Modeling the Repair Process of a Power Distribution System

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***Abstract*—One remedial action for improving service reliability in a power distribution system is to faster crew response to reduce outage durations. For planning activities, the application of this kind of remedial action requires the modeling of the repair process performed in the power distribution system. Thus, this paper presents a methodology which models the repair process performed in each service territory of a power distribution system using concepts of queuing theory and stochastic point processes and assesses the repair process performance by means of a procedure of sequential Montecarlo simulation. Results of the application of this methodology to three power distribution systems show: 1. The input and service of the repair process model are not necessarily homogeneous Poisson processes; thus the Monte Carlo simulation method is required for the assessment of the repair process performance. 2. The index that better reflect the repair process performance is the mean waiting time. This methodology gives a base for the optimal scheduling of the repair resources in accordance with the failure process and the targets for reliability indices.**

***Index Terms*—Maintenance, power distribution reliability, reliability modeling.**

I. Introduction

DISTRIBUTION reliability is a field of great interest all around the world because the distribution functional zone of a power system contributes at least with 90% of the failures that affects service continuity. Thus, it has a great potential for the improvement of system performance and savings [1].

There are several ways to improve the reliability of a power distribution system. R. E. Brown in [2] explains the following: special protective schemes, automation, faster crew response, reduce failure rates and system reconfiguration. Regarding faster crew response, this remedial action can improve service reliability because it reduces outages durations.

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For planning activities, the application of this kind of remedial action requires the explicit modeling of the repair process performed in the power distribution system.

For maintenance activities the power distribution system is split into several zones or service territories, each one assigned to a repair team [3], as shown in Fig 1.

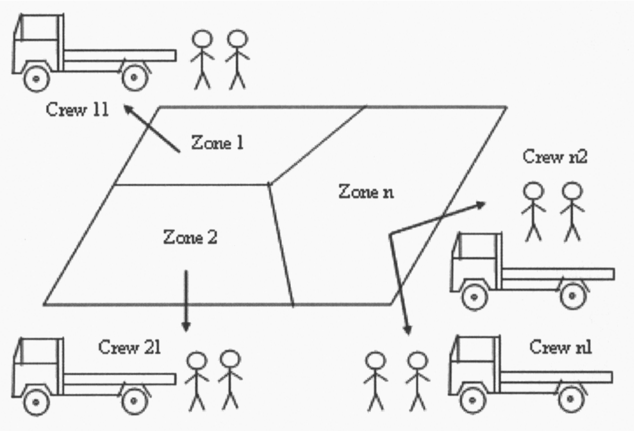

Fig. 1. Zones for maintenance in a power distribution system

The resources for repairs are the personnel, trucks, tools, spares, etc. available for this work. The way these resources are organized, for example, the number of crews for each zone, is the logistics. The repair resources generate the repair process.

The repair process is the sequence of repairs performed by crews in accordance with the repair orders sent by the control center, which either automatically detects component failures or receives customer calls regarding service interruptions.

Thus, the repair process in each service territory is a queuing system. The input to this system is the sequence of component failures which produce service interruptions that have to be repaired by crews. The output of this system is the sequence of service restorations performed by crews.

The performance of the repair process is dependant on the quality and quantity of repair resources and the logistics. These resources are limited and have to be carefully matched to follow the pace of component failures in order to obtain acceptable outage times.

Traditional methods for studying the repair process of a power distribution system do not model it as it really is. Thus, the subject of this paper is their modeling using concepts of queuing theory and stochastic point processes.

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II. Traditional Methods for Studying the Repair Process

The repair process performed in a power distribution system has been traditionally studied in the following ways:

A. By means of statistical analysis of outage times

These kinds of studies take operating data of the power distribution system and analyses the statistics of outages times by feeders, substations and geographical zones to give guidelines about which zones of the system need improvement on the repair process performance.

Although these kinds of studies can include the modeling of the outages times using probability distributions or stochastic processes [4], [5], they do not include an explicit modeling of the repair process.

As a service territory can include parts of several feeders, these kinds of studies have to be extended to each service territory because, in this case, a global analysis can be misleading.

B. As part of the component reliability models

This approach is extensively applied in power distribution reliability assessments [6], nor matter the methodology, cut-sets [7]-[8], analytical simulation [9], Markov process [10] or Montecarlo simulation [11]-[12]: the repair process is included as part of component reliability models, by means of the probability distribution of times to repair.

This approach has the following disadvantages:

- No matter the probability distribution used, it is assumed repair resources are unlimited because every time a component fails a crew is available to repair it. So, the repair time only depends on the particular actions taken to fix each kind of component.
- As the repair process is represented by means of a probability distribution, it is assumed it is a stationary process i.e. the performance of repair teams is not affected by internal or external factors. However, in real life, the crew performance is affected by external factors like weather, traffic, etc. and also by internal factors like, available tools, available skills, workload, etc.
- The tendency of the repair process performed in the power distribution system is lost because the times to repair are classified by component type and thus the chronological sequence in which they occur is lost.
- Most methods apply the $n-1$ loss of component criteria what it not a true assumption because a failure can occur independently if other failures which occurred before have been repaired or not.
- Reliability assessments of power distribution systems only include high voltage and medium voltage components. However in real life, repair teams also have to repair the low voltage components what represents an important demand on repair resources. Moreover, reliability surveys shows in some power distribution systems the low voltage components are the ones that fail more frequently [13].

III. Stochastic Point Processes

A. Definition

A stochastic point process (SPP)[1] is a random process in which the number of events N that occur in a period of time Δt is counted, with the condition that one and only one event can occur at every instant. Fig. 2 presents a pictorial representation of a SPP where x_i denotes an inter-arrival interval and t_i an arrival time. If the date when the observation of the process started is taken as reference, $\Delta t = t - 0$, only t appears in the equations that describe the process.

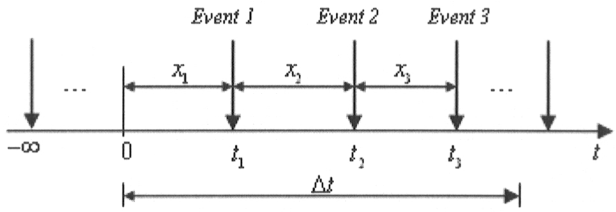

Fig. 2. The concept of SPP

The mathematical model of a SPP is defined by means of the intensity function $\lambda(t)$, which is the rate of change of the expected number of events. This parameter allows the calculation of:

- The expected number of events:

$$E[N(t)] = \Lambda(t) = \int_0^t \lambda(t)dt \qquad (1)$$

- The variance:

$$VAR[N(t)] = \Lambda(t) \qquad (2)$$

- The probability that k events occur:

$$P[N(t)=k] = \frac{1}{k!}[\Lambda(t)]^k * e^{-\Lambda(t)} \quad for\ k = 0,1,2,\cdots \qquad (3)$$

B. The Concept of Tendency

The tendency, defined as the change with time in the number of events that occur, is a very important feature of a SPP.

In Fig. 3 the following three kinds of tendency are depicted [14]:

- Positive tendency: Events increase with time and inter-arrival intervals decrease. $\lambda(t)$ is an increasing function.
- Zero tendency: Events that occur and inter-arrival intervals do not show a pattern of increase or decrease. $\lambda(t)$ is constant.
- Negative tendency: Events decrease with time and inter-arrival intervals increase. $\lambda(t)$ is a decreasing function.

[1] The Singular and plural of acronyms are spelled the same.

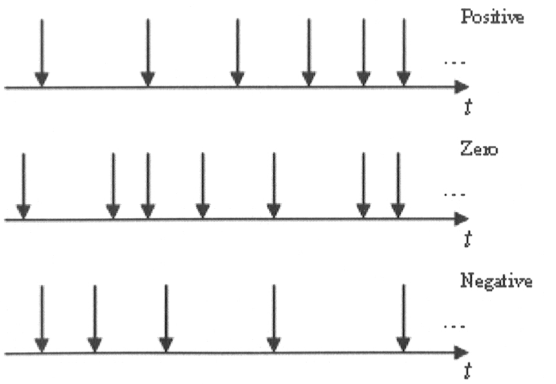

Fig. 3. Tendency on SPP

C. Types of SPP

A SPP without tendency is stationary or time-homogeneous. Homogeneity means inter-arrival intervals are independent and identically distributed. So, events that occur are independent. The opposite is true for a SPP with tendency.

The tendency allows the basic classification of SPP shown in Fig. 4.

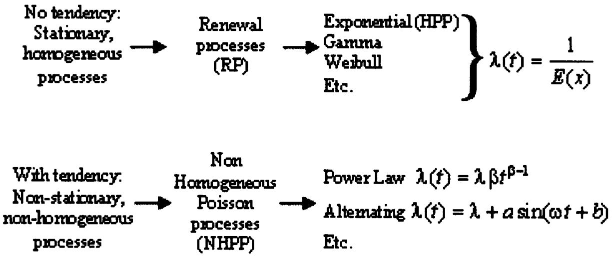

Fig. 4. A basic classification of SPP

Stationary SPP are called renewal processes (RP) preceded by the name of the inter-arrival intervals distribution. The intensity function of a RP is the inverse of the expected value of inter-arrival intervals. The most famous RP is the exponential one, commonly called Homogeneous Poisson Process (HPP). Non stationary SPP are in general called Non Homogeneous Poisson Processes (NHPP).

D. Procedure for the Selection of a SPP Model[14], [15]

The procedure for fitting a SPP model to a sample data taken from a random point phenomenon is as follows:

1. Determine if there is a tendency in the arrival times sample by means of the Laplace test or graphic methods [16].
2. If there is evidence of a tendency, select a NHPP model, estimate its parameters and apply a goodness of fit test. A problem with NHPP is that methods for parameter estimation and goodness of fit are specific for each kind of model and for some of them are not developed yet.
3. If there is no evidence of a tendency, apply an independence test to inter-arrival intervals such as the scatter diagram or the correlation plot [17].
4. If inter-arrival intervals are independent, fit a probability distribution using the traditional methods for parameter estimation and goodness of fit. In this case, a RP model is obtained.

E. The Power Law Process

While there are many NHPP models, the approach here is to use the Power Law Process (PLP) developed by L. Crow in 1974 [18] because:

- It is an accepted model to represent the failure process of repairable components [19].
- There are methods for parameter estimation and goodness of fit [19], [20], [21], [22].
- It can represent a process with or without tendency
- It can represent the HPP.

The intensity function of this process is:

$$\lambda(t) = \lambda\beta t^{\beta-1} \tag{4}$$

Where:

λ: Scale parameter greater than zero.

β: Shape parameter greater than zero.

The shape parameter controls the tendency of the model in the following way:

If $\beta > 1$: Positive tendency

If $\beta < 1$: Negative tendency

If $\beta = 1$: Zero tendency. In this case, the PLP represents the HPP.

F. How to Generate Samples from SPP Models

1) Renewal Processes

1. Let $t_0 = 0$.
2. Generate a uniform random number U_i
3. Get an inter-arrival interval $x_i = F^{-1}(U_i)$ using the probability distribution function of the inter-arrival intervals.
4. The arrival time is $t_i = t_{i-1} + x_i$.
5. Go to step 2 until the stopping rule is reached: a given number of events or a sample period T.

2) Non homogeneous Poisson Processes [17]

1. Generate a sequence of n arrival times from an HPP with intensity function $\lambda = 1.0$ which covers sample period T.
   These times are called $t_1', t_2', \cdots, t_n'$.
2. Find the inverse function of the mean cumulative number of events of the NHPP under study (Λ^{-1}).
3. Calculate the arrival times of the NHPP as $t_i = \Lambda^{-1}(t_i')$

As pointed out by Law and Kelton [17], the application of this algorithm depends on how easy the inversion of Λ is.

In the case of PLP the recursive equation is:

$$t = \left(\frac{t'}{\lambda}\right)^{1/\beta} = \Lambda^{-1}(t') \tag{5}$$

IV. Modeling of the Repair Process

The repair process of each zone (service territory) of a power distribution system is modeled as the queuing system shown in Fig. 5.

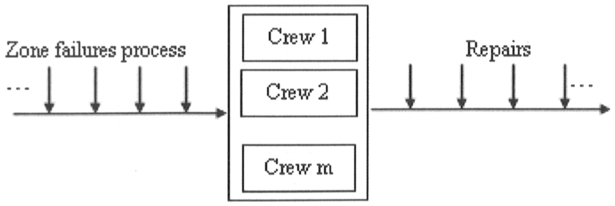

Fig. 5. Queuing model of the repair process in a service territory of a power distribution system

For this queuing system the following is defined:

- Clients: Failures which produce service interruptions and have to be repaired by crews
- Resources: The number of crews in the zone. A crew corresponds to a server in queuing theory terminology.
- Capacity: Infinite, because all the failures considered here have to be repaired.
- Queuing discipline: First Come – First Served (FCFS)
- Input process: The zone failure process. It is the superposition of the failure processes of the components located in the zone. Only failures which produce service interruptions and have to be repaired by a crew are considered. This process has an failure intensity $\lambda_F(t)$.
- Service process: The SPP that represents the equivalent capacity of all crews assigned to the zone in the form of a repair intensity $\lambda_R(t)$.
- Output process: The SPP of the repairs performed by crews. These repairs are related to service restorations. The output process is the result of the interaction between the input and the service processes.

Using Kendall's notation [23] this queuing system is described as follows:

$$G/G/m/\infty/FCFS$$

The first and second "G" indicate that both the input and service processes are general SPP (RP or NHPP). m, ∞, and $FCFS$ indicate, respectively, the number of crews, the system capacity and the queuing discipline.

The traffic intensity index $a(t)$ is defined as [23]:

$$a(t) = \lambda_F(t)/\lambda_R(t) \tag{6}$$

Although $a(t)$ is dimensionless, it is measured in Erlangs. A traffic intensity of 1.0 Erlang means one failure uses or occupies the repair resources 100% of the time. Traffic intensity higher than 1.0 means the failures arrives faster than repairs can be performed. Thus, $a(t)$ have to be less or equal to 1.0 in order to have a stable queuing system.

V. Assessment of the Repair Process Performance

A. Obtaining the zone failure process

From operating records, obtain a sample of arrival times of those component failures which caused service interruptions and were repaired by crews. It is recommended the sample covers at least one year of system operation.

It is important to remember that:

- Not all service interruptions are solved by crews; some of them are solved by means of a reconnection performed by a circuit breaker or recloser.
- Low voltage components also cause service interruptions which in most of the cases have to be repaired by crews.

Apply to the failure arrival times sample the procedure for selecting an SPP model.

In accordance to the tendency on the resulting zone failure process it can be concluded the following:

- Zero tendency: The population of components located in the zone are in their useful life. This is, their reliability is not improving neither deteriorating.
- Positive tendency: The population of components located in the zone shows aging.
- Negative tendency: The population of components located in the zone shows reliability improvement.

This kind of modeling implies repairs are minimal [24], i.e. they only return the components to the operating state without improving or deteriorating their reliability condition.

B. Obtaining the zone service process

For each failure that caused a service interruption and was repaired by means a crew action obtain the time to repair (ttr).

Time to repair includes: the transportation time to the place where customers are without service, time to find the failed component, time to fix the failed component and reconnection time.

A ttr does not include the waiting time (tw) the period while the crew receives the repair order and is free to go to repair the failure. The waiting time is result of the congestion on the repair process, the fact that when a crew receives a repair order it can be busy repairing a failure that occurred before.

Apply to the sample of times to repair the procedure for selecting an SPP model.

In accordance to the tendency on the resulting service process it can be concluded the following:

- Zero tendency: The crew performance is not increasing not decreasing
- Positive tendency: The crew performance is increasing because as time evolves repairs take less time to be performed
- Negative tendency: The crew performance is decreasing because as time evolves repair take more time to be performed.

C. Assessing the repair process performance

The repair process is observed artificially for a period T of one or more years by means of a sequential Monte Carlo simulation procedure [25]. A simulation consists of N iterations or artificial observations of the repair process performance during T.

In each iteration, the sequence of component failures and repairs is generated using the input and service processes. Fig. 6 shows the interaction between the failure and service processes for a zone with one crew or one equivalent crew.

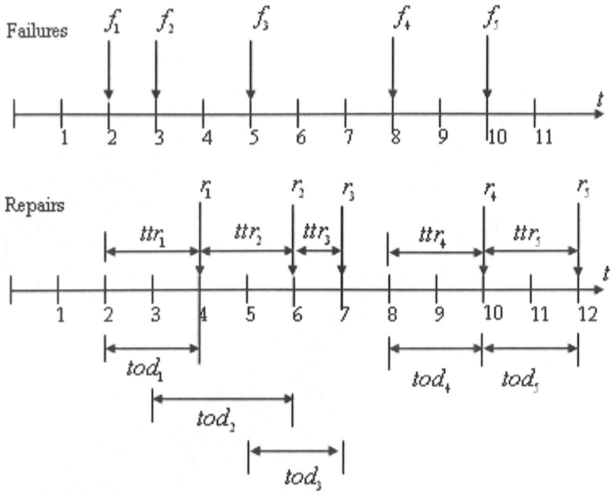

Fig. 6. Calculation of outage durations

Every time a failure f_i arrives, it is assigned to a crew that performs a repair r_i in a time ttr_i. The arrival times of f_i and r_i are tf_i and tr_i, respectively.

Each iteration produces a sample of number of failures (nf), times to repair (ttr), outage duration (tod) and waiting times (tw).

Two stopping rules are used for the simulation: A fixed number of iterations or the coefficient of variation of a load point index.

D. Iteration Procedure

1. Generate the input process for a period T using the zone failure SPP model and algorithms of section III.F.
2. Generate the service process. This is, for each failure f_i generate a ttr_i using the zone service SPP model and algorithms of section III.F.
3. Compute the mean traffic intensity $ma(t)$
4. The arrival time of the first repair is:

$$tr_1 = tf_1 + ttr_1 \quad (7)$$

5. The arrival time of the next repair is determined in the following way:

- If all crews are busy when failure i arrives, this failure has to wait until some crew finishes a repair j and fixes it (Congestion).

$$tr_i = tr_j + ttr_i \quad (8)$$

- If a crew is free when failure i arrives, the repair for this failure starts immediately (No congestion)

$$tr_i = tf_i + ttr_i \quad (9)$$

6. Calculate the outage duration

$$tod_i = tr_i - tf_i \quad (10)$$

7. Calculate the repair waiting time:

$$tw_i = tod_i - ttr_i \quad (11)$$

8. For T or its sub-periods (month, semester, etc.) compute the mean waiting time (mtw), the mean outage duration ($mtod$) and the congestion (C) defined as:

$$C = mtw / mtod * 100\% \quad (12)$$

VI. Examples

Traditional queuing analyses assume the input and service processes are Markovian (Both HPP) or semi-Markovian (One HPP and the other a RP). However, for the repair process of a power distribution systems it is not known which SPP models can represent this processes.

Thus, data of three Colombian power distribution systems was gathered in order to know these models and to apply the proposed methodology. Table I shows general description of the studied systems.

For each system an assessment of the repair process performance was carried out for $T = 1.0$ year with simulations of 150 iterations. Tables II to VII shows results. Confidence level of input and service process models is 95%.

These results show:

- For Pereira and Pasto systems the input and repair processes are non-stationary with positive tendency. This means although the reliability of the components is deteriorating, the repair process is adjusting to follow the increasing pattern of failures arrivals.
- For Casanare system the input and repair processes are stationary but they do not correspond to the HPP.
- The performance of the repair process is directly connected with the size (area) of the service territory. For Pereira and Casanare systems the worst indexes corresponds to zones (service territories) with highest areas. The effect of remedial actions proposed to reduce outage durations can be tested with this methodology.
- A low congestion or traffic intensity does not mean a low waiting time or consequently a low outage duration.
- Results of mean outage time corresponds to those values observed during operation of the studied systems.

TABLE I
GENERAL DATA OF STUDIED SYSTEMS

	System		
	Pereira	Pasto	Casanare
Region	Municipality of Pereira	Municipality of San Juan de Pasto	Department of Casanare
Utility	Empresa de Energía de Pereira S. A.	Centrales Eléctricas de Nariño S. A.	Empresa de Energía del Casanare S. A
Area [km^2]	702	1181	44640
Urban population	371239	312377	200952
Rural population	72315	70241	94401
Service territories	3	1	3
Crews per zone	3	2	2

Notes:
1. In Colombia a department is a group of municipalities
2. The capital of Department of Casanare is Yopal city (Inhabitants: 90218 urban and 16604 rural)
3. Population in given in inhabitants
4. Source for population data: Colombian census of year 2005 (www.dane.gov.co)
5. Casanare Department is mainly grassland plains with very difficult transport conditions during rainy season which last at least 6 months.

A. Results for Pereira System

TABLE II
PEREIRA SYSTEM -INPUT AND SERVICE PROCESSES

Zone	Input process [Failures/hour]	Service Process [Repairs/hour]
1	PLP $\lambda_F = 0.1471$ $\beta_F = 1.0539$	PLP $\lambda_R = 0.3765$ $\beta_R = 1.0291$
2	PLP $\lambda_F = 0.0363$ $\beta_F = 1.1584$	PLP $\lambda_F = 0.4278$ $\beta_F = 1.0560$
3	PLP $\lambda_F = 0.0715$ $\beta_F = 1.1254$	PLP $\lambda_F = 0.2313$ $\beta_F = 1.1133$

Note: These models were built with data of year 2005

TABLE III
PEREIRA SYSTEM -REPAIR PROCESS PERFORMANCE

Zone	$mttr$ [Hours]	$mtod$ [Hours]	mtw [Hours]	C [%]	$ma(f)$ [%]
1	2.08	4.13	2.05	49.63	49.11
2	1.53	2.00	0.47	23.50	21.74
3	1.72	2.79	1.07	38.35	34.53

B. Results for Casanare System

TABLE IV
CASANARE SYSTEM - INPUT AND REPAIR PROCESSES

Zone	Input process [Failures/hour]	Service Process [Repairs/hour]
1	Weibull RP $\lambda_F = 0.1814$ $\alpha_F = 0.3133$ $\beta_F = 0.7547$	Weibull RP $\lambda_R = 0.2732$ $\alpha_R = 0.5150$ $\beta_R = 0.6611$
2	Weibull RP $\lambda_F = 0.1971$ $\alpha_F = 0.4492$ $\beta_F = 0.6285$	Weibull RP $\lambda_R = 0.3086$ $\alpha_R = 0.5179$ $\beta_R = 0.7001$
3	Weibull RP $\lambda_F = 0.2175$ $\alpha_F = 0.3917$ $\beta_F = 0.7154$	Weibull RP $\lambda_R = 0.3125$ $\alpha_R = 0.6668$ $\beta_R = 0.5772$

Notes:
1. These models were built with data of years 2004-2006
2. The Weibull density function is defined as $f(t) = \alpha\beta t^{\beta-1}\exp(-\alpha t^{\beta})$

TABLE V
CASANARE SYSTEM - REPAIR PROCESS PERFORMANCE

Zone	$mttr$ [Hours]	$mtod$ [Hours]	mtw [Hours]	C [%]	$ma(f)$ [%]
1	3.66	19.72	16.06	81.44	68.0
2	3.24	18.22	14.98	82.22	65.0
3	3.19	23.41	20.22	86.37	70.0

C. Results for Pasto System

TABLE VI
PASTO SYSTEM - INPUT AND SERVICE PROCESSES

Zone	Input process [Failures/hour]	Service Process [Repairs/hour]
1	PLP $\lambda_F = 0.5589$ $\beta_F = 1.0464$	PLP $\lambda_R = 1.6853$ $\beta_R = 1.0189$

Note: These models were built with data of year 2006

TABLE VII
PASTO SYSTEM - REPAIR PROCESS PERFORMANCE

Zone	$mttr$ [Minutes]	$mtod$ [Minutes]	mtw [Minutes]	C [%]	$ma(f)$ [%]
1	32.34	53.49	21.15	39.54	37.10

VII. CONCLUSIONS

1. The repair process performed in each service territory of a power distribution system is a queuing system. Thus, it has to be modelled using queuing models, not as part of component reliability models, the traditional approach applied in reliability assessments. Also, it is not realistic to apply the deterministic criteria $n-1$ for the system reliability assessments because a failure can occur independently if the previous failure has been or not repaired.
2. As shown in the examples, the input and service of the repair process of a power distribution system are not necessarily HPP; they can be RP or NHPP, and for this reason, the system reliability assessment has to be performed by means of a sequential Monte Carlo simulation. The approach presented here, that considers stationary and non-stationary SPP for the failure and the

service processes, is very different from traditional queuing modeling, which assumes that these processes are Markovian (HPP) or semi-Markovian (One HPP and the other a RP).

3. The index that better reflects the performance of the repair process is the waiting time. A low congestion or traffic intensity does not necessarily mean a low waiting time or consequently a low outage duration.
4. The proposed methodology explicitly evaluates the performance of the repair process performed in a power distribution system and gives an analytical base for the optimal scheduling of the repair resources in accordance with the failure process generated by the components and the targets for reliability indices.

VIII. Acknowledgment

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