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Simulation of the Rupture of the Contact Wire of a High speed Catenary

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Abstract. The rupture of the contact wire (CW) of a railway overhead contact line (OCL or catenary) of a high-speed line is expected to be a rare event, however, its occurrence can have catastrophic consequences due to the failure of the pantograph against the catenary, possibly enlarging the extension of the damage portion on the catenary. The prevention of such events through proper catenary monitoring is gaining high interest, with several proposal of direct catenary monitoring of the catenary. The purpose of this work is to find the signature of variables measurable at the end of an OCL section, so that it is possible to reveal the presence of a failure in the contact wire, and to stop the traffic before a train runs under the broken catenary. The paper investigates, by means of numerical simulation, the dynamical behavior of the catenary, when a failure in the contact wire of the OCL occurs. The dynamical response of the OCL is simulated through nonlinear dynamical analysis, to define existing pattern of the variables that can be measured at line's extremities, where the tensioning devices of the conductors are located. Several scenarios of failure locations are investigated, so that the measured force signature, to get a more general view of the pattern of the alert signals to be recognized.

Keywords: Railway catenary, broken contact wire, damage detection, force measurement

1   Introduction

Among the critical elements of the railway infrastructure that can suffer damage with heavy consequences on traffic regularity there is the Overhead Contact Line (OCL or catenary), necessary to feed the electrical power to the drives of the motors of the train. Possible failure of the OCL involve the droppers ([1-3]), or elements of the suspension of the span [4]. In case of heavy damage of the OCL, such as the rupture of the contact wire (CW), not only severe disruption on the traffic occurs, but also life danger for the operators ([5]) can be caused. An extreme phenomenon such as the rupture in the CW must be considered with a proper risk analysis [6]. To prevent the transit of the train after the occurrence of a CW rupture a direct monitoring of the

OCL would be needed, but this appears unfeasible due to the extension of any railway network.

To tackle this issue, this paper investigates how, with the use of a limited set-up, it is possible to send an alert to the traffic management unit before a train passes under the damaged section. Taking advantage of the configuration of the OCL infrastructure, that is composed of so-called "regulations" with a length of 800÷1400 m, measuring set-up would be located only in correspondence of the ends of each regulation, For completeness, it is worth recalling that the breakage of the CW is not revealed by an electrical tension loss detectable from the powers station supply (unless also the MW is broken), so that a train can potentially approach the damaged section without the possibility of any alert, and causing the impact of the train and the pantograph against the broken CW, surely increasing the extension of the damage on the infrastructure, and causing damage to the train too.

The proposed set-up starts from the physical consideration of the effects of the rupture of the CW, to define possible variables to be measured at the end of the regulation. The breaking of the CW interrupts its mechanical continuity, consequently, the mechanical tension of the portion of CW is subjected to a sudden change, like a pulse, that travels along the line and reaches the extremity of the regulation, where measurements are taken. without any train running under the OCL. The paper investigates the dynamical behavior of the catenary following the occurrence of a failure in the CW. The dynamical response is simulated by means of nonlinear dynamical analysis, to define the pattern of the acceleration, displacement and the tensioning force at line's extremities. Several scenarios of failure locations are investigated, so that the signature of the alert signals can be recognized, taking into account possible locations of the damage along the line. The paper is organized as follows:

- description of the model of the OCL and of the procedure for simulating the CW breakage;
- results of the simulations in the examined scenarios;
- final remarks.

2 Model of contact wire failure

2.1 Model of the OCL

The standard Overhead Contact Line (OCL) of the Italian high-speed network is considered for the analysis. It is composed of a single messenger wire (MW), a single contact wire (CW) suspended to the former through a set of nine droppers. The MW is in turn connected to suspensions, in correspondence of each span section, the suspension frames are connected to poles. The overhead contact line is organized in sections (also named regulation), each having a length usually in the range 800 m÷1400 m. In each regulation the conductor of the MW and the CW are continuous, with the same length of the regulation. This implies that there are no junctions on the conductors with a regulation. Overlap sections enable the pantograph to transit from one regulation to the subsequent one. The CW and the MW are tensioned respectively at 20 kN and 16 kN. The mechanical tension is applied to the conductors

by means of tensioning devices, based on the force provided by counterweights connected on a series of pulleys, to transfer the gravity load of the counterweights to the conductors, with a transmission ratio of 2, that amplifies the forces from counterweights to the conductor's connection and correspondingly reducing the displacement form the counterweight to the conductor end.

In the middle of the regulation, a fixed-point section restrains the longitudinal movement of the MW and the CW, supporting the tensions applied to the CW and the M. If a breakage occurs along the contact wire, the tension in the portion of CW between the damaged position and the fixed point goes to zero, while in the portion of the CW between the damaged location and the end of the regulation the mechanical tension is transferred from the CW to the MW, through the droppers.

To investigate the dynamical behavior of the regulation after the breakage of the CW, a finite element model was built with Abaqus®. Beam elements are adopted for conductors and droppers, the fixed point is modelled as a fixed boundary condition, so that only half of the entire regulation needs to be modelled. The applied mechanical tension is reproduced by constant force applied to CW and MW extremities. The boundary condition in this extremity is simplified as a longitudinal sliding constraint. The stagger (i.e. the zig-zag configuration of the conductors of the OCL is not considered and the problem is schematized in the vertical plane.
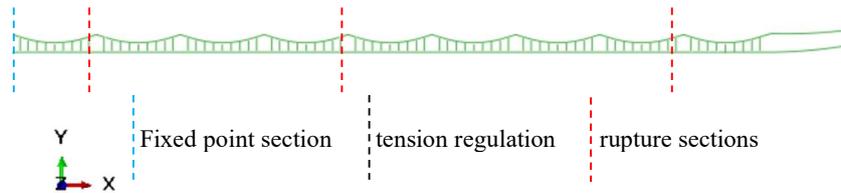

Fig. 1. Scheme of the half regulation of the OCL. Fixed point section (left side) realizes a longitudinal restrain for the conductors. Mechanical tensions are applied by means of counterweights (not reported in the sketch) at regulation's ends (right side).

Table 1. High speed OCL conductors' main parameters.

conductor	Section [mm²]	Mechanical tension [kN]	Linear mass [kg/m]
Contact wire	150	20	1.34
Messenger wire	120	16	1.08

2.2 Modeling of the breakage of the contact wire OCL

To simulate the breakage of the CW two analyses have been performed. The first is a linear Static Stress Analysis to calculate the balanced configuration of the structure under the action of the gravity distributed load and the mechanical tension of contact and Messenger wires. The second is a non-linear, full explicit dynamic analysis in which the balanced configuration calculated by static linear analysis is imported as Initial State. The explicit dynamic analysis simulates the rupture of the CW at time 0, and the subsequent nonlinear dynamics response for 10 sec. The breakage is re-

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produced by means of a type Beam connector with an assigned Failure criterium. The connector element is regulated to fail at a load level slightly over the value of the static configuration. To activate the rupture the applied tensile load of the con-tact wire is increased just over the limit set for the breaking of the connector, by an amount of 1%: this causes the rupture in the selected section. During the braking process, no other failures are considered, such as failure in the droppers. A Rayleigh damping with α = 0.1 and β= 0.001 is assumed.

The rupture of the CW is applied in three sections along the half-regulation, respectively in the first span, in the last one and in between. Inside the span involved in the breaking, the rupture point is in correspondence of the dropper immediately before the suspension.

3 Results

The variables to be measured in correspondence of the final section are:
- the dynamical variation of the mechanical tension in correspondence of the measured section on the CW and on the MW;
- the longitudinal displacement of the CW and MW;
- vertical acceleration of the conductor CW.

The time history of the axial loads of the conductors is obviously directly related to the effect of the breakage events, additional information can be obtained also from the axial displacement of the conductors. The acceleration is related to the dynamical response to the step variation of the lost continuity of the CW. The purpose of observing more than one output, is to observe how their combination adds some robustness to the revealing of the rupture.

3.1 Results for scenario "A"

The first examined scenario concerns the breakage of the CW close to the fixed point, at a distance of 513 m from the measurement section. First, the dynamical axial force in the MW and CW are shown in Fig. 2, as a function of time, for the entire duration of integration. The breakage occurs immediately after the initial time, a negative pulse of 1.5 kN occurs after a short delay (0.14 s) associated to the travel speed of the longitudinal wave c in the CW, that is expressed, in m/s, as:

$$c = \sqrt{E/r}$$

(1)

with E=1.18x10^{11} N/m^2 and ρ=8890 kg/m^3 (values for copper) and the distance between breakage section and regulation's end. No pulse is observed in the axial tension of the MW. The dynamical behavior following the pulse arrival is composed of high frequency and low frequency contributions, the latter related to the overall motion of the OCL, that can be observed in the results of axial displacement, reported in Fig. 3. The effect of the rupture acts as a step, so a long transient at the frequency of the first vertical mode of the span about 1 Hz can be observed.

The final positions of conductors' extremities are different for MW and CW, being the latter larger than the former. Fig. 4 is used to clarify the behavior of the overall half-regulation. The vertical displacement of the CW at midspan from span I to span VIII, where span I is the first span after the span where the rupture occurs and span VIII is the closest to the final one. The variables reported are not clearly used for alert purpose, since it is not conceivable to measure the vertical CW displacement in all the mid spans. It can be observed that moving away from the rupture section, located before span I, the maximum amplitude decreases, first by 30% and then more gradually up to the end of the line. The last parameter, useful for the real measurement set-up, concern the vertical acceleration of the CW, close to regulation's end. The pattern of the acceleration is oscillatory, so that it is more robust to examine a processed version of this signal. The moving r.m.s is superposed to the time history, considering windows of 0.15s, shifted with a step equal to the length of the window. The trend of moving r.m.s. (red line) is superposed to acceleration raw data, to show the mean power of the signal during the development of the transient vibration.
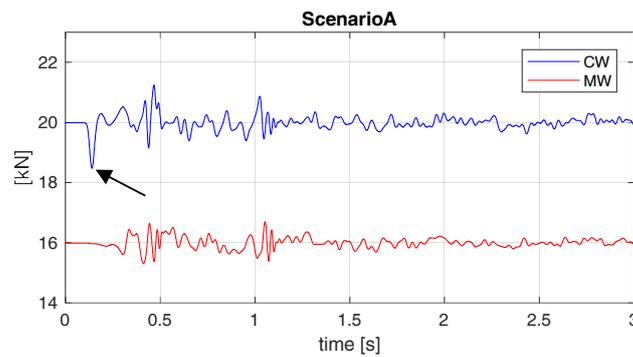

Fig. 2. Time history of the axial load in the CW and in the MW following breakage of the CW in scenario A. The arrow identifies the location of the negative impulse at 0.140 s.
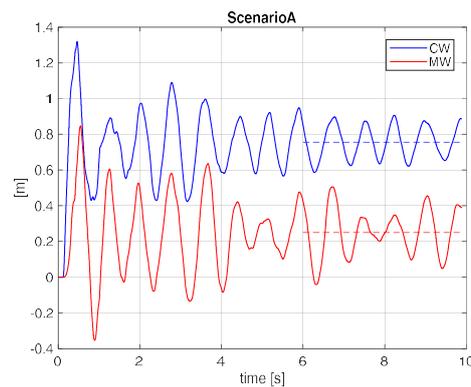

Fig. 3. Time history of the longitudinal displacement in the CW and in the MW following breakage of the CW in scenario A.
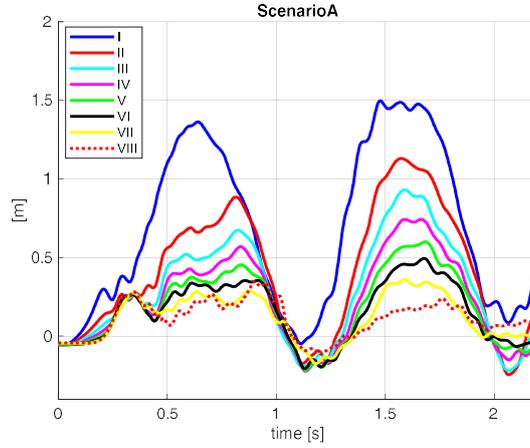
Fig. 4. Scenario A. Time history of the vertical displacement of CW along the half-regulation. Detail of the first 2 s of the transient time history following the rupture.
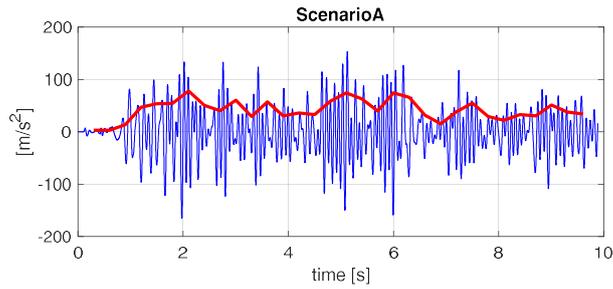

Fig. 5. Time history of the vertical acceleration in the CW close to the end section, in scenario A. Red line indicates the moving rms processing of the acceleration.
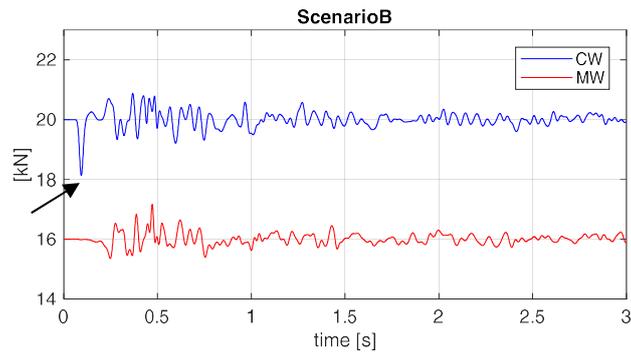

Fig. 6. Time history of the axial load in the CW following breakage of the CW in scenario B. The arrow identifies the location of the negative impulse at 0.093 s.

3.2 Results for scenario "B"

The axial force for scenario B (Fig. 6) has a very similar appearance to scenario A (compare Fig. 2). The negative pulse (indicated by the arrow) occurs earlier, correspondingly to the lower distance between the rupture section, now at a distance of 342 m. Longitudinal displacement (**Fig. 7**) is larger, 1100 mm for the CW and 470 mm for the MW. The vertical CW displacement at midspans, reported in Fig. 8, reflects the new position of the rupture section, located between spans III and IV, that show the larger amplitude. Finally, Fig. 9 shows the vertical acceleration of the CW at the measuring section, the trend is similar to that of scenario A.
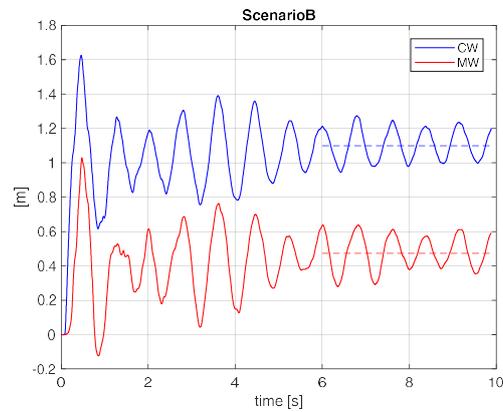

Fig. 7. Time history of the longitudinal displacement in the CW and in the MW following breakage of the CW in scenario B.
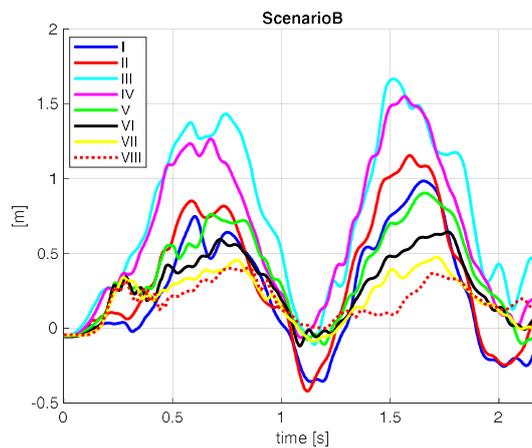

Fig. 8. Scenario B. Time history of the vertical displacement of CW along the half-regulation. Detail of the first 2 s of the transient time history following the rupture.
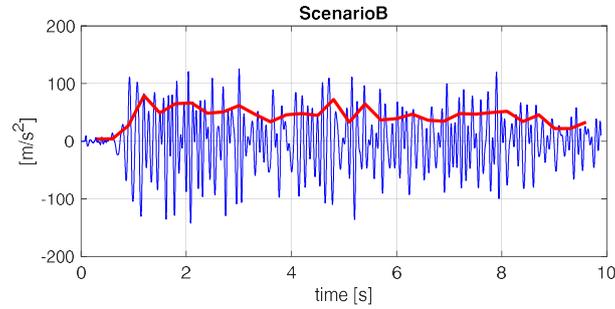
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Fig. 9. Time history of the vertical acceleration in the CW close to the end section, in scenario B. Red line is the moving rms.

3.3 Results for scenario "C"

The last examined scenario corresponds to the rupture in the span before span VIII. In this case the negative pulse is the largest (3.2 kN), as they are the longitudinal displacement, now reaching 1240 mm for the CW, while MW remains at 450 mm. Considering that a minimum allowance of 1800 mm of free longitudinal motion is allowed, there is still room for such large longitudinal movement.

The vicinity of the rupture section causes a large distortion of the geometry of the OCL, that might have other effect on the droppers, that in the current analysis are not considered. Vertical displacement of the CW at midspans, reported in Fig. 12, indicates the propagation of the motion from the rupture section back to the fixed-point section, at the beginning of the model: maximum amplitudes are decreasing gong from span VII to span I. The processing of the vertical acceleration of the CW at the measuring section exhibits values large by about a factor 2.
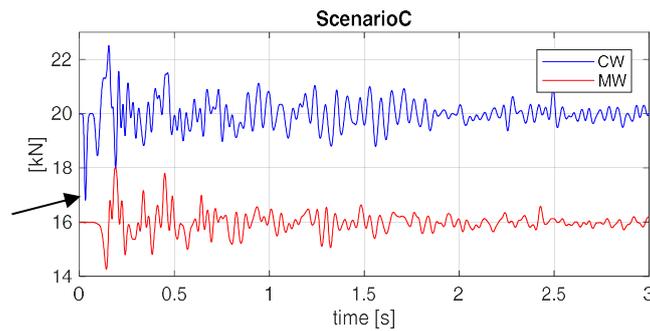

Fig. 10. Time history of the axial load in the CW following breakage of the CW in scenario C. The arrow identifies the location of the negative impulse at 0.032 s.
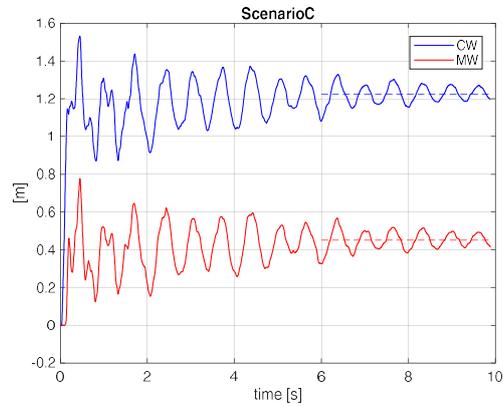
Fig. 11. Time history of the longitudinal displacement in the CW and in the MW following breakage of the CW in scenario C.
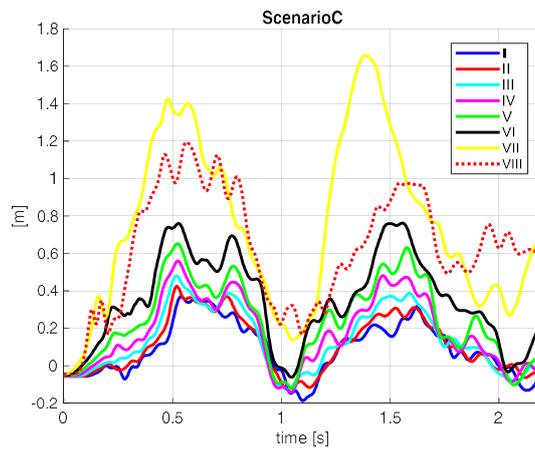

Fig. 12. Scenario C. Time history of the vertical displacement of CW along the half-regulation. Detail of the first 2 s of the transient time history following the rupture.
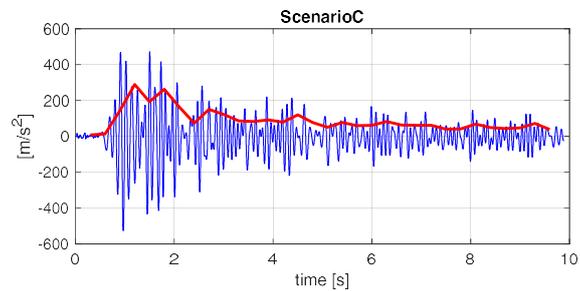

Fig. 13. Time history of the vertical acceleration in the CW close to the end section, in scenario C. Red line is the moving rms.

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4 Summary and conclusions

The paper presented an analysis of the transient dynamics following a rupture in the CW of a high speed OCL, carried out by means of numerical simulation in Abaqus®. The output variables of the analysis are measurable in correspondence of the ends of the regulation, where the tensioning devices apply the axial load to the conductors (the CW and the MW). The outcomes of the simulated transient, following the CW rupture, are the following:

A) the axial load in the CW reveals the presence of a negative force pulse, consequence of the rupture, between 8% and 16% of the static value, followed by a dynamical pattern. The identification of the pulse enables to reveal the presence of the rupture.

B) The extremities of both conductors show a considerable longitudinal motion during the transient dynamics. Predominant frequency is equal to the first vertical frequency of the single span, is linked to the longitudinal motion by the second order geometrical effect associated to the shape of the catenary. An identification process should look for modification of longitudinal position of conductors' ends, in a time interval of about 10-20s, so that gradual thermal expansion of the same order of magnitude would be excluded.

C) The vertical acceleration of the CW close to the tensioning devices connection is dominated by frequencies higher the first flexural one. The moving rms on short window (duration 0.3 s) applied to the acceleration raw signal can reveal the general increase of the signal power, in a more stable way than considering the levels of the raw acceleration signal.

The combination of the above listed variables enables to make the identification more robust, with respect to false alarms or out of service of some of the transducers.

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