Repair Models of Power Distribution Components

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***Abstract*—For reliability assessments of power distribution systems it has been customary to represent the failure and repair processes of the components by exponential models. A problem with this practice is that in many cases it is not checked if component operating data really fits to exponential models. Regarding repair times, several references have claimed they are generally not exponentially distributed but lognormally. For the case of power system components, a review of the literature shows this subject is not treated in dept and the most common information about repair times is given in the form of mean values i.e. point estimators not probabilistic models. Thus, using real data, a study on the modeling of repair times for 46 classes of power distribution components was carried out. The main results are: 1. Repair times have a very high variability; thus, results of analysis based only on their mean values should be used with caution. 2. Only for a half of the studied classes the exponential model is valid, but in contrast, the log-normal distribution is valid for all them; this means, if a model for repair times of power distribution components is to be assumed the lognormal distribution is the one to be chosen, and, for system reliability assessments, analysts should consider the Montecarlo simulation method that is not restricted to exponential modeling.**

***Index Terms*-- Power distribution reliability, reliability modeling, maintenance.**

I. INTRODUCTION

FOR power system reliability assessments, the modeling of the components is an aspect that deserves especial attention because:

- The system reliability assessment method to be applied greatly depends on the kind of modeling used to represent the components. For example, the cut-set method is based on exponential models while the Montecarlo simulation allows the use of any kind of distributions.
- Results of system reliability assessments will be only valid if the component reliability models are valid representations of their failure and repair processes.

The basic and most popular reliability model for repairable components is the two-state "alternating renewal process" shown in Fig. 1 [1].

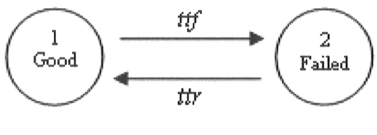

Fig. 1. Two state component reliability model

It is defined by means of the probability distributions of time to failure (ttf) and time to repair (ttr).

These distributions must be obtained applying statistical procedures which estimate the parameters of a given probabilistic model (Exponential, Gamma, Weibull, etc.) and verify its fit to component operating data.

However, for reliability assessments of power distribution systems it has been common to assume these distributions are exponential, a practice that in part is justified by the following reasons:

- Most popular methods for system reliability assessments such us cut-sets [2], [3], analytical simulation [4] and the Markov process [5] are based on exponential modeling.
- It is very easy to estimate the parameter of the exponential distribution from operating data for failures and repairs simply doing $\hat{\lambda} = 1/mean(ttf)$ and $\hat{\mu} = 1/mean(ttr)$, respectively.

The problem with this assumption is that some facts show it is not always valid:

- For the failure process of a component, an exponential model applies only if the component is in its useful life; for aged components, this model is not valid [6]. And many power distribution systems have aged components.
- Some references show times to repair are in general not exponentially distributed but lognormally [5], [7], [8].

As pointed out by R. E. Brown, failures have historically received the most attention [9]. This is the cause why information about repair times is generally given in the form of mean values ($mean(ttr) = MTTR = r$) i.e. point estimators not probabilistic models.

Thus, in order to know more about this important subject, this paper presents a study of repair models for 46 classes of power distribution components using operating data that at least covered a period of four years.

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II. Definition of Repair Time

The definition of repair time [10], [11] depends on where the failures are located. So, let us considerer the typical medium-voltage distribution feeder shown in Fig. 2.

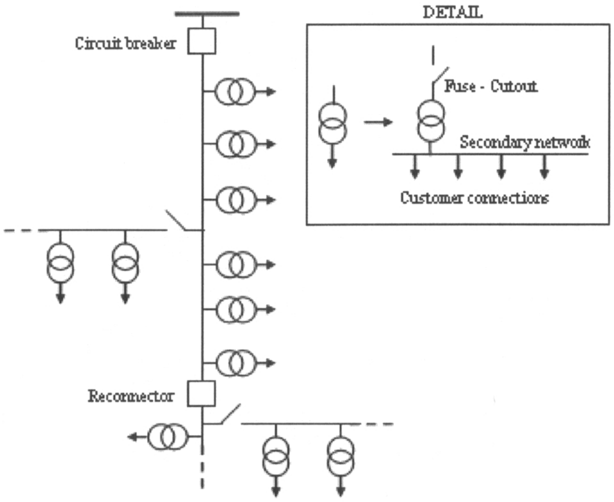

Fig. 2. A typical distribution feeder

Failures located down-stream fuse-cut outs are reported to the utility by customers. The sequence of events when a failure occurs in this part of the system is (See Fig. 3):

- At a random time t_f a failure occurs.
- If the failure involves short-circuit, at time t_{si}, a fuse melts to clear the failure.
- At time t_{cc}, the call of a customer reporting the service interruption is registered by the utility service center.
- At time t_{oa}, the utility service center creates a repair order and assigns it to a crew. However, at this time, the crew could be busy repairing other failure.
- At a time t_r the crew finishes the repair of a previous failure and proceeds with the current repair order.
- At a time t_{sr} the crew finishes the repair and service is restored to customers.

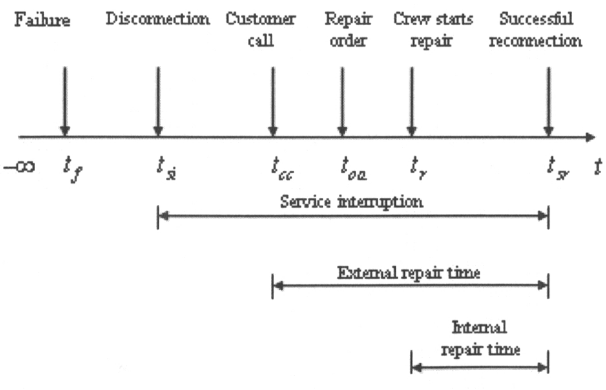

Fig. 3. Repair time for failures down-stream fuse cut-outs

Failures located up-stream fuse-cut outs are detected by protective relays which disconnect a zone of the feeder to clear the fault and after an intended dead time reconnect to restore the service. Two cases arise after the reconnection: the fault is not more present or the fault is still present. The sequences of events for these cases are shown in Fig. 4 and Fig. 5, respectively.

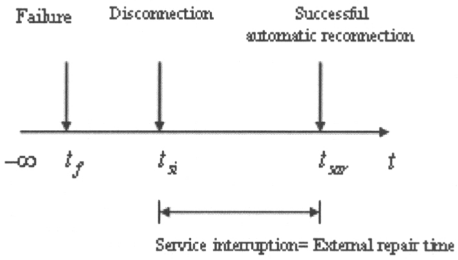

Fig. 4. Repair time for failures up-stream fuse cut-outs and successful automatic reconnection

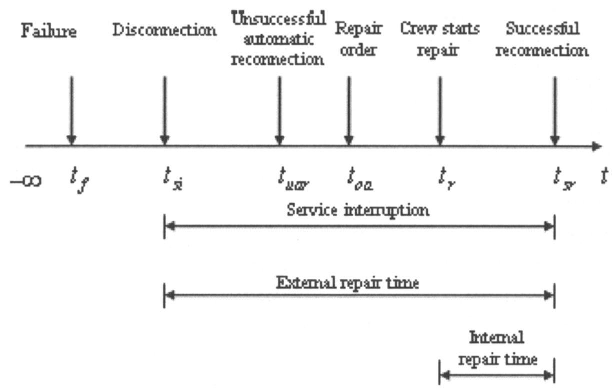

Fig. 5. Repair time for failures up-stream fuse cut-outs and unsuccessful automatic reconnection

While service interruptions due to failures upstream cut-outs can be momentary (≤ 5 minutes) or permanent (> 5 minutes), service interruptions due to failures downstream cut-outs are permanent [12], [13].

The repair time seen by crews, the utility service center and customers are different:

- The repair time seen by the crew, called here "internal repair time", is the period ($t_{sr} - t_r$). It includes the travel time to the place where the failure is located, the time to identify the failed components and the time to take actions that leads to restore the service.
- The repair time seen by the utility service center, called here "external repair time", is the period ($t_{sr} - t_{si}$), the time that officially the customers are without service.
- The repair time seen by customers is the period of service interruption.

In this paper, the term "repair time" or "time to repair" is applied to external repair times, the outage times used for the computation of reliability indices.

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III. Repair Times for Components

Although repair times can be studied from a system point of view [14], [15], the approach here is to associate them to main components classes.

Power distribution systems have thousands of components and by this reason it is impractical to build a particular reliability model for each component. Thus, it has been a common practice to build a model for each group of similar components. This means, a single model typifies or can represent all components in the group. The groups of similar components are also known as categories or classes. The procedure to build a repair model is:

1. Define classes: groups of similar components
2. For each class, collect repair times of those failure events where this kind of component was involved (it failed). This is, obtain a sample of repair times for each class.
3. Apply the procedure of fitting a distribution to a sample data. Next section describes this procedure.

A failure can involve more than one component and more than one kind of component. In this case, the repair time is assigned to all involved components because, in general, is very difficult to know which part of the recorded repair time correspond to each involved component.

IV. Procedure for Selecting a Probabilistic Model

As a repair time is a random variable, a probabilistic model should be chosen for it. In short, the procedure for choosing a probability distribution applied in this study is (See Fig. 4):

1. Review sample data: Units of measurements, outliers, repeated data, severe events, etc.
2. Independence test: The procedure of maximum likelihood for parameter estimation and the goodness of fit tests are developed under the condition of independence on sample data. Thus, it is very important to check if this condition is fulfilled [6], [16]. Ref. [17] presents two tests for independence: the correlation plot and the scatter diagram. The scatter diagram was applied in this study.
3. Candidate probability models: normal, lognormal, exponential, Gamma and Weibull distributions were considered as possible models for repair times.
4. Parameter estimation: For the five distributions considered, the parameters were estimated applying the maximum likelihood method. However, graphical methods or the moments one can also be applied.
5. Goodness of fit test: The goodness of fit test says if a given probability distribution is a valid model to represent the random phenomenon under study. Several goodness of fit test are available, for example, Chi-square test, Kolmogorov – Smirnov test, Anderson Darling test and graphical methods tests such as the TTT plot. Graphical tests do not give a confidence level as the other ones and the decision of the fit resorts on the judgment of the analyst. In this study the Kolmogorov-Smirnov test was applied [17], [18].

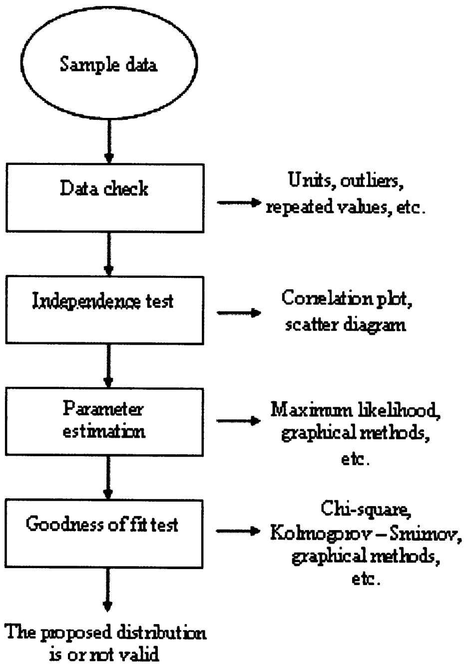

Fig. 6. Procedure for selecting a probabilistic model

V. Results

This study uses operating data from the power distribution system in the city of Pereira, Colombia. This data was collected in several reliability surveys [19]-[26] which covered most types of distribution components; for some components more data was added [27]. Data for capacitors, reclosers, sectionalizers and power transformers was taken from reliability surveys performed in the city of Bogotá, Colombia [28]-[30]. Instrument transformers of all tension levels and 33 kV distribution transformers are not presented because available data was not enough to apply the procedure of fitting a distribution.

Table I shows studied component classes, period covered by records, statistical descriptors and the result of fit to probability distributions considered in this study. The following nomenclature is used:

X :	Number of components in a group
T :	Period in years covered by collected data
N :	Number of failures reported during period T. It is equal to the number of repairs
r :	Mean repair time.
s :	Deviation of repair time.
cv :	Coefficient of variation of repair time ($cv = s / r * 100\%$)
NOR :	Normal or Gaussian distribution
LOG :	Lognormal distribution
EXP :	Exponential distribution
WEI :	Weibull distribution
GAM :	Gamma distribution

As the lognormal model is the only one that fits for all component classes, tables II and III shows it in detail.

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TABLE I
DATA OF COMPONENTS AND FIT TO DISTRIBUTIONS PROPOSED AS REPAIR MODELS

Component	X	T [years]	N	r [Hours]	s [Hours]	cv [%]	Fit to distribution?				
							NOR	LOG	EXP	WEI	GAM
115/13.2 kV power transformer	84	4	58	1.6445	2.3362	142.07	No	Yes	No	Yes	Yes
115/33 kV power transformer	20	4	12	1.8956	3.3143	174.84	Yes	Yes	Yes	Yes	Yes
115 kV SF6 circuit breaker	8	8	11	1.1607	1.9306	166.33	Yes	Yes	Yes	Yes	Yes
115 kV disconnector	14	8	12	3.8278	5.9295	154.91	Yes	Yes	Yes	Yes	Yes
13.2 kV SF6 circuit breaker	25	10	31	1.1710	2.0876	178.27	No	Yes	No	Yes	Yes
13.2 kV vacuum circuit breaker	43	9	113	0.6199	1.1127	179.50	No	Yes	No	Yes	Yes
13.2 kV oil circuit breaker	51	13	95	1.8594	3.6743	197.61	No	Yes	No	Yes	Yes
33 kV oil circuit breaker	34	15	40	1.6776	4.1969	250.17	No	Yes	No	Yes	Yes
33 kV SF6 circuit breaker	24	11	26	2.7778	5.9940	215.78	No	Yes	No	Yes	Yes
13.2 kV disconnector	32	10	12	1.6194	2.1328	131.70	Yes	Yes	Yes	Yes	Yes
33 kV disconnector	43	11	46	12.2931	36.9073	300.23	No	Yes	No	Yes	No
13.2 kV aerial urban feeder	154.65	5	1263	0.3811	0.8798	230.85	No	Yes	Yes	Yes	Yes
13.2 kV underground urban feeder	13.70	5	96	0.4628	1.0715	231.52	No	Yes	No	Yes	Yes
13.2 kV aerial rural feeder	671.79	5	1351	0.4206	1.9002	451.77	No	Yes	Yes	Yes	Yes
33 kV aerial feeder	42.31	5	303	0.3575	0.9571	267.70	No	Yes	Yes	Yes	Yes
13.2 kV urban recloser	250	5	34	3.0362	4.8145	158.57	No	Yes	Yes	Yes	Yes
13.2 kV rural recloser	63	5	40	5.2499	17.8489	339.99	No	Yes	No	No	No
33 kV urban – rural recloser	38	5	15	4.5320	5.3359	117.74	Yes	Yes	Yes	Yes	Yes
13.2 kV urban – rural sectionalizer	128	5	13	7.0691	15.7317	222.54	No	Yes	Yes	Yes	Yes
33 kV urban – rural sectionalizer	7	5	3	5.8088	4.2516	73.19	Yes	Yes	Yes	Yes	Yes
13.2 kV capacitor bank	55	5	26	5.1725	19.0402	368.11	No	Yes	No	Yes	Yes
33 kV capacitor bank	23	5	7	2.6098	4.3973	168.49	Yes	Yes	Yes	Yes	Yes
13.2 kV urban surge arrester	6395	5	142	2.4380	3.9897	163.78	No	Yes	No	Yes	No
13.2 kV rural surge arrester	4877	5	226	4.5344	6.3756	140.61	No	Yes	No	No	No
33 kV surge arrester	212	5	14	2.1831	2.1807	99.89	Yes	Yes	Yes	Yes	Yes
13.2 kV urban fuse cut-out	6200	6	103	2.4857	3.1773	127.83	No	Yes	No	No	No
13.2 kV rural fuse cut-out	6281	6	261	0.3126	1.8751	599.89	No	Yes	No	Yes	No
33 kV fuse cut-out	168	6	138	2.3607	2.2214	94.10	No	Yes	No	Yes	Yes
13.2 kV single phase urban transformer	790	5	168	3.6283	5.2128	143.67	No	Yes	No	No	No
13.2 kV three phase urban transformer	1428	5	280	2.6602	3.4216	128.63	No	Yes	No	No	No
13.2 kV rural transformer	2065	5	1494	5.0707	6.3842	125.90	No	Yes	Yes	Yes	Yes
Aerial urban secondary main	1335.65	5	2117	3.6005	5.1924	144.21	No	Yes	Yes	Yes	Yes
Underground urban secondary main	263.17	5	434	3.1357	4.5420	144.85	No	Yes	Yes	Yes	Yes
Aerial rural secondary main	1554.61	5	2233	5.0232	7.1864	143.06	No	Yes	Yes	Yes	Yes
Urban single phase service drop	679.36	5	2234	3.7645	6.5338	173.56	No	Yes	Yes	Yes	Yes
Urban two-phase service drop	196.73	5	524	3.2176	4.9815	154.82	No	Yes	Yes	Yes	Yes
Urban three-phase service drop	76.51	5	176	3.5237	5.7665	163.65	No	Yes	No	No	No
Rural single phase service drop	233.44	5	842	4.6648	6.7270	144.21	No	Yes	Yes	Yes	Yes
Rural two-phase service drop	20.72	5	219	3.9071	4.6301	118.50	No	Yes	No	No	No
Rural three-phase service drop	5.17	5	205	4.6777	6.1201	130.83	No	Yes	Yes	No	No
Urban single phase watthour meter	66758	5	2301	3.6493	5.8413	160.07	No	Yes	Yes	Yes	Yes
Urban two-phase watthour meter	20169	5	462	3.0198	4.8009	158.98	No	Yes	Yes	Yes	Yes
Urban three-phase watthour meter	7854	5	159	2.5846	2.9628	114.63	No	Yes	No	Yes	Yes
Rural single phase watthour meter	10603	5	116	4.8515	8.6519	178.33	No	Yes	No	No	No
Rural two-phase watthour meter	942	5	122	5.2663	9.7775	185.66	No	Yes	No	Yes	No
Rural three-phase watthour meter	236	5	92	5.2118	10.6572	204.48	No	Yes	No	Yes	No
						Percentage of fit [%]	17.4	100	50	80.4	69.5

Notes:

1. In most cases, X is an estimate because of change of component populations with time
2. X for feeders, secondary mains and service drops is measured in kilometers
3. Power transformers ratings are in the range 20 MVA to 30 MVA
4. Substation components of 33 kV and 13.2 kV includes outdoor and indoor types
5. Data of medium voltage distribution feeders refers to failures upstream cut-outs
6. Capacitor banks ratings are in the range 0.6 kVA to 4.8 kVA.
7. Fuse cut-outs are porcelain type
8. Surge arresters include SiC (90%) and ZnO (10%) types.
9. Rural distribution transformers include single phase and three phase types.
10. Secondary mains includes the following types: four wire three-phase and three wire single-phase
11. Mean length of urban and rural service drops are 10 meters and 25 meters, respectively
12. Almost all watthour meters are electromechanical type.
13. For some categories it was not possible to classify data by urban or rural
14. For substation equipments repairs include replacement of failed components with an spare

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TABLE II
THE LOGNORMAL DISTRIBUTION

$f_{ttr}(t)$	$\frac{1}{t\sigma\sqrt{2\pi}} * e^{-(\ln(t)-\mu)^2/2\sigma^2}$	(1)
$E(ttr)$	$e^{\mu+\frac{\sigma^2}{2}}$	(2)
$VAR(ttr)$	$e^{(2\mu+\sigma^2)}[e^{\sigma^2}-1]$	(3)

TABLE III
LOGNORMAL MODEL FOR REPAIR TIMES OF POWER DISTRIBUTION COMPONENTS

Component	μ	σ
115/13.2 kV power transformer	-0.0549	1.0510
115/33 kV power transformer	-0.0607	1.1834
115 kV SF6 circuit breaker	-0.5141	1.1516
115 kV disconnector	0.7305	1.1062
13.2 kV SF6 circuit breaker	-0.5571	1.1958
13.2 kV vacuum circuit breaker	-1.1983	1.2001
13.2 kV oil circuit breaker	-0.1749	1.2610
33 kV oil circuit breaker	-0.4737	1.4079
33 kV SF6 circuit breaker	0.1553	1.3163
13.2 kV disconnector	-0.0209	1.0030
33 kV disconnector	1.3571	1.5179
13.2 kV aerial urban feeder	-1.8873	1.3584
13.2 kV underground urban feeder	-1.6955	1.3602
13.2 kV aerial rural feeder	-2.3980	1.7504
33 kV aerial feeder	-2.0787	1.4492
13.2 kV urban recloser	0.4822	1.1211
13.2 kV rural recloser	0.3930	1.5907
33 kV urban – rural recloser	1.0763	0.9326
13.2 kV urban – rural sectionalizer	1.0638	1.3356
33 kV urban – rural sectionalizer	1.5449	0.6550
13.2 kV capacitor bank	0.3046	1.6363
33 kV capacitor bank	0.2867	1.1598
13.2 kV urban surge arrester	0.2386	1.1417
13.2 kV rural surge arrester	0.9662	1.0445
33 kV surge arrester	0.4347	0.8319
13.2 kV urban fuse cut-out	0.4263	0.9841
13.2 kV rural fuse cut-out	-2.9680	1.9001
33 kV fuse cut-out	0.5419	0.7964
13.2 kV single phase urban transformer	0.7289	1.0582
13.2 kV three phase urban transformer	0.4903	0.9880
13.2 kV rural transformer	1.1486	0.9746
Aerial urban secondary main	0.7186	1.0606
Underground urban secondary main	0.5775	1.0634
Aerial rural secondary main	1.0570	1.0555
Urban single phase service drop	0.6309	1.1787
Urban two-phase service drop	0.5572	1.1058
Urban three-phase service drop	0.6083	1.1412
Rural single phase service drop	0.9776	1.0606
Rural two-phase service drop	0.9242	0.9366
Rural three-phase service drop	1.0440	0.9988
Urban single phase watthour meter	0.6594	1.1271
Urban two-phase watthour meter	0.4749	1.1228
Urban three-phase watthour meter	0.5301	0.9160
Rural single phase watthour meter	0.8641	1.1960
Rural two-phase watthour meter	0.9152	1.2216
Rural three-phase watthour meter	0.8284	1.2826

Notes:

1. Parameters are calculated for t measured in hours
2. Confidence level: 95%

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VI. Conclusions and Recommendations

1. Repair times for all components classes considered in this study show a very high coefficient of variation; in most cases it is higher than 100% the standard value of the exponential model. This high variability is because a repair time involves aspects like: utility response to create repair orders, waiting time to serve a repair order, transportation time of the crews and many different kinds of failures.
2. Due to the very high variability of repair times, results of analysis based on their mean values should be used with caution. The analyst should instead use a probability model.
3. Only for 50% of the 46 classes of power distribution components included in this study, the exponential distribution is valid as a repair model, but in contrast, the log-normal distribution is valid for all them. This means, if a model for repair times of power distribution components is to be assumed the lognormal distribution is the one to be chosen
4. A repair time is the sum of several random variables, so it could be expected its fit to a Gaussian model because of the Central Limit Theorem property [31]. However, results of this study shows, there is fit to a Gaussian model only for 17.4% of the cases.
5. For power system reliability assessments, analysts should consider the Montecarlo simulation method [32]-[33] that is not restricted to exponential modeling and so valid models obtained by means of statistical procedures can be applied.

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VIII. Biographies

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