Multiple Stress Life Analysis on Underground Power Cables from Distribution Networks

Larisa Mariut[1], Elena Helerea[1],

[1] Transilvania University of Brasov, Faculty of Electrical Engineering and Computer Science, Electrical Engineering and Applied Physics Department,
29 Eroilor Str, 500024 Brasov, Romania
{Larisa.Mariut, Elena.Helerea}elena-larisa.mariut@unitbv.ro

Abstract. The implementation of underground distribution lines has grown significantly over the last decades due to the rapid increase of electric energy demand. But, the life of underground lines is determined by strong single or multiple stresses, developed during manufacturing and operation. Establishing and predicting the end of life of a distribution underground line is a task for researchers, designers and manufacturers, too. In this respect, the multiple stress life analysis may be used as efficient tool to predict the life of lines and cables. In this paper, a multiple stress analysis is developed, applying the Arrhenius-Weibull life-stress model, in order to identify the effects of multiple stresses on power cables. An application to an underground power line in a Romanian Electric Network Company is developed, in ALTA software package. The multiple stresses of temperature, humidity, and vibrations are considered, and the life distributions and reliability plots are obtained.

Keywords: Power Cables, Multiple Stresses, Weibull Distribution, Life Distributions, Arrhenius-Weibull Model.

1 Introduction

According to the European Union directive 2005/ 32/ EC, the need to develop electrical systems with respect to the lifecycle and energy efficiency [1] is highlighted. Proper reliability and maintenance practices [2] have a direct impact on the electrical systems availability and also that practices can improve energy costs by an average of 5 to 20%. For electrical systems, there is a need to develop a procedural framework to manage all the operating performance and the aging degradation mechanism under multiple stress-asset management [3], [4]. The multiple life stress analysis on power equipment has been developed to create effective tools for lifetime prognoses, to improve the operation performances and to substantiate the quality/ reliability indices [3], [4], [5], [6]. This technique, applied to power cables insulation, requires the identification and characterization of stresses, in connection with cable insulation aging.

In general, for power cables [6], [7], [8], [9], the aging mechanisms are complex and occur under synergetic electrical, thermal, mechanical and environmental stresses (Table 1). Their impact on the power cable performances and life estimations is different, depending on their intensity and synergistic effects.

Table 1. Factors and aging mechanisms for power cables

Aging factors	Aging mechanisms
Thermal	
-High temperature	-Thermal extinction
-Thermal cycling	-Diffusion
	-Insulation melting
-Low temperature	-Thermal contractions
Electrical	-Partial discharges
- AC/DC Voltage impulse	-Electrical trees
	-Dielectric and capacitive losses
-Current	-Overloading
Mechanical	
-Cycling distortion	-Materials flexibility
-Vibrations	-Cracking
-Fatigue	
-Stretch	
-Compression	
Environment	
-Water	-Water trees
-Humidity	-Corrosion
-Contamination	-Dielectric and capacitive losses
-Liquids	
Radiations	-High rate of chemical reactions

In the case of power cables for power distribution applications the main aging factors are: mechanical (vibrations), thermal (variable temperature depending on cable load), environmental (mostly high humidity) and electrical (overvoltage, breakdown) stresses.

The objectives of the current research are: to define a procedure for finding the stress with the greatest impact on life distribution for distribution power cables; to establish the cable life distribution relationships under multiple stresses; to identify the upper limit of a stress that could affect the power cable performances. The following scientific hypotheses were considered: (1) main stresses: temperature T, humidity H, and vibration V; (2) levels of the applied stresses, which were set according to the distribution power cables guides [10], [11], [12]. The normal duty cycle rating stress levels were set: for temperature, T_n= 348 K, for humidity, H_n= 45 RH, for vibrations, v_n= 12.5 Hz; (3) the Arrhenius relationship, which is admitted as life-stress model, and the failure life distribution, which is the Weibull distribution. With these scientific assumptions, a life analysis under multiple stresses was determined, based on the Accelerated Life Testing Data Analysis (ALTA) package software developed by ReliaSoft Corporation [11].

2 Contribution to Value Creation

The novelty of the study is the development of a procedure for multiple life stress analysis, applied to underground power lines. The procedure is based on the determination of the Arrhenius-Weibull parameters and reliability plots for the distribution power cables, using the data obtained from exploitation. In this respect, the Weibull distribution was applied as the underlying life distribution. The Arrhenius model was selected as a model that describes the characteristic life of the distribution from one stress level to another. The values of the parameters were fitted using the Maximum Likelihood Estimation Method (MLE). Once the parameters of the underlying life distribution and life-stress relationships have been estimated, the life estimation and reliability plots were derived.

Based on the determined life prognosis, considering as input the incidents from exploitation, it was identified the remaining life for an entire underground power line, not only for the insulation system. The current study provides new insights for life analysis under multiple stresses based on failure times recorded from exploitation. The results have a great applicability for condition based maintenance strategies and for the underground power lines performances prognosis.

3 Theoretical Approach

For power cable failure characterization, the two-parameter Weibull life distribution is appropriate, because it facilitates the degradation processes modelling of electrical insulating systems considering their aging mechanisms. For an analytical description of the life distribution, the following relations were considered [12]:

- the cumulative density function (CDF) of Weibull distribution:

$$F(t,\eta,\beta) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \quad (1)$$

- the probability density function (PDF) of Weibull distribution:

$$f(t,\eta,\beta) = \frac{\beta}{\eta}\cdot\left(\frac{t}{\eta}\right)^{\beta-1}\cdot\exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \quad (2)$$

where β is the shape parameter, η is the scale parameter (characteristic life), and t is the time until the failure ($t \geq 0$). A change in the scale parameter η has the same effect on the life distribution as a change of the abscise scale. The experimental plot must be a straight line in a coordinate system:

$$x = \log t\,; \quad y = \log\left(\ln \frac{1}{1-F}\right). \tag{3}$$

For a specified reliability, and for the life evaluation starting at age zero, the reliable life of the cable can be determined with the relation:

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]. \tag{4}$$

Taking into account the degradation mechanisms of the underground cable insulation under the stress *S*, described by Arrhenius model, the average of life *L*(*S*) is appropriately described by the relationship:

$$L(S) = C \cdot \exp\left(\frac{B}{S}\right), \tag{5}$$

where *S* is the stress level, *C* and *B* are the Arrhenius model parameters.
If the Arrhenius model is valid, the experimental Arrhenius plot should be a straight line in the coordinate system:

$$x = \frac{1}{S}; \quad y = \ln L(S). \tag{6}$$

The *C* parameter is obtained from the Arrhenius plot analysis, as the first term of (5) is the intercept of the Arrhenius line. The combined Arrhenius-Weibull model of the failure is appropriate for life-stress description. In this model, the characteristic life η is considered as the average of life under S stresses *L*(*S*):

$$\eta = L(S). \tag{7}$$

To obtain the power cable life expectations, a procedure is proposed [13]:

i) Collecting the experimental data: the considered input data have been the records from exploitation-times to failure and the numbers of incidents;
ii) Selecting a life distribution, more appropriate for the current study: the Weibull distribution has been considered as the appropriate life distribution;
iii) Selecting the model that describes a characteristic point or a life characteristic of the distribution from one stress level to another;
iv) Parameter estimation: this step involves fitting the model to the experimental data, and the maximum likelihood estimation method (MLE) may be applied.
v) Deriving reliability information-plots, mean life, future performances.

4 Related Work

For the proposed analysis, a power cable (Fig. 1) implemented in a Romanian Distribution Network Company has been chosen.

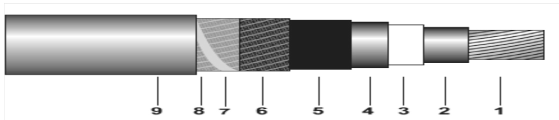

Fig. 1. Power cable structure (*1-Aluminium stranded conductor; 2-Inner semiconducting layer; 3-Polyethylene insulation; 4-Outer semiconducting screen; 5-Semiconducting tape; 6-Copper screen*)

According to the Romanian Company catalogue, the N2XSY cable has the following characteristics: U_0/U=12/20 kV; admissible temperature of conductor about + 363 K; cross-section area of 150 mm^2; the manufacturer is ICME Bucharest and the mounting year is 1981. To perform the analysis, the following input data were considered (Table 2).

Table 2. Input data

Times to failure [h]								
116136	1381.36	1607.61	3542.02	3832.1	4625.5	4659.26	5355.76	5490.92

All the cumulative data are related to times of failure developed on a 20 kV underground power line for a period of 12 months and, according to the Romanian provider, the power line degradation is about 25%-50%. Starting with this assumption, there is a need to predict the remaining lifetime. In order to develop the life analysis, different stress profiles were proposed (Table 3).

Table 3. Power cable stress profiles

Stress	Description
S1	Temperature test values are: 338 K, 343 K, 353 K, 358 K. Humidity and vibrations are kept at normal duty cycle rating stress levels.
S2	Humidity test values are: 30 RH, 40 RH, 50 RH, 60 RH. Temperature and vibrations are kept at normal duty cycle rating stress levels.
S3	Vibrations test values are: 5 Hz, 10 Hz, 15 Hz, 20 Hz. Temperature and humidity are kept at normal duty cycle rating stress levels.

The stress profiles have been chosen so that they should not induce failure modes that would never otherwise occur under normal duty cycle rating stress levels.

5 Results and Discussions

With the considered hypotheses regarding life-stress-failure and stress profiles, the Weibull plots (Fig. 2, Fig. 3, and Fig. 4) and the Arrhenius-Weibull parameters (Table 4) have been developed.

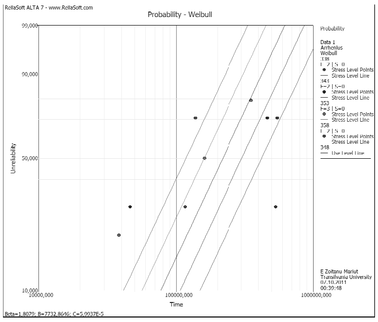

Fig. 2. Arrhenius-Weibull Probability plot for S1 stress level (temperature: 338 K, 343 K, 353 K, 358 K) and the duty rating temperature stress level 348 K

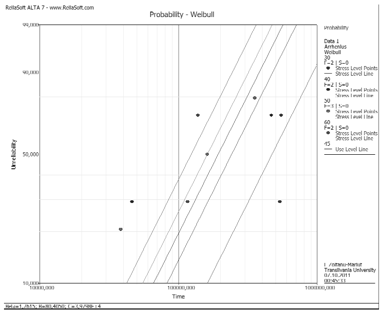

Fig. 3. Arrhenius-Weibull Probability plot for S2 (humidity: 30 %RH, 40 %RH, 50 %RH, 60 %RH) and the duty rating humidity stress level 45 %RH

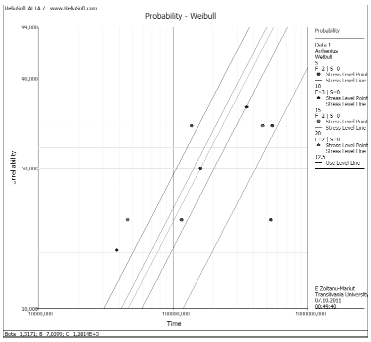

Fig. 4. Arrhenius-Weibull Probability plot for S3 (vibrations: 5 Hz, 10 Hz, 15 Hz, 20 Hz) and the duty rating vibration stress level 12.5 Hz

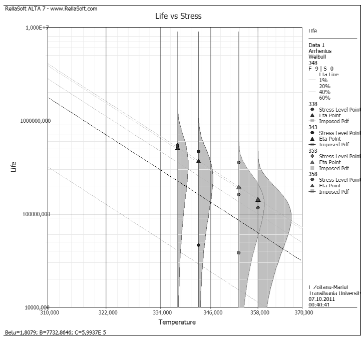

Fig. 5. Life vs. Stress for profile S1 (temperatures: 338 K, 343 K, 353 K, 358 K) and the duty rating stress level 348 K.

Table 4. The Arrhenius-Weibull model parameters

Stress	S1	S2	S3
β	1.8079	1.7615	1.5171
η	0.6664	0.0069	0.0006
B	7732.8646	80.4050	7.0399
C	5.9937e-5	3.9798e+4	1.2814e+5

In order to assess the effect of each stress profile on the failure the of the power cable, the Life vs. Stress curves were plotted (Fig. 5, Fig. 6, Fig. 7).

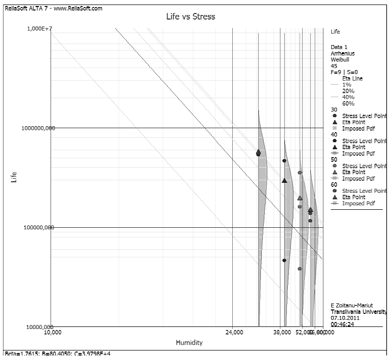

Fig. 6. Life vs. Stress profile S2, with the four humidity stress level points (30 %RH, 40 %RH, 50 %RH, 60 %RH) and the duty rating stress level 45 %RH.

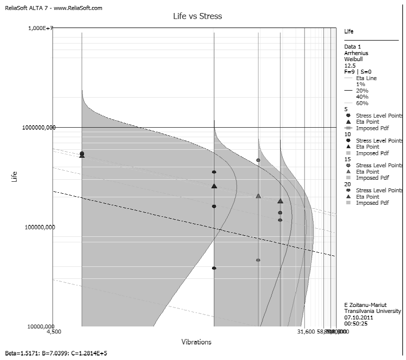

Fig. 7. Life vs. Stress profile S3, with the four vibration stress level points (5 Hz, 10 Hz, 15Hz, 20 Hz) and the duty rating stress level 12.5 Hz.

The shaded areas are the imposed PDF*s* at each stress level and it helps to determine the range of the life at each stress level. In Table 5 the values for life estimations are presented considering all the applied stress profiles.

Table 5. Mean life estimations

S1	338	343	353	358	**348**
L_T [years]	57	40	23	6	**26**
S2	30	40	50	60	**45**
L_H [years]	68	34	23	17	**26**
S3	5	10	15	20	**12.5**
L_V [years]	62	28	23	10	**26**

If the power cable is subjected to higher stresses that exceed the duty cycle stress levels, then its remaining lifetime (L)/ reliability (R) decreases considerably (Table 6).

Table 6. Lifetime expectations under higher stresses levels

Higher stresses	T [K]=383	H [RH]=70	v [Hz]=40
Life [years]	3.5	1.27	1.57
R	0.4583	0.5861	0.6744
β	1.5171	1.7615	1.5171
B	7.0399	80.4050	7.0399
C	1.2814e+5	3.9798e+4	1.2814e+5

According to Table 5 and 6, if the power cable is loaded at constant values, close to 348 K, then its remaining lifetime will be of about 26 years. At the same time, there is a need to develop efficient strategies to maintain humidity and vibrations at very small values in order to increase the future performances of the power cable.

6 Conclusions

The development of a multiple stress life analysis on a distribution power cable was done. In this respect, for different stress profiles there were modeled: the Arrhenius-Weibull probability plots and the life vs. stress plots. It was shown that the power cable was affected significantly by the multiple proposed stresses, near multiple stress analysis. Related to power cable failure rate, it will increase quite quickly, according to the determined reliability value. Based on the current study, asset management actions can be established in order to increase the performances in exploitation. As future work, the currently obtained results will be applied in order to develop a mathematical model on the effects of synergistic stresses on the power cable.

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References

1. Smith, N., Murtagh, T., Bamba, K.: An Evaluation Tool for Eco-Design of Electrical Products. First International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 766--770 (1999).
2. Tanaka T.: Aging of Polymeric and Composite Insulating Materials - Aspects of Interfacial Performance in Aging. IEEE Transactions on Dielectrics and Electrical Insulation, 9, pp. 704--716 (2002).
3. May, H., Penrose, W.: Simple Time to Failure Estimation Techniques for Reliability and Maintenance of Equipment. IEEE Electrical Insulation Magazine, 25, pp. 14--17 (2009).
4. May, S., Bahadoorsingh, S.: A Framework linking knowledge of insulating aging to asset management. IEEE Electrical Insulation Magazine, 24, pp. 38--46 (2008).
5. Marazzato H., Barber K., et.al.: Cable Condition Monitoring to Improve Reliability. In: Conf. TechCon, pp. 1--14, (2004).
6. Peng C. Y., Tseng S. T.: Progressive-Stress Accelerated Degradation Tests for Highly Reliable Products. IEEE Transaction on Reliability, 25, pp. 14--17 (2009).
7. Montanari G.C., Mazzanti G., Simoni L.: Progress in Electrothermal Life Modeling of Electrical Insulation during the Last Decades. IEEE Transactions on Dielectrics and Electrical Insulation, 9, pp. 730--745 (2002).
8. Schavemaker P., van der Sluis, L.: Electrical Power System Essential. John Wiley &Sons, Ltd, Southern Gate, Chichester, (2008).
9. Lanz G.C. B. T., Broussard B. E.: Maximizing Cable Reliability at the Lowest Possible Cost. In: International Symposium on Electrical Insulation-ISEI, Vancouver, pp. 535--538 (2008).
10. Mariut L., Helerea E.: Enhancing Reliability for Medium Voltage Underground Power Lines, In: Proceedings of the 7th International Symposium-ATEE, Bucharest, pp. 419--424, (2011).
11. ReliaSoft Coroporation: Reliability Growth & Repairable System Analysis. ReliaSoft Publishing, Tucson (2009).
12. S.C. Transelectrica S.A: Standard on the methods and elements for the operational safety calculation of power installations (NTE 005/06/00), Technical Guide, (2006).