotation speeds correspond to different quenching distances and arc characteristics. The experimental setup is used to generate arcs with controlled and repeatable parameters and under conditions as close as possible to those of a DC railway supply system.


(a)

(b)

Fig. 1: Experimental setup and detail of contact

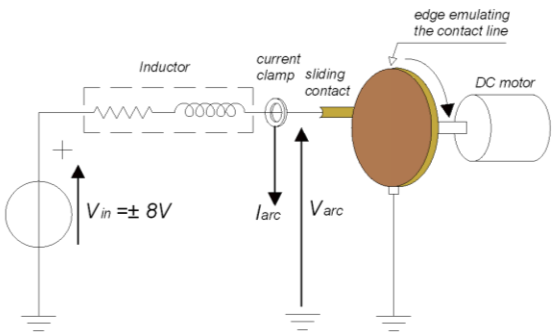


Fig. 2: Simplified circuit of experimental setup

Fig. 3 shows the time behavior of voltage across the sliding contact and current flowing in it. When there is a good connection between the two contacts, the current increases following the typical behavior of a LR circuit. When the arc occurs, the energy charged in the inductor is employed to sustain the arc event and, as a consequence, the current decreases exponentially. A voltage drop across the sliding contact immediately arises with an amplitude of about 15 V – 20 V and, depending on the evolution of the arc length its value can increase. Because of the limited energy stored in the inductor, arc quenching finally occurs.

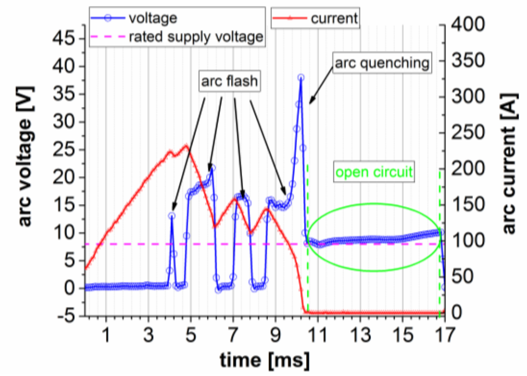


Fig. 3: Time behavior of arc voltage and current during the random arc events.

3. Modeling activity

3.1 Arc model for conducted effects analysis

The voltage drop across the arc terminals has a behavior depending on the time evolution of the relative position between the two electrodes. Assuming this, the arc event is introduced in the circuital model as a voltage generator that imposes an arbitrary voltage drop between the overhead-line and the pantograph that is not correlated with the current exchanged between the two electrodes. The arc is a dissipative event; therefore, the sign of the voltage generator has to be like a passive load. Fig. 4 provides the voltage drop direction for traction (a) and regenerative braking (b). During traction, an arc event generates a voltage dip at the pantograph and a voltage swell at the contact line; the opposite occurs in case of regenerative braking.

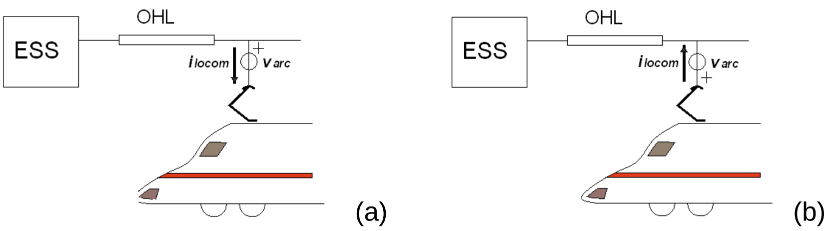
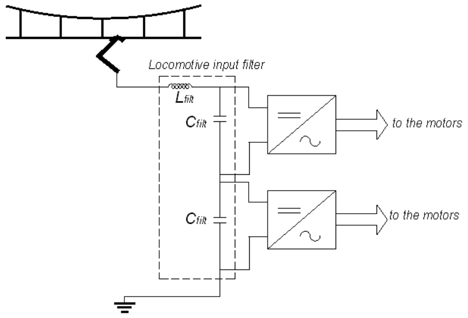


Fig. 4: Direction of the voltage drop emulating the arc for (a) traction and (b) braking phases

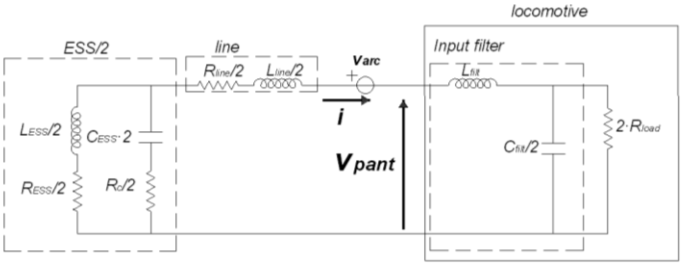
3.2 Analysis of conducted effects through a simplified model

The following scenario is considered: a DC section line supplied by two electrical substations (ESSs) and a locomotive placed exactly in the middle. This allows simplifying the supply system focusing on one half of it. The 3 kV DC locomotive E464 owned by Trenitalia, an Italian railway operator, is considered for the simulation. It is characterized by a rated power of 3.5 MW and a maximum speed of 160 km/h. The input stage is made of an inductor of 8.5 mH feeding the DC link from which two series connected inverters are derived, each driving two electrical motors. A capacitor bank of 17.1 mF is connected in parallel to each inverter, resulting in two series connected capacitors seen from the DC link inductor L_S; their combination represents the 2nd-order low-pass filter of the locomotive. A simplified scheme of the E464 is provided in Fig 5(a). Since the arc event duration can range between tens to hundreds of milliseconds, the mechanical load of the locomotive can be considered in steady state conditions. Therefore, inverter loading can be simulated with two equivalent resistors with a value given by the ratio of the DC link voltage and the absorbed current before the arc occurrence. Thanks to the symmetry of the traction system, the circuit simulating the E464 can be summarized as highlighted in Fig. 5(b).

When the arc event occurs, two generators are present in the circuital model: the DC supply and the arc voltage generator. In the following analysis, we apply the superposition of effects and focus on the effects due to the arc voltage generator, leading to the equivalent circuit shown in Fig. 5(b). The stray capacitance of the overhead line has been neglected.



(a)



(b)

Fig. 5: (a) E464 input filter and traction system, (b) simplified equivalent circuit.

Table 1 summarizes the parameters of the circuits of Fig. 5(b). The line resistance and inductance are expressed in per unit length and are based on known values for simple lines for a low frequency interval: equivalent values given by the parallel of the two line sections between the loco and each of the ESSs are calculated as simple electric parallel and inserted in the model (for the simplified configuration with the loco exactly in the middle of a 20 km ESS-ESS section, the parameters are shown in Fig. 5 as half of those reported in Table 1). Considering the arc voltage profile shown in Fig. 2, a pulsed voltage generator v_{arc} with the time behavior shown in Fig. 6(a) is selected for the simulation.

Table 1: Circuital Parameter

Parameter	*Description*	*Value*
L_{tr}	Equiv. transf. sec. inductance	0.6 mH
L_{ESS}	ESS filter inductance	6 mH
C_{ESS}	ESS filter capacitance	360 µF
R_{ESS}	ESS filter resistance	0.04 Ω
r_{line}	Line resistance p.u.l.	0.1 Ω/km
l_{line}	Line inductance p.u.l.	1.5 mH/km
L_{filt}	Loco filter inductance	8.5 mH
C_{filt}	Equiv. loco filter capacitance	8.55 mF
R_c	Equiv. loco load resistance	10 Ω

3.3 Simulation Results

The quantities of interest of the simulation are the waveforms of the pantograph voltage and current to compare with the measurement results. As can be seen in Fig. 6, the pulse voltage introduced by the arc event triggers a dip on the voltage at the pantograph the time shape of which is similar to the applied arc voltage pulse and a damped oscillation of the current at low frequency caused by the loco filter, at about 15 Hz. When the arc voltage goes to zero, the arc extinguishes and a new damped frequency oscillation is induced on both voltage and current.
A simple explanation of this behavior is provided by the circuital model: the main oscillation frequency is

set by the capacitance of the E464 filter and the equivalent inductance of the circuit (series of the ESS, line and E464 filter inductance). This frequency in general ranges from 10 Hz to 20 Hz.

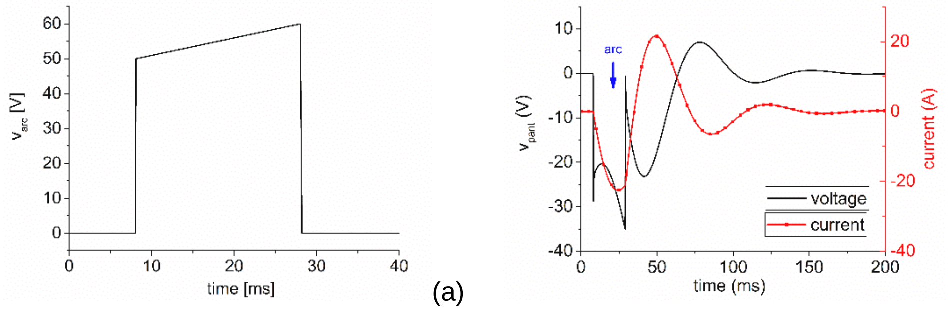


Fig. 6: (a) Voltage waveform of the arc generator, (b) computed transient oscillation of voltage and current triggered by the arc voltage profile

4. Observed experimental arc phenomena

By means of a measurement setup installed on board the E464 operating in commercial service, the pantograph voltage and current were recorded with a sample rate of 50 kSa/s. In one of the recorded runs on the Novara–Domodossola line, two arc events could be clearly recognized (see Fig.6). Fig 6 (a) provides waveforms of the pantograph voltage and current of the first event that occurred close to one of the ESSs supplying the line. As it can be seen, there is a small burst of arc events, the biggest that occurs at relative time of 10 ms has the same shape described in the previous section. The arc event generates a voltage dip of about 30 V, triggering a slower oscillation of the current.

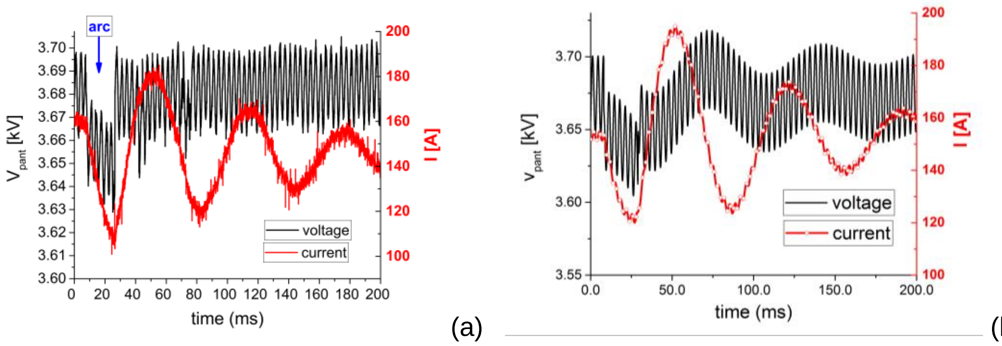


Fig. 7: (a) Measured and (b) simulated conducted effects of arc event

Thanks to a more complete model that allows simulating an arbitrary position of the train along the line supplied by the two ESSs located at its ends and introduces the dominant 300 Hz voltage ripple of the substation six-pulse rectifier, the simulated conducted effects of a 20 ms long arc event are provided in Fig. 7(b). The arc voltage shape is the same shown in Fig. 6(a); the train position is at 350 m from the ESS: line impedance was estimated considering one short section prevailing in the parallel with the other much longer one; an amplitude of 70 V was set for the 300 Hz generator of rectifier ripple.

As shown in Fig. 6, the model well reproduces the damped oscillation of the train current triggered by the arc. The simulated pantograph voltage following the arc event conversely shows a significant oscillation at the loco filter resonance frequency that does not appear in the measurements (the simulated value is initially about 30 Vpp, whereas the fluctuation at the same frequency appearing in the measurement is less than 5 Vpp). It is evident that this is caused by the voltage drop along the line (short, 350 m) and at the substation; it means that the overall impedance is too large at the low frequency of the oscillation of about 14-15 Hz. Neglecting the equivalent line impedance for the very short length (accounting for about 0.5 mH of inductance), it is necessary to reduce substantially the substation impedance in the model: it was observed that the removal of the substation filter solves the problem, because the overall ESS inductance is reduced to the equivalent transformer secondary inductance of about 0.6 mH, and the filter capacitor C_{ESS} is in reality still ineffective at such a low frequency, accounting for about 30 Ω of reactance.

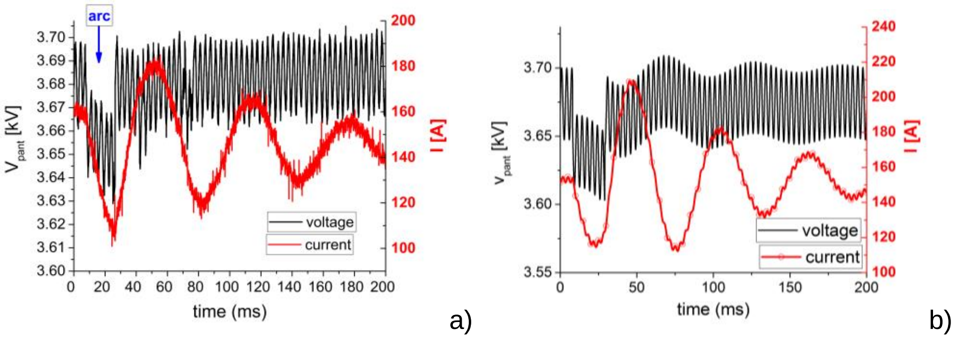


Fig. 8: (a) Measured and (b) simulated conducted effects of arc event (no ESS filter)

4. Conclusions

This work has presented the problem of modeling and recognizing the effects of electric arc phenomena occurring at the sliding contact, that is the interface between the pantograph and the overhead line. The purpose is a better understanding of the system dynamics triggered by arc events, with the objective of identifying arcs through measurements of electrical quantities, without a specific additional measuring system for e.g. light or electromagnetic emissions from the arc.

A good matching between simulated and measured quantities have been observed, although the analysis is preliminary, based on a simplified circuit model of the system. It is underlined that there is a superposition of various dynamic responses at different frequency intervals, dominated by the transient response of the locomotive onboard filter. Different types of rolling stock may thus give different signatures in terms of oscillation frequency and damping, if the overall pantograph and current waveforms are observed, whereas more accurate and focused analysis of the waveform may be needed, identifying a series of characteristics that distinguish a transient triggered by an arc event compared to other types of transients (e.g. due to driving).

The development and tuning of a circuit model is in any case a valid and necessary step to understand system dynamics and which parameters influence which characteristics of the observed responses, in order to predict variations across different systems, by knowing their electrical characteristics.

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