Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2017) 25: 1082 – 1094

doi:10.3906/elk-1509-5

A methodology to include real-life failure data in the failure rate estimation of power distribution systems

Mojtaba GILVANEJAD[1,*], **Hossein ASKARIAN ABYANEH**[2], **Kazem MAZLUMI**[3]
[1]Department of Transmission & Substation Equipment, Niroo Research Institute, Tehran, Iran
[2]Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran
[3]University of Zanjan, Zanjan, Iran

Received: 01.09.2015 • **Accepted/Published Online:** 24.03.2016 • **Final Version:** 10.04.2017

Abstract: Random failure rates are usually assumed as constant values in reliability calculations. In this paper, this topic is investigated using stochastic models of uncertain phenomena like lightning, cold load pickup, and overloading, which result in random failures. An algorithm is developed to estimate the random failure rates in distribution networks during their lifetime. This algorithm stochastically generates the random failures as well as sustained failures as a result of equipment wear-out state due to the aging process and finally estimates the total number of temporary/sustained failures in a period of the network lifetime. The results of applying this algorithm to a real case study show that there is slight time-dependency between the random failure rate of the network and its lifetime.

Key words: Cold load pickup, lightning, overloading, random failure

1. Introduction

The reliability of electrical distribution systems has a major role in the design and operation of such systems. Reliability can be even more important when the majority of failures occur in the distribution part [1]. In this regard, many studies were carried out in recent years to achieve the optimum level of reliability indices in distribution systems. Some of them tried to define new regulations in order to evaluate the economic performance of higher reliability levels. In [1], the authors provided a method to investigate the impact of power quality regulations on the economic performance of an investment strategy. The reliability of the distribution system was also studied in the literature in terms of maximizing the availability and reducing the restoration time of the network [2]. As [2] noted, the main part of the activities carried out in distribution networks to increase the reliability levels involves finding the optimum plan for the protection system [3–6].

The starting point for all reliability studies is assigning failure rates to the network equipment. Reliability indices are affected by two types of failures: aging failures and random failures. Aging creates an increase in the failure probability of the equipment during its lifetime. The trend of the aging failure probability along the network lifetime has been the subject of many papers in recent years [7–10]. This probability is under the influence of operational and environmental conditions. Random failures, on the other hand, are not as predictable as aging failures. This type of failure has a stochastic nature and randomly happens during the network lifetime. The random failure rate is commonly assumed as a constant value during the lifetime of the network. These failures constitute a significant part of the failures in distribution systems and correct estimates

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[*]Correspondence: mgilvanejad@nri.ac.ir

of the random failure rates can greatly affect the precision of the reliability results. Accordingly, decision making in the asset management process may go wrong if the assumed failure rates do not have enough accuracy in reliability calculations.

The exactness of the constant random failure rate is studied in this paper by comparing its results with the case in which temporary failures are generated through a stochastic process using stochastic models of uncertain phenomena like lightning, cold load pickup (CLPU), and overloading, which result in random failures. An algorithm is developed to estimate the random failure rates in distribution networks during their lifetime. This algorithm stochastically generates random failures as well as sustained failures as a result of equipment wear-out state due to the aging process and finally estimates the total number of temporary/sustained failures in a period of the network lifetime. The results of the analyses are presented for a real case study in Tabriz, Northwest Iran.

2. Problem statement

The equipment failure rate plays a vital role in reliability calculations of distribution systems. The failure history exploration shows that the total failure rate of any device in a distribution system changes during its lifetime [11,12]. The routine method for accommodating these observations is on the basis of categorizing the whole failures into two groups, namely random failures and aging failures. The random failures are estimated based on a constant average value, which is called the random failure rate and is obtained by dividing the total number of random failures within the sampling interval. Another group, aging failures, is used to define a conditional probability function in which the aging failure depends on the age of the related device [7,11,13].

Apart from the aforementioned existing method, there is also another method that models all the failure happenings including random and/or aging failures during the network lifetime by using only one time-dependent formula, which is very similar to the shape of the aging relationships [12,14,15].

Statistical analyses of historical failure data indicate that a constant value for the random failure rate cannot realistically afford the frequency variation of the random failures during the network lifetime. It is also seen that the changes of the random failure rate are not in accordance with the aging failure rate; hence, it is not possible to define a unique relationship for both types of failures. To better verify this issue, the authors performed statistical analyses of the available historical failure data of distribution systems. The findings of the survey also confirmed the previous instances of random failure variations in different years of the network lifetime. For example, the results of a 10-year failure analysis for a network with 38.4 km of length in the medium voltage level are shown in Figure 1. The feeder contains overhead lines as well as cable parts and serves 111 distribution transformers.

As shown in Figure 1, the number of random failures has significant changes during different years of the network lifetime and the average value appears to not be a good estimate for modeling the random failure rate. Hence, the authors tried to study the origins of the random failures in distribution systems. This study aims to find an appropriate approach for modeling the uncertain variation of the random failure rate during the network lifetime, which can result in more accurate calculations for assessment of future network reliability indices.

In other words, it seems that random failures make the aging process of the electrical devices faster and, accordingly, the accelerated aging results in more aging failures. It is thought that more aging failures can cause more random failures, too. The existence of such mutual effects is going to be studied and simulated in this paper.

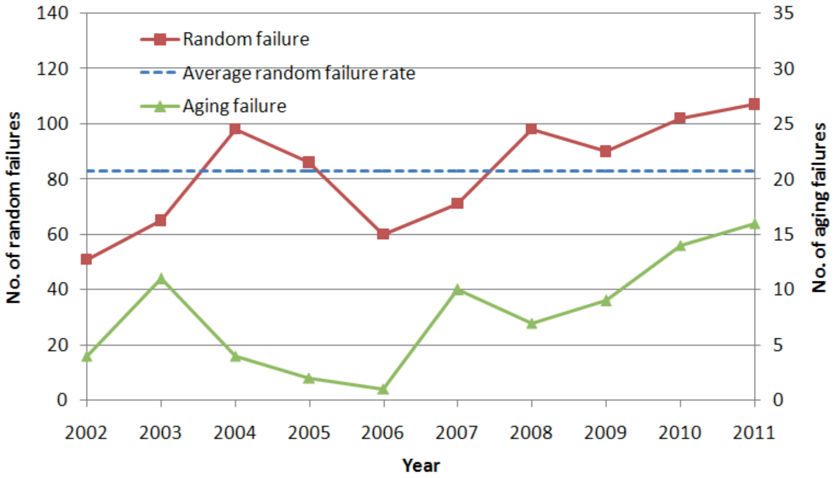

Figure 1. Failure statistics of a real medium voltage network.

3. Random failure causes

Random failures are normally subdivided into temporary failures and sustained failures. Both types of these failures can result in sustained outages if the network is not equipped with any countermeasure device or system such as a recloser and/or automation system. On the contrary, the existence of such devices or systems may lead to reenergizing of the network after a short-duration outage (temporary outage) if the fault cause is cleared at this time [16]. The original causes of temporary outages in distribution networks usually remain undiscovered because such causes usually disappear after a short interruption in the electric service. These original causes also have a stochastic nature and occur randomly during the lifetime of the network. Several causes have been identified to date as the random failure causes in distribution systems. Some of the most important causes are lightning, overloading, cold load pickup, pollution, and bird collision/wildlife causes. There are some other less important causes that can result in random failures in rare events, e.g., resonance/ferroresonance, that are usually neglected in reliability studies.

Lightning is a major cause of the faults on overhead distribution lines. A number of works were carried out to study the different aspects of this phenomenon [17–19]. From the random failure point of view, estimation of the insulation breakdowns within a year as a result of lightning strikes has the major importance. The annual number of breakdowns is a random value that depends on different parameters affecting the lightning intensity.

The overload phenomenon is also a prevalent event that yields single-phase, two-phase, or three-phase outages in distribution systems. This phenomenon mostly happens when a sudden coincidence of the electrical load consumption occurs in the distribution system, which results in temporary network overloading. The method for stochastic modeling of this phenomenon in distribution systems was fully described in [20]. However, a brief description is also provided here for thoroughness.

The cold load pickup phenomenon is also prevalent in networks where there exists a considerable amount of thermostatically controlled loads. In such networks, a prolonged outage means that all of the thermostatic loads must be connected to the network after the network recovery. The resultant excessive load leads to undesired operation of the protection devices and produces unwanted temporary outages in the system. The stochastic model regarding the random occurrence of this phenomenon was also investigated in [21]. A brief description is presented in the next section.

The other less important causes, namely pollution, bird collision/wildlife, and resonance/ferroresonance, have lower impact on the total number of temporary failures in comparison with the former mentioned causes. Hence, the three main causes (i.e. lightning, overload, and cold load pickup) are taken into account in this paper for modeling the resultant random failures. It is necessary to mention that a great number of studies have already been carried out on different aspects of these three causes and different worthwhile models were provided to justify the behavior of these phenomena in different conditions [22–27]. However, only a small part of them was devoted to the stochastic modeling of the random occurrence of these phenomena.

4. Stochastic models of temporary failure causes

Two random failure causes are stochastically modeled using the methods described in the authors' previous works [20,21] and the stochastic model of another one is extracted from the IEEE guides according to [28].

4.1. Lightning

A procedure is developed for stochastic assignation of the values affecting the lightning resultant breakdowns in overhead lines based on IEEE Standard 1410 [28]. This procedure yields a random number of annual lightning flashovers that result in the overhead lines' temporary or sustained outages. Details of this procedure are not given here, however; the general approach is similar to [28].

4.2. Cold load pickup

According to [21], the excessive load value as a result of CLPU is calculated as:

$$I_{peak} = [NPM \cdot CL \cdot I_{tot}] + [(1 - CL) \cdot I_{tot}], \tag{1}$$

where I_{peak} indicates the peak current that passes through the protective device during the initial moments after network restoration and I_{tot} is the normal load value before the outage. *NPM* and *CL* are defined as follows [21]:

$$\begin{array}{l} NPM = \frac{CLPUPM}{\text{rated load}} \\ CL = \frac{I_{TCL}}{I_{tot}} \end{array}, \tag{2}$$

where *CLPUPM* is the peak load magnitude that occurs because of CLPU and I_{TCL} denotes the magnitude of thermostatically controlled loads. Details about the method of stochastically modeling the CLPU using Eqs. (1) and (2) and the way of modeling the effect of ambient temperature and outage duration were fully given in [21].

4.3. Overloading

According to [20], modeling the stochastic variation of the electrical loads during different hours of the day was segmented to 24 stochastic models, each one for a specific hour of the day. Statistical analysis of the real measured load data indicated that a normal distribution function is the best estimator for modeling the load stochastic variation. Figure 2 illustrates the method of applying the normal function to estimate the load random value. After estimation of the load random values, the pickup currents of the protective devices were used as a criterion for judgment about the occurrence of the overload-related outages. Details of the stochastic model of the overload-related outages were described in [20].

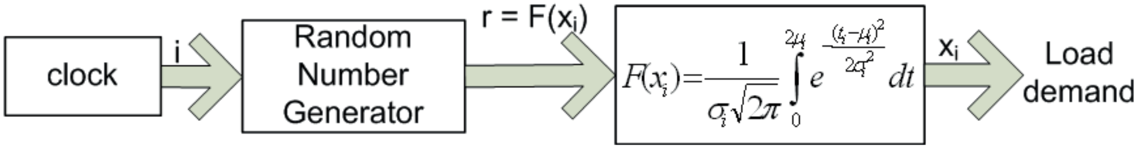

Figure 2. Block diagram for the stochastic estimation of the load demand [20].

5. Lifetime reliability assessment algorithm incorporating random failure causes

Since in this paper an attempt is made to investigate the trend of random failures during the whole lifetime of distribution networks, modeling the aging effect of the network equipment seems to be mandatory. In distribution systems, aging of the two types of devices including the underground cables and the distribution transformers needs more attention. Fortunately, many studies have focused on the aging process of these two devices in different conditions and their findings are used here in this paper [29–31].

Having the stochastic models of the temporary failure causes (i.e. lightning, cold load pickup, and overloading) as well as the values of sustained failure rates and adding the aging process to the network, it is possible to integrate all of them into one algorithm to simulate the whole lifetime reliability of the distribution network. In other words, the idea is to simulate the distribution network with all of the failure causes in such a way that they really happen during the lifetime of the network. The sequential Monte Carlo method is utilized for the random sampling of all influential factors in 1-h time steps. The flowchart of the developed algorithm for the stochastic simulation of the system from the reliability point of view is shown in Figure 3. Since sustained random failure causes in distribution systems such as wire cutting, car accidents, or pole fallings are another part of the random failures, they are considered by their average rate of occurrence as a constant value. The assumption of assigning constant values to sustained failure rate and repair rate means that the related time to failure and repair time correspond to the exponential distribution function. Hence, the random values of time to failure TTF_r and repair time t_{outage} of this type of failures are determined by random sampling of their related exponential distribution functions, as is shown in Figure 3. The abbreviation of TTF_a in Figure 3 also refers to aging time to failure.

Since different types of failures in different existing devices in distribution systems cause system failures with different consequences, the chronology of the faults should be observed. First failure time FFT declares the nearest failure that affects the distribution system. In the flowchart of Figure 3, the lifetime of the distribution system is typically supposed to be 30 years. In this way, different factors that affect the distribution system are taken into account simultaneously. In the next section of this paper, the results of applying the developed algorithm to a real distribution system with actual data are presented and the results are compared with the case of constant-failure-rate assumption.

6. Case study

The real case system used in this study is a 20-kV feeder that has 9.8 km of length. This feeder has both overhead line and underground cable parts and serves industrial and commercial loads. The schematic view of this feeder is depicted in Figure 4. The cross-section of the overhead part is 200 mm^2 and the cross-sections of the first and second cable parts are 240 mm^2 and 50 mm^2, respectively. The section number of each section as well as the capacity of transformers in kVA is also cited in Figure 4. The real daily load curves according to measurements for the industrial and commercial loads of the feeder under study are shown in Figure 5.

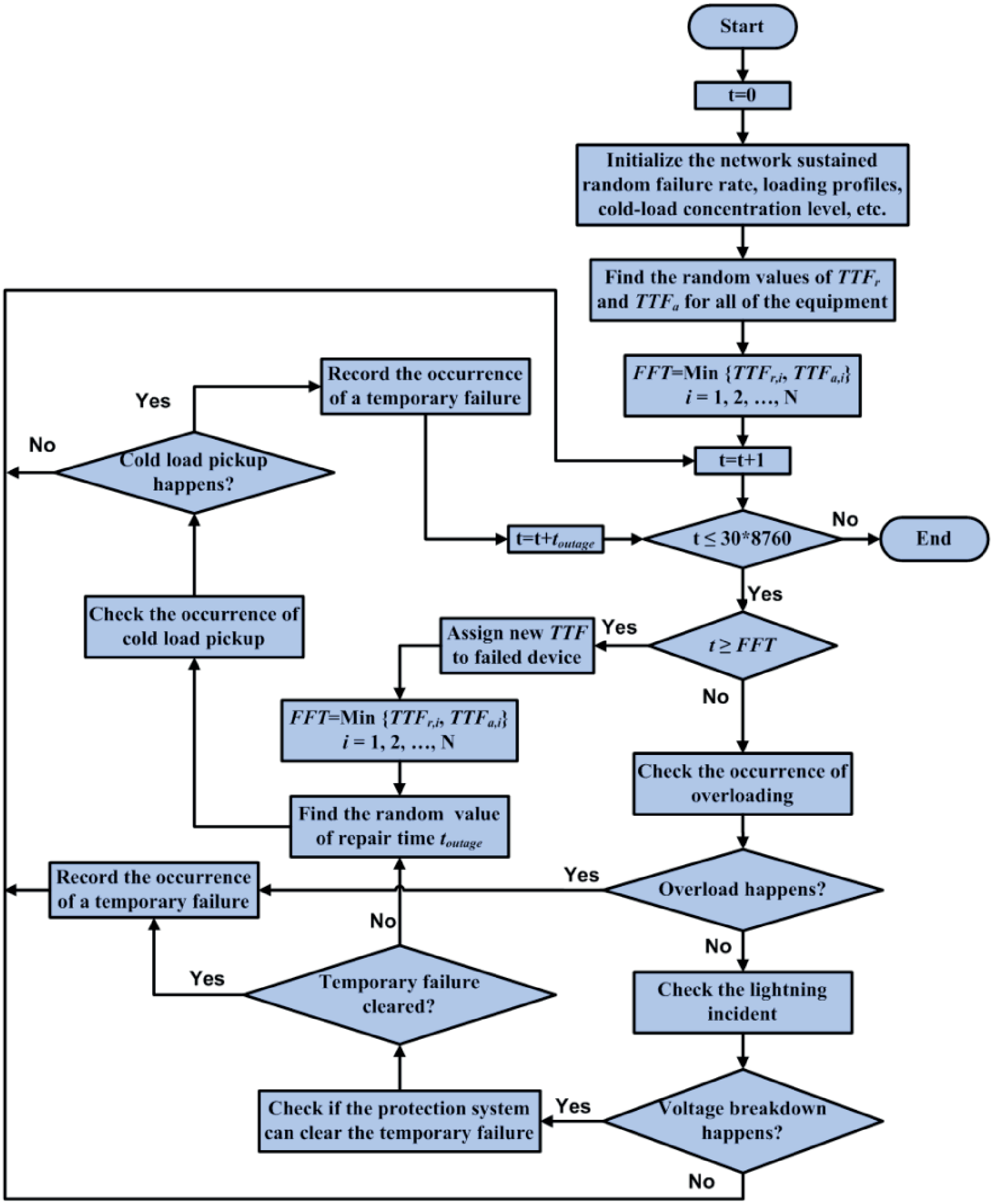

Figure 3. Flowchart of distribution system lifetime reliability assessment.

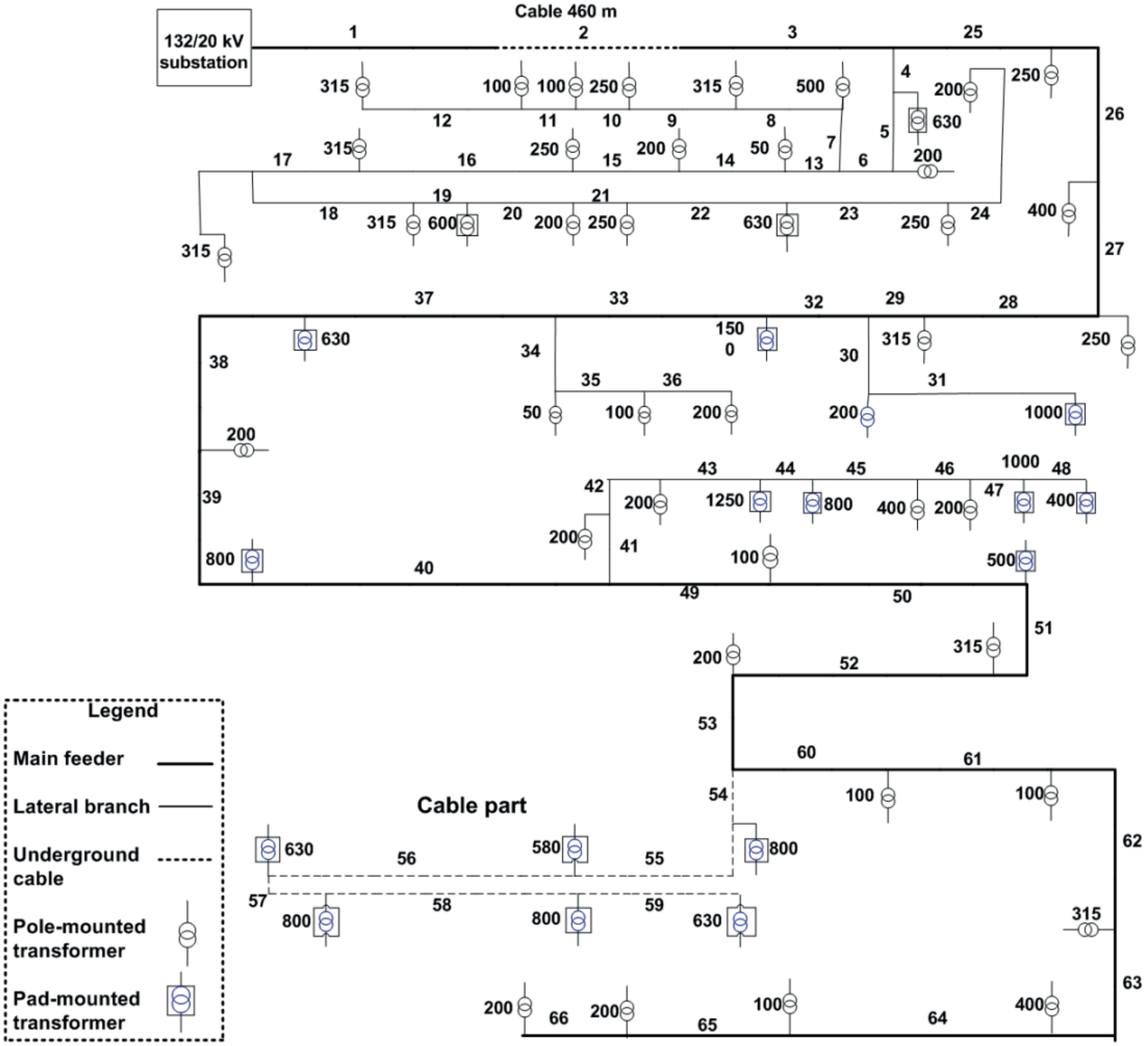

Figure 4. Schematic of the case study feeder.

The total load of this feeder is about 8 MW. After analyzing the 4-year failure history of this network, the average failure rates for the system under study are reported in Table 1.

Table 1. Failure rates of the system under study.

	Overhead line [per km]	Underground cable [per km]	Transformer
Sustained failure rate [occ./year]	1.4	4	0.04
Temporary failure rate [occ./year]	2.5	-	-
Repair time [h/failure]	1	2.5	5

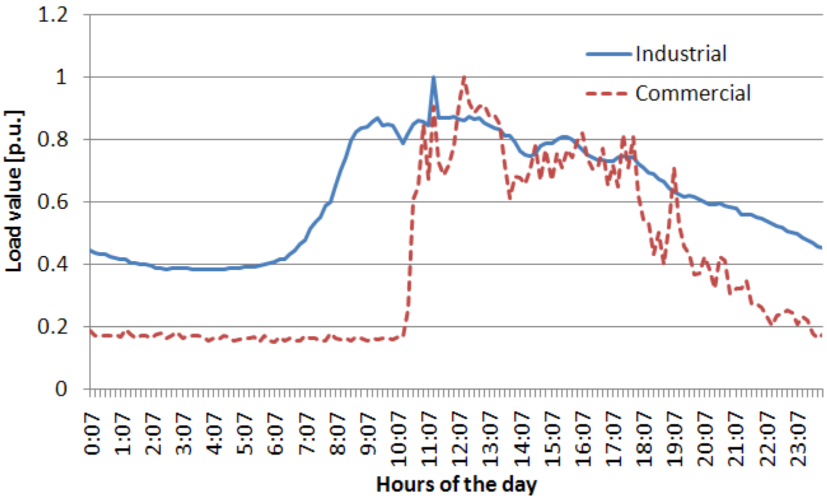

Figure 5. The measured daily load curves for two types of loads.

As mentioned before, modeling the effect of the CLPU on network reliability requires the data of the ambient temperature. These data are provided by a meteorological center at the place of the network under study. Other data taken into account for stochastic modeling of the temporary failure causes are listed in Table 2.

Table 2. The parameter values used for modeling different phenomena in the system under study.

Cable aging*		Transformer aging**		Lightning	
E [kV/mm]	7.2	Rated life [years]	30	N_g [occ./km^2 per year]	2.7
E_0 [kV/mm]	5	Θ_A [°C]	20	h [m]	10
b [K mm/kV]	4420	$\Delta\Theta_{TO,R}$ [°C]	55	CFO [kV]	125
B [K]	12430	τ_{TO}[h]	3	Sf	0.2
n_0	15	$\Delta\Theta_{H,R}$ [°C]	25	Cold load***	
		τ_w [h]	0.08	DF	0.7
		m	1.6	CL_0	0.4
		n	1	A	1.2×10^{-8}
		β_t	2.8	B	8.099

*For more details, refer to [9].

**For more details, refer to [10].

***For more details, refer to [21].

The first and second columns of Table 2 (i.e. cable and transformer aging) list the parameters used for cable/transformer electrothermal life models.

The protection system in the network of Figure 4 is arranged according to Table 3.

Table 3. Location of protection devices.

Type	Section number
Overcurrent relay	1, 29, 30
Fuse	2, 4, 8, 13, 32, 34, 41, 55, 60

The section numbers cited in Table 3 refer to Figure 4. Using all of these data, a lifetime reliability simulation is carried out for the sample network based on the procedure of Figure 3.

After finishing the algorithm calculations, the most interesting output is the random temporary failures during the network lifetime, which is shown in Figure 6. Because of the time-independency of the stochastic models presented for temporary failures, it is expected that temporary failures also vary randomly without any time-dependency within the network lifetime. However, the simulation results show that the density of temporary failures in the second part of the network lifetime is higher than in the first part. As can be seen in Figure 6, it seems that the temporary failures do not completely have random behavior and show some time-dependency during the network lifetime.

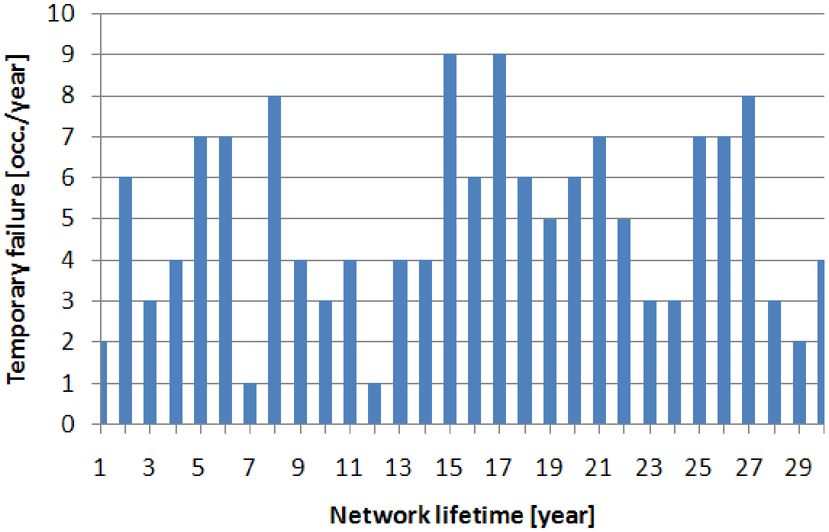

Figure 6. Distribution of temporary failures within the network lifetime.

On the other hand, the simulation results of the sustained random failures show random behavior, as illustrated in Figure 7.

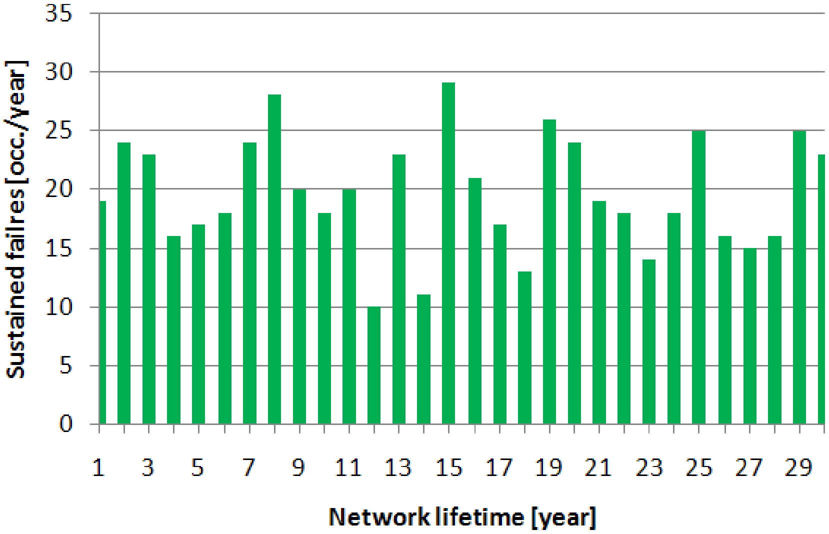

Figure 7. Distribution of sustained failures within the network lifetime.

Investigating the reason for the observations depicted in Figure 6 yields that interactions between the temporary failures and the aging failures lead to changes in the temporary failure abundance with respect to time. For instance, whenever the number of aging failures increases within the last years of the network lifetime, the number of CLPU phenomena increases due to long-duration outages resulting from equipment wear-out failures. On the contrary, whenever the overload phenomenon occurs successively during the network lifetime, it makes the aging process faster and results in more equipment failures. Finally, it gives nonuniform distribution to temporary failures. In this case, the distribution of the aging failures within the network lifetime is shown in Figure 8. In order to make a comparison between the results of the developed algorithm and the conventional method that uses a constant random failure rate, the simulation is run again with the values of Table 1. The trend of total random failure rate in both cases is shown in Figure 9. As can be seen, the random failures in the proposed method follow an ascending order as the dashed line shows the trend of variation. On the other hand, the failures modeled by the conventional method (using a constant failure rate) keep almost a constant value during the network lifetime.

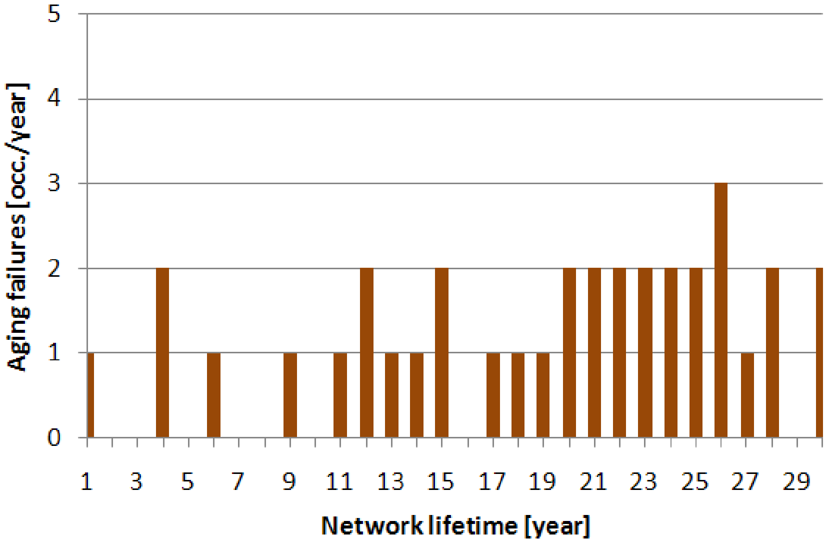

Figure 8. Distribution of aging failures within the network lifetime.

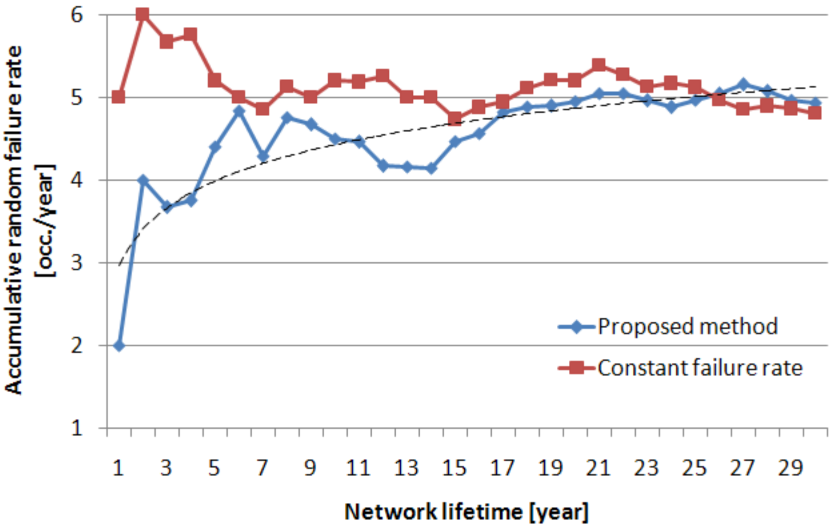

Figure 9. Comparison of the trend of random failure rate in the proposed and conventional methods.

These findings show the necessity of further contemplation about the assumption of assigning a constant value to the random failure rate. The nature and frequency of the random failures in distribution networks can highly affect the problem of locating protective devices like reclosers. In this regard, the developed algorithm, which enables a more realistic view of the network reliability situation, can improve the network design and operation level.

7. Conclusion

The random failure rate is commonly assumed as a constant value during the lifetime of the network. These failures constitute a significant part of the failures in distribution systems and correct estimates of random failure rates can greatly affect the precision of the reliability results. The exactness of the constant random failure rate is studied in this paper by comparing its results with a case in which temporary failures are generated through a stochastic process. In this paper, the issue of time-dependency of random failure rates during the distribution network lifetime was raised by analyzing the historical failure data for real networks. In this regard, three stochastic phenomena, namely lightning, cold load pickup, and overloading, were mentioned as the main causes for random failures and their stochastic models were briefly explained. Next, an algorithm was developed to stochastically simulate the occurrence of random failures during the lifetime of the distribution network based on stochastic models of the temporary failure causes. The algorithm was applied to a real case study and the results clearly indicated the time-dependency of the temporary failure rate. The idea of modeling the random failure based on its stochastic nature helps utility owners to better estimate the reliability indices in their networks and provides proper condition assessment for engineers to take corrective actions for upgrading the reliability levels of their networks.

Nomenclature

A	Constant of the outage time exponential function
b	Parameter that rules the synergism between electrical and thermal stress
B	ΔW/k (ΔW is the activation energy of the main thermal degradation reaction and k is the Boltzmann constant)
CFO	Critical flashover voltage
$CLPUPM$	Peak load magnitude that occurs because of the cold load pickup
CL_0	Concentration level of cold loads right before the outage
DF	Decrease factor of the loads due to seasonal variation
E	Maximum electric field
E_0	Value of the electric field below which electrical aging is deemed negligible
h	Height of the uppermost conductor at the pole
I_{peak}	Peak current that passes through the protective device during the initial moments after the network restoration
I_{TCL}	Magnitude of thermostatically controlled loads
I_{tot}	Normal load value before the outage
m	An empirically derived exponent used to calculate the variation of $\Delta\Theta_H$ with changes in load
n	An empirically derived exponent used to calculate the variation of $\Delta\Theta_{TO}$ with changes in load
n_0	Voltage endurance coefficient
N_g	Ground flash density
Sf	Shielding factor

Θ_A	Average ambient temperature during the load cycle to be studied
$\Delta\Theta_{TO,R}$	Top-oil rise over ambient temperature at rated load on the tap position to be studied
$\Delta\Theta_{H,R}$	Winding hottest-spot rise over top-oil temperature at rated load at tap position to be studied
τ_{TO}	Oil time constant of transformer
τ_w	Winding time constant at hot-spot location
β_t	Shape parameter

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