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Aging Modeling in Reliability Evaluation of Power Distribution System

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Abstract: **Electrical power distribution systems are formed from many components which become aged during the time. This aging has a large effect on the reliability level of these systems which cannot be simulated using traditional approaches in reliability assessment of power systems such as renewable models. In this paper, three non renewable models have been investigated to simulate the aging of distribution system equipments. The reliability of a distribution test system has been evaluated using these models and the results are reported and the three models have been compared.**

Keywords: **Power distribution systems, reliability evaluation of power systems, aging equipments, Monte Carlo simulation.**

1. INTRODUCTION

Equipment aging is an undeniable reality in the life of power systems. Many companies around the world have equipments called aged due to their bad performance and increasing failure rate. The failures and outages of these equipments are higher than the acceptable level and also are increasing during the time. The increase of failure rates and outages have a direct effect in the increase of operating and maintenance cost of the power systems. Thus evaluating the effect of equipment aging has a great importance in the power system reliability assessment.

A large part of studies on power system reliability assessment is devoted to electric power transmission systems due to the massive investment and a large amount of energy transferred by them. Studies corresponding to the equipment aging modeling so far have also focused on the transmission system [1-3]. In recent years, however, beginning the process of privatization and the presence of private power companies in the market and increasing customer expectations of these companies for a continuous supply of electrical energy, assessment of electrical power distribution system reliability has become more important over time.

Electrical power distribution systems are formed from components such as overhead lines and underground cables, distribution transformers, circuit breakers, etc. With the passage of time, the more the life of a distribution system, the more its components become aged and are so called old. No repairing and possibly a lack of timely replacement of old equipment and the overloading different elements of this system can be mentioned as reasons of aging the distribution system [1].

Fig. 1 graphically shows the basin curve which indicates the relationship between fault rate and age of the component [1]. As it can be seen in this figure, this curve includes three stages. The first stage (infant stage) is associated with the reduction of failure rate during the time and precocious fault may occur in this stage. In the second stage (normal operating stage) which is the main part of the life of equipment, the failure rate is almost constant with time. And the third stage (wear-out stage) represents the onset of aging in equipment where the failure rate increases with the passage of time; therefore, the equipment is approaching the end of its life.

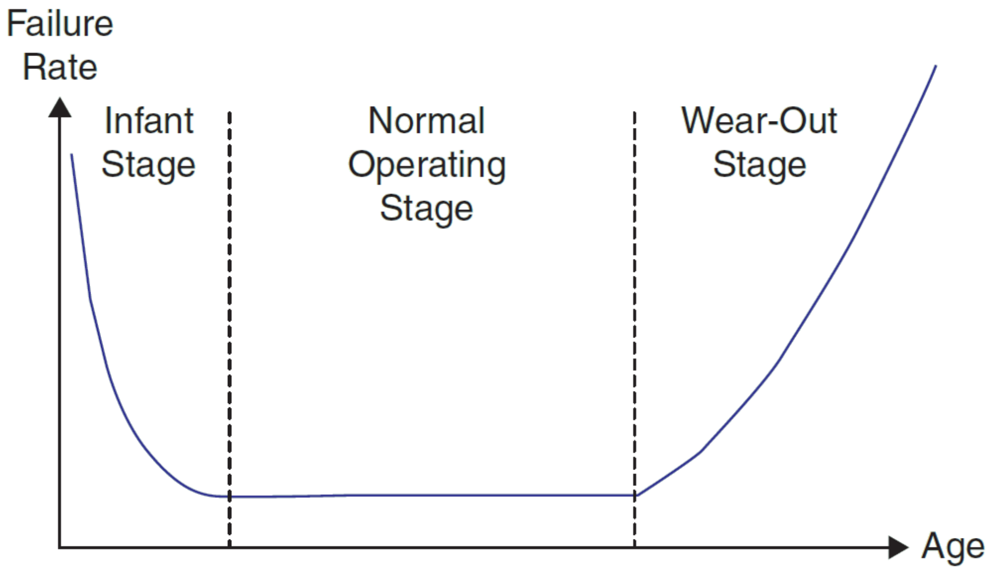

Fig. 1. Basin curve for the equipment fault rate.

Noteworthy point is that in most studies the reliability of distribution systems with the equipment being on the second stage is evaluated that is an unrealistic approach. In this mode, it is assumed that after failure occurrence and repair, the component is restored to as good as new condition from the reliability perspective. It`s clear that in an aged system the fault process is non renewable and the failure rate varies with time.

In this article, aging of a distribution test system [4] is simulated using different methods and the results are reported in various cases. Finally the performance of the different methods is compared.

2. RELIABILITY ASSESSMENT OF POWER DISTRIBUTION SYSTEMS

The main task of the electrical power distribution system is to supply continuous electric energy to customers (consumers). Distribution system reliability indices are also defined by the approach of better provision of load. Three major indices are defined in the distribution system for each load point that we will consider them as follows.

The average failure rate index of load Point: This index represents the average number of occurring interruption at the supplying of a load point that is usually expressed yearly.

$$\lambda_p = \frac{N_{fp}}{\sum T_{up} + \sum T_{dp}} \qquad (1)$$

Where N_{fp} is the number of interruptions occurred in supplying pth load in a certain period of time (usually a year), $\sum T_{up}$ is total time in which the pth load has been fed in the same period of time, $\sum T_{dp}$ is total time in which the pth load has been in interruption mode in the same period of time.

The average annual unavailability or average annual outage time Index of load point: This index represents the number of hours in a period of one year in which supplying a load point is interrupted.

$$U_p = \frac{\sum T_{dp}}{\sum T_{up} + \sum T_{dp}} \tag{2}$$

where U_p is the average annual unavailability or average annual outage of pth load point.

The average outage time index of load point: This index represents the average time needed to resolve the interruption at a certain load point.

$$r_p = \frac{U_p}{\lambda_p} = \frac{\sum T_{dp}}{N_{fp}} \tag{3}$$

It should be noted that the other indices of distribution system reliability can be calculated using these three basic indices described in [3] that they are not repeated here again.

3. MONTE CARLO SIMULATION

Given the large extent of the power system and the large number of its equipment, analytical evaluation of the reliability of these systems is largely complicated and sometimes impossible [5]. Hence, in recent years, various methods have been presented based on probability and statistics to assess the reliability of power systems. One of these methods is Monte Carlo simulation which is briefly explained here. Monte Carlo simulation is based on random process simulations by sampling the random variables of that process.

Supposing that TTF is time to failure and TTR is time to repair or replace, the sampling process of these parameters in Monte Carlo simulation in non aging model is as follows.

In this way, the exponential probability distribution function for TTF and TTR random variables is used. x is inter-transition time (or) and can be obtained from Eq. (4).

$$Z = \Pr\left(x \le Z\right) = F(x) \tag{4}$$

And thus:

$$x = F^{-1}(Z) \tag{5}$$

Where Z is a random number with uniform distribution function in the interval (0, 1] and F represents the cumulative distribution function of x . x Given that is an exponential distribution, we have:

$$x = \frac{-\ln(Z)}{\rho} \tag{6}$$

If is x , TTF represents the failure rate and if is an expression of TTR , ρ represents the repair or replacement rate. Eq. (7) and (8), represent relations concerning failure rate λ and repair or replacement rate , μ respectively.

$$\lambda = \frac{1}{\mathrm{MTTF}} \tag{7}$$

$$\mu = \frac{1}{\mathrm{MTTR}} \tag{8}$$

where MTTF is the mean time to failure (the average duration of being in a normal operation state) and MTTR is the mean time to failure to repair or replace (The average duration of being in interruption state).

The Monte Carlo simulation steps are described below to evaluate reliability of a distribution system [5-7].

1) Produce a random number with uniform distribution for each of the equipments and regarding the distribution function of that equipment, convert it to the TTF of that equipment.

2) Specify the equipment that has the lowest TTF value and put its related TTF in TTF_{min}.

3) Subtract TTF_{min}. from all TTF s.

4) Produce a random number with uniform distribution and convert it to the TTR of the equipment that has the least amount of TTF

5) Save interruption duration of each load point.

6) Produce a random number with uniform distribution and convert it to TTF of the equipment that has failed (Equipment that had the lowest TTF . If the simulation time is not a year, back to the second step and otherwise go to Step seventh.

7) Calculate the number and duration of the failure at any load point in the current year.

8) Calculate failure rates and failure duration at each load point in the current year.

9) Calculate the average values of indices in the eighth step in the years having been studied so far.

10) If the number of years under study does not reach to its preset limit or a convergence of all calculated indices is not created, back to the second step and otherwise report the calculated indices as output from the simulation.

4. EQUIPMENT AGING MODELING

Equipment aging usually causes to reduce up-times. In other words, the aging can lead to a relative reduction of TTF with time and it normally has no effect on the TTR . Therefore, the method described in the previous section can be used for sampling the time intervals.
Reference [2] has presented three methods to impose the effect of aging on performance of power system equipment that here we just explain the way of TTF samplings in these methods. Generally, these methods are based on increasing the failure rate over time. Thus, the equipment failure rate formula is shown in terms of time as follows:

$$\lambda(t) = \lambda_{eq}\beta t^{\beta-1} \tag{9}$$

$$\lambda_{eq} = \lambda_0{}^{\beta}\left[\Gamma\left(1+\frac{1}{\beta}\right)\right]^{\beta}$$

In which λ_0 is the average failure rate of equipment, regardless of equipment aging, t is time, $\Gamma(\bullet)$ is gamma function and β is a variable for modeling equipment aging.

If β is equal to one, Eq. (9) does not show aging effects and the failure rate will be fixed over time (normal operation stage in Fig. 1). If β is greater than one, the failure rate of equipment increases over time that this ageds equipment is being aged (Stage of aging in Fig. 1). If the value is less than one, failure rate decreased over time and equipment reliability is increased (initial stage in Fig. 1).

The way of TTF sampling through the three mentioned methods is presented in the following. It is necessary to mention that it is assumed that by doing any repair and maintenance operations, the reliability of the equipment returns to the state before the failure occurred.

- ***Interval by interval method***

If we assume k th failure occurs at the moment t_k , for $k=1$ we will have:

$$\mathrm{TTF_k} = \left(\frac{-\ln(Z)}{\lambda_{eq}}\right)^{\frac{1}{\beta}} \tag{10}$$

and for k > 1:

$$\mathrm{TTF_k} = \left\{\left(\sum_{i=1}^{k-1}\mathrm{TTF_i}\right)^{\beta} - \frac{\ln(Z)}{\lambda_{eq}}\right\}^{\frac{1}{\beta}} - \sum_{i=1}^{k-1}\mathrm{TTF_i} \tag{11}$$

- ***Time scale transform method (TST):***

for k = 1:

$$\mathrm{TTF'_k} = -\ln(Z)$$

$$\mathrm{TTF_k} = \left(\frac{\mathrm{TTF'_k}}{\lambda}\right)^{\frac{1}{\beta}} \tag{12}$$

and for k > 1:

$$\mathrm{TTF'_k} = -\ln(Z) \tag{13}$$

$$TTF_k = \left(\frac{\sum_{i=1}^{k} TTF'_i}{\lambda} \right)^{\frac{1}{\beta}} - \sum_{i=1}^{k-1} TTF_i$$

- ***Thinning algorithm (TA):***

In this algorithm using the Last time that failure occurred (t_k), next time the failure occurred (t_{k+1}) and thus TTF_{k+1} is determined. Fig. 2 shows how these algorithms work.

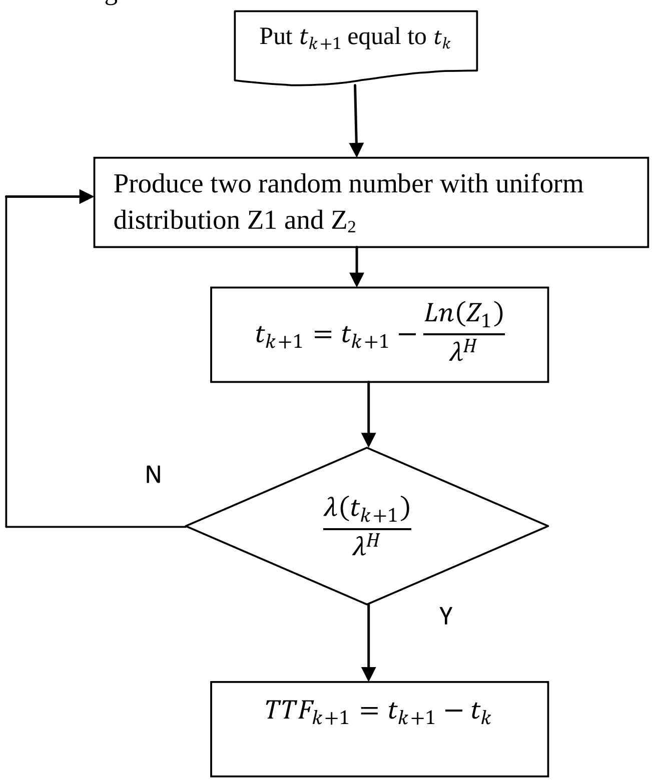

Fig. 2. Flowchart for thinning algorithm.

λ^H is defined as follows:

$$\lambda^H = \max_{t \in [0,T]} (\lambda(t))$$

$$T = \frac{1}{\lambda_{eq}} \tag{14}$$

With considering the fact that $\lambda(t)$ is ascendant in Eq. (14), it can be deduced that:

$$\lambda^H = \lambda(t)\big|_{t=T} = \lambda_{eq}\beta\left(\frac{1}{\lambda_{eq}}\right)^{\beta-1} \tag{15}$$

As it was mentioned above, in each of the above methods with β greater than one, aging of equipments can be considered in a distribution system reliability evaluation that we will consider it as follows.

5. SIMULATION AND RESULTS

The test system introduced in reference [3] is used to assess the effects of aging on distribution system reliability evaluation. Fig. 5 shows the single line diagram of this system. This system has 4 feeders and 22 load points which 20 load points out of them are fed by distribution transformer and 2 points are fed directly from the medium voltage level. The system also has 36 sections that sub-sections which are connected to the load are protected with a fuse. As it can be seen in this Figure, reclosers and switches are placed in such a way that if it is needed they transfer part of the load of a feeder to another one.

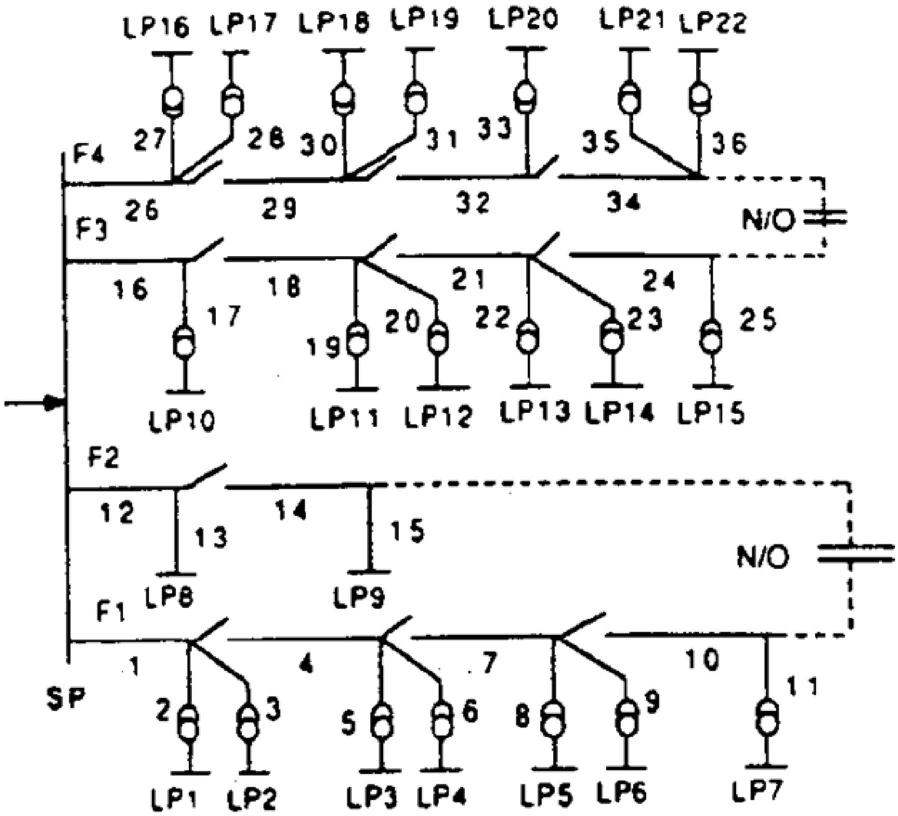

Fig. 3. Single-line diagram of the test distribution system.

It is assumed that the protective devices and also the supply point of the system are ideal and do not suffer from failure or interruption. TABLE I and II show the results of reliability assessment of load point number 1, 8, 11 and 22 of the test system using Mont Carlo simulation and without the consideration of aging.

TABLE I. Reliability assessment of the test system without the consideration of aging.

Load Point	λ_p (f/y)	U_p (h/y)	r_p (h/f)
1	0.2363	0.6949	2.9407
8	0.1406	0.5362	3.8127
11	0.2527	0.7838	3.1018
22	0.2544	0.7344	2.8865

TABLE II. Reliability indices of the test system without the consideration of aging.

SAIFI	SAIDI	CAIDI	ENS	AENS	ASAI	Simulation Time
0.247795	0.749159	3.023301	704.8169	0.372919	0.999914	402.5 (sec)

TABLE III and IV show the results of reliability assessment of load point number 1, 8, 11 and 22 of the test system with consideration of aging using different methods mentioned in section 4 and different values of β . Considering the Eq. (9) it`s clear that the results of the case in which β=1 is near to the results of non aging model. This fact can be seen by comparing the columns in TABLE IV corresponding to β=1 with TABLE II. Also as can be seen in TABLES III and IV, the values of indices λ_p and U_p are increased by inthe reliability levelmeter β which means reduction of reliability level of the system and is the direct effect of equipment aging.

TABLE III**.** Reliability assessment of the test system considering the effect of aging using different methods.

Load Point	Method	λ_p (f/y)			U_p (h/y)			r_p (h/f)		
		β=1	β=1.2	β=2	β=1	β=1.2	β=2	β=1	β=1.2	β=2
1	IIM	0.2391	0.2637	0.3955	0.7253	0.7634	1.0807	2.9933	2.8946	2.7328
	TST	0.2416	0.2778	0.4214	0.7111	0.8617	1.2251	3.10140	3.1014	2.9073
	TA	0.23811	0.25960	0.4222	0.71696	0.74667	1.0484	3.01105	2.87625	2.4829
8	IIM	0.1386	0.1533	0.2479	0.5428	0.6081	1.0362	3.8392	3.9668	4.1804
	TST	0.1395	0.1586	0.2653	0.5478	0.6142	1.0799	3.87266	3.8727	4.0707
	TA	0.13904	0.15059	0.2554	0.54895	0.58325	1.0450	3.94807	3.87310	4.0920
11	IIM	0.2536	0.2782	0.4473	0.7903	0.8420	1.3458	2.9907	3.0271	3.0091
	TST	0.2532	0.2961	0.4696	0.7836	0.9626	1.4443	3.25064	3.2506	3.0754
	TA	0.25111	0.27480	0.4534	0.77737	0.81818	1.3522	3.09577	2.97736	2.9821
22	IIM	0.2579	0.2842	0.4600	0.7545	0.7922	1.2123	2.9181	2.7875	2.6352
	TST	0.2551	0.2977	0.4822	0.7571	0.9048	1.3301	3.03894	3.0389	2.7583
	TA	0.25814	0.28214	0.4488	0.75449	0.78424	1.1655	2.92284	2.77960	2.5968

TABLE IV**.** Reliability indices of the test system considering the effect of aging using different methods

		SAIFI	SAIDI	CAIDI	ENS	AENS	ASAI	Simulation Time
β=1	**IIM**	0.249026	0.750755	3.014761	706.8806	0.374011	0.999914	635.2 (sec)
	TST	0.248252	0.815010	3.009158	703.339	0.372137	0.999914	758.9 (sec)
	TA	0.247583	0.751521	3.035427	707.41307	0.374293	0.999914	1025.0 (sec)
β=1.2	**IIM**	0.274297	0.815010	2.971272	767.2542	0.405955	0.999907	812.4 (sec)
	TST	0.289742	0.923031	3.185702	868.827	0.459697	0.999894	1056.6 (sec)
	TA	0.270169	0.798577	2.955837	752.000999	0.397884	0.999909	1807.9 (sec)
β=2	**IIM**	0.431665	1.236607	2.86474	1163.938	0.61584	0.999858	1148.1 (sec)
	TST	0.455127	1.356713	2.980952	1277.589	0.675973	0.999845	1762.4 (sec)
	TA	0.438514	1.225093	2.793740	1155.735270	0.611500	0.999860	2732.8 (sec)

Fig. 4 shows the failure frequency histogram for different values of β in load point number 1, 8, 11 and 22 of the test system. As it can be seen in these figures, the probability of not having failed in load points is decreased and the probability of failure increases which is the expected result of equipment aging.

It is worth noting that λ_p and U_p have approximately the same increment rate with regard to increasing of β and thus the index r_p is approximately constant. It`s because that we did not consider the effects of aging in parameter TTR . In other word despite the aging of equipments has the effect of increasing in the failure rate of equipments but it has no effects on the average time required for clearing the faults or replacing the equipments.

According to the obtained results by applying the three models for the simulation of equipments aging which are given in TABLES III and IV, they are similar and there is no priority of one over the others. However, as it is shown in TABLE IV, one can see that compared to TST and TA methods, the IIM method is much faster and the priority of this method over the other methods is clear.

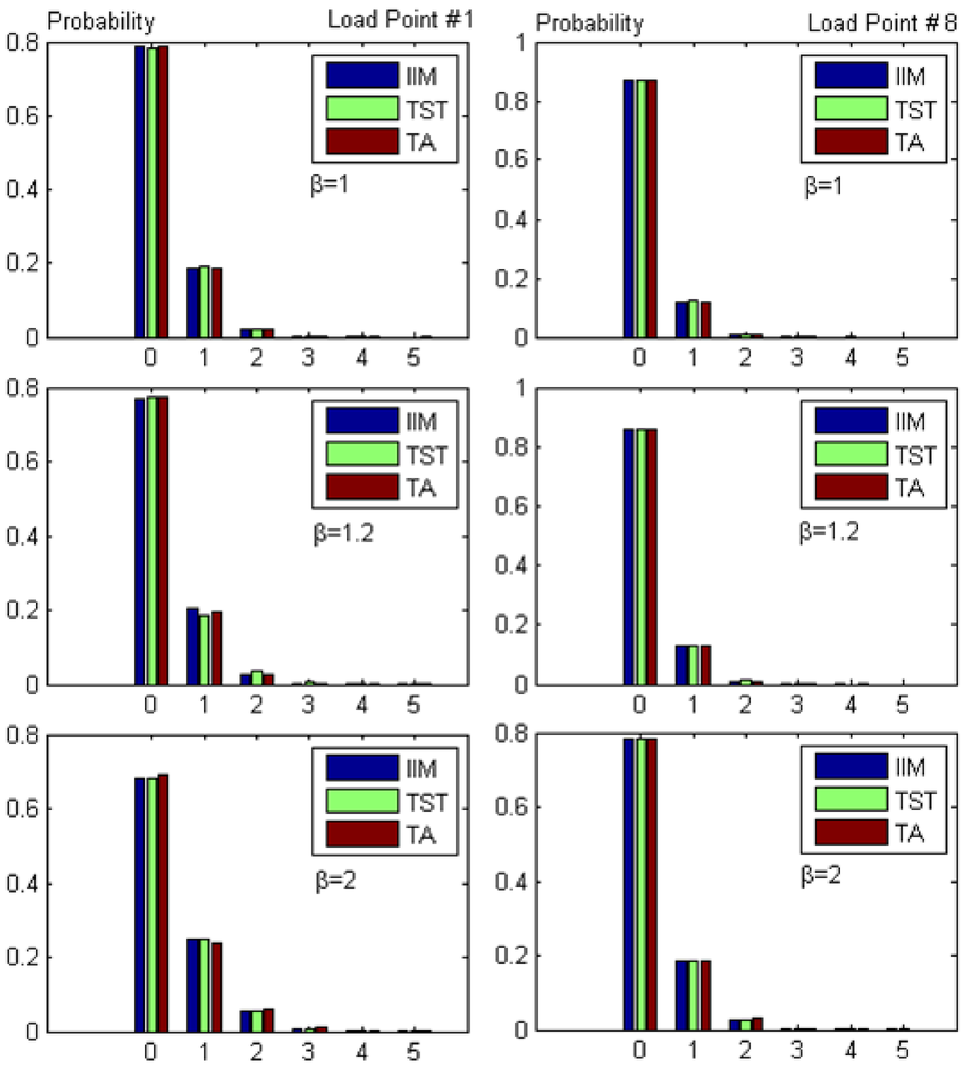

Fig. 4. The failure frequency histogram for different values of β.

6. CONCLUSION

In this paper, we modeled the aging equipments in distribution system reliability assessment. Three methods IIM, TST and TA were studied. These methods have been applied to a distribution test system by increasing the parameter β and the obtained results which indicate a lower level of system reliability than non-aging model, have been reported and compared. From the results we can find that all three methods have similar performances; However, IIM has strict priority over other methods in terms of simulation speed. Also, it was revealed that aging has no effect on the index r_p.

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