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MEDIUM VOLTAGE POWER LINES: OUTAGES DATA ANALYSIS AND MODELLING

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Abstract – Obtaining a reliable model that takes into account the counting nature of outages occurrence in Medium Voltage (MV) lines is a very prominent issue for Distribution System Operators (DSO). As a matter of fact in distribution system planning and management, accurate assessment of reliability performance is essential for making informed decisions. In addition, performance based regulation directs towards a more deep understanding of differences in reliability performance between networks.

In this paper two Negative Binomial regression models are proposed for modelling yearly long and short duration outages occurrence in MV feeders; consequently a Monte Carlo simulation is performed in order to obtain a confidence interval for the yearly number of interruptions in a collection of feeders. The results are compared to real failure data from a distribution cluster of feeders in Italy.

***Keywords*: MV power lines, outages, regression analysis, modelling.**

1. INTRODUCTION

The electrical distribution system represents a key element in overall electrical power system performances [1-4]. Despite the radial configuration of distribution system, the remarkably high number of component jointly with the presence of non-uniform put-in-service equipment and periodical maintenance make it difficult to develop the classic component-based reliability techniques [5-7].

As a part of the distribution network, MV feeders modelling could be handled by computing failure rate [8] for an analytical technique or by means of discrete probability mass function to model the number of outages in a fixed time lapse. Because of the need of reliable confidence measure of common continuity of service indices, lines interruptions modelling is better developed for simulation purpose.

In the context of non-sequential simulations, Negative Binomial distribution has been proven to be satisfactory for modelling yearly number of failures in MV distribution lines [9],[10]. Some authors suggest that Bayesian estimation is an effective analysis tool when dealing with scarcity of data for modelling the MV feeders failure rate [11].

The use of Non Homogeneous Poisson Process (NHPP) for repairable system analysis has been applied to MV cable lines because of the less dependence on weather impact [12]. The application of NHPP has been evaluated in modelling overhead distribution lines failure rate in [13], where problems connected to the use of a common Rate of Occurrence of Failures (ROCOF) over four year failure data record are pointed out.

In this paper, two Negative Binomial regression will be proposed, and a cluster simulation is run obtaining confidence interval for annual subnetwork outages. With a more performance-based regulation view [14], long duration (i.e. more than three minutes long) and short duration outages (i.e. less than three minutes long) will be separately analyzed. The results are compared to real failure data for the area in study.

2. DATA FEATURES

As for a typical DSO outage register, in this case data are collected with the necessary information to characterize the fault: event identity code, sub-network code, feeder reference code, time and date of the outage, outage cause and duration class, fault equipment (if present) etc. Details related to the weather state are also registered, but are usually not reliable or not much descriptive. The study area includes 202 MV feeders, with a total exposed length of 4302,362 km. The mainly operating voltage being used in the service area under study is 20 kV, and the network presents both overhead bare conductors/cable lines and underground cable lines. Cable fraction lines length implies much less exposure to environmental stress factors, including lightning storms, ice storms and wind storms. In the following, for sake of simplicity, only underground and overhead length fraction will be considered, not distinguishing the aerial cable sections from the aerial bare conductor ones; as a matter of fact it has been difficult to separate this data from the aerial total length in DSO management system. Actually overhead cable line branch suffer less than bare conductor fraction the ice and lightning events and may be considered in a future work. The outage data record covers five year time span from 2009 to 2013, but outage data from year 2014 are also available for the total subnetwork to make comparison with simulation cluster output. In the following we will make use of the only 2013 outage data but the procedure has been successfully applied to all the record of interruptions.

The longer the line is the higher number of yearly events is expected to be. Moreover, different underground cable fraction length modifies the rate of failure from the all overhead reliability behavior to all underground cable outage process.

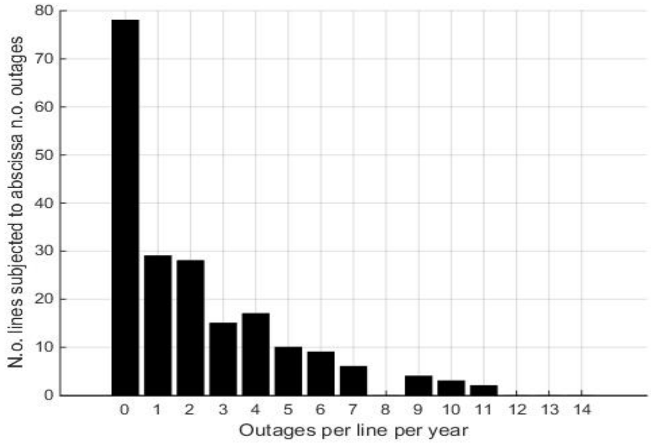

Fig. 1. Line count per number of long duration outages per year, 2013.

In Fig. 1 the empirical unconditional distribution is shown, irrespective to the feeders length and type. However the need of a distribution which is prone to produce small numbers is confirmed.

Fig. 2 shows the annual line outages per km of line length for 2013 long duration outages only; the cluster of lines under study was split in two parts on the basis of the underground cable percentage of feeder length: more or less than the half of the total line length.

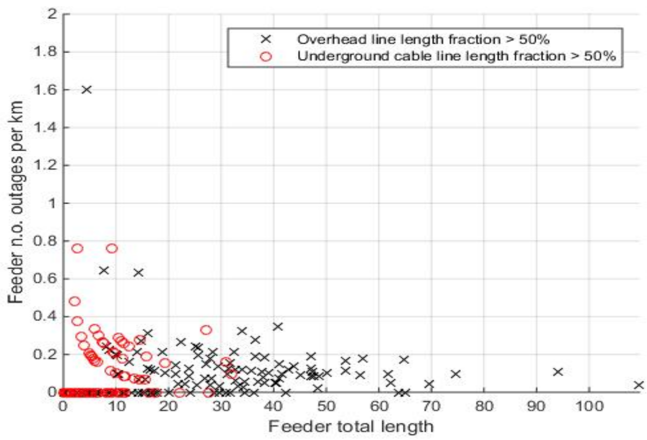

Fig. 2. Annual line long duration outages per km: lines for which more than 50% of length is of underground cable in red, less than 50% in blue, year 2013.

Even with a rough partition the more dispersion of underground cable feeders is prominent. However underground lines are those of the shortest length among the cluster, suggesting that this kind of dispersion is partly due to a relatively short annual time lap for 10km or less feeder length.

3. NEGATIVE BINOMIAL REGRESSION

The most commonly used count models are Poisson and Negative Binomial (NB). Poisson regression has been already applied in the context of electrical distribution system reliability whereas NB has not been considered yet. The most common implementation of Negative Binomial regression is the so called NB2 model [15], where the responses follow a NB distribution with mean μ_i and variance function defined as:

$$\mu_i + \alpha \cdot \mu_i^2 \qquad (1)$$

Failure of the Poisson assumption is strictly related to the outage data overdispersion, which cannot be correctly described using Poisson distribution. In addition, the proper way of modelling annual number of outages for MV lines has been proven to be NB [9],[10], which suggests that the use of a parametric model like NB2 leads to more helpful results.

As in Poisson regression, the mean of the response process is assumed to be function of some explanatory variables:

$$\mu_i = \mu(X_i, \beta) \qquad (2)$$

In NB2 model, the link function $\mu(.)$ being used is the natural logarithm and consequently the mean function is exponential. The so called linear term is enclosed by brackets in (2) and is in the form $\mathbf{X}^T\boldsymbol{\beta}$:

$$\mu = \log(\mathbf{X}^T\boldsymbol{\beta}) \qquad (3)$$

It is convenient to consider a regression model in which the mean of the annual line outage process depends on both overhead line length fraction and underground cable line length fraction by Eq. (2).

$$\mu_i = \mu(l^u{}_i, l^o{}_i, \boldsymbol{\beta}) \qquad (4)$$

where l_i^u is the underground cable section of feeder i and l_i^o is the overhead section of the same feeder.

NB distribution is an alternative way of modelling rare events occurrence for which variance is greater than mean. For the service area under study we plot the histogram of the annual number of long duration outages per feeder, as depicted in Fig. 1 for year 2013.

3.2. Model equations

Two regression equations are proposed for modelling feeders annual long and short duration outages. This choice takes account for the differences in the analysis that have been previously underlined.

For long duration outages the following NB2 model is used:

$$\ln(\mu_i) = l_i^o \beta_1 + l_i^u \beta_2 \tag{5}$$

In this manner differences in technological reliability performance are effectively pointed out. β_1 and β_2 assumes necessarily positive values. In this case MLE routine gives $\widehat{\beta_1} = 0.0331$ and $\widehat{\beta_2} = 0.0234$ with $MSE = 0.9184$.

For short duration outages another model is needed, because of the low occurrence rate of underground cable sections a different equation is proposed:

$$\ln(\mu_i) = \beta_1 \cdot \ln\left(l_i^o + l_i^u\right) + \beta_2 \cdot \frac{100 \cdot l_i^u}{l_i^o + l_i^u} \tag{6}$$

The second model exhibits a different formulation for the explanatory variables l_i^u and l_i^o , allowing β_2 to assume positive or negative value. In this case total line length behaves as an elasticity term. MLE routine gives $\widehat{\beta_1} = 0.5053$ and $\widehat{\beta_2} = -0.0126$, with $MSE = 1.1273$.

A three dimensional (3-D) regression plane is depicted in Fig. 3 for long duration interruptions.

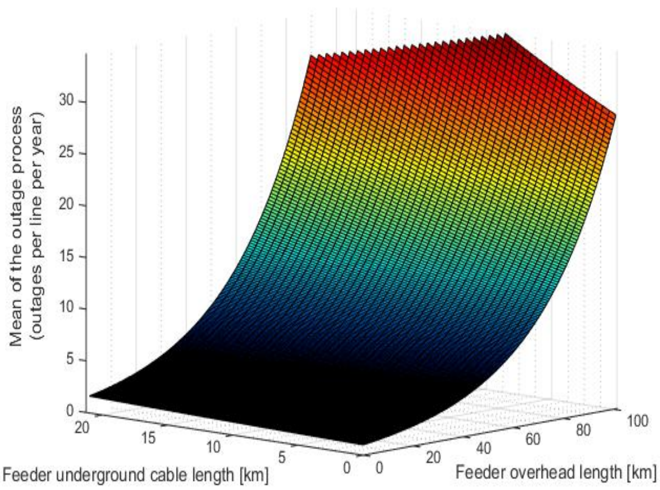

Fig. 3. Long duration outages regression plane, year 2013.

Underground line sections are generally shorter than the overhead line sections and so the mean of the interruption process varies in a more large span as function of l_i^o variable rather than as function of l_i^u .

Equation (6) shows an exponential link between underground cable percentage and mean of the outage process whereas total exposure length is modelled via a power law function. In Fig. 4 a contour plot based on (5) and (6) is shown. Contour plot is of a great value for a DSO whenever the increasing trend of annual failure rate of a feeder is needed as a function of technological solution and total length.

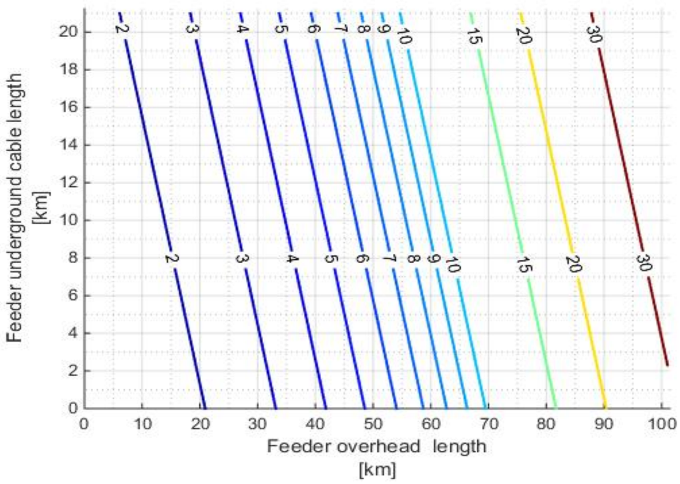

Fig. 4. Mean of the long duration outage process (outages per line per year 2013).

4. SIMULATION

The means of the long and short duration outage process are estimates computed by using averages of statistical estimators. This type of variance is due to the non-infinite number of MV feeder from which the statistical inference is developed. Another variance is due to the random nature of the annual outage process itself, which cannot be reduced and that is NB distributed.

Even if the means of the annual number of failure are exactly the same, the yearly number of outages for feeder i is a random variable. Monte Carlo simulation is the best way to handle process variability for the area under study and more in general whenever the analytical solution of a function of random variable is hard to obtain [16].

The annual number of unscheduled outages for one area is the plain sum of the annual number of interruption per feeder, which is a random number. In addition, as we mentioned above, the mean of the process is a random number itself, leading to another variability. It is common practice to perform three simulation, one for each extreme value of the input parameters and one for the best estimate of the parameters.

Fig. 5 illustrates annual failure distribution for the Area01 sub-network in year 2013 obtained from 10000 Monte Carlo simulation based on the regression model (5) and using the best estimate of $\boldsymbol{\beta}$. Aggregating feeder number of failures results in cluster number of outages.

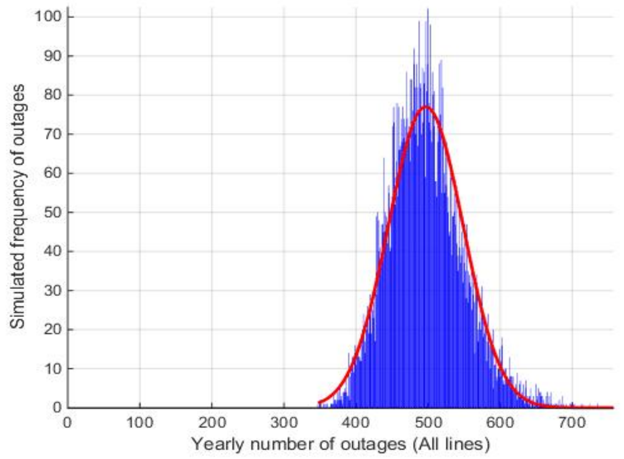

Fig. 5. Yearly number of long duration outages for Area01, year 2013.

In Fig. 5 the best normal fit has been superposed to the simulation results. The empirical cumulative distribution function (ECDF) is shown in Fig. 6 along with the best normal and negative binomial fit for the cluster.

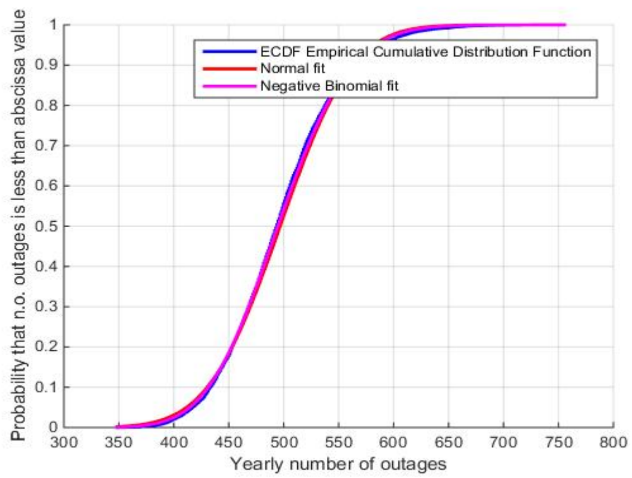

Fig. 6. Empirical Cumulative Distribution Function for total number of long duration outages, year 2013.

Post simulation fit confirms that number of outages distribution for the cluster is well approximated by both normal and negative binomial distribution, as these two distributions converge for large counts. However it is common to extract ECDF statistic directly from the simulation results; 5th and 95th quantiles along with the mean of the ECDF are reported in Table 1 for long and short duration outage process. In the same table the observed 2013 record of interruptions for the zone is collected, confirming the goodness of fit of the proposed line failure models.

Table 1: Total number of 2013 unscheduled outages by scenario.

Class	N.o. outages	Best Scenario	Best Estimate	Worst Scenario	Observed
long	*Lower CI*	280	404	609	446
	Expected	338	497	783	
	Upper CI	403	609	1031	
short	*Lower CI*	334	481	702	584
	Expected	419	598	862	
	Upper CI	510	727	1047	

It is remarkable that the observed values for the total number of unscheduled outages for the area under study fall within the 95% C.I. of best estimate scenario not only for year 2013, but also for the year 2014, whose failure data as shown in Table 2.

Table 2: Failure data record for 2014 number of unscheduled outages.

Class	N.o. outages	Best Estimate	Observed 2014
long	*Lower CI*	404	426
	Expected	497	
	Upper Ci	609	
short	*Lower CI*	481	658
	Expected	598	
	Upper CI	727	

This fact is of great interest for DSO which need to be confident on a reliable measure of unscheduled outages. Although aging and annual weather impact stress the distribution network with a different magnitude, the CI predicted on the basis of the most recent year is still an useful tool for a first attempt evaluation.

4. CONCLUSIONS

This scope of this paper is to analyze the outages data related to medium voltage power lines in order to obtain a detailed analysis and modelling of such faults and their distribution.

The proposed approach performs both a good fit of the outage data and underlines the reliability performance of the two technological solutions considered. Furthermore this method allows DSO to make comparison between different area performance both in term of overhead and underground contribution to the total number of interruptions. In this context it is of a great use to compare the individual annual feeder performances with the representative random variable for that feeder length and on the basis of the technological installation, detecting the less reliable feeders among the cluster.

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