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Optical Sensors for Railway Infrastructure Monitoring

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***Abstract* – The goodness of the current collection of the pantograph from the contact line in railway vehicles requires many analyses on the dynamics of their interaction. To this purpose, it is necessary a monitoring system that is able to control the sensitive parameters that describe the real status of the components involved. The scope of this research is framed in the context of the systems for the monitoring of the contact line and its interaction with the pantograph due to the running of trains in 3,000 VDC railway lines. In particular, the optical technology is proposed for the measuring of the catenary height.**

A measurement campaign has been carried out in the year 2014 and the recorded data have been treated through a dedicated algorithm in order to define suitable indices and thresholds that allow to understand the goodness or the badness of the current collection.

I. INTRODUCTION

In a deregulated EU rail market, the monitoring of the train-infrastructure interface is essential for an enhanced availability of operation of the transportation system [1].

However, with the increase of the speed in the railway operation, a particular care has to be addressed to the interaction between pantograph and catenary. The contact between pantograph and catenary is an electromechanical contact and then when a contact loss occurs electrical arcing phenomena arise [2]. One of the most important effects of arcing phenomenon is the increase of wear for both contact wire and contact strip [3].

The monitoring of the contact between pantograph and catenary in the high frequency range should be useful to put in evidence problems on the interaction between these components [4, 5].

A serious failure of a pantograph not only can damage contact wires at the point where the pantograph fails but can also inflict widespread damage on the catenary system network. Pantographs are subject to recurring verifications at the rolling stock workshop, but there are some defects that are difficult to detect by the visual inspection. In addition, the visual check at the depots cannot directly help to quickly detect pantograph failures in operation [6, 7].

For these reasons, the integration of an optical technology can be useful in order to assess the abnormalities of the catenary-pantograph interaction. These sensors can be fixed to the contact wire and their components [8].

These sensors are useful to measure the catenary status in a wide range of operating conditions. Such a system reduces the need of visual inspections since they are replaced by continuous monitoring of the component that warnings when maintenance is required before a failure occurs [9 - 11].

The aim of this work is framed in the context of the systems for the monitoring of the contact line and its interaction with the pantograph due to the running of trains in 3,000 VDC railway lines. In particular, the optical technology is proposed for the measuring of the catenary height.

A measurement campaign has been carried out in the year 2014 and the recorded data have been treated through a dedicated algorithm in order to define statistical indices and thresholds that allow to understand the goodness or the badness of the current collection.

The paper firstly presents the current collection through a pantograph-catenary system in railway vehicles (Section II). In section III, the monitoring system of the catenary installed in a real railway line is reported. Section IV presents the statistical indices considered in this work. Analysis and discussion results are presented in section V. Finally, conclusions are reported in section VI.

II. PANTOGRAPH – CATENARY SYSTEMS

The function of the pantograph in a railway vehicle is the current collection from the catenary systems (Fig. 1), to provide continuous and reliable transmission of the electric energy supplied to the trains. The energy is drawn from the contact wire and sent to the electrical driving units of traction vehicles by means of suitable pantographs shaped to the size of the catenary [12]. The decisive criterion for assessing the contact quality and therefore the quality of the energy transmission is the contact-force time response occurring between the pantograph slipper and the contact wire [13]. The contact force is composed essentially of a static force component given by the application force and a dynamic component dependent on the running speed and the vibrational behavior of the catenary and the pantograph. Too low contact forces result in contact interruptions. Technical specifications in most countries have stated that the lost of contact between the pantograph and the overhead line should be less than 1% at normal operating speeds [14, 15].

However, with today's strict requirements concerning electromagnetic compatibility, the interference caused by arcing associated with loss of contact needs to be kept to a minimum.

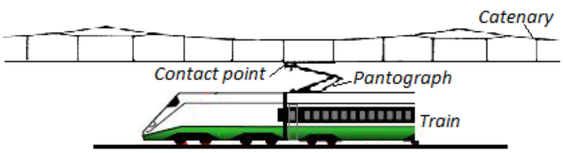


Fig. 1. The combined system pantograph/catenary.

Since catenary equipment demands a very large volume of investment in general, it must be designed in such a manner that a long service is guaranteed with the least possible amount of maintenance. In order to keep wear, such as contact wire abrasion, material fatigue, etc., low and to achieve satisfactory contact quality at the same time, there must be optimum harmonization between the pantograph and catenary through a suitable monitoring system.

III. MONITORING SYSTEM INSTALLED

The monitoring system used for the in-field analysis is based on passive optical sensors and systems for real-time monitoring (24 hours) of the catenary tensioning status, reporting season extension (encoder), tensioning status (load cell) and temperature (optical thermometer) and the impact of the pantograph on the contact wire as shown in Fig. 2 [16].

Fig. 2. Passive optical sensors [16].

The data acquired on the field are transmitted throughout the optical fiber. The software interface guarantees to share and control the data from remote control units.

The recording of the measurements is activated at each passage of a pantograph, by measuring hundred heights of the contact line by the top of rail with a sample frequency of 10 Hz. The data are then sent to a dedicated server via wifi transmission. The monitoring device has been installed near a level crossing in the North Italy railway network as shown in Fig. 3. All the monitoring system is supplied from a photovoltaic panel and a battery storage system [17].

Fig. 3. Monitoring system installed in railway infrastructure.

It is possible to access the recorded data at any time through a web page. Once connected to the server, it is possible to select the period of interest and download the data concerning to the height of the wire and the outside temperature.

Figure 4 reports the typical representation of the height variation of the contact line in a winter day. It is possible to evaluate the presence of a train and the subsequent vibrations induced by its passage.

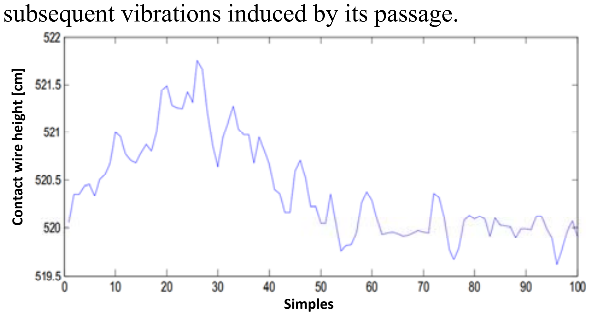


Fig. 4. Variation of the contact line height during the transient of the pantograph.

IV. STATISTICAL ANALYSIS

In this study, it has been carried out a statistical analysis on the recorded data. The use of statistical indices allows the estimation of the order of magnitude of the events and how they are distributed.

The first four indices here considered are:

- Mean Value

It is obtained by dividing the sum of observed values by the number of observations, *n*. The formula for the mean is given by (1):

$$\bar{x} = \frac{\sum_{i}^{n} x_i}{n} \quad (1)$$

where x_i is the i^{th} measure and *n* is the number of the all samples of the considered population.

- Variance

This value measures how far a set of numbers are spread out and can be calculated as indicated by (2):

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \quad (2)$$

- Standard deviation

The standard deviation is the square root of the variance as reported in (3):

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (3)$$

- Crest factor

A value that is worth identifying is the maximum value of the population x_{max} known as crest factor:

$$x_{\max} = \max x_i \quad (4)$$

There are further statistic indices that describe the shape of the distribution, in particular:

- Skewness index

It measures the degree of asymmetry exhibited by the data as shown in (5):

$$skewness = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{n\sigma^3} \quad (5)$$

- Kurtosis index

It quantifies whether the shape of the data distribution matches the Gaussian distribution indicated in (6):

$$kurtosis = \frac{\sum_{i}^{n}(x_i - \bar{x})^4}{n\sigma^4} - 3 \quad (6)$$

With this definition, a Gaussian distribution is expected to have a kurtosis equal to 0.

In the case of the kurtosis < 0, it indicates a relatively flat and wide distribution. Whereas, if the kurtosis > 0, in this case there are high frequencies in only a small part of the curve (i.e, the curve is more peaked). Figure 5 represents these different conditions for the kurtosis index.

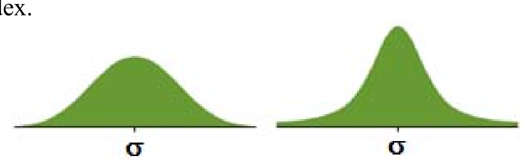


Fig. 5. Different distribution for kurtosis index.

The first step of this analysis is to find the normal condition, i.e. the expected raising of the contact wire when the catenary-pantograph system is well calibrated.

The idea is the identification of a first range in which the height of the contact wire is considered acceptable, and a second range in which a warning signal is produced since the pantograph can be uncalibrated. Outside this range an alarm signal is generated since the pantograph can stress too much the catenary.

The first interval has been identified in this way: starting from the mean value, the upper threshold has been calculated multiplying the standard deviation by a coefficient k1w, while the lower limit has been obtained multiplying the standard deviation by a coefficient k2w.

Since the raising of the contact wire during the train running is higher than its drop after the train passage these two coefficients k1w and k2w are generally different.

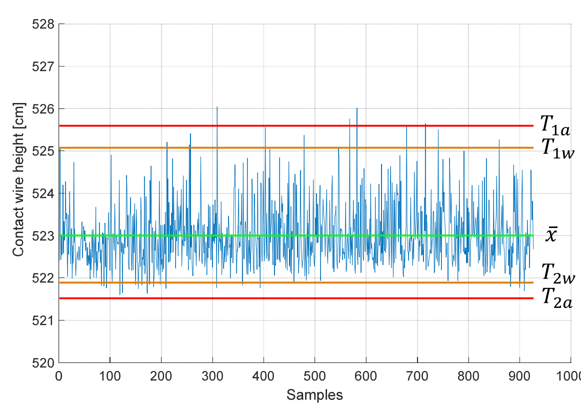
For the second interval, the upper and lower thresholds have been calculated multiplying the standard deviation respectively by the coefficients k1a and k2a.

The choice of these values can dramatically impact the relationship between the infrastructure manager and the railway undertakings. Indeed, too tight intervals require a fine calibration of the pantograph and of the contact line that barely can be kept during the normal operation. On the contrary, too wide intervals can affect the goodness of the current collection or the mechanical stress produced on the contact wire can be too high and such that to cause the damage of the catenary.

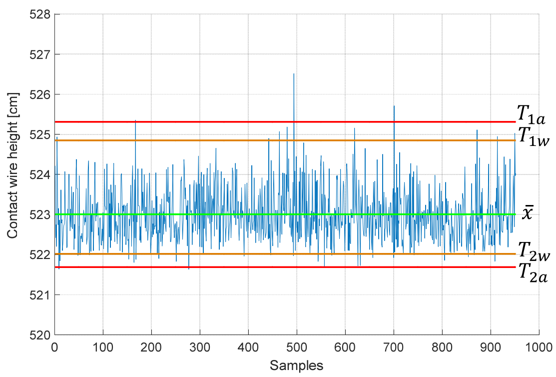
By analyzing a 1-year observations, that imply the seasonal effects due to the temperature variation, the suitable coefficients for this application are:

- $k_{1w} = 2.8$;
- $k_{2w} = 1.5$;
- $k_{1a} = 3.5$;
- $k_{2a} = 2$;

Fig. 6 shows the monthly diagrams of the catenary height for different seasons. The mean value and the two upper (T_{1w} and T_{1a}) and the two lower (T_{2w} and T_{wa}) thresholds have been highlighted.



(a)



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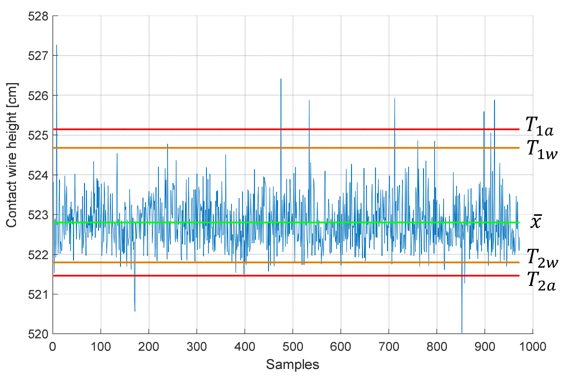

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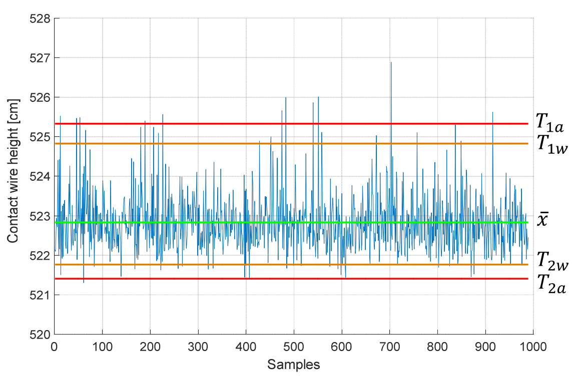

(d)

Fig. 6. Contact wire height for different months: (a) January, (b) April, (c) July and (d) October.

As it is possible to note, with the coefficients above determined the normal operation is well defined. Some trains reach the warning thresholds and only a few trains overcome the alarm thresholds.

Another important aspect is that the mean value does not vary significantly with the seasons, so the contact wire height is quite constant during the year.

V. ANALYSIS OF DATA AND DISCUSSION OF RESULTS

The analysis has been focused in the year 2014. The data have been processed by an algorithm (Fig. 7) in order to assess the goodness of the contact between pantograph and catenary.

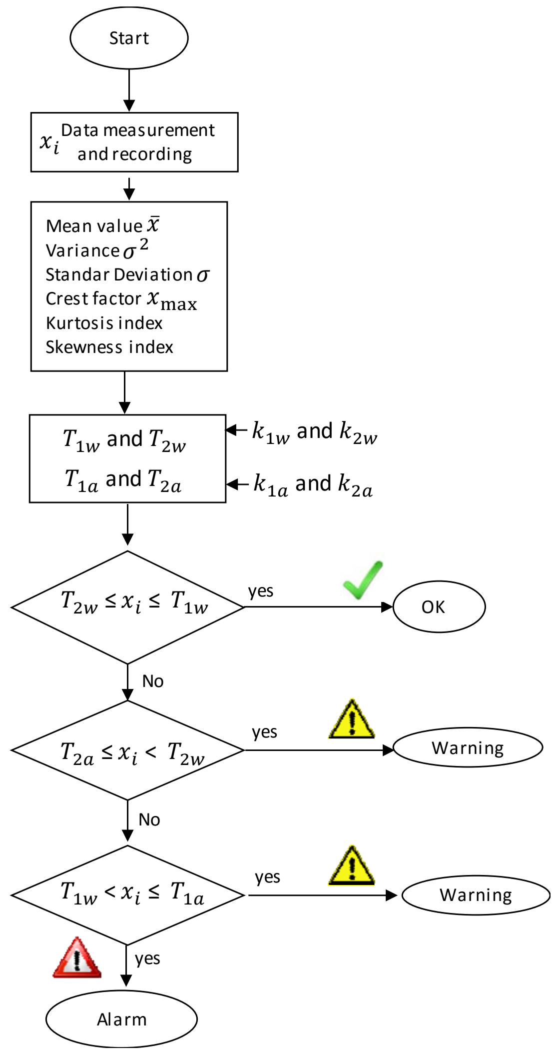

Fig. 7. Details of the algorithm.

Table 1 shows for each month the total number of the trains that the device has detected.

Table 1. Number of the trains detected by the monitoring.

Months	Trains
January	928
February	861
March	960

April	953
May	996
June	993
July	973
August	836
September	990
October	990
November	932
December	656

It is possible to observe lower values of the detected trains in August and December, because August is a vacation month, while in December there is Christmas holiday therefore the train traffic is reduced. During the other months, the little differences are probably due to the suppression of the rides or work in progress on the line.

Figure 8 represents the mean values for each month, and shows that during summer months the contact wire height is little lower than in winter months. This is due to the temperature variation that changes the mechanical properties of the material even if its tension is kept constant by the tensioning device.

In general, the average value of the catenary height for the whole 2014 is equal to 522.9 cm.

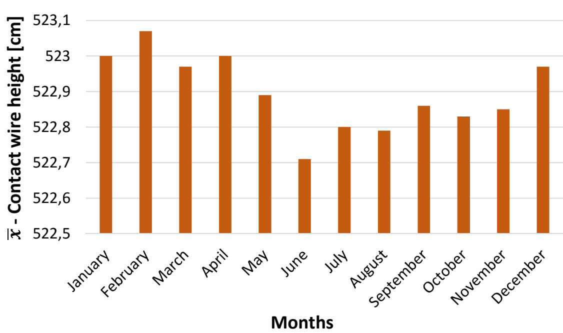

Fig. 8. Mean value of the variation of the contact wire height.

Figure 9 indicates the maximum value (crest factor) detected by the monitoring device for each month. It is worth noting an anomaly during February due to a train with a very uncalibrated pantograph.

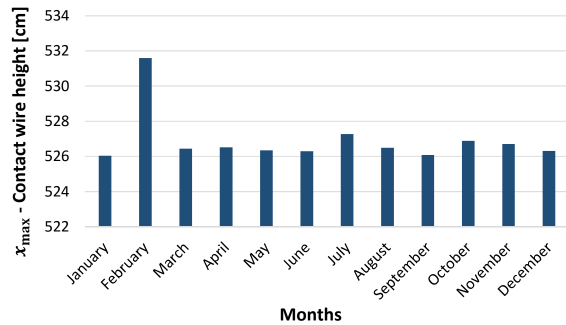

Fig. 9. Crest factor detected for each month.

The algorithm created specifically for the analysis of the data allows, once the different statistical coefficients are calculated, the sending a warning or an alarm signal to railway network control room. The identification of the train that produced this event can be determined through the comparison between the time alarm and the actual passage of the train detected by the traffic control room. Other ways can be based on Radio Frequency Identification (RFDI) of the train directly along the line in correspondence of the monitoring device.

This information is useful to acting for a timely maintenance or to determine the responsibility among the infrastructure manager and the railway undertakings.

VI. CONCLUSIONS

The interaction between pantograph and the contact wire is at the basis of the quality of the current collection and the reduction of maintenance costs.

This work helps to understand the role of the mechanical tension, essential to keep the contact between pantograph and catenary. Indeed, the loss of contact between the contact strip of the pantograph and the contact wire causes the formation of electric arcs that increase the wire wear and produce electromagnetic disturbances towards electric and electronic equipments.

The optical technology introduces many advantages compared to other ones, as the electromagnetic transducers. At first, optical sensors and fibers do not suffer or produce electromagnetic interferences with the surrounding environment.

The low electric power required for their working allows their supply through photovoltaic systems coupled with batteries and simplify their installation since no electric power connections are needed.

Another advantage is the possibility to place the optical sensors directly on live parts since they are constituted with insulating materials. This is important because the sensor is very close to the quantity that it has to measure, therefore the interference with the actual value is dramatically reduced.

In this research optical sensors for the contact wire elevation monitoring following the passage of the various trains have been used. In particular, the monitoring system has been installed in the railway network in the Northern Italy and the recorded values are referred to the whole 2014.

From this analysis, based on the application of statistical indices such as mean value, variance, standard deviation, coefficient of Skewness and Kurtosis, a suitable range in which the elevation of the contact wire can be considered adequate has been defined. Subsequently, the warning and alarm thresholds have been identified in order to act for a timely maintenance of the pantograph calibration or of the catenary geometry and tension.

The overcoming of the alarm signal is a sign of a great problem generally due to the uncalibration of the pantograph that requires a prompt work for the restoration of the system.

The analysis showed that the actual configuration of the catenary-pantograph interaction is quite good in every working and ambient conditions. However, can happen that some trains present uncalibrated pantographs that can really affect the goodness of the current collection and can stress the catenary too much.

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