Electrical Engineering (2022) 104:3881–3891
https://doi.org/10.1007/s00202-022-01596-3

ORIGINAL PAPER

Subtransmission overhead lines mechanical monitoring for fast detection of damaging events

Stefano Quaia[1] · Alessandro Mauri[1] · Matteo Marega[1] · Alessio Marchesin[2] · Davide Rampazzo[2] · Chiara Vergine[2]

Received: 18 March 2022 / Accepted: 15 June 2022 / Published online: 20 July 2022

Abstract
Different harmful events affecting high voltage overhead lines (OHLs) cause changes in the mechanical tension (tensile strength) of conductors. A mechanical monitoring of OHLs, therefore, can provide useful additional information (compared with the information provided by the widely used SCADA systems) about the power system state. The tension measurements combined with a few environmental measurements (air temperature, wind speed) can be used for an automatic (fast) detection of different events and for their approximate location along an OHL, reducing the impact of these events. Referring to 132–150 kV sub-transmission OHLs, this paper proposes some original algorithms, based on the mechanical monitoring of OHLs, for the automatic detection of the following events: conductor breaking, fall of trees on the conductors, ice/snow sleeve accretion on the conductors, strands breaking and galloping. The proposed algorithms require a limited number of sensors placed along the OHLs for measurements of the conductor tension and weather-related quantities.

Keywords Power transmission lines · Automatic fault detection · Overhead line conductors · Wire breakage · Wind-induced conductor oscillations · Galloping

1 Introduction

Statistics show that extreme atmospheric events have increased in recent years, in terms of frequency and intensity, and that damaging events caused by bad weather are clearly growing. This trend suggests a revision of the power systems managing methods, with the purpose of limiting the effects of faults and/or abnormal conditions. In this regard, a significant improvement compared with the current standards can be obtained collecting additional information about the system state. Indeed, additional information can allow automatic detection of different types of damaging events.

This work proposes some original algorithms for automatic detection of specific events on the 132 kV and 150 kV OHLs of sub-transmission networks. OHLs are concerned because at least 90% of the total number of faults in HV networks occur on them, whereas much fewer faults involve the other system components (busbars, transformers, generators). Moreover, compared with the transmission networks, sub-transmission networks generally have larger extension, lower towers, and narrower right of way, and this finally leads to more faults and higher fault rates. With regard to Italy, the overall extension of 132–150 kV OHLs is about 45.000 km, more than twice the total extension of the 380 kV and 220 kV OHLs considered together. Table 1 reports, for these different voltage levels, rounded average values of fault rates (faults/year/100 km) and percentages of the total faults involving OHLs. These data derive from internal statistics collected over the years by the Italian TSO and concern all types of faults (electrical, mechanical, environmental, and so on).

Table 1 Fault rates for OHLs in Italy (rounded indicative values)

Nominal voltage [kV]	380	220	132–150
Faults/year/100 km	3.0	6.5	7.0
Percentage of total faults	10%	20%	70%

Table 1 shows that about 70% of faults in the HV networks occur in the 132–150 kV OHLs. These data clearly explain

✉ Stefano Quaia
quaias@units.it

[1] Department of Engineering and Architecture, University of Trieste, Via Valerio 10, 34127 Trieste, Italy

[2] Terna Rete Italia S.P.A, Via Volta 32, 30037 Scorzè (VE), Italy

the importance of developing new protective logics that can allow an automatic detection (or at least a faster detection, compared with the standard practices) of the main causes of faults and damaging events in 132–150 kV OHLs. Another important target is to improve the location of a fault/event along the involved OHL.

Regarding the most frequent causes of faults, Italian statistical data show that long interruptions of the supply voltage are mainly caused by atmospheric events (which include lightning, wind, snow, ice), contact with plants and fall of trees, conductors breaking and conductors and components wear. In various practical cases, a chain of different causes and effects can be found: for example, strong wind can cause the fall of trees on the OHLs conductors and their possible break.

This work proposes some original algorithms conceived to detect automatically the following events: conductor breaking[1]; fall of trees on conductors; snow/ice sleeve accretion on conductors; breaking of conductor strands; galloping. All the algorithms proposed are based on a mechanical monitoring of the OHLs. A synthetic description of these events is provided below.

(1) Conductor breaking

Primary causes of conductor breaking are atmospheric events: a tension exceeding the mechanical resistance of the conductor can be caused by ice/snow sleeves and/or extremely strong wind, fall of trees, galloping, pylons inclination due to landslides. The automatic detection of a broken conductor, useful to prevent manual and slow auto reclosure on permanent faults, can be challenging because the conductor fallen to the ground may cause just a low fault current, depending on the fault resistance. Obviously, conductor earthing is not a condition that can reveal a break, and the automatic detection of this event must rely on different conditions.

(2) Fall of trees on the OHL conductors

Contacts between the OHL conductors and the surrounding vegetation are frequent and often due to fall of trees, which in turns are caused by adverse weather. The consequences are often single-phase faults, resistive or highly resistive, even though multi-phase faults sometimes occur. The additional mechanical tension due to a fallen tree can lead conductors to break and even damage the pylons. The situation aggravates when snow/ice weighs down the tree.

[1] The Italian 132–150 kV OHLs are equipped with a single conductor per phase.

(3) Snow/ice sleeve accretion on the OHL conductors

Snowy events in Italy show a significant increasing trend in recent years [1]. In particular, wet-snow sleeves on OHLs form more frequently than in the past. Wet snow forms with air temperatures between 0 °C and + 2 °C and is characterized by high liquid water content, cohesion (snowflakes stick easily among them), adhesion (snowflakes stick to the conductors' surface), and density (that can reach 500 kg/m^3) [2]. The accretion of snow/ice sleeves on the surface of conductors and ground wires causes their progressive mechanical overload and can lead to ground faults and even conductor breakings. The situation aggravates by strong wind.

Events caused by wind

Three basic types of wind-induced vibrations/oscillations of the OHLs conductors can be identified: (1) aeolian vibrations, the most frequent type; (2) subspan (or wake-induced) oscillations; (3) galloping. These phenomena depend on different variables, the wind speed being especially important. Roughly speaking, aeolian vibrations occur with wind speed up to 7–8 m/s, subspan oscillations with wind speed between 8 and 20 m/s, and galloping with wind speed higher than 15 m/s [3]. Wind-induced oscillations of conductors can affect the operation of OHLs and their need for maintenance. Possible damages include break of strands, insulators and fittings and, in the worst cases, conductors breaking, and pylons collapse. In galloping events, the large oscillations can cause repeated interventions of the line breakers

Subspan oscillations are not treated in this work since they occur only with bundled conductors and, therefore, not in the 132–150 kV OHLs that are equipped with a single conductor per phase.

(4) Strands breaking caused by aeolian vibrations

Aeolian vibrations of phase conductors and ground wires are characterized by oscillation frequencies between 5 and 100 Hz and very small amplitude, in the order of the wire's diameter [3]. They take place under steady wind of moderate speed and are excited by the 'vortex shedding', i.e. the alternate detachment of vortices that gives rise to alternate forces on the conductor, in direction orthogonal to the wind. Aeolian vibrations are not a negligible problem for OHLs as, in the long term, they are the main cause of fatigue breaking of the conductor strands caused by the conductor bending near the suspension clamps or other devices installed on the wire. Strands breakage reduces the effective cross-section of the conductor, its carrying capacity and its mechanical resistance. In the breakpoints, the higher electrical resistance increases power losses and gives rise to 'hot spots'. Strands breaking is usually detected through thermographic inspection from helicopters using Passive Infrared (PIR) sensors to reveal the hot spots.

(5) Galloping

Galloping is a large amplitude, low-frequency oscillation (between 0.1 and 1 Hz) that can occur either on single or bundled conductors [3]. Statistically, the galloping events with one or two half-waves (loops) in the span are the most frequent and also the worst cases since the lower the loop, the larger the oscillation amplitude. Typical amplitudes are between 0.1 and 1 times the maximum conductor sag in the span, which can mean various meters.

Galloping can arise with strong constant wind orthogonal to the OHL and low air temperature, compatible with the accretion of snow/ice sleeves on the conductors. Snow/ice accretions increase the exposed surface and the force applied by wind and can give an airfoil to the conductor, giving rise to lift forces that produce vertical oscillations.

Galloping can cause supply interruptions due to contacts among different phases or with the ground and, in the worst cases, fatigue break of conductors/components and damages to the pylons. Moreover, line breakers openings are followed by automatic reclosures and then contacts reoccur and the cycle continues, leading to possible damage to line breakers and reduction of their operative life.

Control room operators can detect galloping from the repeated line breakers openings and with the support of meteorological data. Operators can manually open the involved line, which will be finally closed only when the meteorological data will suggest that galloping cannot continue or reoccur. Despite the low frequency of occurrence, automatic detection of galloping would be useful as it would allow a faster manual line opening (avoiding repeated line breakers interventions) and a faster final reclosure, as soon as the end of the event is detected (in this way, also supply interruptions can be significantly shortened).

Automatic (fast) detection of the previous events can be achieved by collection of additional data concerning the OHLs state. The additional data required by the proposed algorithms, which will be illustrated in Sects. 4–8, are:

- tension (tensile strength) of the conductors;
- a few basic weather-related quantities (air temperature and wind speed);
- oscillation frequency of the conductors (only for broken strands detection).

All these quantities can be measured by cheap sensors placed along the OHLs. Automatic detection of the previous events can provide important advantages that include:

1) inhibition of the slow automatic and manual reclosure sequences[2] (in case of permanent fault);
2) additional information to the control room operators, supporting the manual reclosure sequences (reenergization and restore management);
3) approximate event location along the involved OHL;
4) reduced time and costs for interventions of the maintenance units, thanks to the knowledge of the event and of its approximate location;
5) realize de-icing actions on OHLs in order to avoid failures;
6) power quality improvement, depending on the event type/location and network topology.

The next section briefly reports an overview of various methods/proposals for detection of faults/damaging events, with special regard to the five events considered in this paper.

2 Detection of damaging events

Even though contacts of OHLs with the surrounding vegetation are a serious issue, the literature mainly includes proposals/methods dealing with maintenance scheduling and, thus, prevention. As to the automatic detection of the fall of trees on the line conductors, Ref. [4] proposes a method based on the measurement of partial discharges, but this method only holds for OHLs with covered conductors.[3] More generally, an interesting overview of the possibilities provided by modern remote sensing sensors in power line corridor surveys is reported in [5]. Making special attention to vegetation monitoring, this literature review article discusses the potential and limitations of different approaches, which include synthetic aperture radar (SAR) images, optical satellite and aerial images, thermal images, airborne laser scanner (ALS) data, land-based mobile mapping data, and unmanned aerial vehicle (UAV) data.

Concerning conductor breaking, Ref. [6] proposes an algorithm that uses only single-ended electrical measurements to detect broken conductors and estimate their location by using the charging current of the line. However, the method is only suitable for lines that have significant charging current. Also Refs. [7–9] propose different detection methods (tuned on MV systems) based on measurements of electrical quantities (currents/voltages).

[2] In the 132–150 kV networks, the fast automatic reclosure acts after 300 ms and, therefore, the available time for its inhibition is very limited.

[3] Covered conductors (also called tree wires or weatherproof wires) are conductors with a thin insulation covering. The covering is not rated for a full conductor line-to-ground voltage, but it is thick enough to reduce the chance of flashover when a tree branch falls between conductors.

For detection of ice/snow sleeves on the conductors, many TSOs use data collected by weather stations equipped with sensors of wind, temperature, and in some cases humidity [10]. These data may be integrated by web-camera images (UK, Norway, Slovak Republic: the measurements of icing are both visual and by instruments) and in some cases by the measurements of load cells. In Finland, a sensor that continuously measures the ice load on towers has been tested, and other ice detectors—many sensors designed and labeled as ice detectors are available today—were also tested [10]). Also in Norway, where icing is a very real problem, monitoring of these events is made using dynamometers/load cells.

In general, ice accretion can be measured either directly or indirectly by measuring the variables that cause icing. For direct measurements, various possibilities include instruments measuring the changes of a vibrating frequency, changes in electrical properties, the ice load, the ice growth rate by yielding a yes/no output at regular intervals by a heating cycle, optically (obstruction of light path, IR or reflection technologies) [10]. Unfortunately, most of these methods cannot be operated in an automatic way.

Conductor strands breakage is usually detected through periodic thermographic inspections from helicopters using PIR sensors to reveal hot spots. A more timely automatic detection would be useful to improve the scheduling of OHLs' maintenance. Several papers deal with the problem of broken strand detection, and various works deal with the approach based on inspection robots equipped with specific sensors. Ref. [11] proposes to use a HTS-SQUID gradiometer to detect broken strands in compressive conductor joints by measuring the magnetic field gradient above the wire caused by an injected AC current. Ref. [12] proposes to use a magneto-electric transducer such as Hall sensor to detect broken strands of the steel core in ACSR conductors resorting to the leakage magnetic flux theory. Ref. [13] proposes to use an inspection robot equipped with a PIR sensor and proposes wavelet analysis for data processing. Ref. [14] proposes to use an eddy current transducer (ECT) able to reveal magnetic field changes. Other papers have proposed to equip inspection robots with image sensors [15, 16]. This approach can be used to detect external aluminum strand breakage, but the internal ones are more difficult to detect.

Ref. [17] proposes a continuous online monitoring method for wire break detection in OHLs, based on ultrasonic elastic waves generated in the conductor by means of a sending/receiving transducer attached to the surface of the conductor. Other proposals are based on recognition of images collected by visual detectors: an image detection method with Gabor filter is proposed in Ref. [18]. The drawbacks of this approach include visual detectors placement, presence of blind areas, dirt on conductors. In addition, experience with the traditional ACSR conductors has shown that they are vulnerable to significant deterioration of the aluminum conductor and internal steel core before there is visible external evidence.

Different approaches are needed for galloping detection, as the event is not localized at a specific point along the OHL. A first approach is based on visual monitoring/image systems [19, 20]. A different approach concerns the use of acceleration sensors [21]. In this case, the conductor twist can reduce the accuracy of the results. Smaller errors can be obtained by means of inertia sensors [22, 23]. Ref. [24] proposes a novel monitoring scheme based on the fiber Bragg grating sensor. The method requires the presence of optic fibers on the line and is based on the relationship between the galloping amplitude and the horizontal mechanical tension of the conductors. Finally, MEMS (Micro Electro-Mechanical Systems) technology makes available today ever smaller and cheaper sensors for acceleration, angular speed, and position measurements, which could be used for galloping detection [25, 26].

3 OHLs mechanical monitoring

The information on the power system state provided by the current SCADA systems concerns various electrical data. However, these data are not sufficient to identify the type of many harmful events. For this purpose, a monitoring system of the mechanical state of OHLs can provide very useful additional information. Properly managed, this additional information can allow an automatic (fast) detection of some harmful events. Depending on the type of event, a timely detection allows to achieve the important advantages already listed in the introduction.

Mechanical monitoring field tests have started in the North-East of Italy in 2019–20. Field tests involve 26 HV OHLs, in an area that has been heavily affected, in autumn of 2018, by the Vaia storm, one of the worst natural disasters occurred in Italy in the last decades. More generally, the Italian TSO has recently started a pilot project with the installation of distributed sensors and advanced analysis tools for fault localization, pylons structural and environmental monitoring, and the creation of a platform for data centralization.

In connection with these topics, the basic idea developed in this paper is that changes in the mechanical tension of the conductors can allow a timely detection of some harmful events. For this purpose, the OHLs must be equipped with strain gauges that measure the axial tension T of each conductor (phase), being $T[N]$ the vector sum of the horizontal and vertical components T_h and T_v:

$$T = \sqrt{T_h^2 + T_v^2} \tag{1}$$

The strain gauges are contained in 'load cells', installed on each dead-end tower. In Fig. 1, the load cells are indicated with small black squares close to the strain insulators (grey rectangles).

Figure 1 also shows the small connection cabinets, attached to the dead-end towers, which collect the signals received from the local sensors (strain gauges, accelerometers, and others if required) and contain the supply and the remote connection necessary for data transmission. In the pilot project mentioned above, communication from load cells to connection cabinets is based on LoRa (long range) transmission methods, with LTE backup technology. The data are finally sent to the remote data centers through the optical fibers placed in the ground wires.

A weather station installed on (some of) the connection cabinets contains the environmental data sensors which include (at least) a thermometer and an anemometer.

In each line section between two dead-end towers, the horizontal tension T_h is assumed to be constant. On the contrary, the vertical tension T_v can change in the spans of the section, depending on:

1) the 'weight span', which can be different at each tower (and should be understood as known);
2) the total mechanical load per unit length of the conductor qS, being:

- $S[mm^2]$ the conductor cross-section;
- $q[N/m{\cdot}mm^2]$ the total weight per unit length and unit cross section of the conductor, which takes into account the conductor natural weight q_p, the weight of the snow/ice sleeve q_s, and the wind push q_w (assumed horizontal and perpendicular to the line) according to:

$$q = \sqrt{(q_p + q_s)^2 + q_w^2} \tag{2}$$

Clearly, T_v depends, in addition to the known quantity q_p, on the possible presence of wind and snow/ice on the conductor.

T_h can be computed as a function of the thermo-mechanical state of the conductor, and depends on q and, thus, also on the wind. The wind pressure on the conductors, $W_p[N/m^2]$, depends on the wind speed $W_s[km/h]$. Assuming the wind perpendicular to the line and parallel to the soil, W_p can be expressed as:

$$W_p = 0.043\ W_s^2 + 0.002\ W_s \tag{3}$$

Equation (3) is obtained by interpolation with a second-degree polynomial of the pressure values on a cylindrical surface at different wind speeds reported in [27]. The pressure values reported are based on the assumption of wind perpendicular to the surface and hold for any height from the ground of the conductors.

With a snow/ice sleeve on the conductor, the exposed surface increases, depending on the external diameter (the sleeve is conventionally assumed cylindrical in shape), and accordingly the wind push q_w increases.

Since the wind speed W_s is continuously measured by the weather stations placed along the line, W_p can be considered a (more or less) known quantity.

Changes in T_h caused by changes in the thermal and mechanical state can be computed by means of the well-known 'change of state' equation. Dividing the parameters by the cross section S of the conductor ($t = T/S;\ t[N/mm^2]$), the 'change of state' equation can be written as:

$$t_{h_2}^3 - t_{h_2}^2 \left\{ t_{h_1} - E\left[\alpha(\tau_2 - \tau_1) + \frac{q_1^2 l^2}{24 t_{h_1}^2} \right] \right\} = E\frac{q_2^2 l^2}{24} \tag{4}$$

where:

- $E[N/mm^2] = (S_c E_c + S_a E_a)/S$ is the resulting modulus of elasticity of the ACSR conductor (the subscript 'c' indicates the inner steel core and 'a' the outer aluminum);
- $\alpha[°C^{-1}] = (\alpha_c S_c E_c + \alpha_a S_a E_a)/(S_c E_c + S_a E_a)$ is the resulting thermal expansion coefficient;
- $\tau[°C]$ is the conductor temperature;
- $q[N/m{\cdot}mm^2]$ is the total mechanical load (weight) of the conductor (2);
- subscripts 1 and 2 indicate the initial and final states, respectively;
- $l[m]$ is the span.

The conductor temperature can be either evaluated using a thermal model, taking the weather conditions and the actual line current as input values, or operating a direct measure on the conductor. In this regard, the Italian TSO has already developed a thermo-mechanical model (named Dynamic Thermal Rating—DTR) with the goal to increase the short-term transport capacity of OHLs with respect to the design limits. The DTR estimates the main parameters of the conductor, including the temperature, for each span of the line (and the maximum current the line can carry for the following 30 min). Therefore, the conductor temperature is an already estimated and available parameter.

For each phase of the line, the measures provided by the two load cells (T_{MA} and T_{MB}) give the current (real) conductor tension at the two ends of the line section. The conductor

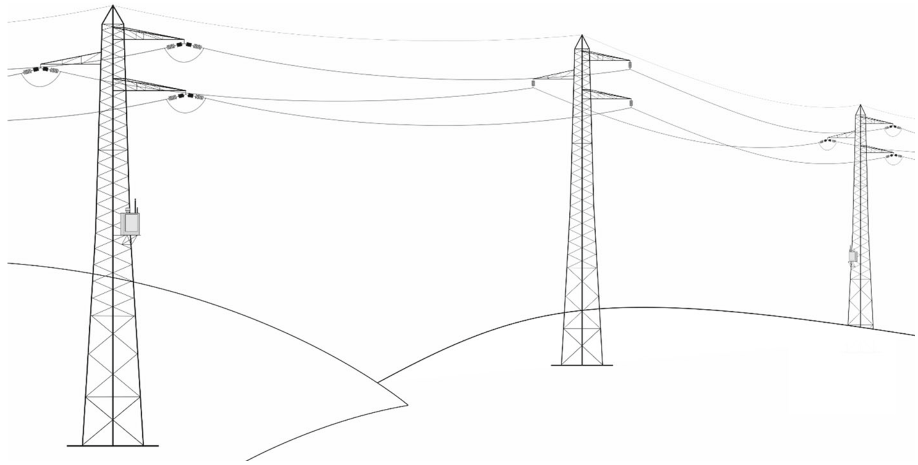

Fig. 1 Section of line, composed of two spans, between two dead-end towers. Dead-end towers are equipped with strain insulators, whereas the central tower is equipped with suspension insulators

tension can be also predicted (computed) using the 'change of state' Eq. (4) and the environmental data provided by the weather stations.[4] The difference between the real and predicted tensions (T_{PA} and T_{PB}) can be used for automatic detection of some events.

Sections 4 through 8 describe the algorithms proposed for automatic detection of the five types of events considered in this work.

4 Automatic detection of a broken conductor

When a conductor breaks, the tension measured by the load cells located at the extremities of the involved line section suddenly decreases. This variation can be exploited for the automatic detection of this event and for its approximate location along the OHL.

Consider first the case where the break happens in an extremity span of the line section. In this case, the 'local' load cell detects a big tension drop since before break the measured tension T is mainly given by the horizontal component T_h[5] that vanishes after break when the remaining tension is due only to the weight of the conductor hanging from the strain insulator. Conversely, the load cell installed at the other end of the line section is 'far' from the breakpoint and detects a smaller tension drop because of the mechanical action of the suspension insulators. After break, the conductor tension is not easily predictable, but it is lower than the minimum tension of the healthy conductor.

If the break happens in an internal span of the line section, both load cells are far from the breakpoint and measure a limited tension drop.

Therefore, in any case, a conductor break causes a sudden drop of the tension measured by the load cells (T_M) below a proper threshold T_{LIM} lower than the minimum possible tension (corresponding to the maximum conductor sag in the spans) of the healthy conductor. Accordingly, the logical scheme proposed for automatic detection of a broken conductor is illustrated in Fig. 2, where the 'No tension' states indicate the condition $T_M < T_{LIM}$.

Tension transients due to wind-induced oscillations, snow detachment, and so on, may cause detection errors. To avoid this (unlikely) possibility and to increase the robustness of the methodology, the proposed algorithm complements the previous mechanical condition with a further electrical condition consisting of the starting signals of the distance protections located at the OHL ends. In Fig. 2, the starting signals are represented as output signals from the BPU (Bay Protection Unit) of each line end, labeled 1 and 2. When both these conditions occur, the alarm 'broken conductor' is generated.

5 Automatic detection of a fallen tree on the line conductors

The fall of trees increases the tension of the involved conductors. If the event occurs in an extremity span of the line section, the tension increase is measured by the local load cell. Conversely, the tension increase measured by the far load cell is much lower. Compared to the case of conductor break, the tension change caused by a fallen tree has opposite sign and is usually smaller. If the event occurs in an internal span of the section, both load cells will measure a small tension increase.

The algorithm for the automatic detection of this event is built on the difference, continuously calculated, between the

[4] The conductor tensions at the two ends of the line section (T_{PA} and T_{PB}) are computed using the following input data: conductor and line parameters (S, E, α, l), horizontal tension in EDS condition, air temperature and wind speed.

[5] For example, a practical value of the tension of a standard conductor can be 15,000 N.

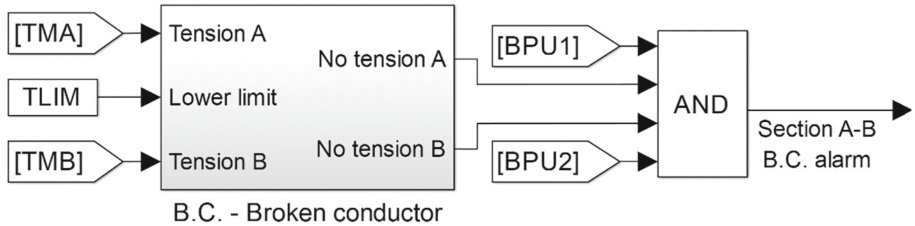

Fig. 2 Logical scheme of 'broken conductor' alarm generation

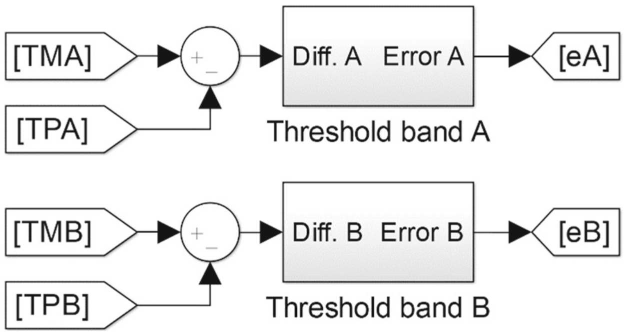

Fig. 3 Error signal conditioning

tension T_M and the computed (or predicted) tension T_P, at both ends of the line section. In Fig. 3, these differences are *Diff. A* = T_{MA}—T_{PA} at the section end A, and similarly at the section end B.

T_P is computed using the change-of-state Eq. (4), in which the line and environmental variables (for example, the current air temperature) are known and, of course, no mechanical overload due to the surrounding vegetation is considered.

Measurement errors in T_M, approximations in the calculation of T_P, and (variable and not predictable) wind push on the conductors can lead to wrong detection (false positives). In order to limit these problems, the algorithm generates an output error signal (named e_A and e_B in Fig. 3) only when the difference T_M—T_P exceeds a threshold value. However, a wrong detection could be generated also by a short transient tension change due, for example, to a strong wind gust lasting for a short time. To increase the robustness of the method, these situations must be discarded. In view of this, the algorithm is built to identify a 'fallen tree' event only when the error persists more than a preset time[6] (this condition is indicated by the labels 'persistent overload' in Fig. 4).

Finally, as Fig. 4 shows, the algorithm generates the alarm 'fallen tree' if, in addition to a persisting measured conductor tension higher than expected at least at one of the section ends A and B, the OHL protection startings are also detected (distance protections or, if present, the protection against highly resistive faults). Clearly, also, in this case, the detection of a fallen tree event is based on the contemporary occurrence of mechanical and electrical conditions. Moreover, the line section involved is identified allowing to speed up crew intervention and reducing the OHL downtime.

6 Automatic detection of snow/ice accretion on the line conductors

In accordance with (2), the accretion of snow/ice sleeves on the conductors increases their mechanical load. The accretion normally involves the whole (or most of the) line section between two dead-end towers, causing a more or less uniformly distributed mechanical overload on the conductors. However, compared with the previous two event types, the tension change is much slower and gradual over time. Accordingly, the load cells along the line are expected to measure a progressive and slow tension increase.

The aim of the automatic detection logic is to avoid that snow/ice sleeves can become too heavy[7] and damage the OHL or cause faults. The proposed algorithm considers the difference T_M–T_P over a sufficiently long time period (for example, one or more hours). Since T_P is computed assuming no snow/ice overload, the basic condition for detection of snow/ice accretion is a progressive increase of the difference T_M–T_P. Likewise explained in the previous Sect. 5, the algorithm generates the error signals e_A and e_B shown in Fig. 5 when the difference T_M–T_P exceeds a threshold value. The progressive increase of the errors can be detected in different ways. For example, the algorithm can store the highest values of e_A and, respectively, e_B collected over a certain time interval (for example some minutes) and compare a certain number of consecutive stored values. For the automatic detection of this event, the algorithm illustrated (in a simplified way) in Fig. 5 requires two further conditions:

- - air temperature (τ_a) and wind speed (W_S) consistent with snow/ice accretion;
- - no starting signals of the line protections (because this event is not a fault).

[6] The time of persistent overload could be estimated in about 10 s, or in any case in a time sufficiently shorter than the automatic or manual slow reclosing time (generally 60 s in the Italian grid for any voltage level).

[7] The weight of wet-snow sleeves can reach 20 kg/m, i.e. ten times the weight of a standard conductor.

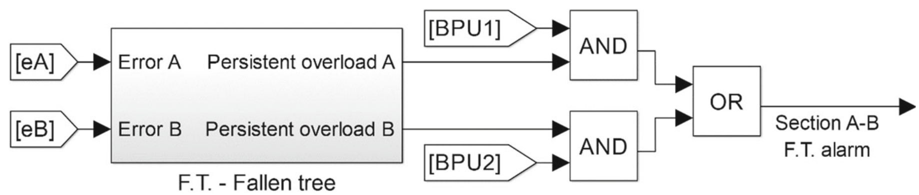

Fig. 4 Logical scheme of 'fallen tree' alarm generation

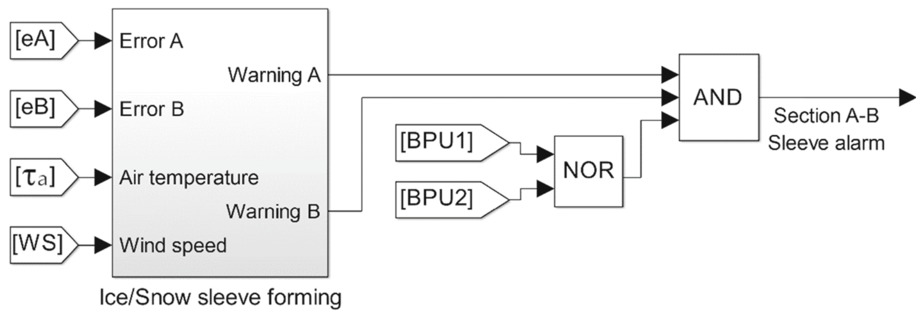

Fig. 5 Simplified logical scheme of 'snow/ice accretion' alarm generation

7 Automatic detection of broken strands

The break of one or more strands reduces the stiffness of the wire and, thus, its natural frequency of oscillation (conductors have several oscillation modes and relevant oscillation frequencies) [28, 29]. Therefore, automatic detection of broken strands in the wires can rely on detection of falls in their natural oscillation frequency.

The n-th natural oscillation frequency, $f_n[Hz]$, depends on the conductor data (diameter, cross section, length in the span $L[m]$, weight per unit length $\mu[N]$, stiffness $EI[N{\cdot}m^2]$, etc.), on the air temperature (which affects L and EI) and on the mechanical tension, T. It can be computed as [28]:

$$f_n = \left(\frac{n\pi}{L}\right)^2 \sqrt{\frac{EI}{\mu}} \sqrt{1 + \frac{TL^2}{EIn^2\pi^2}} \tag{5}$$

Therefore, the n-th natural oscillation frequency changes during time according to the changes in temperature and tension (which can be caused by wind and/or other events).

The actual oscillation frequency can be measured by an accelerometer (f_o). The signal provided by the sensor (considering the typical frequencies of the aeolian vibrations, a suitable sampling frequency can be 1 kHz) must be processed by a dedicated software. The oscillation frequency can be extracted by means of FFT-Fast Fourier Transform.

A low measured frequency (f_m), compared with the frequency computed assuming the conductor undamaged (f_n), can reveal the presence of broken strands (see Fig. 6).

Actually, the experimental results reported in [28] show that the largest reduction of the oscillation frequencies, in the range 3–4%, occurs when only one strand is broken. With two broken strands, the reduction is valued in the range 4–5%, etc. Therefore, the main difficulty connected with this approach consists in the limited reductions of the oscillation frequencies, and this requires small overall measurement errors. The threshold for the generation of a 'broken strands' alarm can be set around 4%, as indicated in Fig. 6, and should be chosen on the basis of experimental results involving the specific conductors of the line.

Note that in this case, the proposed algorithm relies only on a mechanical condition and that the mechanical tension of the conductors is not involved. Finally, the proposed method allows to identify the involved span (not just the line section).

8 Automatic detection of galloping

Damaging galloping events cause variations (at the same frequency of the conductors oscillations and with amplitudes large enough to allow detection) of the axial tension of the conductors. Therefore, we propose to detect such events through a spectral analysis of the tension measured by the load cells and contemporary check of the data provided by the weather stations. Indeed, galloping can occur with specific meteorological conditions: constant wind with speed higher than 15 m/s and air temperature lower than 2 °C, needed to form snow/ice sleeves that make conductors unsymmetrical.

In order to detect the tension oscillations, a quite low sampling frequency, eg 10 Hz, is sufficient. The oscillation frequency is obtained through FFT of the signal of the measured tension. Conditions for galloping detection are a tension oscillation frequency (indicated as f_t in Fig. 7) in the range 0.1–1 Hz and an amplitude higher than a proper threshold. The latter condition has the objective to avoid any protective intervention in case of non-dangerous oscillations. Of course, the threshold should be chosen case by case.

In addition, the above-reported conditions for wind speed (W_S) and air temperature (τ_a) can be also imposed. As

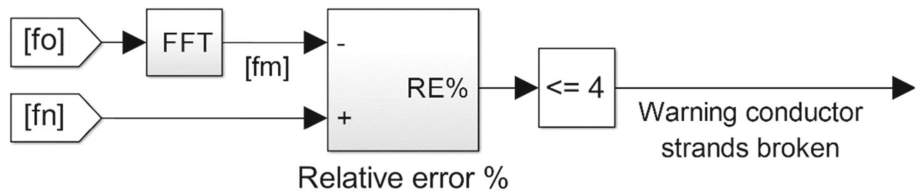

Fig. 6 Logical scheme of broken strands automatic detection

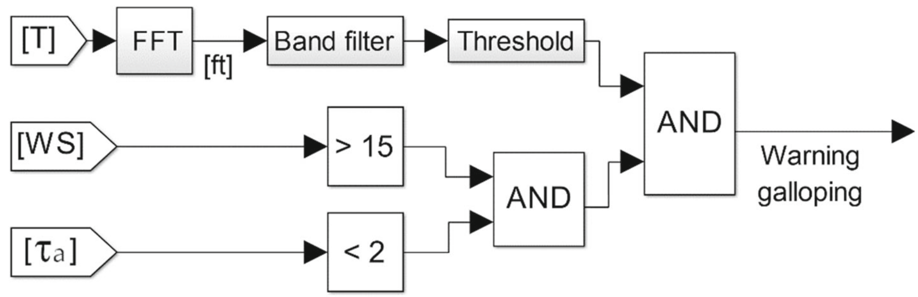

Fig. 7 Logical scheme of galloping automatic detection

Fig. 7 shows, a 'galloping' alarm is generated when all these mechanical and environmental conditions are verified at the same time.

9 Discussion

This section discusses the practical implementation of the five algorithms described above.

1) Sensors required.

All but one of the proposed automatic detection methods require only strain gauges placed on the dead-end towers and some thermometers (for the measure of the air temperature) and anemometers (for the measure of the wind speed) placed along the line. For example, a single circuit OHL requires installation of 6 load cells and 1 connection cabinet on each dead-end pylon, and 1 weather station on some of the cabinets along the line. Considering a 30 km long OHL with an average span length of 300 m and 5 spans per section, this means a total number of 120 load cells, 20 cabinets, and a few weather stations.

The further installation of inclination sensors on the conductors could increase the robustness of the algorithms for detection of conductor breakings and fall of trees. In this case, the inclination measurements should be synchronous with the tension measurements.

On the contrary, the algorithm for broken strands detection (for which mechanical tension measurements are not needed) requires the installation of accelerometers at the ends of each span.

2) Sampling frequency.

1 Hz or less is a suitable sampling frequency for detection of the sudden tension changes caused by conductor breakings and fall of trees. Clearly, a higher sampling frequency increases uselessly the amount of data, whereas a too low frequency is not suitable to detect a sudden change and slows down the automatic detection.

For detection of snow/ice accretion on the line conductors, an increasing trend of the conductor tension over a relatively long time period can be detected under-sampling (for example over a time interval of 1 to 5 min) the maximum values of the tension measurements.

In conclusion, suitable sampling times/frequencies for automatic detection of the different events considered in this study are:

- conductor break and fall of trees: ≥ 1 s / $f \leq 1$ Hz;
- snow/ice accretion: ≥ 60 s / $f \leq 0.016$ Hz;
- broken strands: 1 ms / $f = 1$ kHz;
- galloping: 0.1 s / $f = 10$ Hz.

3) Practical difficulties in the proposed detection methods.

Automatic detection of conductor break, fall of trees, and snow/ice accretion requires installation of a limited number of sufficiently simple and cheap sensors. Field measurements enter as direct input data (without any processing) in the detection algorithms. The practical implementation of the proposed algorithms requires a careful setting of the threshold values that, obviously, are case-specific. A possible difficulty is given by the high reliability requested for strain gauge operation.

Also the automatic detection of galloping can be considered easily achievable: the required processing of the tension measurements is not a significant problem. Some attention must be paid to the bigger amount of data that derives from the higher sampling frequency.

Conversely, more critical appears the automatic detection of broken strands, because of:

- wider set of sensors;

- accurate and precise sensors and small overall measurement errors required for a correct detection;

- possible interference between the oscillations of conductors and towers and between consecutive spans;

- higher sampling frequency that results in bigger amount of data.

Finally, for its implementation, the proposed method must be extended to several natural oscillation modes.

4) Reliability.

The reliability of the whole detection system is mainly connected with that of the load cells (obviously, this does not hold for broken strands detection). The other equipment (weather stations, connection cabinets, and communication systems) do not pose particular reliability concerns. Communication systems are robust, and also the sensors power supply can be duplicated using PV panels and/or microeolic turbines.

Load cells are requested to be robust and enough accurate. Interesting information about their practical operation is expected from field tests like those mentioned at the beginning of Sect. 3.

5) Cost/benefit assessment.

In view of practical realization, the installation along an OHL of load cells, connection cabinets, a few simple weather stations and the relevant communication systems entails a limited additional cost compared with the expected benefits that include increased resilience and quality of supply, and lower risks.

10 Conclusions

Referring to 132–150 kV sub-transmission OHLs, this paper proposes some original algorithms for the automatic detection of conductor breakings, fall of trees on the conductors, ice/snow sleeve accretion, strands breaking, and galloping. The five proposed algorithms are mainly based on the mechanical monitoring of the OHL conductors and can be used for revision of the sub-transmission networks management criteria, with the aim of reducing the impact of these damaging events. Indeed, an automatic (fast) detection of these events can provide significant advantages that include:

- inhibition of the slow automatic and manual reclosures in case of permanent faults;
- reduced maintenance/intervention times, allowed by the knowledge of the event type and its (approximate) position along the line;
- reduced OHL downtime and line breakers stress in galloping events;
- avoidance of faults/damages caused by heavy ice/snow sleeves.

In addition, the first two items can improve the continuity of supply and, thus, power quality.

For practical implementation, the conductors tension and a few weather-related quantities must be continuously measured. All these quantities can be measured by means of a limited number of sensors (strain gauges, thermometers, and anemometers) placed along the OHLs. Installation of the required equipment and data communication systems entails a limited additional cost compared with the expected benefits. The only exception concerns broken strands detection, which requires accelerometers on each span of the line. The algorithm for broken strands detection requires also higher sampling frequency and small measurement errors and, among the proposed algorithms, is clearly the most critical. All the other algorithms are cost-effective and require low sampling frequencies with limited amount of data.

Author contribution All authors contributed to the study conception and design.

Funding Open access funding provided by Università degli Studi di Trieste within the CRUI-CARE Agreement. No funding was received to assist with the preparation of this manuscript.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval All authors read and approved the final manuscript.

References

1. Quaia S, Marchesin A, Rampazzo D, Mancuso C (2019) Anti-icing measures in the Italian power system. IET Gener Transm Distrib 13(24):5577–5585. https://doi.org/10.1049/iet-gtd.2019.0287
2. Dalle B, Admirat P (2011) Wet snow accretion on overhead lines with French report of experience. Cold Reg Sci Technol 65:43–51. https://doi.org/10.1016/j.coldregions.2010.04.015
3. Electric Research Power Institute EPRI (2006) Transmission Line Reference Book: Wind-Induced Conductor Motion. Palo Alto, CA, USA.
4. Pakonen P (2007) Detection of incipient tree faults on high voltage covered conductor lines. Master Thesis, Tampere University of Technology, Finland.
5. Matikainen L et al (2016) Remote sensing methods for power line corridor surveys. ISPRS J Photogramm Remote Sens 119:10–31. https://doi.org/10.1016/j.isprsjprs.2016.04.011
6. Dase K, Harmukh S, Chatterjee A (2019) Detecting and Locating Broken Conductor Faults on High-Voltage Lines to Prevent Autoreclosing Onto Permanent Faults. Proc. of the 46th Annual Western Protective Relay Conference Spokane, Washington, USA.
7. Pongthavornsawad A, Rungseevijitprapa W (2011) Broken Conductor Detection for Overhead Line Distribution System. Proc. 2011 Asia-Pacific Power and Energy Engineering Conference. DOI: https://doi.org/10.1109/APPEEC.2011.5749066
8. Garcia-Santander L, Bastard P, Petit M, Gal I, Lopez E, Opazo H (2005) Down-conductor fault detection and location via a voltage based method for radial distribution networks. IEE Proc - Generation Transmission & Distribution, 152(2):180–184. https://doi.org/10.1049/ip-gtd:20041300
9. Bhalja B, Shah P, Rakholia B, Shah J (2011) A new digital down conductor detection scheme for overhead electrical power distribution systems. International J Emerg Electric Power Syst. https://doi.org/10.2202/1553-779X.2782
10. Fikke S et al (2006) COST 727: atmospheric icing on structures, measurements and data collection on icing: state of the art. Publ MeteoSwiss 75:1422–1381
11. Miyazaki A, Hatsukade Y, Matsuura H, Maeda T, Suzuki A, Tanaka S (2009) Detection of wire element breakage in power transmission line using HTS-SQUID. Physica C 469(15–20):1643–1648. https://doi.org/10.1016/j.physc.2009.05.086
12. Jiang Xingliang, Xia Yunfeng (2010) A LMF based broken strand faults detection scheme for steel core in ACSR. Proc. Int. Conf. on High Voltage Engineering and Application, New Orleans, LA, USA. DOI: https://doi.org/10.1109/ICHVE.2010.5640790
13. Zhou FY, Li YB, Feng GR (2010) A Real-Time Online Method for Detecting and Diagnosing Broken Strand of High Voltage Transmission Line with Inspect Robot. Transactions of China Electrotechnical Society.
14. Xia Y, Jiang X, Zhang Z, Jianlin Hu, Sun C (2013) Detecting broken strands in transmission line - part 1: design of a smart eddy current transducer carried by inspection robot. I Trans Electr Energy Syst 23(8):1409–1422. https://doi.org/10.1002/etep.1669
15. Sawada J, Kusumoto K, Maikawa Y, Munakata T, Ishikawa Y (1991) A mobile robot for inspection of power transmission lines. IEEE trans power delivery 6(1):309–315. https://doi.org/10.1109/61.103753
16. Toussaint K, Pouliot N, Montambault S (2009) Transmission line maintenance robots capable of crossing obstacles: stage-of-the-art review and challenges ahead. J Field Robot 26(5):477–499. https://doi.org/10.1002/rob.20295
17. Haag T, Beadle BM, Sprenger H, Gaul L (2009) Wave-based defect detection and inter-wire friction modeling for overhead transmission lines. Arch Appl Mech 79(6):517–528. https://doi.org/10.1007/s00419-008-0282-x
18. Jiang X, Xia Y, Zhang Z, Hu J, Hu Q (2011) Image detection for broken strand faults of transmission conductor based on optimized Gabor filter. Autom Electric Power Syst 35(15):78–83
19. Aota H, Yaguchi Y, Oka R (2008) Feature Detection of Electrical Feeder Lines with Galloping Motion. Proc. of the 8th IEEE Int. Conf. on Computer and Information Technology, Sydney, Australia. DOI: https://doi.org/10.1109/CIT.2008.4594696
20. Tadano S, Takeda R, Miyagawa H (2013) Three dimensional gait analysis using wearable acceleration and gyro sensors based on quaternion calculations. Sensors 13(7):9321–9343. https://doi.org/10.3390/s130709321
21. Huang X, Tao B, Feng L (2011) Transmission Lines Galloping On-Line Monitoring System Based on Accelerometer Sensors. Proc. of the 2011 IEEE Power Engineering and Automation Conference, Wuhan, China. DOI: https://doi.org/10.1109/PEAM.2011.6134881
22. Lv ZB, Li Q, Ni YQ, Huang Q, Wu WL, Zhang C (2015) An Efficient Method for Galloping Profile Monitoring of Power Transmission Lines by Use of an Inertial Unit: Theoretical and Experimental Investigation. Proc. of the 2015 World Congress on Advances in Structural Engineering and Mechanics, Incheon, Korea.
23. Huang X, Zhao L, Chen G (2016) Design of a wireless sensor module for monitoring conductor galloping of transmission lines. Sensors 16(10):1657. https://doi.org/10.3390/s16101657
24. Chen Y, Zhang Z, Chen X (2011) Novel monitoring method of power transmission line galloping based on fiber Bragg grating sensor. Opt Eng 50(11):114403. https://doi.org/10.1117/1.3646404
25. Nakao T, Han H, Koshimoto Y (2010) Fundamental study of magnetically levitated contact-free micro-bearing for mems applications. Int J Smart Sens Intell Sys 3(3):536–549. https://doi.org/10.21307/ijssis-2017-407
26. Santhiranayagam BK, Lai DTH, Begg RK, Palaniswami M (2010) Correlations between end point foot trajectories and inertial sensor data. Proc. of 6th Int. Conf. on Intelligent Sensors, Sensor Networks and Information, Queensland, Australia. DOI: https://doi.org/10.1109/ISSNIP.2010.5706797
27. CEI - Comitato Elettrotecnico Italiano (1998), Italian Standard CEI 11–4, Installation of overhead lines (in Italian).
28. Zhao L, Huang X, Jia J, Zhu Y, Cao W (2018) Detection of broken strands of transmission line conductors using fiber bragg grating sensors. Sensors 18(7):2397. https://doi.org/10.3390/s18072397
29. Zhao L, Huang X, Zhang Y, Zhu Y, Jia J, Zhu C (2020) Aeolian vibration-based structural health monitoring system for transmission line conductors. Struct Control Health Monit 27:e2538. https://doi.org/10.1002/stc.2538