Carlos VILACHÁ PEREZ, Antonio FERNANDEZ OTERO, Julio Cezar MOREIRA MEIRA, Edelmiro MÍGUEZ GARCIA

University of Vigo, Department of Electrical Engineering

Applications of an Algorithm for Overhead Power Line Analysis

Abstract. *Overhead Power Lines are the prevailing facilities to carry electric energy across big distances. They have experimented a great development during the last century due the economic expansion, and they have become essential assets for the countries. Although during this time they have reached an outstanding technical status, there are different phenomena, such as short-circuits and heavy weather conditions, which can cause the failure of these facilities. Simulation constitutes a powerful tool to minimize and analyze these failures. This paper presents two applications of a multiphysic algorithm developed by the authors that is able to perform electro-thermal dynamic simulations of overhead power lines. The first application shows a transient evolution for a given overhead power line during an open-close sequence due a persistent short-circuit. Then, a long-time simulation is performed considering the load curve and the environmental temperature variations during a given day. And lastly, a collapse of a conductor when a tree hits the overhead power line is shown.*

Streszczenie. *W napowietrznych liniach energetycznych występują zjawiska, takie jak zwarcia na skutek warunków atmosferycznych, które mogą spowodować uszkodzenie tych urządzeń.. Przedstawiono dwa przypadki zastosowania algorytmu multiphysics opracowanego przez autorów, który jest w stanie wykonać elektro-termiczne dynamiczne symulacje napowietrznych linii energetycznych. Pierwsza aplikacja pokazuje dynamiczne zmiany dla danej linii energetycznej napowietrznej podczas sekwencji ponownego załączania z powodu trwałych zwarć. Drugi przypadek dotyczy długiego czasu symulacji zgodnie z krzywą obciążenia z uwzględnieniem środowiskowych zmian temperatury w danym dniu. Jako trzeci, przedstawiono symulację zerwania przewodu na skutek uderzenia drzewa.* (***Zastosowanie algorytmu symulacyjnego do analizy linii napowietrznej***)

Keywords: dynamic simulation, electro-thermal, overhead power line, simulation tool.
Słowa kluczowe: symulacja dynamiczna, zjawiska elektro-termiczne, linia napowietrzna, narzędzie symulacyjne.

Introduction

Electrical infrastructures are essential to support our current society lifestyle. Home appliances, public transportation system and hospitals are some examples of indispensable and highly dependent-of-electricity services that developed countries are accustomed to. However, keeping a good electrical supply, in terms of quality and reliability, constitutes a huge engineering challenge that involves the proper operation of many electrical facilities; among them, overhead power lines are one of the most important.

Overhead power lines are the prevailing way to carry electrical energy to the different consumption nodes. They are economically and technically affordable to cover large distance—in South America, transmission lines cover thousands kilometers, such as the new 600 kV HVDC line of 2,500 km in Brazil.

Many standards and recommendations concerning overhead power lines design provide equations and calculation hypothesis in order to make a good design. These equations and hypothesis rely on wide safety coefficients, which are valid for most cases. Nevertheless, some designs cannot draw on these generic criteria because of their importance or their cost [1]—the overhead power line over the Bay of Cadiz, in Spain, required using unusual metallic towers as well as stronger conductors. In this case, more relaxed calculations would have increased greatly the final budget.

In order to make more realistic designs, some software applications tools and algorithms have been proposed during the last years, taking advantage of the current computing performance [2]. Most of them only feature steady-state mechanical calculations, that is, they evaluate the force of the wind, the environmental temperature variations and the snow pressure for a given conductor [3], [4]. Other authors have suggested ways to calculate the forces generated during short-circuits events.

This paper presents an application of an already introduced multiphysic algorithm [5], which couples three models: a thermal model, a mechanical model and an electromagnetic model.

The authors have developed a software tool called SEDLA that implements the mentioned algorithm. SEDLA has a user interface that allows intuitively inserting an overhead power line by choosing their parameters inside a customizable database. Once the line is defined, transient and quasi-steady simulations (quasi-steady simulation means to observe the evolution of an overhead power line during a long period of time, such as days or months) can be performed. Indirectly, SEDLA can also calculate a steady case by setting constant input data in a transient simulation.

This work is divided into three additional parts. In the first part, the simulated system is described. Then, three cases are simulated to show the capabilities of the mentioned algorithm. Lastly, some conclusions are presented.

Simulation description

The first step in this work was to specify the overhead power line design, which basically consists of choosing the towers and conductors. The tower characteristics are shown in the Table 1. Regarded with the active conductors, a conductor with a cross-section area of 110 mm^2 (EN 50182:94-AL3/22-ST1A) was selected.

Table 1. Tower main dimensions

Parameter	Value [m]
Height to active conductors	12 m
Distance between conductors	2 m
Number of active conductors	3
Active conductors configuration	Horizontal
Number of ground wires	None

This type of tower and conductor is commonly used on Spanish 15-20 kV distribution lines.

The example line only has a single span of 110 meters length. The initial conditions were supposed to an environmental temperature of 20 ºC, without electrical load and a safety coefficient of 3.5. With these conditions, the tension in the middle of the span is about 1180 daN for each conductor.

Following the input data definition, the speed and direction of the wind, the currents that flow through conductors and the additional external forces must be indicated. Once all these data are ready, the algorithm can be executed.

Algorithm 1 shows how the algorithm is structured. Firstly, the algorithm loads all the data. Then, the system is discretized by dividing the line into segments and. Now, the algorithm is ready to start the simulation. As Algorithm 1 shows, the time is discretized in steps. When the accumulated time *"t"* is higher than the simulation time *"ts"*, the algorithm stops. Nested the main while loop, there is another loop that checks the error for each time step. This verification provides convergence stability to the algorithm.

Algorithm 1. SEDLA algorithm design

```
→ run the application
load overhead power line data;
discretize conductors;
while t < ts
    while e < emax
        integrate dynamic equations;
        evaluate multiphysic models;
        calculate error;
    end while
    t = t + $\Delta t$;
end while
→ exit;
```

Simulations

This section shows two different simulations. These cases demonstrated the entire functionality of the developed application.

Both simulations use as starting situation, the initial conditions described in the section above, and all the resulting data correspond to the middle of the span.

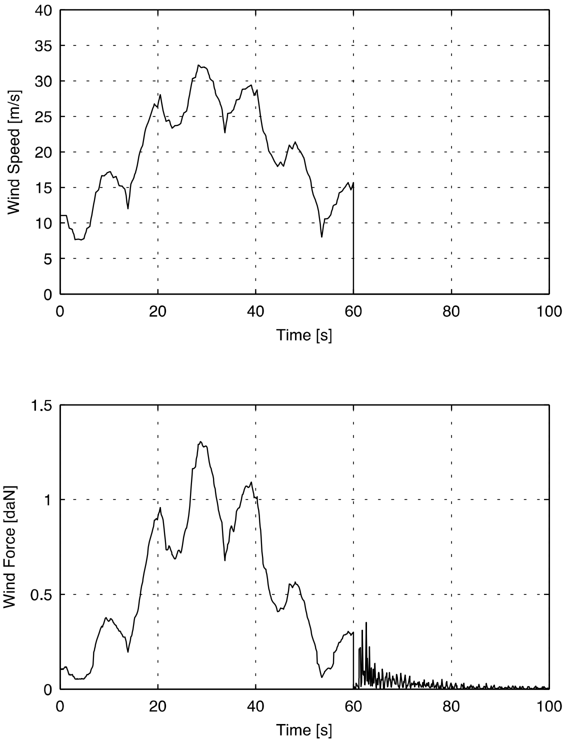

Fig. 1. Wind speed and force over the conductors.

Transient Simulation

In this case, the behavior of the overhead power line is studied when a persistent biphasic short-circuit appears after strong blasts of wind.

The simulation lasts 200 seconds, about 3.3 minutes. During the first 60 seconds, the line carries a current of 100 A, and it is under a strong wind, see the Fig. 1. The wind curve was generated by using a mathematical model of four components [6], [7].

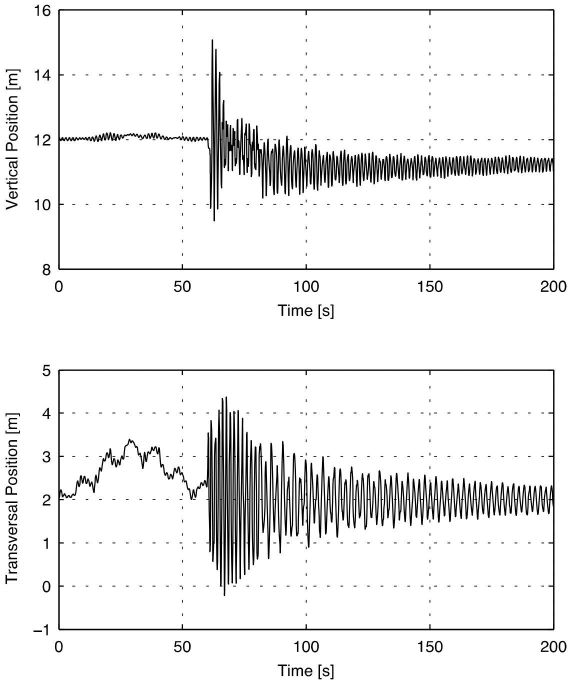

Fig. 2. Conductor position in the middle of the span.

This wind generates a force that reaches a value of 1.4 daN. It is high enough to cause a transversal displacement of more than 1 meter, as the Fig. 2 shows. The vertical position is only slightly perturbed. The normal tension sometimes goes over than 1400 daN, which does not cons

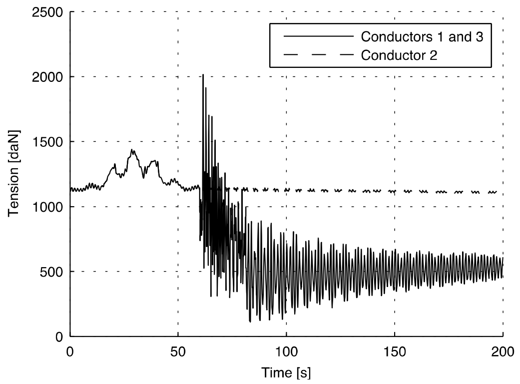

Fig. 3. Normal tension in the middle of the span.

At the instant 60 s, a biphasic short-circuit happens between two of the conductors (conductor 1 and 3), which are adjacent. The RMS value of this current is 9 kA, the relation L/R of the line is 1 and the short-circuit angle is 0 (this implies a maximum peak of current). At instant 60.1 s, the protective relays open the line and the fault is over. During this event, both conductors reach a normal tension of 2000 daN. The Fig.3 shows the tensions of conductors 1 and 3 and conductor 2. The latest is not in fault; as a result its tension becomes stable after the wind stops.

The magnetic field and force are shown in the Fig. 4. Although, the force lasts only 100 ms, its peak value is very high (6 daN), if it is compared with the force generated by the previous wind. This situation provokes a significant displacement of both conductors in fault.

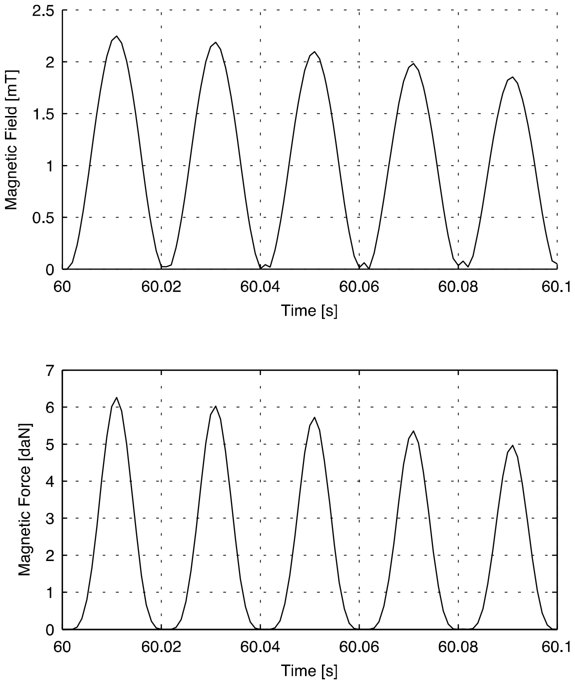

Fig. 4. Magnetic field and force in the short-circuited conductors.

After a second pause, the protective relays try to reestablish the supply by closing the breakers. This is a very common sequence in Spain because non-persistent faults during strong winds are very frequent. In this case, the fault is persistent, so a new short-circuit happens again. The characteristics of the current are the same except for the short-circuit angle, which is now 10 degrees.

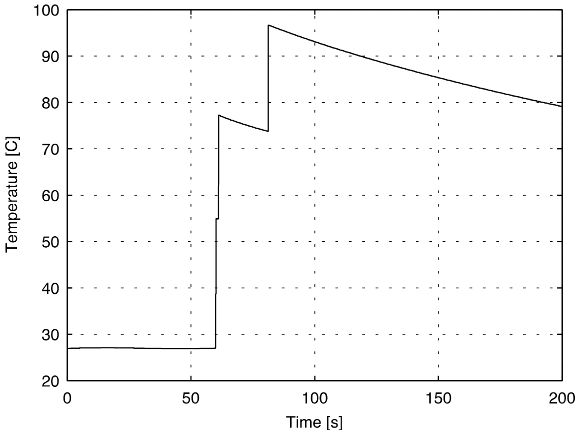

Fig. 5. Temperature in the short-circuited conductors.

This new fault lasts 80 ms and causes another temperature rising, over than 76 ºC, as the Fig. 5 shows. Now, the normal tension is lower than in the previous fault because the conductor is hotter. The protective relays open again the line. This time, they wait 20 seconds before trying another close. During this period of time, the conductors lost heat and slowly become steady.

Fig. 6 shows the big accelerations and speeds caused by the sequence of short-circuits. As a result, although the forces generated by a short-circuit are relatively low, their sudden appearance can break fragile materials (materials with low elasticity) such as ceramic insulators due the big accelerations.

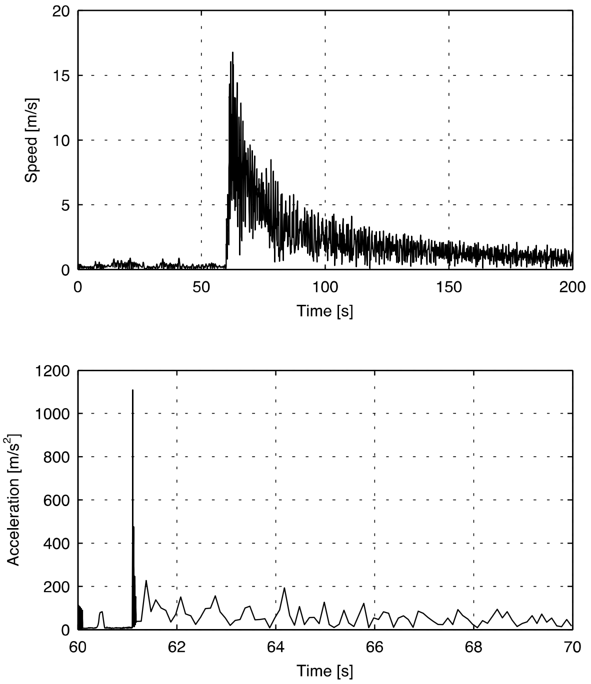

Fig. 6. Speed and acceleration in the middle of the short-circuited conductors.

The third and last reconnection happens at 81.18 s. The fault still persists, so another short-circuit current establishes upon conductors 1 and 3. It has the same value and R/L relation but this time the short-circuit angle is 20 degrees. As the conductors are still waving, it has a minor impact on the system dynamics, but it raises again the conductor's temperature, see the Fig. 5, and, consequently, it decreases the normal tension, see the Fig. 3. After 80 ms, the protective relays open permanently the line, and the line goes slowly towards an equilibrium point.

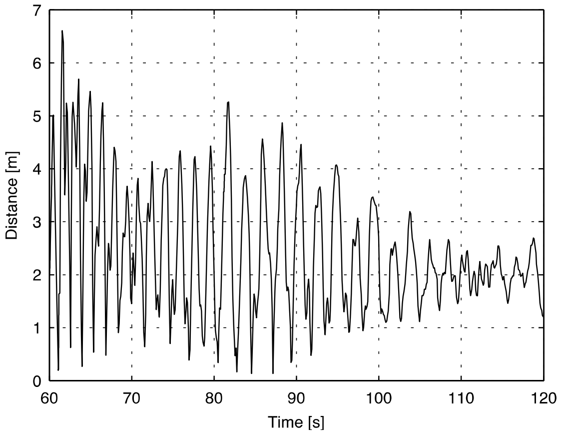

Fig. 7. Distance between the conductors that undergo the short-circuits.

It is also interesting to observe the evolution of the distance between conductors 1 and 3. It can be seen in the Fig. 7. This figure only shows the distance between the instant 60 s and 120 s, because the wind does not modify this distance—the wind impacts almost identically upon the three conductors. They start with a separation of 2 meters. However, the short-circuits cause the conductors start to wave from one side to other with different frequencies. As a result, sometimes they wave in opposition and go toward each other keeping a distance of only 15 centimeters.

Supposing a case where after the second pause and posterior reconnection of the protective relays, the fault had disappeared, it would be possible that the low separation between the conductors were not enough, and a electric arc appeared generating another fault. This is one of hypothesis taken into consideration when the reconnection times of protective relays are set.

Quasi-Steady Simulation

In this subsection, a quasi-steady study using the same model and identical starting point is shown.

This simulation calculates the evolution of the line during 24 hours. The input data are the consumption curve of an average day, which was obtained from REE [8], the environmental temperature evolution, according to the data collected by MeteoGalicia [9], and a hypothetical wind curve of average speeds. This data is shown in Fig. 8; the starting time is at 10 pm.

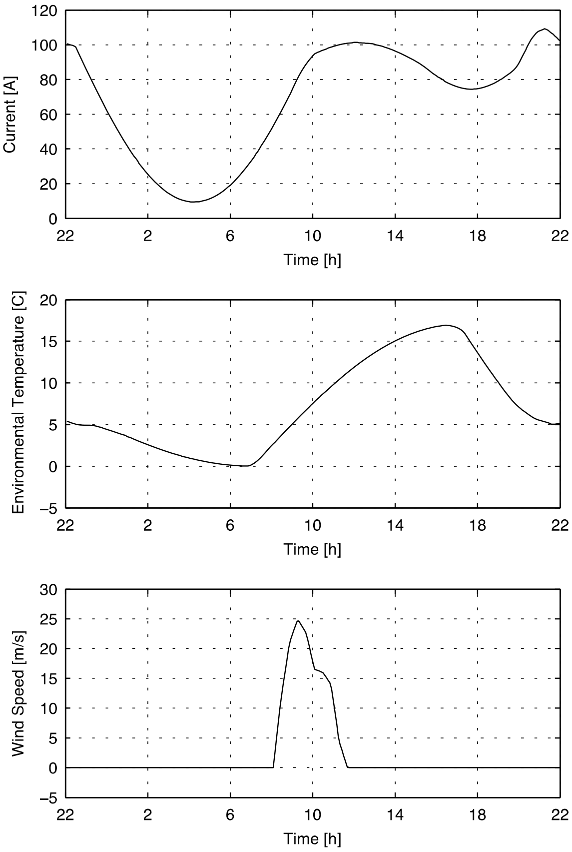

Fig. 8. Input data.

The results are shown in the figures below, Fig. 9 and 10. The conductor temperature evolves basically with the current curve, Fig. 9. Although it is slightly affected by the environmental temperature because the heat loss by convection rises when the surrounding temperature descends. Between 9h to 11h am, the temperature goes down about 10 degrees due the refrigerating effect of the wind; the wind improves the convection coefficient.

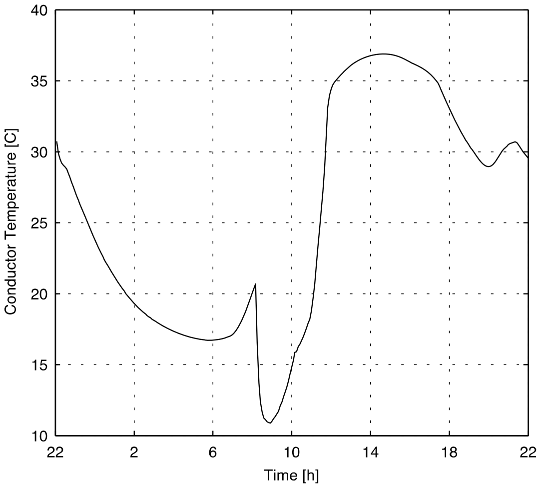

Fig. 9. Temperature of the conductor.

The normal tension is shown in Fig. 10. The conductor temperature and the external forces, such as the wind, are the two variables that affect the mechanical tension. During the 24 h, it varies about 450 daN. The maximum is obtained while the wind blows.

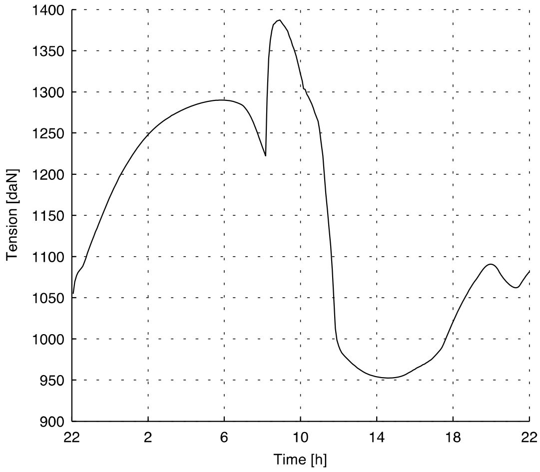

Fig. 10. Normal tension in the middle of each conductor.

Collapse Simulation

This section describes the rupture of a conductor when a tree hits it.

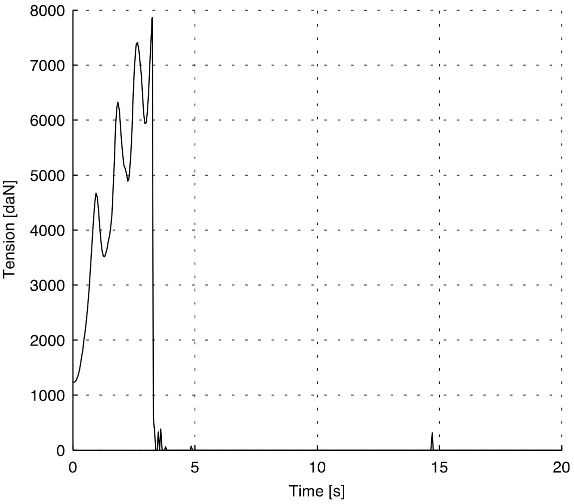

Fig. 11. Normal tension in the middle of the conductor.

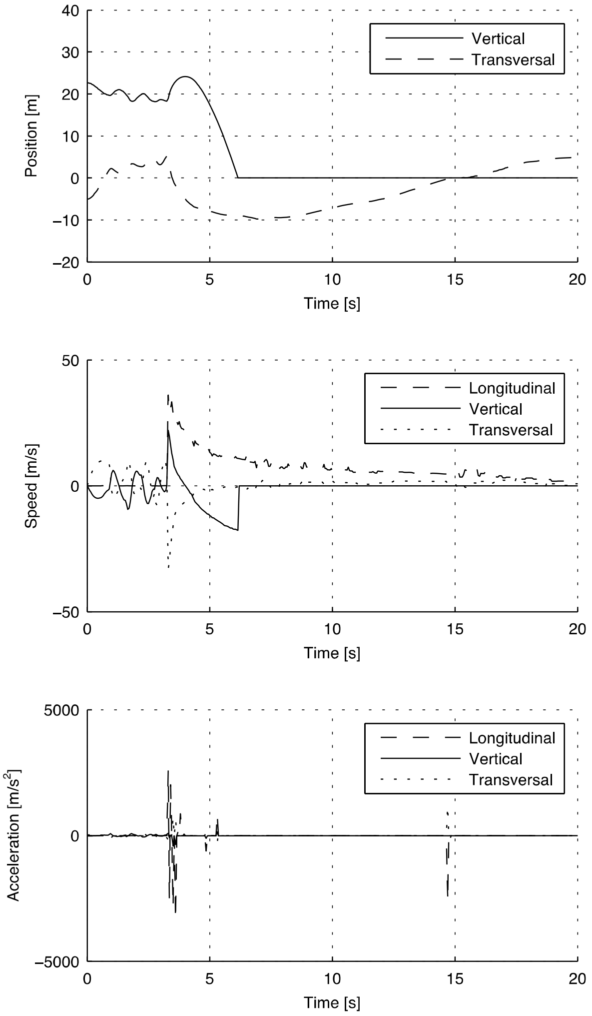

Fig. 12. Dynamics in the conductor.

The tree generates a force of 2000 kg with a growing rate of 500 kg per second, that is, the force reaches its maximum level after 4 seconds. It is exerted downwards with an angle of 30 degrees respect to the horizontal plane, and it is perpendicular to the conductor.

As the Fig. 11 shows, the impact of the tree creates a great increment in the normal mechanical tension of the conductor. The plot shows a succession of ups and downs during the rising. This has to do with the elastic behavior of the conductor. After 3 s, the tension goes over 5000 daN, which means that the conductor undergoes a plastic deformation. This phenomenon was considered in the algorithm by modeling the curve tension vs. deformation of an aluminium steel-reinforced cable. Eventually, the conductor breaks, a bit before of the instant 4 s, after overpassing a tension of 8000 daN (this value corresponds to the rupture tension indicated by the cable manufacturer).

The tree also causes the conductor to displace greatly, as Fig. 12 shows. The displacement is also high enough to cause a short-circuit, since the insulation distance to the adjacent conductor has drastically decreased. When the conductor breaks, huge accelerations appear, see Fig. 12, which could cause the rupture of fragile elements, such as the insulators.

Conclusion

This work demonstrates the capabilities of the used algorithm. It can perform transient and quasi-steady simulations that can be used for different purposes.

Firstly, it can be used at design stage to obtain a more accurate design and to avoid using wide safety coefficients that increments unnecessarily the final budget. Current standards and recommendations provide good results for common designs, however unusual facilities present challenges that those generic formulas do not solve satisfactorily.

Secondly, this algorithm can also be useful as "forensic" tool. Many times, overhead power lines collapse under some conditions, such as severe weather conditions. By using this tool and the appropriate information, those situations can be reproduced and studied in order to make better future decisions.

Because of these two reasons and considering the importance of electrical facilities for the society, the authors think that this algorithm is interesting in the field of the overhead power lines.

Acknowledgments

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***Authors**: M.Sc. C. Vilachá, M.Sc. J. C. Moreira, Ph.D. E. Míguez and Ph.D. Antonio F. Otero are with the Department of Electrical Engineering of University of Vigo, Galicia, Spain, E-mails: cvilacha@uvigo.es; jcmeira@uvigo.es; edelmiro@uvigo.es; afotero@uvigo.es*