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A CUSTOMIZED PULLING-CABLE SOFTWARE

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ABSTRACT

Hydro-Quebec's underground distribution network mainly consists of electric cables installed by pulling through the ducts. In order to improve the estimates of the pulling forces, our company has developed a new customized software. The model upon which this software is based on takes into account several effects related to the bending stiffness of the real cable. Such effects were so far neglected by the available classic Rifenburg-Smith models. The accuracy of the new software has been validated with actual data recorded during cable pulling installations performed at a test site and in Hydro-Québec's underground network.

KEYWORDS

Distribution cables, Pulling forces, Pulling software, Modeling and Characterization, Optimization.

INTRODUCTION

Two mechanical limits must be avoided during the cable pulling operation: the maximum tensile force applied to the cable and the maximum sidewall pressure at bends. Exceeding these limits may lead to damages to the electric insulation, with harmful consequences on reliability and the service life of the weakened cable.

The most practical manner to insure that the allowed maximum tensile force and sidewall pressure are not exceeded is to evaluate by calculation the maximum pulling forces at the design stage of the electric cable route. Therefore, the need arises for a cable pulling software capable of providing reliable results.

All commercial software currently available is based on a classic Rifenburg-Smith model which represents the electrical cable as a rope without any bending stiffness. However, in the case of cable routes with important direction changes, significant bending effects occur at the bends due to the mechanical stiffness of the electrical cable. The numerous measurements performed by Hydro-Quebec have shown that the classic model could grossly underestimate the real pulling forces for some of the more convoluted routes.

In order to improve the estimates of the cable pulling forces, our company has developed in the early 90's a software that considers the various bending effects occurring when a cable is pulled through bends. However, with the new requirements established by designers for our underground network and the fast-paced evolution of PC operation systems, this software has nowadays become obsolete. Therefore, a new customized software has been recently developed, and is described in this paper.

ANALITICAL PULLING MODELS

Two analytical cable pulling models were used when developing the new software: the classic Rifenburg-Smith model [1, 2] has been completed by our bending model [3].

All commercial software so far available was developed exclusively around the Rifenburg-Smith model, which assumes that the cable behaves as a rope without any bending stiffness. Such an simplified approach implies that the pulling force is solely dependent on three factors: i) the longitudinal friction between the cable and the conduit due to the weight of the cable itself, ii) the longitudinal friction resulting from the lateral pressure induced at bends between the inner surface of the cable and the conduit sidewall and iii) the variations in the potential energy of the cable in the case of a route with sloping and/or leveling changes.

Our complementary bending model takes into account the effects of cable stiffness when passing through a bend. As the stiffness of the cable is no longer null as in the case of the Rifenburg-Smith model, additional effects contributing to an overall increase of the required pulling force must be considered: i) additional contact and fiction forces at the cable-conduit interface, ii) internal losses of mechanical energy due to the bending hysteresis effect, including the effect resulting from the relaxation of the bending moments.

The corresponding analytical formulations were presented in previous papers and reports [3, 4, 5]. The electrical cables used for power distribution, especially the medium-voltage three-phase one, represent a complex component, from the point of view of their mechanical behavior. Their bending stiffness is characterized by a strong non linear variation with respect to the cable curvature. Our bending models approximate this non linear moment-curvature relationship by a simplified bi linear variation, defined by only two values for the bending stiffness modulus.

As an example, the influence of the pulling tension and bending stiffness *EI* on the additional axial force at the bend is shown in Fig. 1 for a bend characterized by a radius R=1.5 m. The additional relative axial force at this bend, defined by the relationship of the tensions with and without the bending stiffness, increases with the stiffness of the cable but decreases significantly for higher tension in the bend area. This means that the effects related to cable stiffness will be more important in the first part of the cable run and will eventually decrease towards the conduit end, due to higher pulling tension.

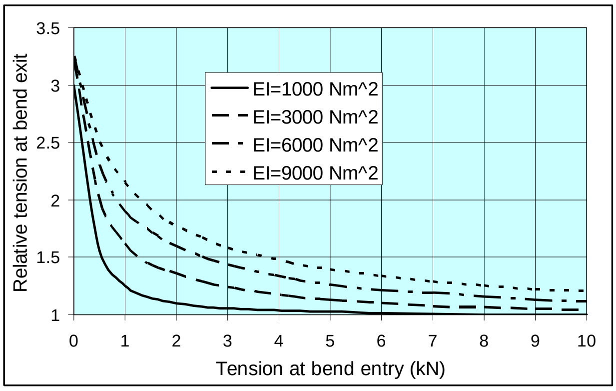

Figure 1: Influence of pulling tension and bending stiffness

PARAMETER CHARACTERIZATION

The increased complexity of the analytical models used in our new software results in an increased difficulty in estimating the additional parameters involved. Some of these additional parameters, such as the bending properties of the cable, are difficult to evaluate using analytical modeling. In such cases, the parameters were determined based on data obtained either from extensive laboratory testing, or through a numerical identification procedure relying on data collected during actual cable pulls. All results obtained from both approaches were implemented in the database of our new software.

Characterization tests

Two types of mechanical characterization tests were performed during laboratory testing: i) testing for bending stiffness and ii) testing for internal energy losses.

Figure 2: Setup for characterization tests in bending

The bending test is aimed to determine the two bending stiffness modulus (the initial modulus EI_a and the reduced modulus EI_b) and also the break-point curvature C_b of the simplified bi linear moment-curvature diagram. During this test, a cable segment kept under constant tension by pulling forces applied at both ends was subjected to a cyclical lateral displacement. This allowed to establish the parameters of the moment-curvature diagram under conditions similar to those present during real pulls. The bending relaxation constant of the cable, maintained at constant curvature, could also be determined from this test.

As an example, Fig. 2 shows a three-phase 25 kV 750 MCM twisted cable, typical for Hydro-Québec's underground distribution network, submitted to the bending test.

In the testing for internal energy losses, a segment of a three-phase 25 kV cable was installed in a closed loop mounted on two wheels kept in motion at constant speed [4]. This setup would allow to measure the energy losses by internal friction between cable components, associated with the repeated bending and straightening, as the cable passes through the wheels.

The objective of this type of test was to reproduce some of the characteristic behavior of the cable during its passage through successive bends in real lines. It should be noted that the interpretation of the test measurements raised some difficulties due to strong mechanical nonlinearities of the electrical cables.

Numerical identification

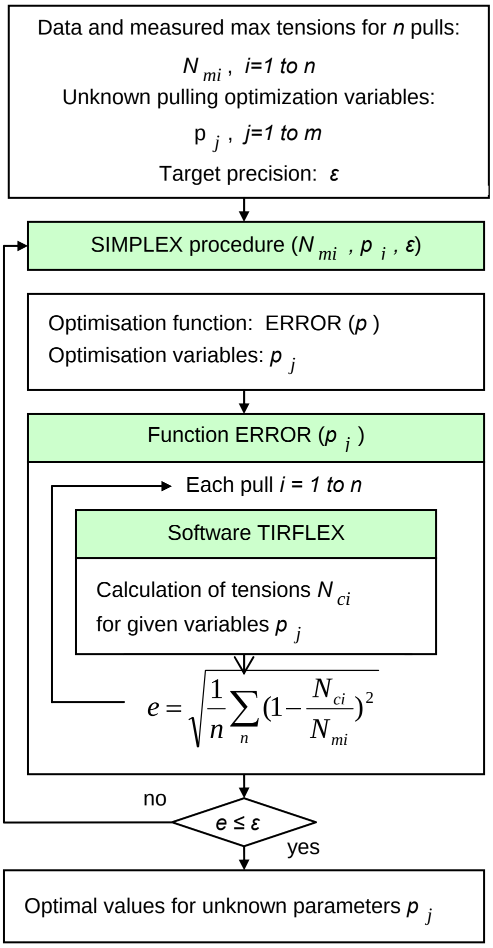

Figure 3: Parameters identification procedure

The laboratory characterization tests did not allow the identification of all mechanical proprieties of the cable-conduit system, which are required by the new computer program. Some parameters were determined through the interpretation of the available measurements taken during the numerous pulling operations performed in the Hydro-Québec underground network, as well as at a special full-scale test site.

In order to identify the values of the unknown parameters, a numerical optimization procedure based on the SIMPLEX dynamic programming was applied (Fig. 3). This procedure consisted in minimizing the total quadratic error between actual measured values and the corresponding values for the maximum pulling tension, calculated using our new software, for all available pulling measurements.

In particular, this approach allowed to obtain a realistic estimate of the apparent cable-conduit friction coefficient for specific conditions prevailing to the Hydro-Québec's underground network and work methods.

COMPUTER PROGRAM

The new analytical pulling models were used to develop a comprehensive computer program named TIRFLEX [6], which is capable of calculating the pulling forces, taking into account the complex bending effects described previously.

This software is intended for underground conduits containing circular bends connected by rectilinear segments. The Rifenburg-Smith formulation is included in vectorial form, allowing any orientation of the bend plane.

The main characteristics specific to the software are:

- High-performance calculation procedures, which take into account the non linear stiffness of the electrical cables and the resulting bending effects
- Extensive database of cables, conduits and pulling parameters, updated to the company's latest standards and norms
- Complete and user-friendly graphic interface, limited to only one window for the standard calculations
- Choice of two methods for data acquisition of route geometry: i) numerical, by entering into a table the data relative to successive segments of the route, ii) graphical, by integrating digital plans of the routes
- Pulling with or without lubricant
- Back-calculation of the effective coefficient of friction, based on tensile forces measured during actual pulling operation
- Extensive database of pulling installations already performed, allowing to store pulling data and measured tensions in order to share acquired expertise between personnel and perform quality assurance.

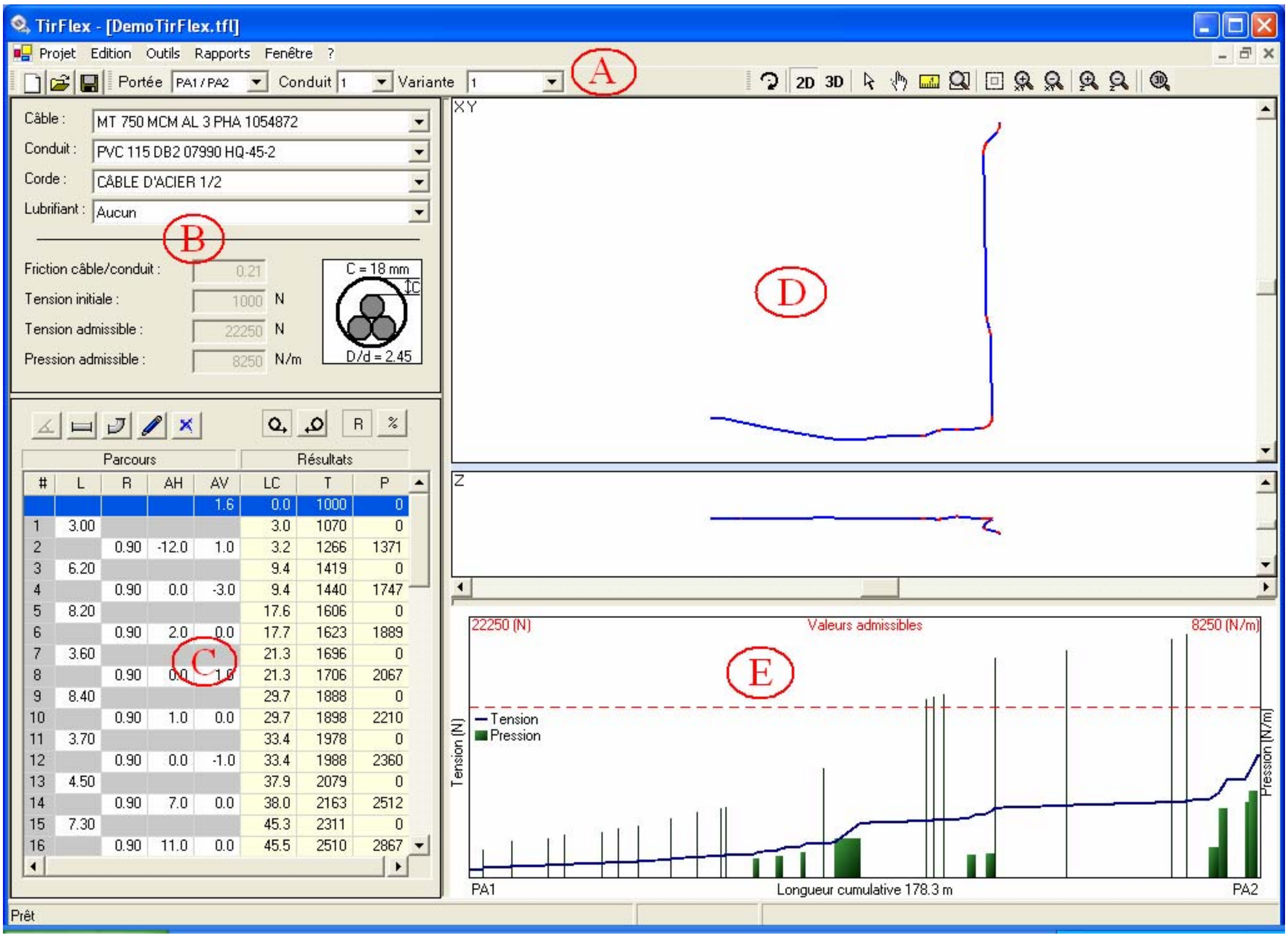

Figure 4: Main menu of graphic interface

The graphic interface of TIRFLEX, which is versatile and user friendly, allows two modes of operation: i) standard mode of operation, which includes the majority of the software's applications and ii) expert mode for special applications, allowing to modify locally the values of certain parameters established in the database.

In standard mode, all calculations can be performed in a single menu, containing all data and the main results on the same window. This main menu of the interface (Fig.4) consists of a series of dynamic fields, such as: **A** - project identification, **B** - component selection with their parameters in the database, **C** - definition of the geometry of the route and also the calculation results, **D** – 2D graphic representation of the route (plane and side views) or, alternatively, 3D representation, **E** - graphic representation of the results.

The program output provides all pulling forces required for the design: the variation in cable tension as pulling progresses along the conduit and the sidewall pressure at each bend. The corresponding allowable limits appear also on these diagrams.

In Fig. 4, one can notice that the value of the sidewall pressure exceeds the allowable limit (in dotted line) for some of the bends with small radius. However, the maximum pulling tension remains under the limit (normalized to the same dotted line).

SOFTWARE VALIDATION

The accuracy of the new software has been verified by comparing the estimates obtained using the software with actual data recorded during cable pulling installations, performed at a special test site and in the Hydro-Québec's underground network.

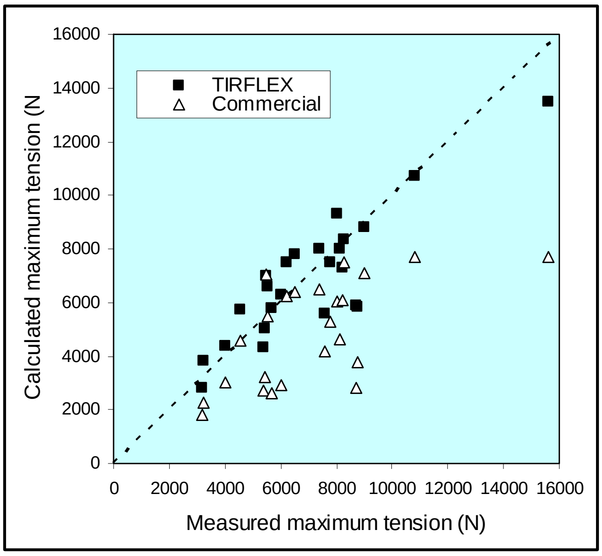

Figure 5: Correlation between measured and calculated values of the maximum pulling tension

Figure 5 presents a global correlation between the measured and the calculated maximum pulling tensions for all routes used for validating the software. By comparison, the corresponding results obtained with a commercially available software (based on Rifenburg-Smith model) are also shown on this figure. A significant improvement of the correlation can be observed for the values predicted by TIRFLEX versus those of the commercial software. Results from our software are particularly better for test-site lines which are characterized by more convoluted paths inducing higher bending effects.

Table 1: Total quadratic error

Raceways	TIRFLEX	Commercial
Test site	25.3%	55,1%
Network	22.2%	38,6%

This observation is confirmed by the total quadratic error calculated for both types of routes. The overall errors are shown in Table 1. These results clearly demonstrate the improvement in the forecast of the pulling forces that can be achieved by using the TIRFLEX software.

The new software has also proved to be a reliable tool when used for special projects involving high economical risk, such as under-river cable pulling. Figure 6 shows the progress of the pulling force recorded during the recent under-river installation of a MT-type tri-phased cable in Montreal, with the length of 450 m.

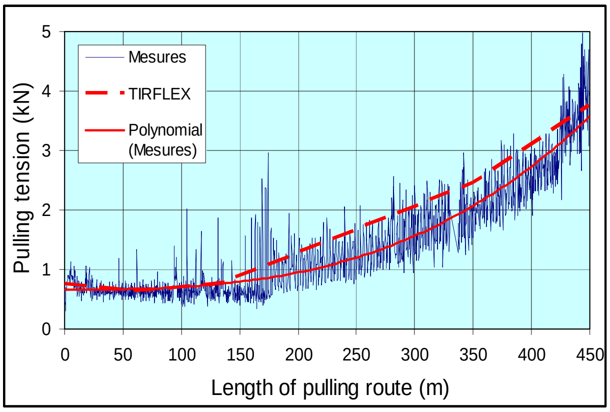

Figure 6: Estimated and recorded pulling tension during cable installation under Saint-Laurent river

The cable was pulled underneath the Saint-Laurent river, between the cities of Verdun and Ile-des-Soeurs. It can be observed that the pulling force does not increase steadily, but in a oscillatory manner. This behavior results in the cable being submitted to locally higher peak tension values. However, the curve of the tension values estimated using TIRFLEX follows very closely the curve of the *average* recorded tension during this cable installation, both almost coinciding towards the end of the pulling procedure.

Other cable pulling experiments are scheduled in the near future, on a new test site and in the actual underground network. Such experiments will allow to complete the validation of some of the crucial design parameters for new cables and pulling methods, as well as to quantify the adverse effects associated with possible stops during cable pulling procedure and other dynamic pulling effects.

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PARAMETRIC STUDY

The new software has been used for a parametric study which aimed to identify the relative importance of various parameters that affect the mechanical forces associated with cable pulling.

The study has been performed based on an actual route, considered as typical of the Hydro-Quebec underground network, consisting of a tree-phase 25 kV cable and a PVC conduit with an inner diameter of 115 mm. The route, with a total length of 178 m, includes near its mid-length a 90^{0} bend with a radius of 3.8 m (Fig. 4).

The study was performed by modifying one parameter at a time, using the original route as a reference. In order to achieve generalized conclusions, all results of the simulation are presented in non dimensional form, normalized with respect to the results obtained for the reference route.

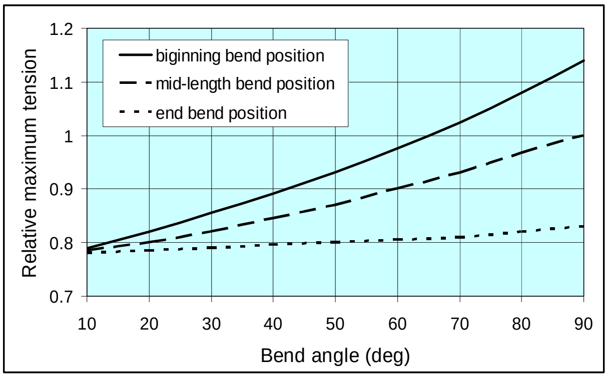

Figure 7: Influence of bend angle and bend position on pulling tension

Various parametric studies were accomplished [6], proving for example that the relative importance of the bending effects depends strongly on the geometry of the route, and also on the number and position of the major bends. Figure 7 demonstrates the effect of the bend angle and bend position along the route. It is observed that, for a bend located towards the end of the route, an increase of the bend angle increases substantially and in a non-linear manner the maximum pulling tension.

The conclusions obtained from these studies help in avoiding disadvantageous combinations of various parameters at the design stage of the electrical route system, which could lead to excessive pulling forces generated in the cable.

CONCLUSION

The new TIRFLEX software is a reliable and accurate design tool for underground electrical line designers. Through the use of advanced analytical models and realistic calculation parameters, it allows to observe the mechanical limits of the pulling force, and therefore to:

- o achieve the expected lifetime and improve the continuity in service of the cables optimize the length of the raceway between the junction chambers
- o reduce the risk of cable jamming during the pulling procedure.

Its modern graphic interface and its convenient route data acquisition menu make TIRFLEX a very efficient and user friendly design tool.

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