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A New Experimental Approach Using Image Processing Based Tracking for an Efficient Fault Diagnosis in Pantograph-Catenary Systems

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***Abstract*—The periodical maintenance of railway systems is very important in terms of maintaining safe and comfortable transportation. In particular, the monitoring and diagnosis of faults in the pantograph catenary system are required to provide a transmission from the catenary line to the electric energy locomotive. Surface wear that is caused by the interaction between the pantograph and catenary and non-uniform distribution on the surface of a pantograph of the contact points can cause serious accidents. In this paper, a novel approach is proposed for image processing based monitoring and fault diagnosis in terms of the interaction and contact points between the pantograph and catenary in a moving train. For this purpose, the proposed method consists of two stages. In the first stage, the pantograph catenary interaction has been modeled; the simulation results were given a failure analysis with a variety of scenarios. In the second stage, the contact points between the pantograph and catenary were detected and implemented in real time with image processing algorithms using actual video images. The pantograph surface for a fault analysis was divided into three regions: safe, dangerous and fault. The fault analysis of the system was presented using the number of contact points in each region. The experimental results demonstrate the effectiveness, applicability and performance of the proposed approach.**

***Index Terms*— Condition monitoring, fault diagnosis, image processing, pantograph-catenary system.**

I. Introduction

THE importance of electricity in the field of transportation is increasing, due to environmental damages and the reduction in fossil fuels. Consequently, the development of alternative energy sources is necessary to reduce the damage from transportation on the environment. Electrical energy is the most reliable and clean energy source. Therefore, all available resources are being applied to increase the use of electrical energy around the world. Electrical railway systems have had a significant position in the transportation industry for many years. This system is an efficient alternative to highway and air transportation.

Pantograph catenary (PAC) systems have been used for a long time in railway systems. Pantograph system is used to transmit the electrical energy from the catenary system for to the train. The quality of this transmission is based on the continuation of contact force. A contact force must occur between the pantograph and the contact wire of the catenary for a train to move on an electrical railway system. This contact consists of friction and results in heat rising. The rising heat is one of the most significant reasons for the wearing on the PAC system. The wear is a result of the contact generated by the friction, which affects the PAC system, especially the mechanical structure of the pantograph [1-4].

To achieve better control of the PAC interaction, the contact force must be regularly measured and the contact losses determined. A low contact force leads to the formation of an arc. An excessively high contact force leads to wearing on the contact strip of the pantograph top and the catenary. If an extreme lifting force is applied to the pantograph, more contact will occur with the contact wire; it may even remove it. This will severely damage the pantograph and the catenary; it will also cause oscillations. In addition, wear increasing on the contact wire, or the pantograph collector, can cause an arc to form. Consequently, the necessary precautions to reduce wear should be taken. This will extend the life of the equipment and reduce the maintenance and repair costs [5-7].

Many methods have been developed for condition monitoring and fault diagnosis in PAC systems. The first is based on current-voltage processing based methods and image processing based methods.

If the interaction between the pantograph and the catenary is not proper, the contact and the energy of the train can be cut off or the catenary can be damaged. The vibrations of the contact wire and external forces can cause variations in the contact force. This generates losses and instability conditions in the system [8- 9].The general scheme of the PAC system for a railway line is shown in Figure 1. The most prominent

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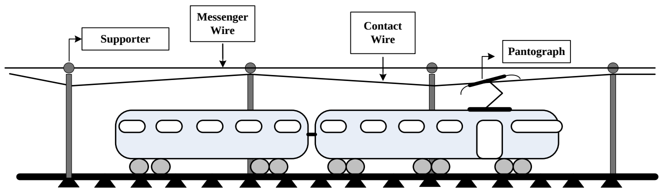

Fig. 1. The pantograph and catenary system for a railway line

parts in this scheme are the pantograph and the catenary; however, all components have a different significance.

Many studies have been achieved by examining the pantograph and catenary systems and the failures that may occur in these systems [7-16]. Wang [7] emphasized that the pantograph slide and the contact wire are a friction pair. A high-performance sliding contact testing machine was used to obtain the experimental data. The mathematical model of wearing was tested to create some testing and curve fitting methods. Electrical and mechanical wear were mentioned, depending on the value of the contact pressure variation.

Pombo [17] focused on using multiple pantographs. When there was a fault in one of the pantographs, the availability of the second pantograph was investigated. The effects of environmental degradation on the PAC system were analyzed; a finite element method was used for the modeling. Xiaodong [18] performed a self-adaptive active control to reduce the vibrations by applying them to the suspension system of the PAC system. Ocoleanu [19] used a thermal analysis to examine the interaction between the pantograph and the catenary. The temperature of the contact point was measured for current values with an infrared camera.

In [20], the mechanical structure of the PAC system and the resonance event at different speeds, with a double pantograph, were investigated. The required software was formed by considering the non-linear pantograph analysis. The effects of the factors that are comprised of wear and their comparisons are presented in [21]. A new test device was improved for a flexible contact action in [22]. Ostlund [23] gave a condition monitoring approach for a pantograph contact strip in winter. However, the wearing in the PAC systems does not only occur as a result of the arcing. Hence, a more detailed analysis for wearing or arcing is necessary for these systems.

Ide [24] accomplished state estimations using a non-linear state feedback control approach to control the contact force at a constant value in the PAC system. A non-linear observer was used to estimate the situations. The estimated situations were linearized with feedback. Figure 2 illustrates a block diagram of the control approach. Bucca [25] proposed a wear model procedure for the contact wire and contact strip of the PAC pair. Laboratory tests were conducted to perform a wear analysis for the contact strips; these were made of different materials, speeds, contact forces and current values. The results obtained from the laboratory test and wear map were used to regulate the wear model.

In the literature, many researchers neglected to avoid the challenges of controller design. The catenary was modeled with a time-varying value of catenary stiffness k(t). The actual

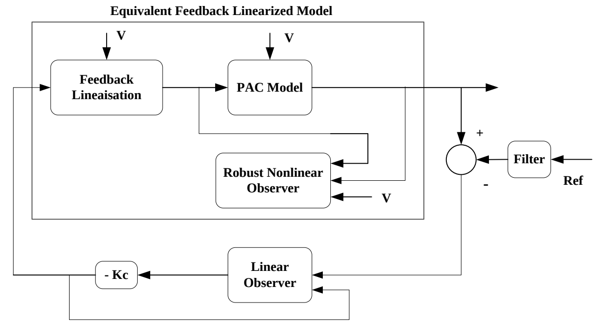

Fig. 2. The block diagram of the control system [19].

values for the contact force and the train speed were used. The results obtained for the constant train speed value exhibited better performance than the variable train speeds. The improvement in the results obtained for the variable speed values and the reduction of the negligence for the PAC system provide a more realistic model.

In the literature, image processing based approaches focus on the detection of arc or contact point. However, the position of the contact between pantograph overhead and catenary wire has not been analyzed. The arc will occur after the wearing of pantograph strip. Only the determination of the contact points is not sufficient to evaluate the pantograph strip. The main contribution of the paper is to analyze the position of contact point. This knowledge is used to evaluate the pantograph overhead condition. The proposed approach was divided into two sections: the contact strip wear model formed by the carbon and graphite materials in the DC line and the wear model formed by the variation in the contact wire's mechanical tension. The wear model schema is presented in Figure 3. The simulation results for the graphite and copper contact strips were obtained and compared. The results reveal that the amount of the contact wire wear and contact strip wear depth were increased when the copper contact strips were used.

In this study, a new approach has been proposed to diagnose pantograph related problems. An image processing based method was proposed to analyze pantograph strip and determine pantograph faults. The main contribution of the proposed method is that both the position of the contact wire and the wear of contact strip are predicted via a contactless system. If it touches the end or the horn of the pantograph, serious problems and faults can occur. The second contribution is to perform the contact point analysis between the pantograph contact strip and the catenary wire based on image processing. The contact point and the position of the contact wire are detected by applying canny edge detection and Hough transform. The data were acquired from a camera mounted on the train. The most commonly touched points of the pantograph strip to the catenary line have been analyzed; the statistical data have been obtained. Thus, the most worn points of the strip and the service life of the pantograph can be determined by condition monitoring and fault diagnostic algorithms.

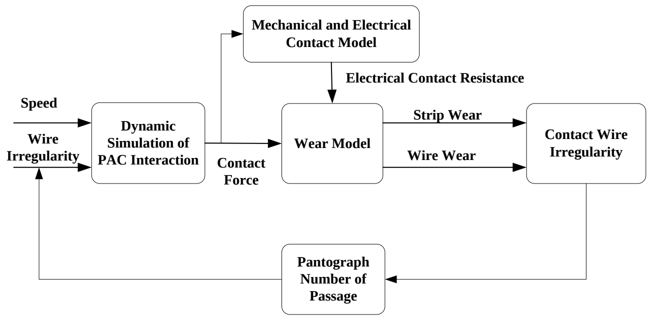

Fig. 3. The wear model [25].

The rest of the paper is organized as follows: section II gives an analysis of PAC systems; section III introduces the proposed experimental approach; Conclusions are given in section IV.

II. Analysis of the Pac Systems

The contact force occurs through the interaction of the pantograph and the catenary. The mean of the current collection quality is used to provide the necessary electrical energy for the operation of trains with a sufficient magnitude of contact force to create a reduction in wear. Due to the friction and heat impact of the contact force exerted by the pantograph, a greater wear occurs. While the train is moving, a force is applied to the catenary contact wire via a pantograph. After the pantograph passes, a small amount of sagging in the wire and oscillations will occur, because of this sagging. The oscillations cause variations in the contact force and vibrations in the pantograph [26].

The flexibility and sagging of the contact wire are very critical in these systems. The contact wire is fixed on the supports at regular intervals. It is close to the support point, while the flexibility and sagging of the wire are less. The flexibility increases at the middle points of the wire. In this case, the faults and pantograph breakage can occur at high speeds. In order to avoid this problem, the sagging of the contact wire is tried to reduce. Various structures are designed to create a flexible structure [27-28]. A wide variety of failures can be encountered in such systems. The contact between the pantograph and the catenary must be in a reliable region. The wrong positions deteriorate the pantograph strip for several reasons, such as:

- Rail or ground. A breakdown of rail or ground affects the interaction between the pantograph and the contact wire. If the train cannot move forward, the contact is always at the same point. The supporter and rail mounting must be appropriately practiced when the ground is very hilly.
- Catenary. Good optimization of the catenary stiffness and sagging is required.
- Pantograph. Irregularities or a very small crack on the surface of the pantograph increases the number of serious problems as the speed increases.
- Weather conditions. These systems are affected by adverse weather conditions, because they usually work outdoors. The effects (e.g., extreme heat or cold, windy weather and ice loads) can disrupt the normal structure of the system.

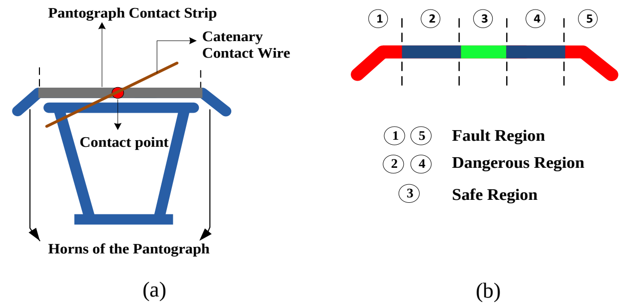

Fig. 4. PAC system: (a) the symbolic representation of the pantograph and the catenary and the (b) Pantograph regions.

The analyzing of the interaction between the pantograph and the catenary should be the most appropriate way to reduce the problems and the costs of the system. For this purpose, different approaches such as simulation based, model based and periodic monitoring have been proposed. The adaptation to catenary structures and working conditions can be achieved with an actively controlled pantograph. The modeling is becoming more difficult with an increase in the speed of the system. In order to realize the required simulation, the electrical railway system needs to be analyzed, step by step, in detail. The establishment of such systems is very difficult and expensive. Due to environmental conditions or unexpected effects, undesirable faults may occur. These faults may lead to accidents or an interruption in the operation. Periodic monitoring, fault detection and the pre-estimation of the required maintenance of railway systems is extremely important worldwide. Monthly checks of railway systems are made with no interruptions in many countries. Due to the technical characteristics of the passive pantographs, the renewal or editing operations cannot be conducted. While the model is developing, the constant contact force variation should be targeted [4, 29-36]. Hence, it is necessary to optimally use and evaluate the existing systems. For this purpose, the necessity of fast, effective, and contactless diagnosis and monitoring methods have been increased. When situations (e.g., the wear of rails, breaking, twisting, catenary line tensions, contact, and the compatibility of the pantograph axis with the catenary line) are examined, the factors that prevent accidents will be pre-determined [31-36].

The symbolic representation of the pantograph, the catenary and the pantograph regions affecting contact, are illustrated in Figure 4. Figure 4 shows the three main regions defined for the contact points on the pantograph surface. The circumstances of each region are examined. The regions depend on the impacts of the contact.

The first region of the pantograph is the fault region. This region corresponds to the horns and the ends of the pantograph. If any contact is realized here, it leads to enormous damage. Breaking or rupturing can occur on the pantograph, resulting in the catenary and the contact being cut off.

The second region is the dangerous region. This region is between the fault region and the safe region. A contact that is in this region does not lead to big problems; it is an undesirable condition. The contact between the pantograph and the catenary should ideally be in the safe region; it depends on the desaxement. It is also important to know where the fault occurred: in the dangerous region or the fault region.

The third region is the safe region. A fault may occur on the right side or the left side of this region.

The separation of these three regions on a pantograph surface is important for powerful condition monitoring and fault diagnosis. Figure 4 shows that the dangerous region and the fault region are divided in itself. The safe region is shown in green, the dangerous region is in blue and the fault region is red.

III. Proposed Experimental Approach

The points of the pantograph that touch the contact wire are very important for this system. The vast majority of problems can occur due to the wear and deterioration on the surface of the pantograph. The contact, which is always at the same point of the pantograph, is not reliable. Therefore, the pantograph surface is divided into specific regions. The situations that might occur for each region are mentioned.

In this study, a contact point monitoring method based on image processing for the PAC systems has been proposed. The pantograph contact strip on the image is determined with the image processing techniques. The pantograph contact strip and the contact wire are detected with the Canny edge detection algorithm and the Hough transform. The block diagram in Figure 5 is used to create the analytical approach. After the mathematical model of the contact point variation between the pantograph and catenary is achieved, the amount of contact is obtained and evaluated with the diagnostic algorithm.

In the proposed method, the contacts on the pantograph regions are analysed by following the contact point. After this review process is complete, the contact status in the critical regions of the pantograph contact area is observed. The probability of faults increases with the contact of the catenary contact wire in the critical regions of the pantograph surface. As such, the probability of a fault is calculated by detecting the fault potential. The contact area with a zig-zag structure, to prevent overheating, is monitored with the enhanced contact point monitoring algorithm. In this way, a scanning area between the pantograph and the contact wire in the PAC systems is formed. This scanning area is illustrated in Figure 6. Figure 6 shows that the scanning area on the surface of the pantograph is formed to avoid contact in the contact wire at the same point on the pantograph. Due to an incorrect adjustment or small problems incurred during system operation, the scanning area may not be at the desired location. If the contact wire is not in the scanning area, the faults increase. The contact occurred in the undesired regions is determined by monitoring the contact point in here. A condition monitoring is performed by estimating the faults on the pantograph surface with the obtained results. The flow chart of the proposed method in this study is given in Figure 7; the block diagram of the proposed algorithm is given in Figure 8.

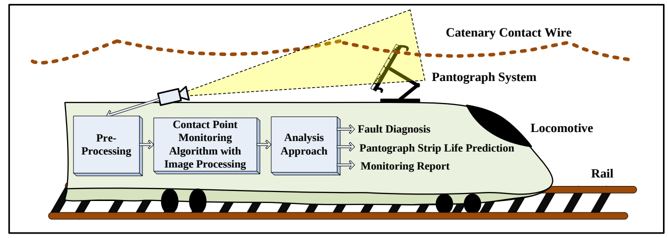

Fig. 5. The experimental arrangement used in the proposed method.

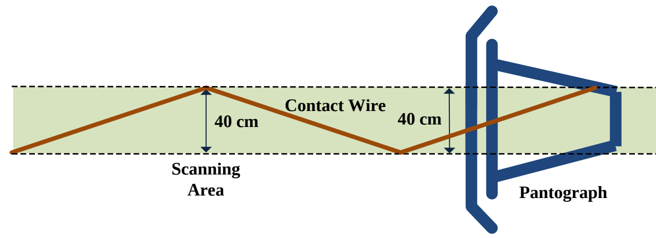

Fig. 6. The scanning area for the contact wire on the pantograph surface.

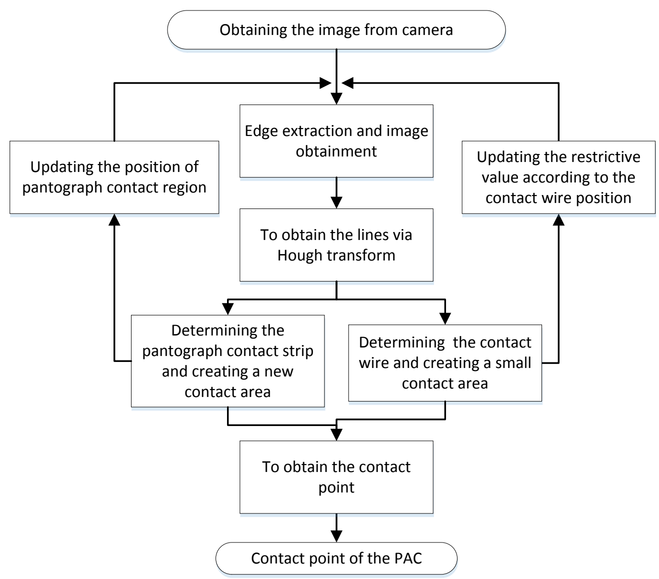

Fig. 7. The flow chart of the proposed method.

As seen in figure 7-9, the image of the PAC system is received from the camera. The Canny edge extraction is applied to this image; straights are obtained with the Hough transform. The pantograph contact strip is determined by taking into account straight angles. A new contact area comprised of a contact strip is formed. New straights are obtained by applying the Canny and Hough within this area. The contact wire of the catenary is detected with the angles of these straights. During the determination of the contact wire, the contact wire can be confused with the messenger wire. Therefore, after the contact wire is detected in the first frame, a small area involving it is formed and the contact wire is searched for in this area for the next image. The block diagram of the Canny edge extraction algorithm is given in Figure 9.

The results of a pantograph image obtained for the Canny edge extraction algorithm, according to the threshold values, are given in Figure 10. The block diagram of the Hough transform is given in Figure 11. The straights for the sample

PAC image obtained from the edge extraction algorithm, according to threshold values, are given in Figure 12.

A sample image of the PAC system is presented in Figure 13. The gray-format of this image, the result of the Canny edge extraction and the straight lines detected by the Hough transform, are illustrated in Figure 13.

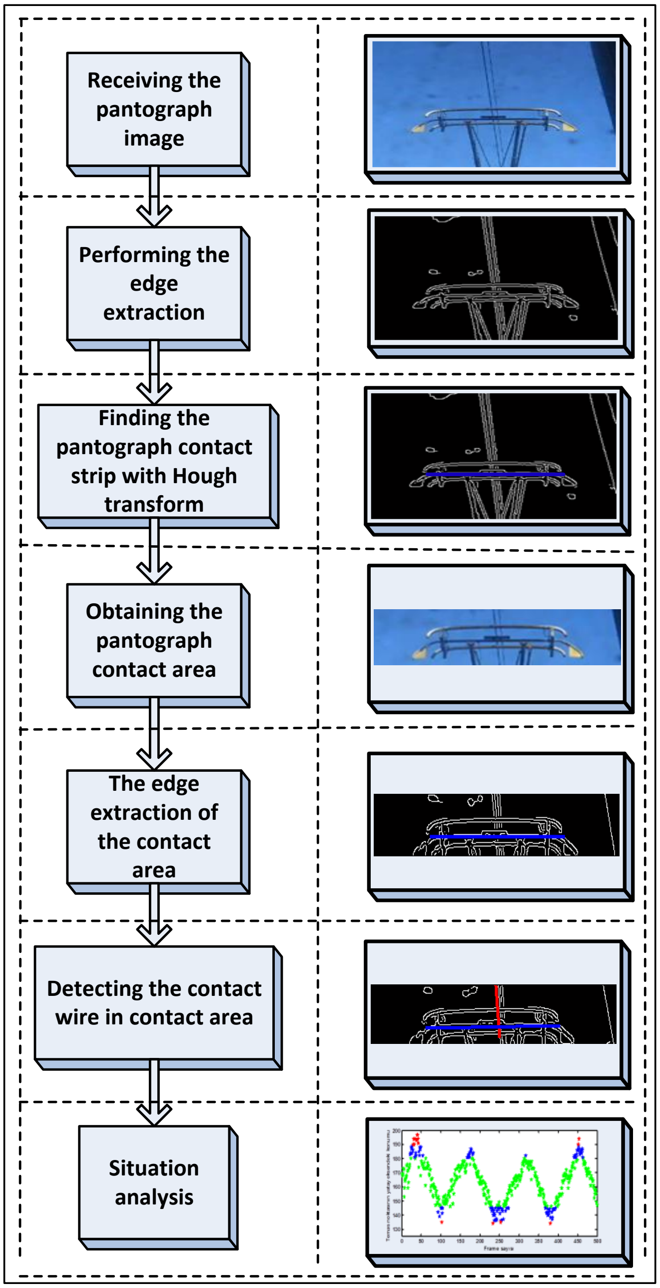

Fig. 8. The block diagram of the proposed method.

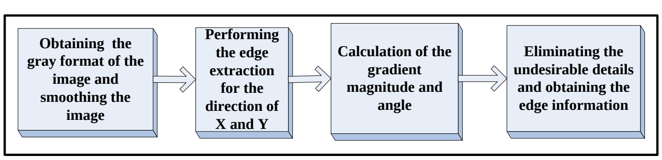

Fig. 9. The block diagram of the Canny edge extraction [37].

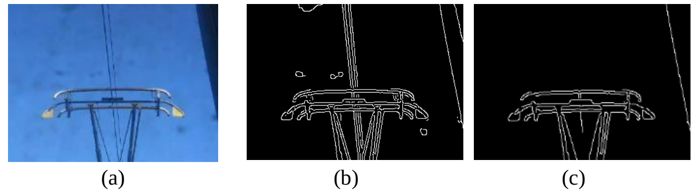

Fig. 10. The implementation of the Canny edge extraction algorithm for the threshold values of the sample pantograph image: (a) normal image; (b) threshold = 0.1; (c) threshold = 0.5.

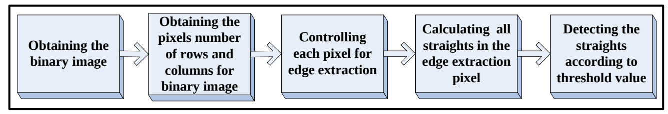

Fig. 11. The block diagram of the Hough transform [38-39].

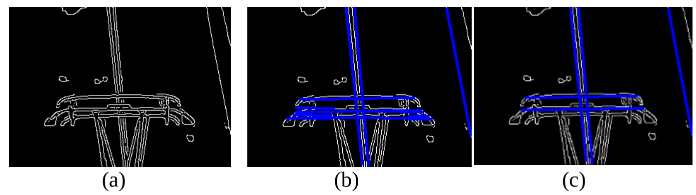

Fig. 12. The implementation of the Hough transform for the threshold values of the sample pantograph image: (a) the image obtained from the edge extraction; (b) threshold = 0.1; (c) threshold = 0.5.

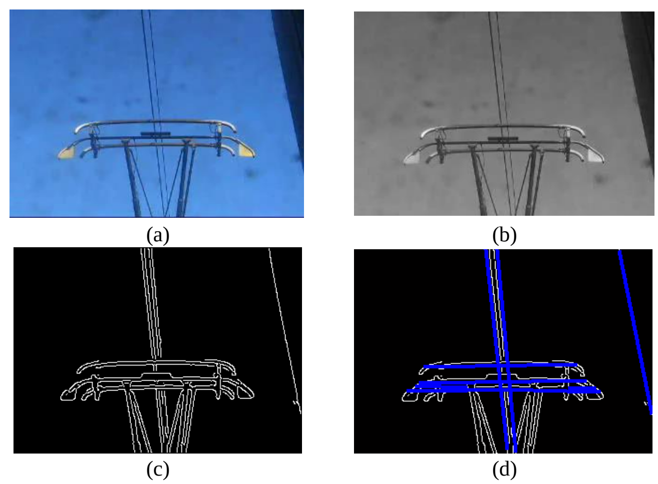

Fig. 13. Obtaining the lines for a sample PAC system image: (a) normal image; (b) gray image; (c) the results of the Canny edge extraction; (d) detecting the straights through the Hough transform.

Fig. 14. Determining the pantograph contact strip and the catenary contact wire: (a) detection of the pantograph contact strip; (b) detection of the catenary contact wire.

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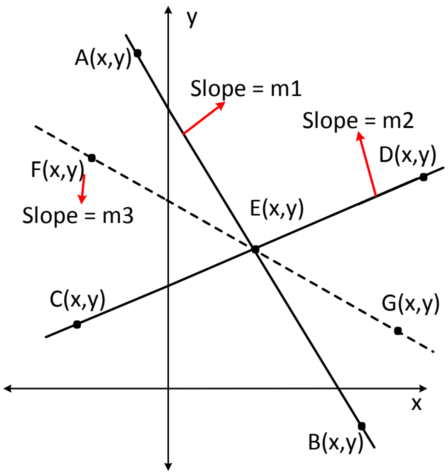


Fig. 15. Intersection of the two straights in the analytic plane.

The contact strip of the pantograph and the catenary contact wire within the obtained straights are determined by considering the angle of the lines. The pantograph contact strip and the catenary contact wire detected in the pantograph contact area are given in Figure 14. The intersection of the two straights in the analytical plane is shown in Figure 15.

The slope equation given in Equation (1), is used to obtain the intersection point of the detected straights for the pantograph contact strip and the catenary contact wire.

$$m = \frac{B_y - A_y}{B_x - A_x} \tag{1}$$

Another straight is drawn; it includes the points of E, F and G, given in Figure 15, to calculate the values of point E. The equation of the straight line with slope m_3 is given in Equation (2).

$$m_3 = \frac{G_y - F_y}{G_x - F_x} \tag{2}$$

The latest state of Equation (2) is given in Equation (3).

$$m_3 = \frac{((D_y - C_y)*(C_x - A_x)) - ((C_y - A_y)*(D_x - C_x))}{((D_y - C_y)*(B_x - A_x)) - ((B_y - A_y)*(D_x - C_x))} \tag{3}$$

The values of E_x and E_y are calculated in Equation (4) and Equation (5) by using the value of m_3 , given in Equation (3).

$$E_x = A_x + (B_x - A_x)*m_3 \tag{4}$$

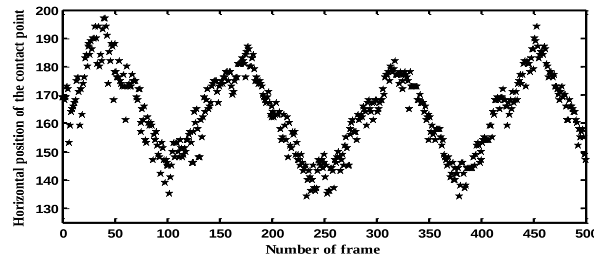
$$E_y = A_y + (B_y - A_y)*m_3 \tag{5}$$

The contact point is monitored by using the values of E_x and E_y on the image of the PAC. The intersection points are taken as contact points.

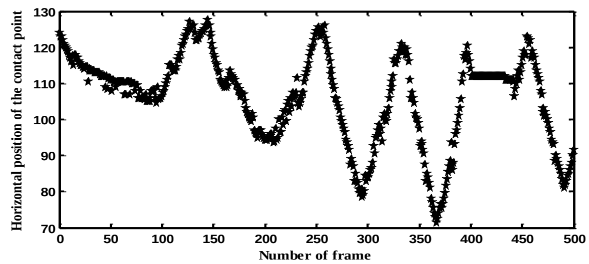
In this study, the videos of the PAC system taken from camera fixed to the roof of the locomotive have been used. The sample images received from the three pantograph videos for 500 frames are illustrated in Figure 16. The location of the contact point is monitored with the image frames received at regular intervals from the videos of the pantographs. The contact point has been identified by using 500 frames taken from the video of the PAC system for each video with the proposed method. The position graph of the detected contact points is shown in Figure 17. The detection of the contact point locations is required according to the regions of the pantograph surface. The location graph is given in Figure 18, by taking into account the position of the contact points obtained in Figure 17 for each frame. Contact should continuously be in the third region for a normal PAC system. However, in the PAC video, the contact points were found to be available in the first region and the second region. Contact in the second region can damage the pantograph surface and can lead to faults. Contact in the first region is more critical and causes major damages and faults. The horizontal and vertical axes positions of the contact wire and regional distribution of the contact points are given in Figure 19 for each frame received from the PAC system videos.

(a) (b) (c)

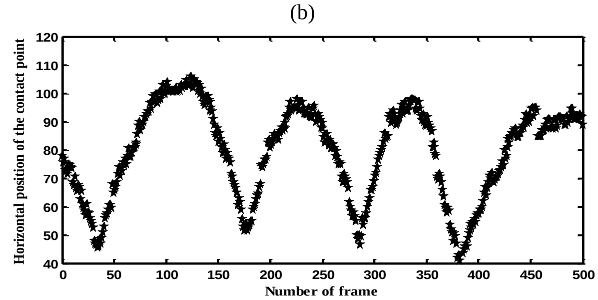
Fig. 16. The images for three pantograph videos: (a) Video 1; (b) Video 2; (c) Video 3.



(a)



(b)



(c)

Fig. 17. Detection of the contact point from the PAC video: (a) Video 1; (b) Video 2; (c) Video 3.

As seen in the figure 18, the vast majority of the contacts occurred in the third region. The number of contact points and contact ratios, according to the regions of the 500 frames, can be seen in Table 1. The contact ratios for the first region are very low. This region is the fault region. The problem must be resolved as soon as possible. The mean operation time for each frame used in this study is 251.3 ms; the standard deviation is calculated as 38 ms.

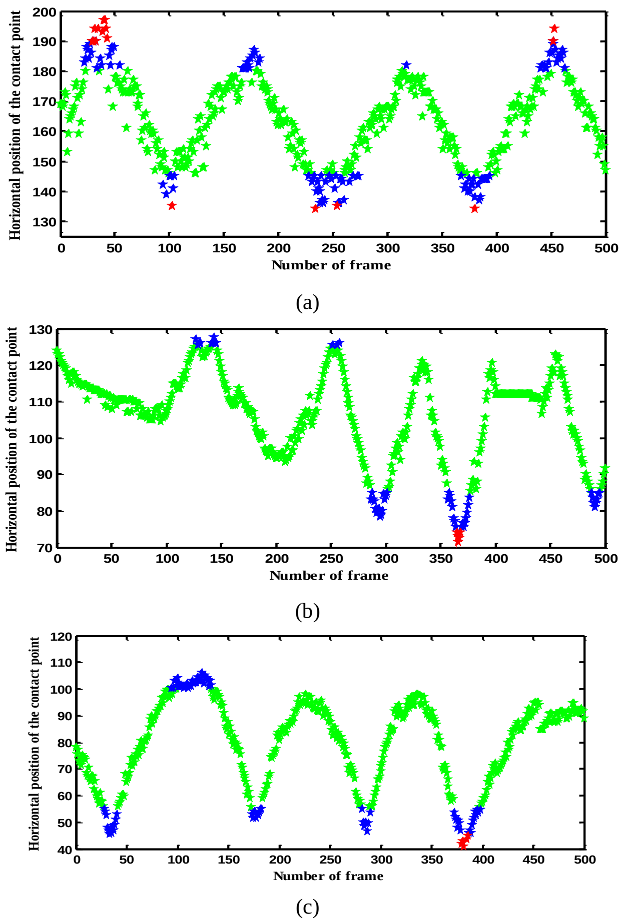


Fig. 18. The distribution of the contact points, according to the pantograph regions: (a) Video 1; (b) Video 2; (c) Video 3.

TABLE I
THE NUMBER OF CONTACT POINTS ACCORDING TO THE REGIONS

Videos	Total number of frames	First region (Fault region)		Second region (Dangerous region)		Third region (Safe region)	
		The number of frames	Contact ratios (%)	The number of frames	Contact ratios (%)	The number of frames	Contact ratios (%)
Video 1	500	10	2	107	21.4	383	76.6
Video 2	500	6	1.2	50	10	444	88.8
Video 3	500	8	1.6	85	17	407	81.4

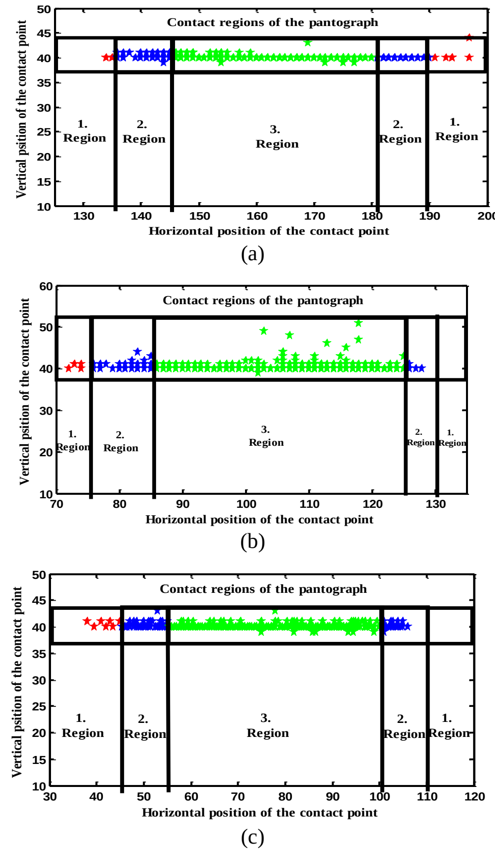


Fig. 19. The horizontal and vertical axes positions of the contact wire and regional distribution of the contact points: (a) Video 1; (b) Video 2; (c) Video 3.

IV. CONCLUSIONS

In this study, the contact point regions on the pantograph surface, formed by the interaction of the pantograph contact strips and the catenary contact wires, have been monitored to identify the faults of the PAC system. The pantograph surface is divided into three regions, depending on the contact situation. These regions include the fault, dangerous and safe regions. The diagnostic algorithm has been established to determine each regions effects on system performance. Ideally, the contact points will be on the pantograph's safe region at all times. The faults are not realized in the third region. If the contact ratio is below 5% in the second region, the probability of a fault is very low. This is determined by the diagnostic algorithm. This is because it is likely a temporary condition and is negligible. An increase in this ratio or a sliding of the contact to the first region leads to major problems. The situations of the contact points for the three values of speed are given. The simulation results are obtained for the fault scenarios.

After this analytical approach for condition monitoring and fault diagnosis was established, an image-processing based method was proposed to predetermine the PAC system faults. A pantograph video taken from a camera fixed to the roof of the locomotive is used in the proposed method. The contact point was identified by applying this method for each frame received from the video. The contact point was monitored by repeating this process for 500 frames. The contact is expected to be in the third region, but when the obtained experimental results were analyzed, the contact points were in the first and the second regions.

The type of fault is detected according to the regions, then repairs can be made and the correctional measures can be determined. The monitoring of the contact point prevents these faults, decreases the maintenance costs and ensures transportation security. Therefore, the monitoring approach of the contact point for the PAC systems is very important. The second region contact ratios are greater than 5%. If the contact wire only touches to the safe region, no fault will be reported. However, a fault is reported according to the position of the contact wire.

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