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Development of an Algorithm for an Anti-theft System for the Rail Transport ContactLine

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Summary

The given article presents the results of the development of algorithms for the operation of elements of the anti-theft system of the contact line dedicated to limit the cases of theft of contact and catenary wires and elements of tensioning devices. The implementation of the system not only reduces the financial losses caused by devastation and theft of infrastructure, but also significantly improves the safety of employees, passengers and bystanders. Constant monitoring of the parameters of the overhead contact line and the transmission of alarm signals in real time to the relevant services (SOK and Police) ensures high efficiency of the system. In addition, the creation of a power supply system for devices mounted on (or near) the contact line, which does not have a galvanic connection to the overhead line, will increase the reliability and availability of traction power supply systems.

Keywords: contact line, theft, security, monitoring

1. Introduction

The theft of overhead line components is a serious problem for infrastructure managers, carriers and passengers alike. Criminal activities result in significant material losses, related to:

- the need to repair the overhead line,
- the need to repair damaged rolling stock,
- train delays,
- launching replacement transport.

Each case of theft of overhead equipment of contact lines results in huge material losses, far exceeding the value of the stolen or destroyed elements, and immeasurable social losses due to train delays. A damaged contact line often results in the destruction of overhead vehicle current collector and further damage to other overhead line components. It is also a threat to the health and life of people - railway workers, passengers and bystanders as a result of electrocution of more than 3,000 V. For this reason, the extent of theft and devastation of railway infrastructure is constantly monitored.

At national level, a joint initiative of three regulatory authorities has been established: the Office of Electronic Communication, the Energy Regulatory Office and the Office of Rail Transport. On the initiative of these offices, a memorandum was issued to take joint action to reduce and prevent theft and vandalism of technical infrastructure equipment, cables and telecommunications, energy and railway equipment [1]. The level of theft and devastation of the railway structure is constantly monitored and statistical information is collected annually from managers and infrastructure managers. As reported in 2017 [2], in the railway sector, theft and vandalism of railway safety equipment (signalling equipment, railway electrification equipment, railway ICT equipment) and elements of the track superstructure are the most common. According to data obtained from PKP PLK S.A., between 2008 and 2012, 2048 thefts and devastation of the upper contact line were recorded on the railway line, during which more than 380 km of catenary wires and almost 387 km of contact wires were cut and stolen. Thanks to the activities of the Railway Security Guard (SOK), the number of crimes and offences committed on the railway area was reduced by 14.49% in 2020 (from 7535 in 2019 to 6443 in 2020, i.e. 1092 fewer incidents) [3]. In 2020, there were 1,309 incidents of theft of railway infrastructure (i.e.

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elements of the track or contact line), while 159 incidents were detected. In 2013, there were more than 3,500, and less than 3,200 in 2014.

When analysing these data, it is apparent that the number of thefts is decreasing. [4, 5] However, the number of cases is still high and most of them remain undetected. The authors of the paper [6] analysed the level of theft of contact line elements based on the data of the Katowice Branch of PLK S.A. Railway Lines and the assumptions for the anti-theft protection system. An analysis of the technical solutions monitoring the state of the overhead lines of many European railway authorities shows that the main idea used in these solutions is to ensure correct operation of the line and safety in the event of a breakage, rather than anti-theft diagnostics. For this reason, there are few solutions on the market that help detect attempted theft and so-called intelligent theft (e.g. when the thief steals only the contact wire or only the catenary wire). This type of theft is not detected by existing systems, which only react to the fact of a voltage interruption. In addition to the material losses associated with the theft itself, "intelligent" theft, has another important dimension. Reduced overhead line height as a result of theft can damage the current collector on the locomotive, which is an additional safety hazard and causes financial losses not only in terms of repairs (replacement costs), but also in terms of delays and stoppages. For this reason, the development of a system to detect attempted theft and theft carried out in an "intelligent" manner (e.g. theft of tensioning weights or of the catenary wire only or the contact wire only) is a priority. The contact line anti-theft system was developed by a consortium involving the Railway Institute (consortium leader) and the Implementation and Production Company NEEL Sp. z o.o.

2. Development of algorithms to detect anomalies in the contact line system

The developed scenarios and algorithms are a key element of the new system, as their task is to analyse the measurement data collected by the system's recorders and generate alarms based on them. The correctness of the algorithms, assuming that correct measurements of the line parameters (hardware) are obtained, is essential for reliable prediction and detection of anomalies occurring in the contact line system.

On the basis of the data, cause-and-effect relationships were established between external influences on the line elements and the change in contact wire and catenary wire tensions, as well as the occurrence of vibrations and voltage interruption in the overhead line. The scenarios and algorithms for generating alarms, of damage or attempted damage to the contact line, took into account the phenomena, their value and variability that can occur during normal operation of the contact line. The anti-theft system (AntyX) must carry out a number of analyses concerning:

- the change in tension of contact wires and catenary wires in the event of failure of the tensioning devices,
- the change in tension of contact wires and catenary wires if a contact wire or a catenary wire is cut,
- the cause of voltage interruption in the overhead line,
- changes in contact line parameters during normal operation;
- the occurrence of vibrations in the contact line caused by factors other than interaction with the current collector,
- correlation of changes in contact line parameters due to external interference.

In addition, the system must link information from the system's sensors to generate alerts or warnings.

2.1. Damage to the tensioning device

The type of damage to the tensioning device depends on its design – weighted or weightless (spring-loaded, gas-loaded, etc.).

In weighted equipment (Fig. 1), changes in the tension force of the contact wires and/or catenary wires can be caused by:

- breakage of the wire rope,
- reduction of the number of weights - theft,
- seizure of the sheaves or their bearings,
- dropping of the wire rope from the sheave guides.

The breaking of the wire rope will result in the complete absence of tensioning force on the contact wires and/or the catenary wires, and their suspension height will be reduced by the value resulting from the extension of the tensioning device protection. The force sensor(s) included in the AntyX anti-theft system will indicate a decrease in the tension force to a value based on the weight of wires from the anchorage to the first suspension.

A reduction in the number of tensioning weights will induce a decrease in the tension force proportional to this number. In the case of a large number of weights in a stack, such as in a device tensioning two contact wires and a catenary wire, the reduction in the tensile force of the individual line elements can be comparable to the change in force resulting from cutting the sheaves. In order to detect a reduction in the number of weights by 1, the AntyX system will analyse the rate of change of the tension in addition to analysing the tension force. In the case of the theft

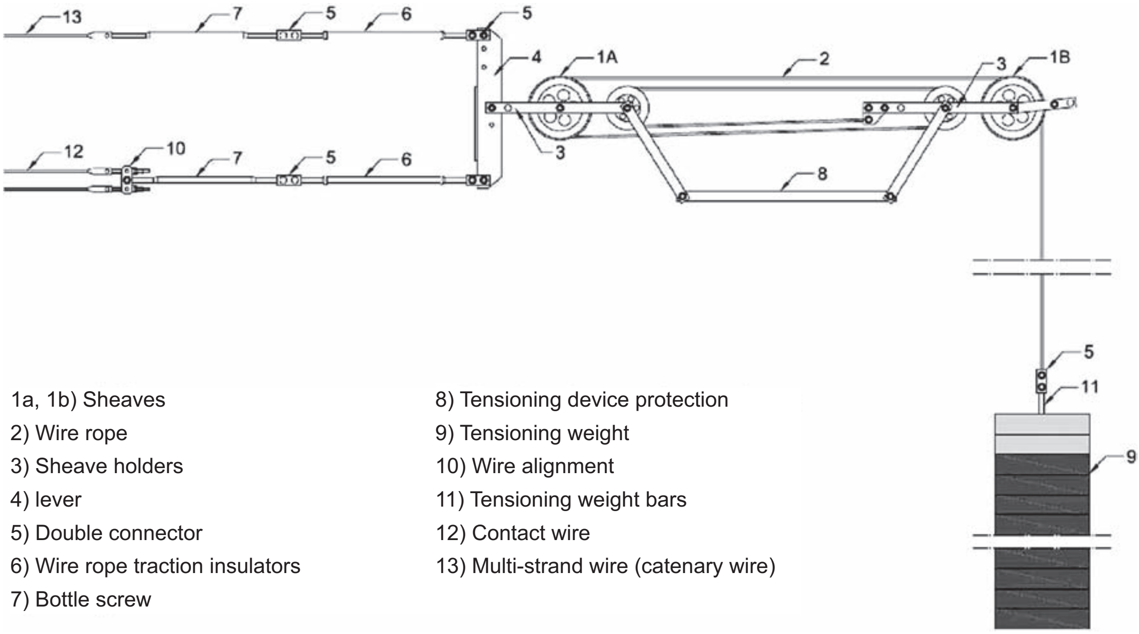

Fig. 1. Weighted tensioning device; own elaboration according to [7, 8]

of a single weight, the change in tension force may be negligible, but it occurs almost stepwise.

In weighted tensioning devices, various types of bearings are used in sheaves, the components of which deform under the influence of forces applied at points. In addition, these bearings and the sheave themselves can become contaminated with, for example, brake pad dust. This means that a slight change in the length of the contact wires or catenary wires due to thermal expansion may not be compensated for by the tensioning device, resulting in changes in the tension of the wires. These changes will occur incrementally at the rate of change in the temperature of wires until the difference in force is no greater than the force required to break the seizure. The force sensor(s) included in the AntyX anti-theft system will indicate a change in the tension force value, and an alarm will be generated if the changes are greater than permissible.

In tensioning devices with parallel sheaves, the wire rope is fed into the sheave guide at a slight angle. This and faults in the installation of the unit can cause the wire rope to fall off the sheaves and jam the unit. In this case, the tensile forces of contact and catenary wires will change as their length changes due to thermal expansion. The line will act as uncompensated or semi-compensated. The force sensor(s) included in the AntyX anti-theft system will indicate a change in the tension force value, and an alarm will be generated if the changes are greater than permissible.

In weightless – spring-loaded tensioning devices, an example of which is shown in Figure 2, changes in the tension force of the contact and/or catenary wires can be caused by the breaking of device components or spring failure.

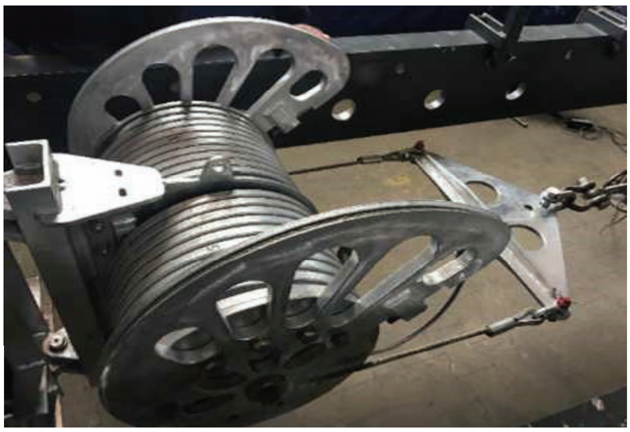

Fig. 2. Spring tensioning device [photo: P. Kwaśniewski]

The breakage of a device component will result in the complete absence of tensioning force on the contact and/or catenary wires, and their suspension height will be reduced by the value resulting from the elongation of the tensioning device protection. The force sensor(s) included in the AntyX anti-theft system will indicate a decrease in the tension force to a value based on the weight of wires from the anchorage to the first suspension.

Damage to the spring by breakage or loss of mechanical properties will result in a reduction in the tensile force of the individual components in proportion to the damage. As spring fracture is a dynamic phenomenon, it can be ascertained by analysing the change in force over time. Force changes due to changes in the mechanical properties of the springs occur over a long period of time, and the anti-theft system should generate an alarm when changes in tension forces are greater than acceptable.

In hydraulic (gas-loaded) tensioning devices, unsealing of the device may occur. In such a case, the change – the rate of decrease in the tension force of the wires will depend on the extent of the damage. Also in this type of device, breakage of the force-transmitting element can be assumed. The breakage of a device component will result in the absence of tensioning force on the contact and/or catenary wires, and their suspension height will be reduced by the value resulting from the elongation of the tensioning device protection.

2.2. Cutting of contact wire or catenary wire

Cutting a contact wire or a catenary wire will cause a sharp drop in the tension force in the damaged element. In the case of a line with two contact wires and a catenary wire, the second, undamaged element will take up the entire tension force, resulting in an almost doubling of this force. Depending on where the contact or catenary wire is cut, the force indicated by the sensor mounted in the damaged element will be greater than zero. This force depends on the weight of the damaged element and from the sensor to the point of the cut, minus the forces resulting from suspension and the transmission of tension of other wires through line elements such as connectors, hangers' arms, etc.

2.3. Causes of voltage interruption in the overhead line

The causes of voltage interruption in the overhead line can be divided into scheduled and emergency shutdowns. Scheduled shutdowns are carried out by the maintenance staff of the traction substation or contact line. The voltage is de-energised by manually opening the high-speed circuit breaker in the traction substation and/or sectioning cabin or opening the disconnector/disconnection switch in the contact line sectioning system.

Emergency overhead line de-energisation is carried out by high-speed circuit breakers in traction substations and sectioning cabins. An emergency shutdown can be caused by a short circuit in the overhead line or traction substation system, an overload in the feeder panel or the tripping of the undervoltage protection in the substation. Immediately after an emergency shutdown, a line test is carried out, i.e. a voltage is applied to the overhead line through a resistor to check for a short circuit in the overhead line system. According to the requirements in the Technical Specifications for Interoperability for the Energy subsystem, the line test should be carried out 5 s after a voltage interruption.

The aforementioned causes of overhead line voltage interruptions are related to the normal operation of the overhead line and its power supply system. The theft of contact line components can be carried out when the voltage is switched on or off. The voltage is de-energised by short-circuiting or opening the disconnector. In the event of a short-circuit, usually caused by a wire being thrown over the contact line, the voltage will be switched off by a high-speed circuit breaker. After de-energising and a negative line test, the short-circuited section of the line will remain de-energised. The fact that the voltage has been switched off and the line test negative is registered in the substation control system and is visible to the signal box staff.

The opening of the disconnector using its drive is also visible to the signal box staff. The situation is different when the disconnector is opened without the use of the actuator, e.g. by lifting the disconnector lever rod after it has been disconnected (cut) from the actuator. In this situation, the main contacts of the disconnector are opened and the auxiliary contacts, from which the disconnector status signal comes, still show that the disconnector is closed.

2.4. Changes in contact line parameters during normal operation

The compensated line should not change its parameters during normal operation. Any changes in the length of contact wires and catenary wires as a result of their thermal expansion should be compensated for by tensioning devices.

In semi-compensated lines, the tension of contact wires should be constant, regardless of their temperature. In the case of the catenary wires, their tension will vary according to their temperature. The range of tension changes (increase in the winter season and decrease in the summer season) is derived from the length of the tension section – the longer the section, the greater the range of changes.

During normal operation, regardless of the type of contact line, the performance of the line may change as a result of the malfunctioning of the tensioning devices described in the previous section and excessive resistance to movement of the suspension systems. With a proper line maintenance, these factors should be eliminated.

In normal operation, the source of vibration of the contact line is its interaction with the current collector. During travel, the current collector interacts with the contact wire and displaces it upwards and then creates a transverse mechanical wave through the contact wire reactions. The wave propagation velocity in relation to the overhead line is defined in section 5.2 of EN 50119 [9]. The wave propagation velocity in a contact wire is directly proportional to the tension in the wire and inversely proportional to the mass of the wire. The wave propagation velocity v_c is equal to the square root of the ratio of these quantities:

$$v_c = \sqrt{\frac{\sum z}{\sum m}}, \tag{1}$$

where:
Σz – sum of the tensions of the contact wire(s) [N],
Σm – sum of the unit mass of the contact wire [kg/m].

There are 37 basic types of contact line in operation on the PKP PLK S.A. line, which differ in the number of contact wires (1 or 2) and tensions. The parameters of these lines, together with the wave propagation speed v_c, are summarised in Table 1, according to which wave propagation velocities from about 151 to over 478 km/h must be reckoned with.

Receiving current from the overhead line and moving along the track, the current collector of the vehicle performs a progressive movement along the track, as well as a variable vertical movement caused by the varying flexibility of the contact line, the varying aerodynamic impact, the unevenness of the track. The uniform span is also a factor in forcing vibration. The vibration frequency f_0 of the current collector – contact line system is expressed using the formula:

$$f_0 = \frac{v}{3,6 \cdot L}, \tag{2}$$

where:
v – travel velocity,
L – span length.

Table 1

Summary of contact line parameters

No. according to catalogue	Line type	Number of contact wires	Nominal tension [N]	Contact wire unit mass [kg/m]	Wave propagation velocity v_c [km/h]
1	YpC120-2C	2	19,620	0.89	336.4
2	YpC95-2C	2	19,620	0.89	336.4
3	C120-2C	2	14,050	0.89	284.7
4	C95-2C	2	12,740	0.89	271.1
10	C95-C	1	9,560	0.89	332.1
11	2C120-2C	2	19,060	0.89	331.5
14	2C120-2C-1	2	14,000	0.89	284.1
20	YC120-2C150	2	26,480	1.335	478.6
21	YC150-CS150	1	12,710	1.335	468.9
23	C120-2C150	2	18,600	1.335	401.1
24	C150-C150	1	12,210	1.335	459.6
26	YwsC120-2C	2	19,180	0.89	332.6
30	YwsC120-2CM	2	19,060	0.89	174.7
32	2C120-2C-3	2	21,180	0.89	184.2
35	2C120-2C-4	2	19,060	0.89	174.7
36	YC150-2CS150	2	29,660	1.335	267.0
37	YC120-2CS150	2	29,660	1.335	267.0
–	YC120-2C	2	14,340	0.89	151.6
–	YC95-2C	2	17,740	0.89	168.6

[Authors' own elaboration].

Formula (2) shows that the current collector vibration frequency depends on the travel velocity and span length. It is directly proportional to the travel velocity and inversely proportional to the span length. If the current collector frequency is close to the overhead line natural frequency, a resonance phenomenon will occur and therefore the vibration amplitude will increase. The natural frequency of the contact line f_s, or rather its first harmonic, can be calculated from the relationship:

$$f_s = \frac{ws}{L} \cdot \sqrt{\frac{X+N}{m_{ln} + m_{Djp}}}, \tag{3}$$

where:

- ws – factor taking into account the design of a single line: $ws = 0.435$ for lines with flexible suspension and $ws = 0.5$ for lines without flexible suspensions,
- L – span length [m],
- X – catenary wire tension [N],
- N – contact wire tension [N],
- m_{ln} – weight of 1 m of catenary line,
- m_{Djp} – weight of 1 m of contact wire.

As can be seen from formula (3), the overhead line frequency is a function of six variables. From the point of view of the analysis to be carried out, the number of 19 types of lines differing in weight and tension force in the contact wire and catenary wire listed in Table 2 is relevant. Each type of contact line has spans of different lengths from 24 to 74 m, representing 50 length possibilities. It must therefore be reckoned that there may be 50 × 19 = 950 different values of the overhead line natural frequencies. A summary of the calculation of the minimum and maximum values of the overhead line frequency f_s for the extreme lengths of the through span, for the different contact line types, is given in Table 2.

Taking wave theory into account, the contact line can be thought of as a system of interconnected strings. As a result of the interaction of the moving current collector with the aerodynamic forces, transverse mechanical waves are generated. Moving along the line, the waves, encountering a point with a changed mechanical impedance parameter, may be totally or partially reflected. The place in the overhead line where the parameter changes is where the contact wire and catenary wire are suspended under the pole.

Another source of vibration resulting from the interaction of the current collector with the contact line is the contact between the overlays and the conductor. The amplitude of these vibrations is determined by the depth of the unevenness of the overlays and the frequency by the granularity – the condition of the overlay surface and the travel velocity. It is estimated that the frequency of vibration, caused by the friction of the overlays against the contact wire, is between a few hundred and a few thousand Hertz.

Table 2

Natural frequency of contact lines [13]

No. according to catalogue	Line type	f_{smax} [Hz]	f_{smin} [Hz]
1	YpC120-2C	2.507	0.662
2	YpC95-2C	2.427	0.665
3	C120-2C	2.591	0.684
4	C95-2C	2.489	0.681
10	C95-C	3.218	0.765
11	2C120-2C	3.07	0.711
14	2C120-2C-1	2.547	0.590
20	YC120-2C150	2.288	0.664
21	YC150-CS150	2.849	0.689
23	C120-2C150	2.347	0.681
24	C150-C150	2.814	0.681
26	YwsC120-2C	2.545	0.691
30	YwsC120-2C-M	2.545	0.78
32	2C120-2C-3	3.133	0.782
35	2C120-2C-4	2.854	0.777
36	YC150-2CS150	2.454	0.739
37	YC120-2CS150	2.373	0.777
–	YC120-2C	2.281	0.602
–	YC95-2C	2.375	0.650

In addition to the vibrations described, there may be vibrations in the contact line from external sources. One of these may be objects that fall on or against the line, such as tree branches. The vibration caused by these sources will be low frequency, close to the frequency resulting from the lifting of the wires by the current collector. The location of this source will be fixed and the nature of the disturbance will be random. The axis of vibration in this case will be horizontal or vertical, depending on the angle at which the object strikes the line. The fundamental harmonic of the vibration will have a frequency close to that determined from the relationship:

$$f = \frac{1}{2L} \cdot \sqrt{\frac{F}{m}}, \tag{4}$$

where:

- f – vibration frequency,
- L – distance between support structures,
- F – tension force of the contact or catenary wire,
- m – weight of the contact or catenary wire,

Another natural source of contact line vibration is the wind. The axis of the wind-induced oscillations is mainly horizontal and their frequency low, defined by formula (4), with *F* being the resultant tension force of the contact line and *m* being the weight of the contact line. The maximum amplitude of the line vibration due to the wind is equal to the maximum deflection of the line from the wind push. This amplitude can be determined using the formulae provided, for example, in Iet-107 [10] or presented in [11]. The described vibrations are damped to the same extent as those from the interaction of the line with the current collector.

External sources are also vibrations caused by cutting the contact or catenary wire or rope with a saw, including a circular saw. The cutting process generates low-amplitude, high-frequency vibrations. This frequency is due to the speed at which the saw teeth move through the component being cut. For example, with 90 teeth on a blade rotating at 2,000 rpm, the vibration frequency will be around 3 kHz when cutting wires. The vibrations caused by the mechanical cutting of a contact or catenary wire propagate through it at a speed more than 100 times greater than in air. They are mainly transmitted through the internal structure of the contact or catenary wire and are therefore poorly attenuated by any type of fixture. Cutting a contact or catenary wire with scissor tools does not generate high-frequency vibrations. Only vibrations caused by the impact of the tool against the line element occur. In this case, it is not possible to use vibration recording to detect damage to the contact line.

2.5. Correlation of changes in contact line parameters due to external interference

As a result of external interference with the contact line system, the contact wire and catenary wire tension and overhead line voltage are altered. The external action of cutting a contact or catenary wire is preceded by a voltage interruption, but not in all cases. Incidents have been reported where wires have been cut while live. In addition, given that a voltage interruption can result from normal line operation (e.g. an overload shutdown), a voltage interruption is not a condition clearly indicative of external interference.

As described in earlier chapters, changes in the tension of contact line elements can be caused by faults in the tensioning devices and by external interference. The source of changes in the tension of the line elements can be indicated by the value and rate of these changes. If the tension on the contact/catenary wires decreases by more than 10% in a few seconds or so, this most likely indicates that some of the tensioning weights have been removed. In this case, an external interference alarm should be generated.

3. Generation of alarms and warnings

The AntyX anti-theft system is equipped with:

- individual tension sensors for each contact and catenary wire,
- individual vibration sensors for each contact and catenary wire,
- overhead line voltage sensor,
- vision system,
- seismic sensors (optional).

Depending on the type of sensor and the value of exceeding acceptable parameters, the AntyX system generates alarms or warnings. The alarm signal is transmitted to the staff supervising the operation of the railway line (signal boxes) and to the Railway Security Guard and police. The alarm signal indicates that the line is damaged as a result of the theft of its components. A warning signal will be generated when the parameters of the line or the activities around it should be verified. The diagram of the generation of alarms and warnings by the AntyX system is shown in Figure 3.

The camera system that is part of the AntyX system continuously records video, which will be stored in the system's primary internal memory. When the capacity of this memory is exhausted, the video files overwrite the oldest ones. The decision on the capacity of the primary memory can be made taking into account the position of the infrastructure manager. It is possible to use the camera system to record the passage of each train and, in the event of a line or current collector failure, the recorded material can be helpful in detecting the cause of the incident.

The AntyX system is also equipped with secondary memory, which is used to save an image whenever the system generates a warning or alarm. The stored image covers a certain time before and after the alarm or warning is generated. Notwithstanding this, the system operator should be able to view the overhead line and its surroundings online via any camera at any time and be able to download files stored in the system memory. The possibility of using this function will be determined by the type of communication available with the AntyX system. Regardless of the various causes of voltage interruption, the signal from the voltage sensor is the basis for generating a warning. The system operator should then verify the cause of the voltage interruption and take further action if necessary.

According to the Iet-2 [12] manual, the tension force of the contact wires and catenary wires should not be less than 10% of the rated force. In normal operation of the contact line, these forces may also increase. For this reason, a 10% increase in tension force was assumed to be acceptable. For tension force

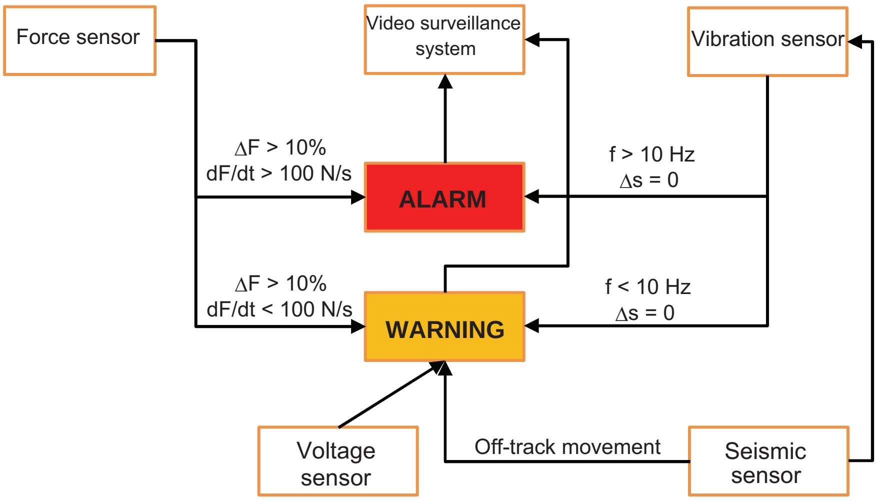

Fig. 3. Diagram for the generation of alarms and warnings by the AntyX system [13]

changes greater than 10%, the rate of change is important. Slow changes, in which the tension force changes at a rate of less than 100 N per second, may indicate a fault in the contact line, e.g. a tensioning device. If this is the case, a warning will be generated to analyse the problem. It is assumed that the tension force of the wires, as well as other parameters determining the generation of warnings and alarms, can be changed remotely.

A line failure, including the cutting of a contact wire or catenary wire, causes rapid changes in the tension of these components. Therefore, a change in force $dF/dt > 100$ N/s, recorded by any force sensor in the AntyX system, is grounds for generating an alarm.

When registering a line vibration, it is important whether the source of the vibration is at a fixed location or is moving. A moving vibration source is indicative of a moving train. A source of vibration with a fixed location can be the wind, an object – a branch on the line or an attempt to cut through its elements.

Due to the fact that low-frequency vibrations are strongly attenuated by suspensions and fittings of all kinds and the high speed of propagation of high-frequency vibrations in metal, an analysis of the amplitude of the vibrations will not be able to determine the exact location of the vibrations and thus whether the location is fixed or moving. Therefore, seismic sensor data will be used to identify the movement of the train along the line.

A vibration sensor will determine the frequency of the vibrations and a seismic sensor will provide data on the movement of the train. If low-frequency vibrations and a moving train are detected, the AntyX system will not react. The registration of a low-frequency signal by the vibration sensor in the absence of train information from the seismic sensors results in the generation of a warning. If this is the case, the cause of the vibration can be identified from the images from the camera system and possible further action can be taken.

The detection of high-frequency vibrations and the simultaneous absence of information from the seismic sensors about a moving train is the trigger for the AntyX system to generate an alarm, as this is highly likely to indicate that a contact or catenary wire is being cut with a saw.

Seismic sensors detect vibrations coming from any direction and, based on their analysis, can determine their source – a walking person, a moving car, a moving train, etc. These properties can be used not only for monitoring the contact line, but also for the railway line environment. It is possible to develop algorithms with which to identify people crossing the tracks in prohibited places or unusual behaviour of vehicles (e.g. stopping a car at night in close proximity to the railway line). Any event that is unusual or identified as undesirable is grounds for the AntyX system to generate a warning and for the camera system to observe the line. It is assumed that a user will be able to change and activate individual system settings remotely.

The AntyX anti-theft system has been installed on the Railway Institute's test track and the access track connecting the test track to Żmigród station. Tests and analyses were performed on a monthly basis. The following analyses of the operation of the anti-theft system were carried out during the operational tests conducted in the third and fourth quarters of 2023:

1) analyses of the operation of the overhead line monitoring devices installed on the access track and the Railway Institute's test track,
2) analyses of the generated alarms,
3) analysis of the effectiveness of the equipment operation.
4) analysis of the performance and correctness of the supply system.

Analysis of the generated alarms showed that the anti-theft system correctly generates alarms and warnings, according to the scenarios and algorithms for generating alarms and warnings developed during stage 4 of the project and presented in this article.

Operational tests of the anti-theft system have shown that continuous monitoring of the overhead line condition based on data from tension, vibration, overhead line voltage sensors in combination with a video surveillance system enables:

- efficient identification of limit deviations in the tension force of catenary wires and contact wires,
- distinguishing between normal and faulty overhead line operation,
- detecting attempts to cut catenary wires and contact wires.

4. Conclusion

1. An analysis of the state of the problem of theft of overhead line components has shown that there are virtually no solutions on the current market for detecting attempted theft or theft of parts of the overhead line (e.g. only one contact wire, only a catenary wire, etc.). Extensive algorithms are needed to detect this type of theft, taking into account changes in the tension of the wires, vibrations and the image recorded by cameras from the location of the attempted theft.
2. To respond to attempts to cut overhead line wires and other types of external interference, an anti-theft system has been proposed, consisting of: individual tension sensors for each wire, vibration sensors dedicated to each wire, an overhead line voltage sensor, a video surveillance system and, optionally, seismic sensors. Depending on the type of sensor and the value of exceeding acceptable parameters, the anti-theft system will generate alarms or warnings.
3. If changes in the tension force of contact line wires occur at a rate comparable to the rate of change in the temperature of the wires, then it can be assumed with a high degree of probability that they are caused by malfunctioning tensioning devices. In this case, an error message should be generated when the line tension forces change by more than 10%.
4. In the case of rapid changes in the tension of wires with high values, it can be assumed that these elements have been cut or broken. Then, irrespective of whether the damage occurred during normal operation (e.g. rupture of a worn or overheated wire) or as a result of external interference, a line failure alarm should be generated.

References

1. Memorandum: Raport o skali incydentów kradzieży i dewastacji infrastruktury telekomunikacyjnej, energetycznej i kolejowej za 2016 r. [Memorandum: Report on the scale of incidents of theft and devastation of telecommunications, energy and railway infrastructure for 2016. Fundacja na rzecz przeciwdziałania kradzieży i dewastacji infrastruktury. 8 p.
2. Coraz mniej kradzieży infrastruktury kolejowej [Less and less theft of railway infrastructure], WWW // Office of Rail Transport. 2018 [Electronic resource] // Urząd Transportu Kolejowego. 2018. URL: https://utk.gov.pl/pl/aktualnosci/14474,Coraz-mniej-kradziezy-infrastruktury-kolejowej.html [dostęp: 15.06.2022].
3. Raport roczny za 2020 rok [Annual report for 2020, PKP PLK S.A.], 2020. 87 p.
4. Bednarek A.: *PKP PLK: kradzieży jest mniej, bo lepiej chronimy* [PKP PLK: there is less theft because we protect better], WWW // Spider's web. 2022. URL: https://spidersweb.pl/2022/04/zlodzieje-kradna-tory-pkp.html [dostęp: 19.06.2022].
5. Informacja o stanie bezpieczeństwa na obszarze kolejowym za 12 miesięcy 2020 roku [Information on the state of safety in the railway area for 12 months of 2020], Straż Ochrony Kolei, 20216.
6. Mikulski J., Młyńczak J., Pawelak M.: *Ochrona antykradzieżowa sieci trakcyjnej* [Anti-theft protection of the traction network], WWW // Logistyka, 2010, nr 6.
7. Katalog sieci trakcyjnej, Podwieszenia rurowe [Catenary network catalog, Pipe suspensions], Kolprojekt, Warszawa, 2010.
8. Katalog sieci trakcyjnej. Sieć trakcyjna PKP. Podwieszenia rurowe [Catenary network catalog, Pipe suspensions], Kolprojekt, 2004.
9. EN 50119:2020: Railway applications – Fixed installations – Electric traction overhead contact lines: EN 50119:2020. CENELEC, 03-Apr-2020. 109 p.
10. Wytyczne projektowania i warunki odbioru sieci trakcyjnej z uwzględnieniem standardów i wymogów dla linii interoperacyjnych Iet-107 [Design guidelines and acceptance conditions for the overhead contact line, taking into account the standards and requirements for IET-107 interoperable lines], 2019.
11. Kaniewski M., Kucińska M.: *Odchylenie poprzeczne przewodu jezdnego sieci trakcyjnej na prostej w procesie certyfikacji* [Lateral deflection of the overhead contact wire on a straight line in the certification process], TTS Technika Transportu Szynowego, 2018, Vol. 25, nr 11. s. 45–48.
12. Instrukcja utrzymania sieci trakcyjnej Iet-2 [Iet-2 traction network maintenance manual], 2019, PKP Polskie Linie Kolejowe S.A., 2019.

13. Opracowanie i wdrążenie elementów systemu antykradzieżowego sieci jezdnej w transporcie szynowym Projekt nr POIR.04.01.01-00-0018/17-00 Etap 4 – Opracowanie scenariuszy i algorytmów generowania alarmów. Praca nr: 03/000002/12. 2020.

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