Failure rates in distribution networks: estimation methodology and application

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Abstract

Electric distribution companies have the responsibility of achieving the standards established by the respective regulating authorities in order to guarantee the highest quality of supply for their customers. To do so, they have to register all the electrical issues produced in the Distribution Network into a database. This paper uses this real database to make a statistical analysis of the failures that occur in distribution networks and identify the interruption causes, in order to estimate failure rates and improve the quality of electrical supply. These failure rates are used to calculate the failure probability of electrical feeders taking into account the different electrical components in them. The expected amount of failures of more than 350 feeders have been calculated and tested with the real database to prove the reliability of the method. This work also shows an application to evaluate the failure probability of alternative network configurations.

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Keywords:

Power system reliability, distribution networks, failure rates, electrical failure analysis, breakdowns.

List of Abbreviations:

FLBS: Fuse load-break switches
IS: Isolation switches
LBS: Load break switch
M&PD: Maneuver and protection devices
OL: Overhead lines
OPI: Oil-paper insulation
SCED: Substation common electrical devices
TR: Transformers
TTI: Thermoplastic and thermosetting insulated cable
UC: Underground cables

I. Introduction

Due to the liberalization of the electrical sector and the establishment of new regulation systems, distribution network operators have to cope with more liabilities. A large proportion of these systems, have the intention to ensure a reasonable network operation and, at the same time, provide the electrical supply sustainability with the highest quality as far as possible [1] .

It is broadly known that the electrical supply is not always available to provide the demand due to technical and economic issues. In fact, the main feature of a power system is to supply the required energy efficiently with acceptable levels of quality and sustainability. The quality supply embraces three important aspects: customer service, electric wave quality and sustainability of supply. The last one is related with the number of power cuts, which affect the service reliability or the ability of the power system to provide a suited and secure electrical supply in any network point at any time, [2]. To quantify these concepts, some international quality indexes are widely used, e.g. in [3], such as ENS, AIT, SAIFI, SAIDI, ASAI, and those in [4] - [5] . Other indexes such as TIEPI and NIEPI [6] are also used in countries as Spain. These indexes allow to evaluate the evolution of the continuity of supply and implement proper corrective action plans for the electrical network. Moreover, if these indexes trespass the permitted thresholds, electric power distribution companies could be sanctioned with an economic fine.

These indexes depend on the duration of the interruptions and their frequency, which is largely studied in this paper. In order to estimate the number of interruptions in a future period of time, it is necessary to know the expected failure rates of the different components that could cause a power supply cut. Some references, like [7]-[8], estimate the failure rate of an electrical component as:

$$\lambda = \frac{\#failures}{\#components * \#years} = \frac{1}{\mathrm{ETTF}} \qquad (1)$$

where ETTF is the expected time to failure.

Different authors have studied databases associated with continuity of supply [9] and have shown the difficulty in having enough raw data to get reliable and meaningful results, [7]. In general, failure rates of high voltage transmission lines seem to be based on more representative data than in the case of medium voltage (MV) networks [10], in which the reliability of their devices count only with a limited number of scientific publications, [8].

Preventive maintenance is currently gaining more interest since it is considered as an efficient alternative to improve the quality of supply. For example, references [11]-[12]-[13] show, through real cases, that the study of utility databases are useful to draw up periodic maintenance plans for the electric network or to estimate electrical quality indices [14].

The paper presents an analysis of failure causes and a methodology to calculate failure rates of the main equipment in a distribution network using the electrical utility real databases. The so obtained failure rates improve failure predictions, not only because of failure rates of aggregate components are obtained with smaller variation ranges than in the generic bibliography [15], but also, because of a greater typology of components can be considered. Since accuracy on the estimation on quality indices can affect the compensation package for the electric utilities, as in Spain, real cases of aggregate prediction have been tested in the paper, with successful result.

II. Description of databases

Two databases have been necessary for this paper, an incident database and a network database. Both of them were analyzed during a collaboration scholarship between the University of Seville and a major Spanish distribution company.

Spanish utilities are required by law to collect information about incidents produced in their electrical network, which is saved in databases.

This paper makes use of unscheduled incidents occurred in the levels of 20 kV and 15 kV in the city of Seville with duration greater than three minutes between years 2001 and 2013. These incidents were registered at two different centers: the Customer Center and the Network Control Center, either from the SCADA system or manually introduced.

Figure 1 shows the different incident types and the number of incidents registered for each voltage level, in kV.

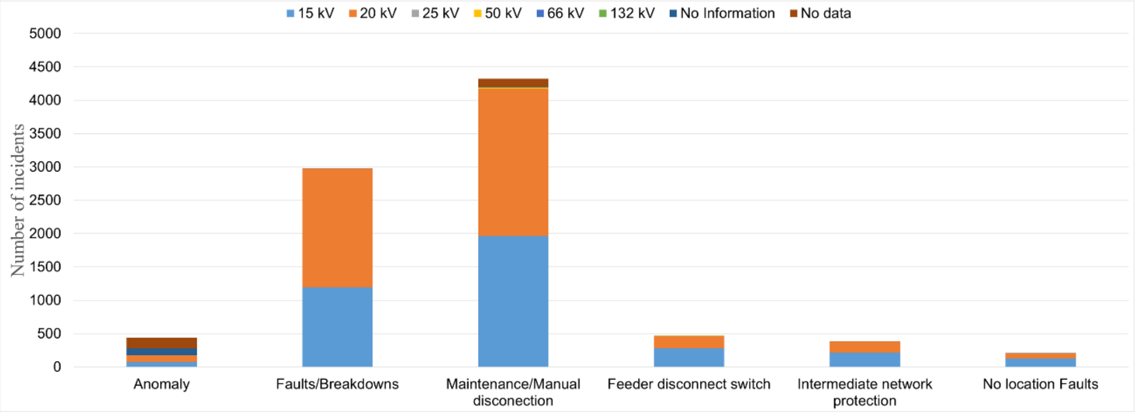

Figure 1: Record of incidents according to their nature

In this figure, the most frequent kinds of incidents are those caused by faults and maneuvers for supply restoration, which together make 83% of the total. However, all of them are explained by the fault incidents, since all the restoration maneuvers are originated by their corresponding faults.

Nevertheless, not only it is important to know the number of power outages, but it is also necessary to identify and characterize the faulty elements using the distribution network length, the numbers of MV/LV substations and transformers, and the amount of control and protection devices. These data are obtained from the network database available in 2013.

From the later database, the state of the MV electric network in 2013 was easily obtained; but the network status in the previous years was quite uncertain due to the growth and evolution in time of the network from 2001 to 2013. Although the database was upgraded while the network was growing, some data of this process had to be purged for the sake of consistency: contrasting available cartographic data with the city urban growth, and checking project documents, layouts and installations by experienced utility technicians.

TABLE 1: Medium voltage installation evolution. 2001-2013.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Underground cables (km)	1029	1043	1067	1081	1127	1118	1124	1126	1131	1146	1203	1236	1248
Overhead lines (km)	450	445	447	444	442	433	428	424	420	416	409	408	404
Transformers	3697	3727	3819	3881	3973	4102	4258	4431	4632	4736	4850	4641	4662
Isolating switches	878	867	872	865	861	843	832	826	818	809	796	795	783
Load-break switches	5607	5640	5785	5882	6023	6220	6467	6721	7006	7158	7327	7064	7098
Fuse load-break switches	2519	2533	2599	2642	2706	2795	2907	3020	3147	3214	3290	3176	3191

Table I shows the evolution in the amount of the most representative network components over the studied period of time. These data reveal a growing trend of all the components except for overhead lines and their associated switches, which are decreasing due to the gradual substitution by underground cables.

III. Analysis and data pooling

To be able to attribute a failure rate to a network sample or element cluster, this sample has to be representative in its population, which affects the way the electrical components can be grouped. This population is considered as the broader group where the statistical analysis results intend to be generalized. A representative sample should be an unbiased representation of what the population is like. For example, there is no sense in trying to assign annual failure rates to those components which are so specific in the whole network that did not have any failure during the study period, which could be considered as a case of data deficiency [16]. The common solution to data deficiency is data pooling, including these components as part of larger groups with more representative information.

In order to achieve proper representative samples while coping with population variability [16], it is required to know the relationships between the different components to be clustered. For this purpose, this paper considers the functionality and the voltage level.

From 2001 to 2013, a total of 2972 failures were registered in 15 and 20 kV. Figure 2 shows the evolution of the number of annual failures in the network for each of the two voltage levels and makes clear that more detailed clustering can be made. The proposed groups are underground cables, overhead lines, MV/LV substations, customer installations, feeder protection and MV substations. Figure 3 shows the same number of failures but classified according to these groups for each voltage.

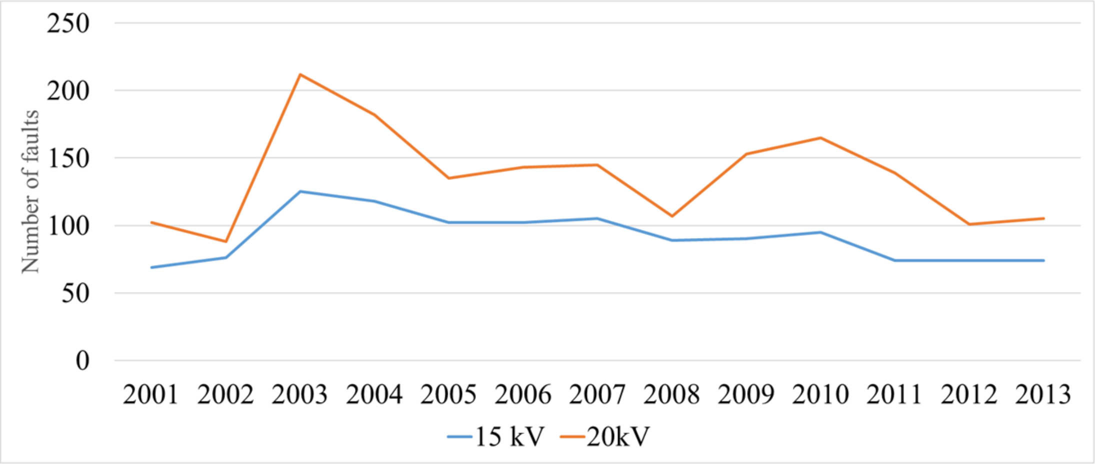

Figure 2: Number of faults produced in the network. 2001-2013.

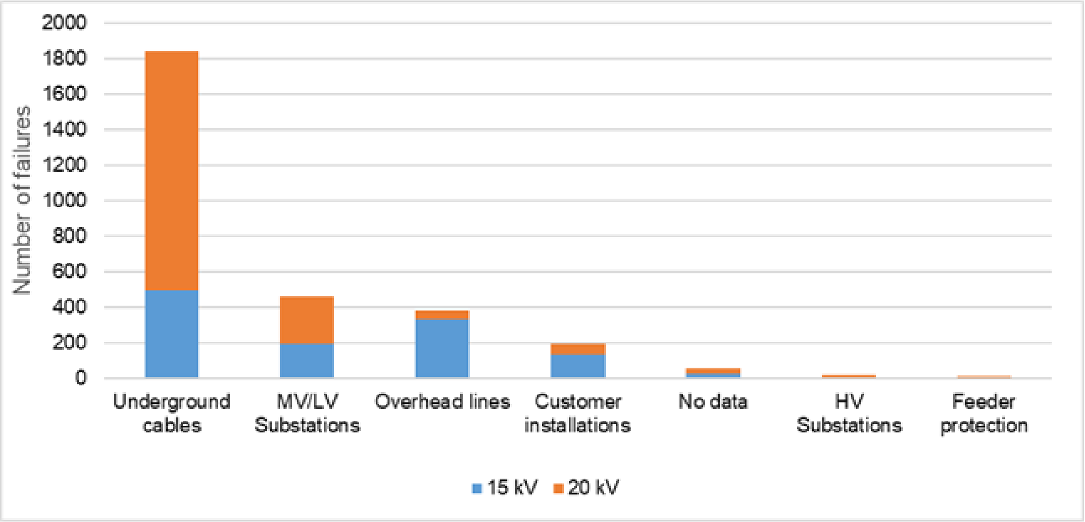

Figure 3: Number of failures according to electric MV network database groups.

From figure 3, it is clear that underground cables have most of the failures, 63.32% of the total. In this group, 26.87% of them are registered in 15 kV and 73.13%, in 20 kV.

This study focusses on the three main groups (underground cables, MV/LV substations and overhead lines) which already cover 90.54% of the failures and are directly related to the electric network, not to the customer installation.

Underground cables

Failures in underground cables include failures along the cable and joints, and are mainly caused by degradation of the isolation layer and excavation activities. Other failure causes are related with animals, vandalism, maneuver failure, MV customers, lack of maintenance, overvoltage, humidity, fire, rain and overloads. Figure 4 classifies the failures in underground cables according to their causes, where material degradation stands out with 59.78% of all the failures in this group. This percentage is even larger if it is added the second more common cause, those failures made by construction work.

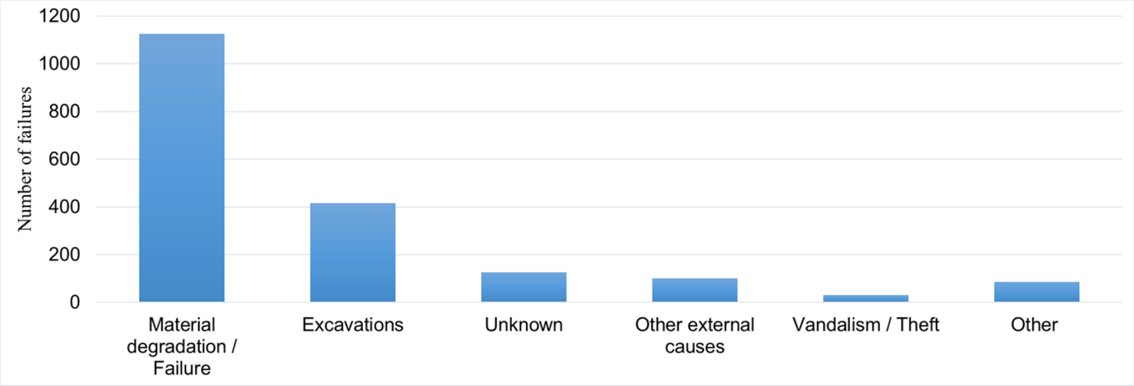

Figure 4: Underground cables failure groups. 2001 – 2013.

Figure 5 shows the evolution of such causes through the studied period showing that failures caused by excavators became of great relevance in the years before the 2008 economic crisis, which were years of increased construction activity.

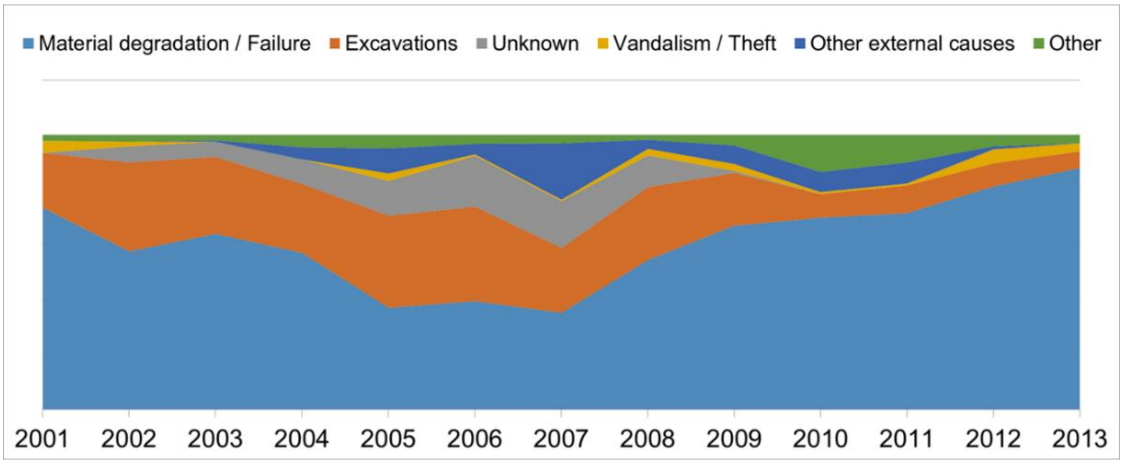

Figure 5: Evolution of the failure causes in underground cables.

Figure 6 shows an analysis of the components of such material degradation. From this figure, it is clear that the cross-linked polyethylene cable (XLPE) is the component with more incidents caused by material degradation, 42%, which grows up to 85% if all the types of cables are grouped.

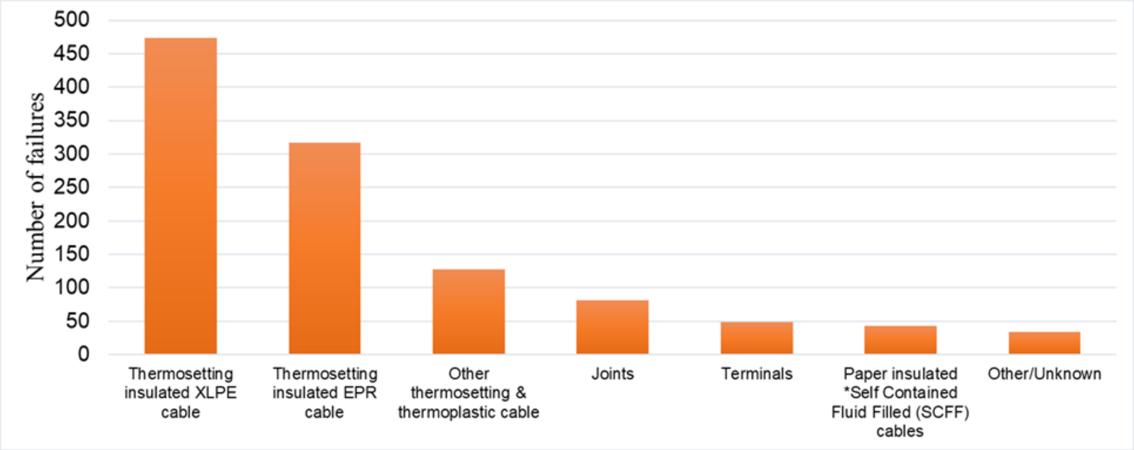

Figure 6: Underground cable components affected by material degradation.

Overhead lines

As seen in figure 3, the number of failures produced in overhead lines is 375, i.e. 12.95% of the total. This group of failures contains failures in aerial conductors, insulators, towers, supports, connectors, lighting rods, jumpers, fuses and cable terminations. These failures can be caused by the action of nature, Fig. 7 , human beings, Fig. 8 , or material degradation, Fig. 9.

In these components, 20 kV overhead-lines have to be grouped together with 15 kV lines, since the former ones do not show enough representativeness. Figure 7 shows the failure causes classified as the action of nature, where it can be seen that the weather conditions are the most common cause, with the 57.53% of the total, followed by animals, especially storks and other birds, with the 23.29% and finally tree branches, with the 19.18%.

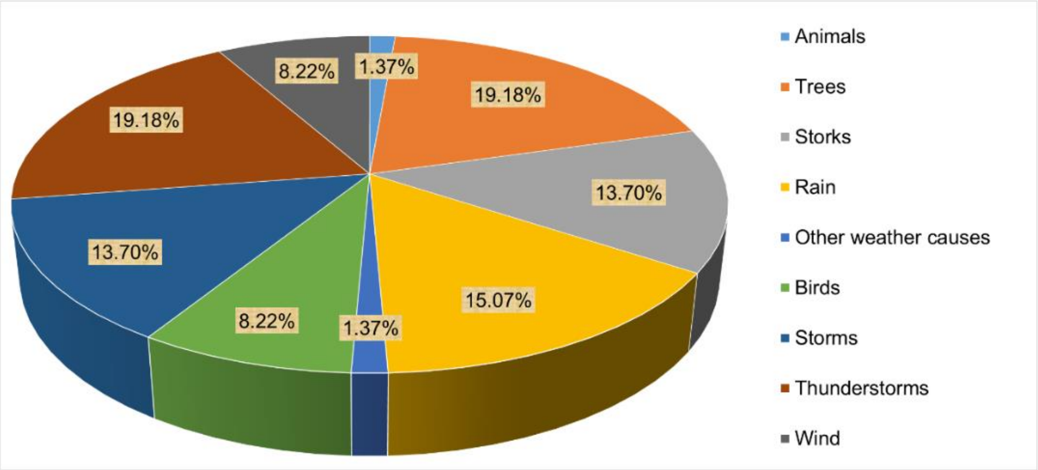

Figure 7. Failures caused by the action of nature in overhead lines. 2001-2013.

Figure 8 shows the failure causes classified as human actions, half of them are due to vehicles and excavators, either touching conductors or crashing into towers.

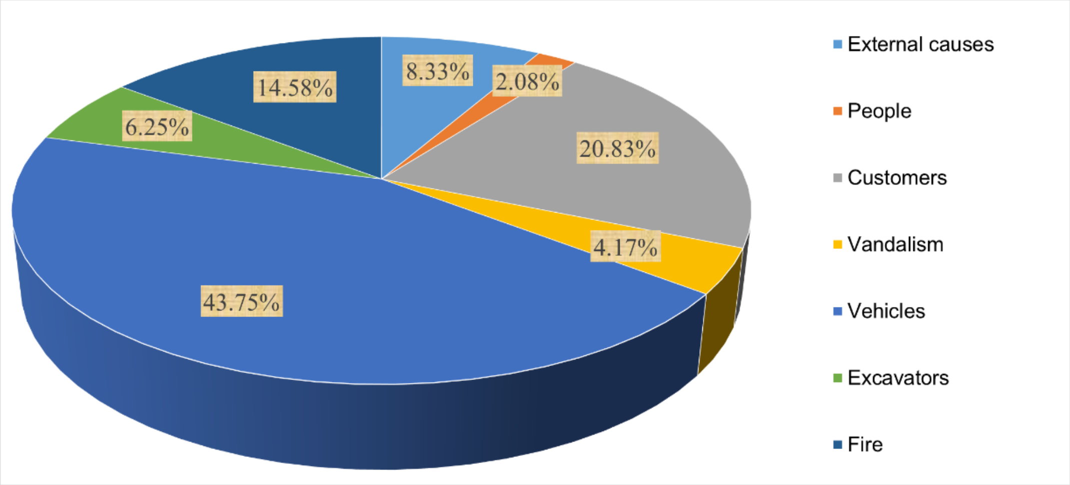

Figure 8: Failures caused by human action in overhead lines. 2001-2013.

Failure causes classified as material degradation are illustrated in Figure 9, showing that conductors are the most affected components, with 73% of all the causes in this group.

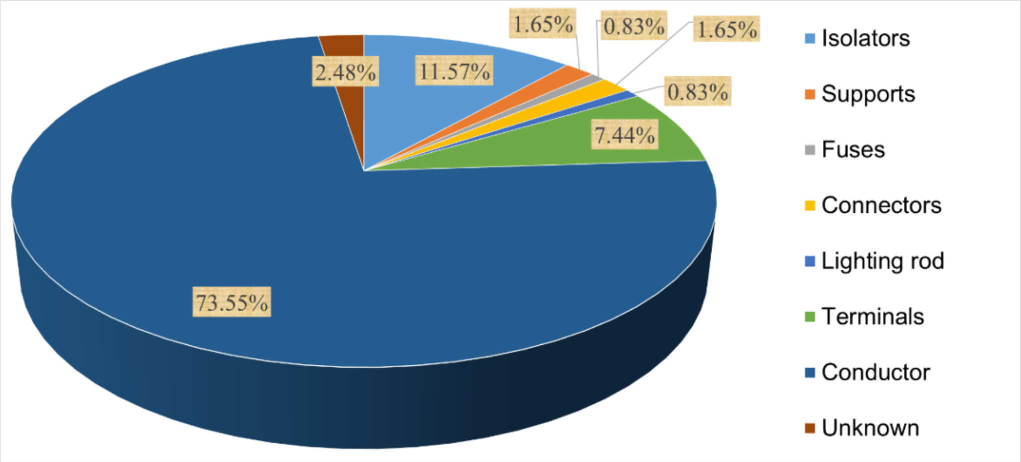

Figure 9. Failures caused by material degradation in overhead lines. 2001-2013.

<u>MV/LV substations</u>

In MV/LV substations, failures can be caused by the action of the weather, flood, fire, thieving, overload, animals, lack of maintenance or material degradation, being the latter the most common cause of failure (54.06 %). Three groups of components in MV/LV substations have been considered with enough representativeness:

- Substation common electrical devices (SCED): this group contains failures produced in all electrical devices in a MV/LV substation except those in transformers, as isolators, busbars, jumper cables, grounding elements, lightning rods, instrument transformers and connectors.
- MV/LV Transformers (TR): this group contains failures produced in transformers, which can be pole mounted, pad mounted or any distribution transformers connected to a feeder.
- Maneuver and protection devices (M&P): this group contains failures produced in isolating switches (IS), load-break switch (LBS) and fuse load-break switches (FLBS)

Figure 10 shows a comparison between the failures in these groups, where failures in MV/LV transformers is the main group, accounting for 42.61% of the total.

Figures 11, 12 and 13 show the evolution of failures produced by these three groups, distinguishing between two voltage levels, 15 kV and 20 kV. Figure 11 shows common electrical device failures, figure 12 shows MV/LV transformer failures and figure 13 the failures of maneuver and protection devices.

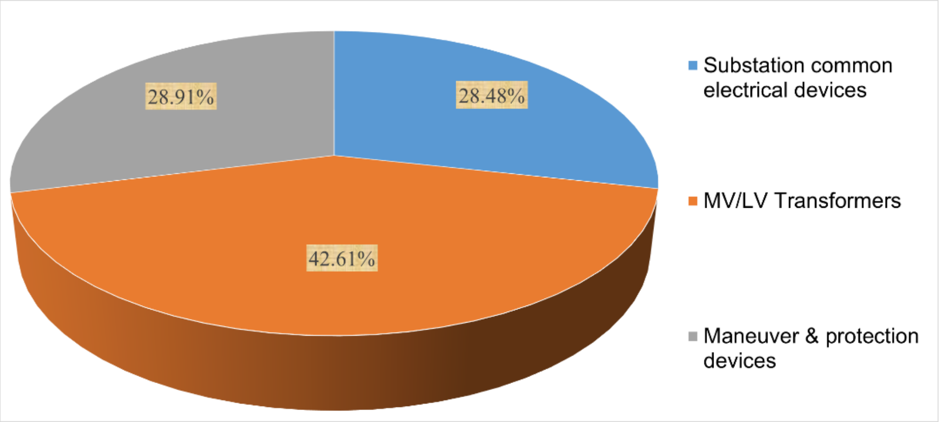

Figure 10: Grouping of MV/LV substation failures. 2001 – 2013.

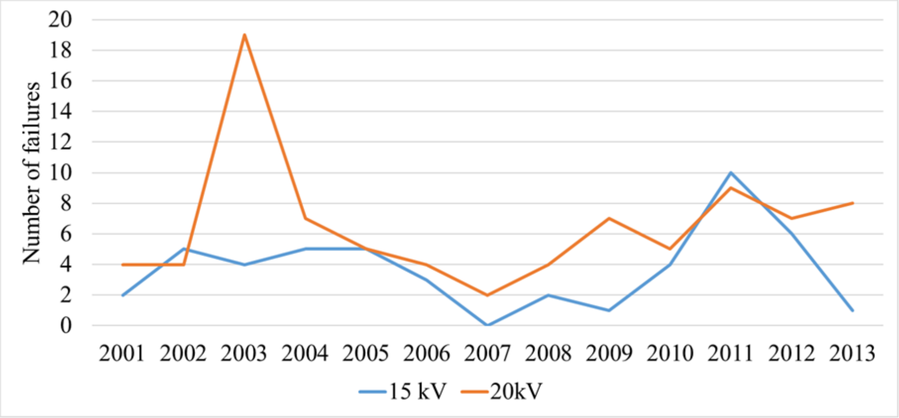

Figure 11: MV/LV substation failures due to common electrical devices. 2001-2013.

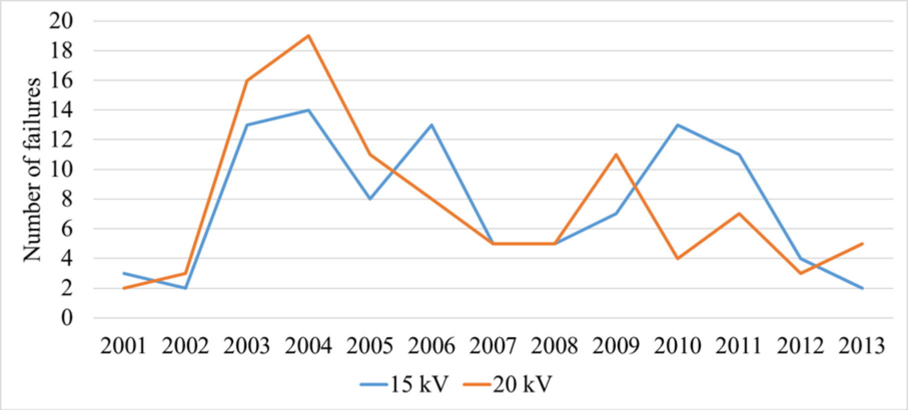

Figure 12: MV/LV transformer failures in MV/LV substations. 2001-2013.

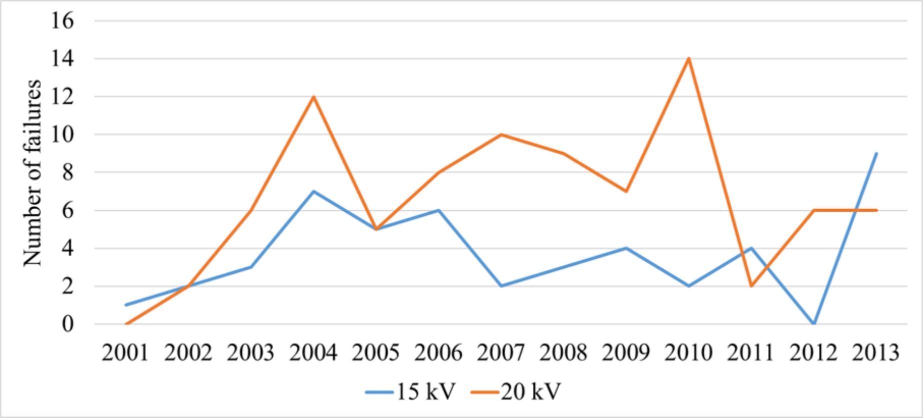

Figure 13: Maneuver and protection device failures in MV/LV substations. 2001-2013

Figure 14 makes a comparison of the number of failures of the different maneuver and protection devices in the MV network. It can be observed that the failures produced by isolating switches and load-breaker switches are the most common in the studied period since they are the most used components in the operation of the distribution network.

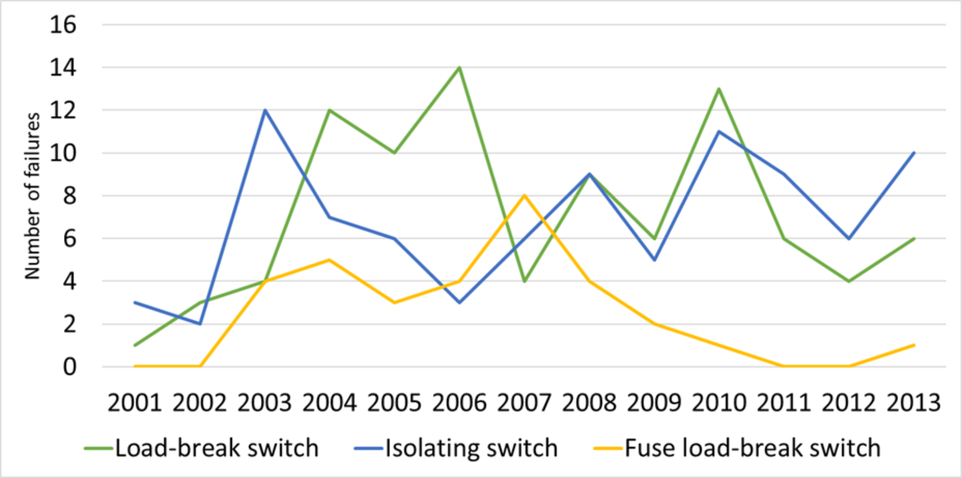

Figure 14: Comparison of maneuver and protection device failures in the MV network. 2001-2013

IV. Failure rate calculation

As stated above, representative element cluster i, either simple elements or element aggregations, have to be chosen in order to calculate their annual failure rates, λ_i, therefore, the following aggregations are proposed:

- Underground cables (UC)
  - Thermoplastic and thermosetting insulated cable (TTI) for 15 and for 20 kV
  - Oil-paper insulation (OPI) for 15 and for 20 kV
- Overhead lines (OL)
- MV/LV Substations (S)
  - MV/LV Transformers (TR) for 15 and for 20 kV
  - Substation Common electrical devices (SCED) for 15 and for 20 kV
- Maneuver and protection devices
  - Isolating switches (IS)
  - Load-break switches (LBS)
  - Fuse load-break switches (FLBS)

Data from 2001 to 2012 are used for failure rate calculation, while the data from 2013 are used for validation purpose. Depending on the kind of element or aggregation, the generic expression for failure rates in (1) has to be adapted, that is, in the case of lines or cables:

$$\lambda_i = \frac{\#faults\ in\ lines\ or\ cables}{total\ length\ (km)} \quad \text{(failures/km)} \qquad (2)$$

And in the case of electrical devices:

$$\lambda_i = \frac{\#faults\ in\ cluster\ i}{\#elements\ in\ cluster\ i} \quad \text{(failures/cluster)} \qquad (3)$$

In the case of underground cables, failure rates for each voltage level are obtained taking into account that only failures by material degradation are linked to the respective voltage level.

Table II shows, for each element cluster i, the annual average value, $\overline{\lambda_i}$, the annual maximum value, λ_{max}, and the annual minimum value, λ_{min}, of the failure rates of period 2001-2012. Additionally, Table II includes relevant failure rates from [15] for comparison purposes. But notice that the case of underground cables it not exactly comparable with [15] since our failure rates do include failures in joints and connectors. Also note that variation ranges in [15] are quite larger than those obtained from the electrical utility databases.

An important issue is to know if annual failure rates are constant or show any trend in the period studied. For this reason, a Laplace test has been applied according to [17] to the elements in Table II. Results show that failure rates cannot be assumed as constant, having, in some cases, a confidence for an upward or downward trend greater than 95%. According with [15], a possible cause is the maintenance action planning, which can vary the distribution of failures along the period of time. For this reason, authors have assumed the sample means in this table as appropriate estimators for predictions. Lower and upper bounds λ_L and λ_U for the 95% c.i. of $E(\lambda)$ are also included in this Table.

TABLE II. Analysis of annual failure rates

		Failure rates 2001-2012					**Benchmarking [15]**			
		λ_{min}	λ_L	$\bar{\lambda}$	λ_U	λ_{max}	λ_{min}	λ	λ_{max}	
Underground cables	**15/20 kV**	**0.0777**	**0.1148**	**0.1335**	**0.1523**	**0.1902**	**0.0019**	**0.0435**	**0.3647**	-/km
	TTI 15 kV	0.0235	0.0779	0.1026	0.1273	0.1670	-	-	-	-/km
	TTI 20 kV	0.0919	0.1254	0.1444	0.1635	0.1853	-	-	-	-/km
	OPI 15 kV	0.0469	0.0788	0.1218	0.1647	0.2823	-	-	-	-/km
	OPI 20 kV	0.0360	0.0800	0.1312	0.1824	0.2921	-	-	-	-/km
Overhead Lines	**15/20 kV**	**0.0244**	**0.0419**	**0.0514**	**0.0609**	**0.0744**	**0.0124**	**0.0621**	**0.1864**	**-/km**
Substation Common Electrical Devices	**15/20 kV**	**0.0006**	**0.0020**	**0.0030**	**0.0040**	**0.0065**	-	-	-	-/unit
	15 kV	0.0006	0.0017	0.0026	0.0034	0.0056	-	-	-	-/unit
	20 kV	0.0006	0.0021	0.0033	0.0045	0.0074	-	-	-	-/unit
Transformers	**15/20 kV**	**0.0013**	**0.0023**	**0.0038**	**0.0053**	**0.0085**	**0.0010**	**0.0100**	**0.0500**	**-/unit**
	15 kV	0.0011	0.0024	0.0038	0.0053	0.0079	-	-	-	-/unit
	20 kV	0.0013	0.0022	0.0038	0.0055	0.0100	-	-	-	-/unit
Load-Break Switches	**15/20 kV**	**0.0002**	**0.0007**	**0.0011**	**0.0015**	**0.0023**	**0.0010**	**0.0030**	**0.0050**	**-/unit**
	15 kV	0.0000	0.0005	0.0011	0.0016	0.0030	-	-	-	-/unit
	20 kV	0.0000	0.0006	0.0011	0.0017	0.0025	-	-	-	-/unit
Isolating Switches	**15/20 kV**	**0.0023**	**0.0055**	**0.0079**	**0.0103**	**0.0138**	**0.0040**	**0.0140**	**0.1400**	**-/unit**
	15 kV	0.0012	0.0054	0.0078	0.0103	0.0139	-	-	-	-/unit
	20 kV	0.0000	0.0000	0.0094	0.0200	0.0572	-	-	-	-/unit
Fuse Load-Break Switches	**15/20 kV**	**0.0000**	**0.0003**	**0.0009**	**0.0015**	**0.0028**	**0.0010**	**0.0030**	**0.0050**	-/unit
	15 kV	0.0000	0.0002	0.0006	0.0010	0.0021	-	-	-	-/unit
	20 kV	0.0000	0.0004	0.0011	0.0018	0.0032	-	-	-	-/unit

Note that, failure rates of underground cables reported in [15] cover a wide range of values with an average slightly lower than that of overhead lines. However, those reported in this work, which include failures in cable elements such as joints, elbow connectors and cable terminations, result in considerably higher averages but in a narrower range.

According to this table, failure rate of TTI underground cables is very sensitive to the voltage, having the highest value for 20 kV and the lowest value for 15 kV. Among the failure rates of single units the isolating switches, commonly used in overhead lines, have the highest failure rates due to their exposure to atmospheric agents.

V. Validation of results

An important use of failure rates in Table II is to estimate the expected number of failures in MV networks. This estimation can be made for each MV feeder and later grouped to obtain the expected number of failures in the network fed by a single distribution substation, or even the whole electric network of a region.

To validate the usability of these failure rates, the MV network in 2013 will be used to compare the real number of failures with the estimated one using failure rates in Table II.

The considered network is designed as weakly meshed, with typical urban rings, but operated radially, with a circuit breaker at the head of each MV feeder. So, in each feeder, the expected number of interruptions in a year can be estimated by

$$NI = \sum_i \bar{\lambda}_{\mathrm{LINE\_i}} \cdot \mathrm{L_i} + N_{TR} \cdot \bar{\lambda}_{\mathrm{TR}} + N_S \cdot \bar{\lambda}_{\mathrm{SCED}} + N_{IS} \cdot \bar{\lambda}_{\mathrm{IS}} + N_{LBS} \cdot \bar{\lambda}_{LBS} + N_{FLBS} \cdot \bar{\lambda}_{FLBS} \quad (4)$$

Where:

- i is an index of the different line sections in the feeder
- L_i is the length of section i
- N_{TR}, N_S , N_{IS}, N_{LBS} and N_{FLBS} are the corresponding number of transformers (TR), MV/LV substations (S), isolating switches (IS), load-break switches (LBS) and fuse load-break switches (FLBS).

Using the average failure rates from 2001 to 2012, the expected number of failures in 2013 has been estimated for a total of 383 feeders. Figure 15 shows these estimations together with the real number of failures in each feeder in 2013, where feeder labels have been chosen according, first, to the ranking of real data, and in case of a draw, to the ranking of estimations.

As can be seen in such figure, there is a disagreement between estimated and real failures, which is even more clear in those feeders that have no real accidents in 2013 but have an expected number of failures.

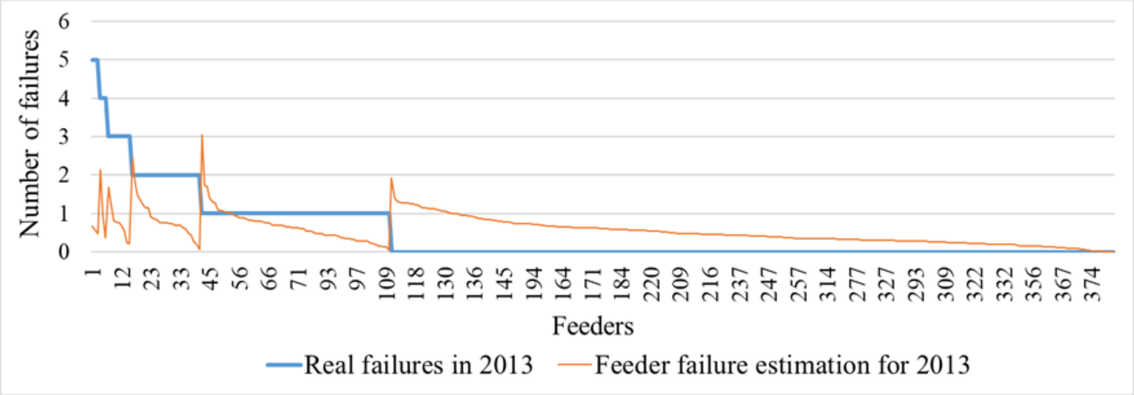

Figure 15. Comparison between expected and real numbers of faults in each feeder in 2013.

However, if feeders are grouped by departing substation, a considerable improvement of the prediction is noticed. Feeders have been clustered in a total of 29 substations, where the aggregated results are shown in figure 16.

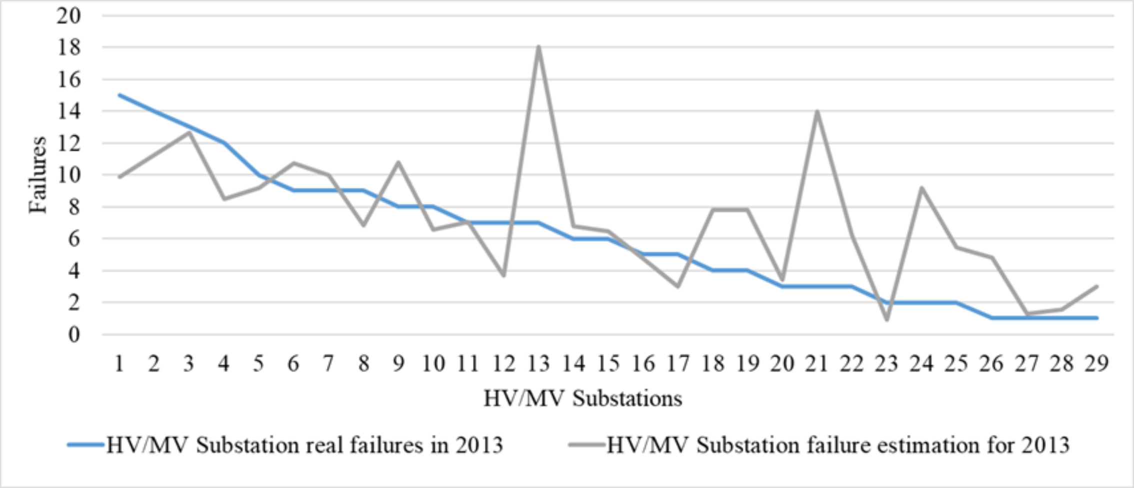

Figure 16. Comparison between estimated and real failures grouped by substations.

Although there is still a small difference between estimated and real data, it can be seen that these predictions are closer to real data than feeder predictions showed before. Moreover, if all estimated predictions are added, the number of total failures estimated in 2013 is 211 and the real one is 177, which shows good accuracy.

To achive higher reliability in the estimations, beyond the average failure rates applied before, maximum and minimum failure rates, λ_i^{max} and λ_i^{min}, are obtained to estimate an interval where the number of real failures should be found. Using these failure rates our worst-case and best-case scenarios for 2013 are 339 and 91 failures respectively.

Figure 17 shows a comparison between real and estimated failures in 2013 based on $\overline{\lambda_i}$, λ_i^{max} and λ_i^{min}. It can be observed that in the majority of substations the real values are between the maximum and minimum estimated values.

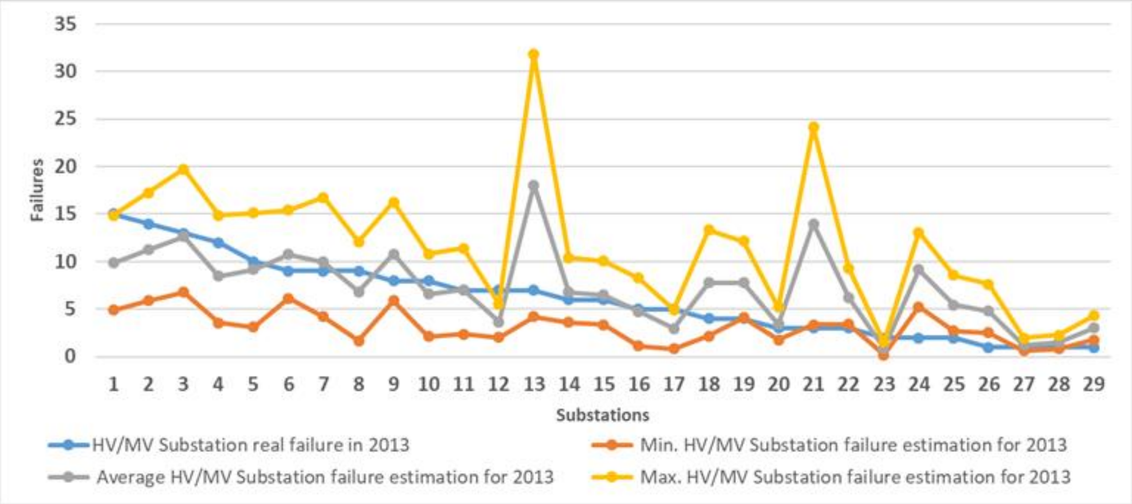

Figure 17. Comparison of different estimated failure amounts in 2013

VI. Application case

As a practical application, the failure rates obtained above are used in a case with two feeders, F1 and F2, fed by a substation in a ring arrangement. Both feeders are radially operated and share an open load-break switch as electrical border point. Figure 18 shows the default operation configuration in which feeder F1 consists of underground cable with cross-linked polyethylene cable (XLPE), and F2 is mostly an overhead feeder.

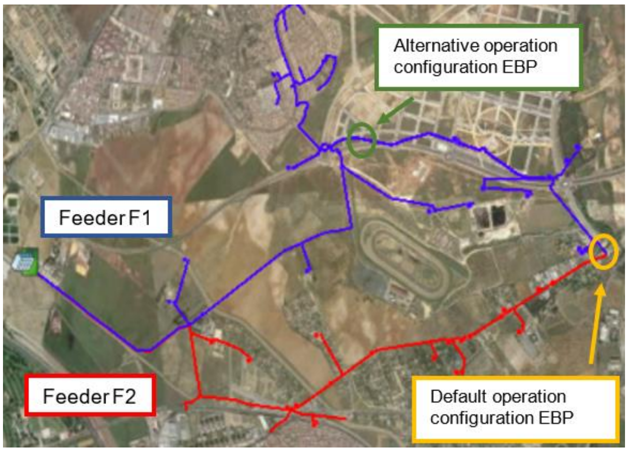

Figure 18. Application case: feeders F1 and F2

The expected number of faults in each feeder has been estimated by clustering all the electrical feeder components according to Table II and using their respective failures rates $\overline{\lambda_1}$, resulting in 2.849 and 0.772 failures/year respectively. If a lower number of expected faults in F1 is required, the proposed alternative border point location could be used to shorten feeder F1 at the cost of worsening F2, resulting in 1.909 and 1.712 failures/year respectively. With this methodology, the expected number of faults of a whole distribution network can be obtained and used to assess its quality of supply by estimating the System Average Interruption Frequency Index (SAIFI) during a period of time [3], [14].

VII. Conclusions

This paper reports the analysis of incident and network databases of 383 feeders from an electrical distribution company in order to estimate element failure rates adapted to the components in the databases, obtaining narrower variation ranges than in the bibliography. Data deficiency has been faced using data pooling, by adopting up to

18 electrical component clusters with enough representativeness. Annual failure rates of these clusters have been estimated and validated through their ability to predict the aggregated number of failures of the studied network.

Finally, the estimated failure rates have been used in a case with two feeders in a ring arrangement to illustrate the estimation of their numbers of faults and the optimization of the electrical border point location.

The knowledge of detailed failure rates as presented in this paper allows the distribution companies for better planning and operation when the quality of supply is considered.

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