Reliability Assessment of Substations using Stochastic Point Processes and Monte Carlo Simulation

C. J. Zapata, *Member IEEE,* A. Alzate, M. A. Ríos, *Member IEEE*

***Abstract*—Reliability assessments of electrical power substations have been traditionally performed assuming that the failure and repair processes are stationary and making a great simplification on the protective systems modeling. Thus, in order to improve the level of detail of these assessments, this paper presents a method that combines the modeling of failures and repairs as stochastic point processes and a procedure of sequential Monte Carlo simulation for computing the reliability indexes. Its main features are: *i.* It can manage time varying rates, a necessity for those scenarios considering improvement/deterioration of component reliability, preventive maintenance and repair process performance. *ii.* It allows the explicit representation of the protective systems, its operating sequence and the effect of their failures. *iii.* It does not require an exhaustive list of operating states as other methods do. Of course, this improvement in modeling detail has a price; it is the long computational time required by the simulation.**

***Index Terms*-- Point processes, Poisson processes, power system reliability, power system simulation, substations.**

I. Introduction

ELECTRICAL power substations are the most critical parts of a power system because they are the point where the main power system components interconnect. A substation failure can produce the outage of many power system components, what can be disastrous for the system. For this reason, substation reliability is a matter of outmost importance.

Reliability of a substation depends on: *i.* The substation configuration, i.e. the arrangement of circuit breakers or busbars [1]. *ii.* The reliability of substation components. *iii.* The reliability of protective systems.

A substation reliability assessment evaluates the effect of these aspects on the service continuity of the main power system components connected to the substation.

C. J. Zapata is a professor at Universidad Tecnológica de Pereira, Pereira, Colombia, and a PhD student at Universidad de los Andes, Bogotá, Colombia. (e-mail: cjzapata@utp.edu.co).

A. Alzate is a planning engineer at Central Hidroeléctrica de Caldas S. A. E. S. P, Manizales, Colombia, and a graduate student at Universidad de los Andes, Bogotá, Colombia. (e-mail: aalzates@chec.com.co).

M. A. Ríos is a professor at Universidad de los Andes, Bogotá, Colombia. (e-mail: mrios@uniandes.edu.co).

This paper focuses on the modeling aspects involved in these kinds of studies and proposes a method based on stochastic point processes (SPP) and Monte Carlo simulation (MCS) which improves the level of modeling detail.

II. Motivation

The following aspects motivated the development of the proposed method.

A. The Necessity of Considering Time Varying Rates

Reliability assessments of substations have been traditionally performed under the assumption that the failure and repair processes of substation components are stationary; it is expressed by means of constant event rates, constant probabilities of failure or constant availabilities. This practice is also reflected in the mathematical methods that have been applied for this task: cut sets, reliability blocks, homogeneous Markov chains, fault trees, etc. [2]-[16]. However, nowadays the application of this assumption ought to be carefully examined because due to factors such us aging [17]-[18], improvement/decrease on preventive maintenance and repair resources, the failure and repair rates of substation components can be time varying functions.

In order to manage time varying rates with the traditional methods, the analyst has the following options:

1. To manually change the input parameters (event rates, failure probabilities, availabilities) to the expected values for the future years under several scenarios of improvement/deterioration of component reliability, preventive maintenance and repair process performance; however, this approach is not very accurate because event rates do not change in discrete steps but continuously.
2. To incorporate the functions which represent the time varying rates into a non-homogeneous Markov process; however, this method has problems for adjusting the operating times and of tractability for some types of time varying rates [19].

Thus, the proposal here is to model the failure and repair processes of substation components by means of SPP. It allows the utilization of time varying rates in an easier way than in the non-homogeneous Markov chain method.

B. *The Necessity of Including the Effect of Protective Systems*

It has been a common practice for reliability assessments of substations to only consider the primary plant components, i.e. the high voltage ones, and assume the effect of items of secondary plant such as protective components, auxiliary services, communication systems, cablings, etc. are included in the reliability models of the high voltage ones. Regarding this practice, Dortolina et. Al. pointed out that [9]: *"There are practical situations where would be important to explicitly evaluate the influence of the protective relaying equipment on the overall substation reliability. These include: (i) evaluating the effect of a given protective scheme on the reliability of different substation arrangements, and (ii) evaluating the effect of the redundancy of the protective relaying equipment on the reliability of a given (and perhaps existing) substation"*. However, this practice is in part justified by the fact that all analytic methods for reliability assessments that allow a detailed system representation require an exhaustive list of operating states; thus, if many components are considered, the amount of system operating states becomes huge. Thus, the proposal here is to perform the reliability assessment by means of a procedure of sequential MCS. It allows including as many components and operating conditions as the analyst wants and does not require an exhaustive list of system operating states.

III. Stochastic Point Processes

A SPP is a probabilistic model in which the N random events occurring during a period T are counted, with the condition that one and only one event can occur at every instant. Fig. 1 shows a representation of a SPP; As $T = t - 0$, only t appears in the process equations.

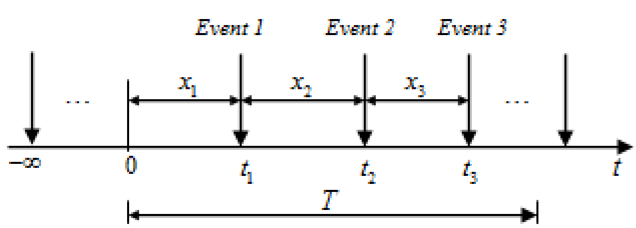

Fig. 1. The concept of stochastic point process

A SPP is defined by means of the intensity function $\lambda(t)$:

$$\lambda(t) = dE[N(t)]/dt \quad (1)$$

A SPP has positive tendency if event arrivals increase with time (inter-arrival intervals decrease), negative tendency if event arrivals decrease with time (inter-arrival intervals increase) and zero tendency if event arrival or inter-arrival intervals do not show a pattern of increase or decrease.

A SPP without tendency is stationary or time-homogeneous; homogeneity means inter-arrival intervals are independent and identically distributed. The opposite is true for a SPP with tendency. The parameter $\lambda(t)$ controls the tendency in the mathematical model of a SPP; Fig. 2 shows a classification of SPP models.

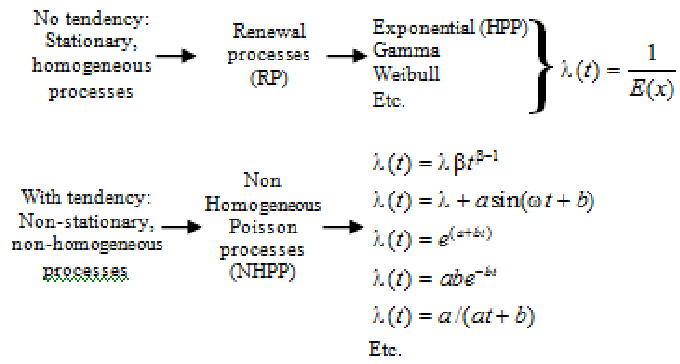

Fig. 2. A basic classification of stochastic point process models

A RP is defined by means of the distribution of the inter arrival times. The most famous RP is the exponential one commonly called Homogeneous Poisson Process (HPP).

The general procedure for fitting a SPP model to a data sample and the algorithm to generate samples from SPP models are presented in [20].

When SPP is applied for modeling failure and repair processes, x represent time between failures and repair durations, respectively, and t time of failure occurrence and time when a repair is finished, respectively.

IV. The Concept of Protection Zones

Each main power system component (transmission line, power transformer, reactive compensation, busbar) connected to a substation defines a protection zone (PZ); this concept is illustrated in Fig. 3.

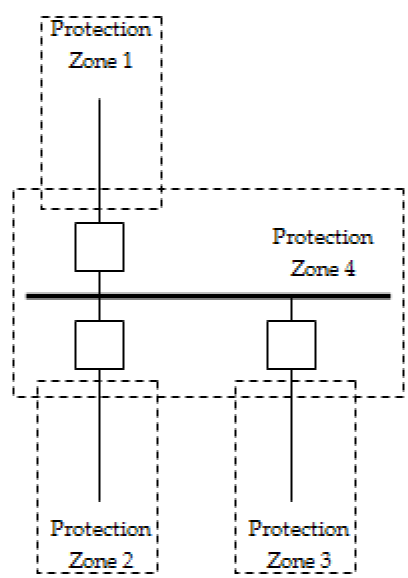

Fig. 3. Protection zones associated to a single busbar substation

Each PZ has a protective system (PS) composed of several protective system components (PSC); PSC include circuit breakers, disconnectors, instrument transformers, relays, trip circuits, etc. Communication and auxiliary service systems can be part of each PS or shared by several of them.

V. Failure Modes of Protective Systems

A PS can take two kinds of actions: disconnection and connection of its PZ. They arise automatically, due to abnormal operating conditions in the PZ, or manually, due to intentional or unintentional orders given by operators. These actions are materialized by means of the opening and closing of the circuit breakers associated to the PZ; thus, requests to the PS to come into action can be calls to open (CTO) or calls to close (CTC).

A PS operates correctly and appropriately if it not fails when it is called to operate neither operates when it is not required; thus, the basic PS failure modes are failures to operate, which include failures to open (FTO) and failure to close (FTC), and false operations, which include false openings (FO) and false closings (FC). Failures to operate include those situations when the opening or closing last more than the specified time.

Failures of PSC are classified here in accordance to their potential effect on PS operation, i.e. as FTO, FTC, FO and FC. The term "potential" is applied because the final effect of a PSC failure on the PS operation depends on the configuration of the protective scheme. Other type of PSC failure is the knocking down (KD) one: it leads to a situation where the PS could fail to operate and could not produce false operations. All these failure modes do not necessarily apply to every PSC.

VI. Failure Modes of Protected Zones

Failures of PZ can be: *i.* Permanent; those failures that have to be repaired by maintenance personnel. *ii*. Temporary; those failures that disappear without taking any repair action; thus, the PZ is reconnected by means of an automatic reclosing action.

VII. Common Mode Failures

Common mode failures are those that simultaneously affect PZ and PSC. Most of these kinds of failures are permanent.

VIII. Tie Sets

In the proposed method, every time a PS is called to operate, or a PSC produces a false opening, the PS outcome is determined using tie sets [21]. A tie set is a group of components which, when are ok, guarantee the system can perform a given action; therefore, they are connected in series from a reliability point of view. As there can be several paths or combinations of components which guarantee the system can perform a given action, there are several tie sets which are connected in parallel from a reliability point of view. A system succeed in performing a given action if at least one tie set is ok and it fails when all tie sets are down.

To illustrate this, let us consider the PS shown in Fig. 4. It includes two circuit breakers (CB1, CB2), instrument transformers (CT, PT), auxiliary services system (AUX), communication system (COMM), opening circuit (OC) and closing circuit (CC). The tie sets are shown in Fig. 5.

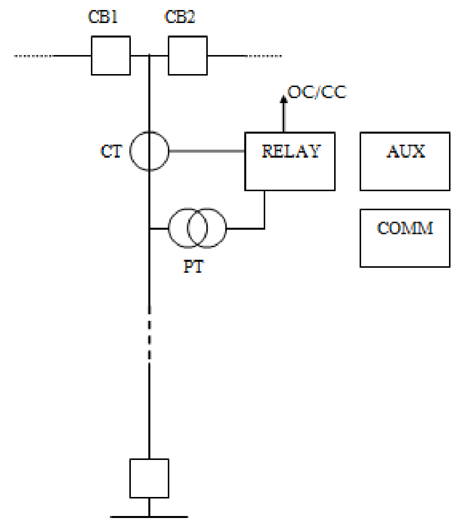

Fig. 4. Protective system of a radial transmission line

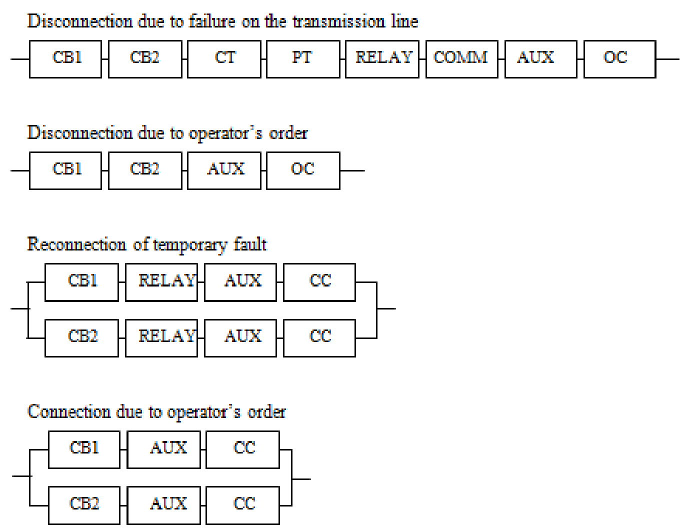

Fig. 5. Tie sets for the PS of the transmission line shown in Fig. 4

Tie sets are used in the proposed method because they have a data structure that can be easily codified in matrix form.

IX. Proposed Method

A. Modeling

Each failure mode that applies to a PZ is represented by means of a SPP model. To obtain these models, PZ failure data is split up by failure mode and the resulting sample data for each failure mode is fitted to a SPP.

Each failure mode that applies to a given PSC is represented by means of a SPP model. To obtain these models, failure data of each PSC is split up by failure mode and the resulting sample for each failure mode is fitted to a SPP.

Each common mode failure is represented by means of a SPP model. Data samples to obtain these models are taken from PZ and PS failure data.

A SPP is fitted to the repair sample data corresponding to each failure mode. It is assumed that repair actions are perfect i.e. they effectively eliminate failures and do not introduce new ones.

For FTO and FTC it is assumed that PSC and PZ repairs can be performed simultaneously; thus, PSC failures only add unavailability to the PZ when they last more than PZ repairs.

Preventive maintenance on PZ and PS include the actions performed by maintenance personnel and the auto diagnostic functions (self-check and monitoring) [22], [23] incorporated in some PSC, such us relays. The time of occurrence of the events of these processes is deterministic because they are programmed in the form of fixed intervals; thus, they are generated using their yearly frequency. Their duration is random and so it is modeled by means of a SPP. These processes are not perfect in their function of finding PSC failures; this feature is represented by means of E, the probability of finding a PSC failure.

B. Reliability Assessment Procedure

The operation of each PZ and its associated PS is observed artificially for a period T of one or more years of interest by means of a procedure of sequential MCS.

A simulation consists of n artificial observations of the operating sequence of PZ and PS under a scenario defined by substation configuration, protective scheme configuration, failure and repair rates and strategy for preventive maintenance. FC are not considered because they do not affect PS operation.

C. Procedure inside a Realization

The procedure inside a realization is depicted in Fig. 6; each downward arrow symbolizes the occurrence of an event of failure or maintenance in a PZ with a PS composed of X PSC. Steps are:

1. Generate the PZ failure process ($f_1 \, f_2 \cdots f_n$).
2. Generate the failure processes corresponding to each PSC.
3. Generate the process of preventive maintenance that requires the PZ disconnection ($m_1 \, m_2 \cdots m_n$).
4. Generate the processes of self-check, monitoring and preventive maintenance on PSC which not require the PZ disconnection.
5. For each f_i or m_i analyze if the PS operates correctly when CTO and CTC; this is, observe if PSC failures have occurred before each call to operate and determine if they lead to a PS failure to operate.
6. If the PS fails to operate, determine if the PS that give local back up operate correctly and the additional PZ that were disconnected. Determine the effect of PS failure in PZ availability.
7. For each PSC false opening generated while PZ is in the operative state, determine if the PS produces a trip. This is performed evaluating the tie sets which guarantee the trip can be performed. Also analyze if the PS operates correctly when CTC. Determine the effect of false opening in PZ availability.
8. Repeat steps 1 to 7 n times or after reaching other stopping rule.

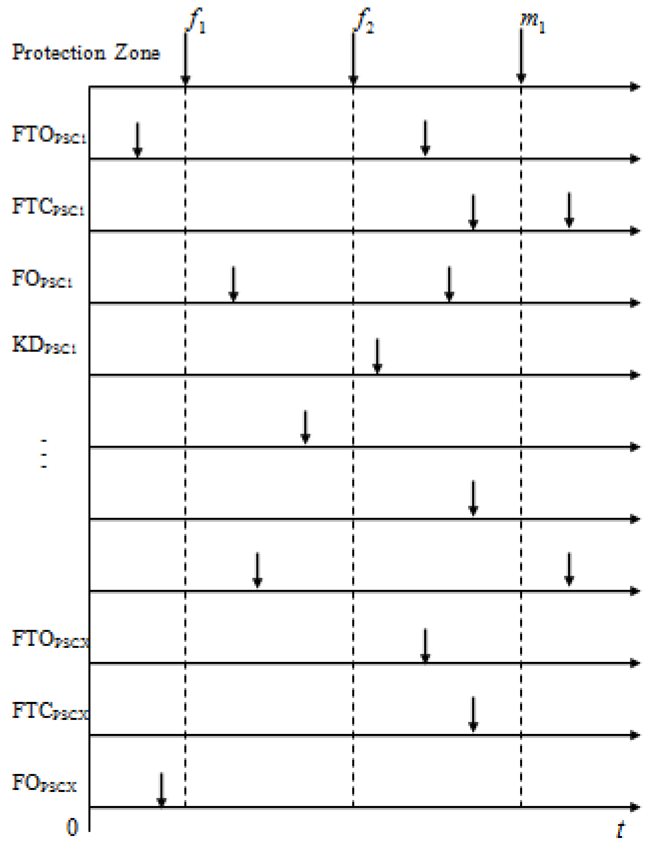

Fig. 6. General procedure inside a realization

9. For each sub period k (week, month, semester, year, etc) of T compute the indexes of the PZ. When using time varying rates, reliability indexes should not be computed for a single sub-period equal to T because variation is lost.

D. Detection of Failures by Preventive Maintenance

For each PSC failure present when these processes are performed, a uniform distributed random number U is generated. If $U \leq E$, it is detected; on the contrary, it remains undetected.

E. Reliability Indexes

Substation reliability is measured by means of indexes related to the service continuity of each PZ. These are expected event rates, expected availability and expected unavailabilities.

Defining:

o : An outage event, i.e. a PZ disconnection.

u : Down time due to an outage.

f : A PZ outage due to a failure in this zone or in an upper hierarchical PZ.

m : A PZ outage due to a preventive maintenance action in this zone or in an upper hierarchical PZ.

fo : A PZ outage caused by a false opening originated in its own PS or in a one of an upper hierarchical PZ

bu : A PZ outage caused by a backup action taken by its own PS or by a one of an upper hierarchical PZ

- Expected Operational Outage Rate

$$\lambda_O = [\sum (f + m + fo + bu)] / [T - \sum u] \qquad (2)$$

- Expected Operational Unavailability

$$U_o = \sum u / T \qquad (3)$$

- Expected Operational Availability

$$A_o = 1 - U_o \qquad (4)$$

The other expected event rates and unavailabilities are computed in the following way:

$$\lambda_e = (\sum e) / (T - \sum_{\forall u \in e} u) \qquad (5)$$

$$U_e = \sum_{\forall u \in e} u / T \qquad (6)$$

For $e = f,\ m,\ fo,\ bu$

X. Example

A. Test system

In order to illustrate how the proposed method works, let us consider the air-insulated single-busbar rural substation shown in Fig. 7. It comprises switchyards for a subtransmission line and two feeders. It is projected the addition of new switchyard for a third feeder.

Table I show the PZ reliability data. It includes the mean failure rate λ and the mean repair time r. Table II shows the PSC failure rates. PSC failure rates were estimated from data obtained in two reliability surveys performed in Colombia [24], [25]. Failure rates for opening and closing circuits and repair times for all PSC were estimated from typical values. PZ data was assumed.

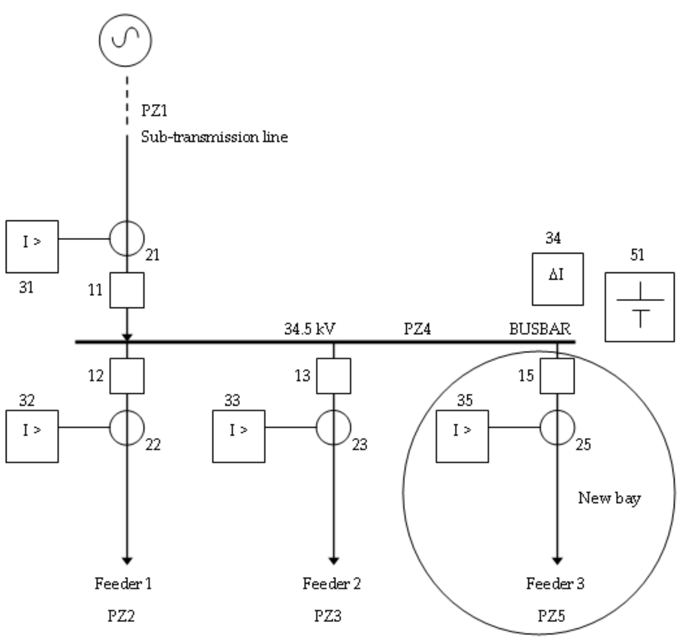

Fig. 7. Test system

TABLE I
RELIABILITY DATA OF PROTECTION ZONES

PZ	Permanent failures		Temporary failures	
	λ	r	λ	r
	[Failures/year]	[hours]	[Failures/year]	[minutes]
1	1.0	6.0	2.0	2.0
2	2.0	6.0	4.0	2.0
3	4.0	6.0	8.0	2.0
4	0.2	12.0	---	---
5	3.0	6.0	6.0	2.0

TABLE II
FAILURE RATES OF PROTECTIVE SYSTEM COMPONENTS [FAILURES/YEAR]

Component	KD	FTO	FTC	FO
Circuit breaker	0.0203	0.0610	0.0610	0.0610
Current transformer	0.0060	0.0008	---	0.0060
Closing circuit	---	---	0.0015	---
Opening circuit	---	0.0015	---	0.0005
Overcurrent relay	0.0022	0.0033	0.0022	0.0033
Differential relay	0.0054	0.0108	---	0.0108
Auxiliary services	0.0183	---	---	---

Preventive maintenance frequency is one event per year in each zone. $E = 80\%$ for FTO and FTC and $E = 20\%$ for FO. Existent relays do not incorporate autodiagnostic functions.

The mean duration of preventive maintenance events is $r = 12$ hours.

It is assumed the PZ failure processes are stationary and that existent circuit breakers and relays are aged.

All stationary failure processes are modeled by means of HPP with $\lambda(t) = \lambda$.

The failure processes of aged components are modeled by means of a Power Law process with scale parameter equal to λ and shape parameter $\beta = 1.2$. A detailed description of this model is given in [20] and [26].

Repair processes and preventive maintenance durations are modeled as normal RP with $\lambda(t) = 1/r$ and variance of 50%. $r = 8$ hours for high voltage switchgear, opening/closing circuits and auxiliary services and $r = 4$ hours for protective relays.

B. Cases of Study

1. A reliability assessment considering the real reliability condition of the components.
2. A reliability assessment considering that all PSC failure processes are stationary.

The study focuses on the substation reliability indexes seen at the connection point of the new feeder.

C. Results

Tables III to VI show the reliability indexes for the new bay with $T = 3$ years and simulations of $n = 10000$ realizations. Fig. 8 and 9 show λ_o and U_o for the cases of study. Required time for simulating these cases was in average 24 hours using common desk computers (Intel Core 2 Processor, 2.4 and 2.66 Ghz, 2 to 3 GB of RAM).

TABLE III
EXPECTED EVENT RATES IN [EVENTS/YEAR] FOR PZ5 – CASE 1

Year	λ_o	λ_f	λ_m	λ_{fo}	λ_{bu}
1	7.2314	4.0330	3.0124	0.0892	0.0968
2	15.2035	11.7570	3.0124	0.1208	0.3133
3	15.6872	12.2442	3.0124	0.1244	0.3062

TABLE IV
EXPECTED UNAVAILABILITIES IN [%] FOR PZ5 – CASE 1

Year	U_o	U_f	U_m	U_{fo}	U_{bu}
1	0.5313	0.1111	0.4110	0.0075	0.0018
2	0.7532	0.3262	0.4109	0.0097	0.0063
3	0.7660	0.3380	0.4118	0.0103	0.0060

TABLE V
EXPECTED EVENT RATES IN [EVENTS/YEAR] FOR PZ5 – CASE 2

Year	λ_o	λ_f	λ_m	λ_{fo}	λ_{bu}
1-2-3	12.1913	8.8914	3.0124	0.0936	0.1939

TABLE VI
EXPECTED UNAVAILABILITIES IN [%] FOR PZ5 – CASE 2

Year	U_o	U_f	U_m	U_{fo}	U_{bu}
1-2-3	0.6652	0.2429	0.4111	0.0077	0.0036

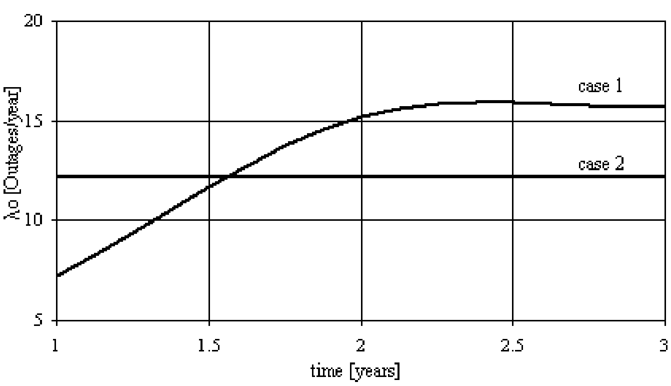

Fig. 8. Expected operational outage rate for the new bay

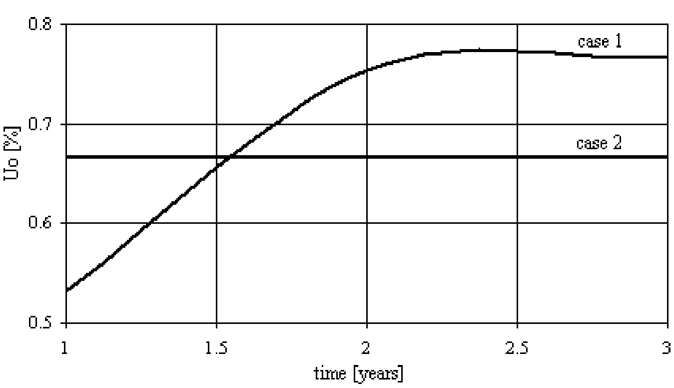

Fig. 9. Expected operational unavailability for the new bay

D. Analysis of Results

Results of case 1 show that although PZ5 has new substation equipment, its reliability indexes increase with time due to the presence of aged substation equipment in the other bays.

On the other hand, for most term of the study, the reliability indexes obtained in case 2 are lower than those obtained in case 1. This show the error that exists when the reliability of a system with aged components is assessed assuming that all component failure processes are stationary.

XI. CONCLUSIONS

Stochastic Point Processes and Monte Carlo simulation allows implementing a method for reliability assessment of substations that greatly improves the modeling detail of these kinds of studies. It can manage time varying rates and allows a detailed representation of the protective systems operating sequence and the effect of their failures. Additionally, it does not require an exhaustive list of operating states as other methods do. However, this improvement in modeling detail has a price; it is the long computational time required by the simulation.

XII. REFERENCES

[1] J. McDonald, *Electrical Power Substations Engineering*, Taylor & Francis Group, 2006.

[2] R. Billinton and R. N. Allan, *Reliability Evaluation of Power Systems*, Plenum Press, 1996.

[3] V. I. Nitu, "The Philosophy of substation reliability", *Electra*, No. 54, 1977.

[4] R. J. Cakebread, K. Reichert, H. G. Schutte, "Reliability in the design of EHV substations availability as a function of component failure rate repair and maintenance times", *Electra*, No. 65, 1979.

[5] R. N. Allan, A. N. Adraktas, "Terminal effects and protection system failures in composite system reliability evaluation", *IEEE Transactions on Power Apparatus and Systems*, Vol. 101, No. 12, 1982.

[6] P. M. Anderson, "Reliability modeling of protective systems", *IEEE Transactions on Power Apparatus and Systems*, Vol. 103, No.8, 1984.

[7] J. C. Declercq, M. P. Van, H. Rohsler, H. G. Schutte, "Substation reliability comparison of two methods and suitable presentation of results", *Electra*, No. 99, 1985.

[8] B. G. Andersson, J. C. Declercq, M. P. Van, H. Rohsler, H. G. Schutte, "The reliability of HV substations with special regard to the secondary equipment", *Electra*, No. 111, 1987.

[9] C A. Dortolina, J. J. Porta, R. Nadira, "An approach for explicitly modeling the protective relaying system in substation reliability evaluation studies", *IEEE Transactions on Power Systems*, Vol. 6, No.4, 1991.

[10] D. O. Koval, J. P. Ratusz, "Substation reliability simulation model", *IEEE Transactions on Industry Applications*, Vol. 29, No. 5, 1993.

[11] R. Billinton, G. Lian, "Station reliability evaluation using a Monte Carlo approach", *IEEE Transactions on Power Delivery*, Vol. 8, No. 3, 1993.

[12] J. Satish, R. Billinton, "Minimum cost analysis of station configurations", *IEEE Transactions on Power Delivery*, Vol. 10, No. 4, 1995.

[13] P. Jourda, E. Bourgade, R. N. Allan, "Evaluating the availability of electrical substation: A dynamic methodology", *IEEE Transactions on Power Delivery*, Vol. 11, No. 4, 1996.

[14] J. J. Meeuwsen, W. L. Kling, "Substation reliability evaluation including switching actions with redundant components", *IEEE Transactions on Power Delivery*, Vol. 12, No. 4, 1997.

[15] D. Atanakcovic, L. T. Mc Gillis, F. D. Galiana, "Reliability comparison of substations desings", *IEEE Transactions on Power Delivery*, Vol. 14, No. 3, 1999.

[16] Y. Y. Hong, L. H. Lee, "Reliability assessment of protection systems for switchyard using fault-tree analysis", *IEEE International Conference on Power System Technology*, 2006.

[17] R. E. Brown, H. L. Willis, "The economics of aging infrastructure", *IEEE Power & Energy Magazine*, May/June, 2006.

[18] CIGRE, *Ageing of the system – Impact on planning,* 2000.

[19] T. F. Hassett, D. L. Dietrich, F. Szidarovszky, "Time-varying failure rates in the availability & reliability analysis of repairable systems", *IEEE Transactions on Reliability*, Vol. 44, No. 1, 1995.
[20] C. J. Zapata, A. Torres, D. S. Kirschen, M. Rios, "Some misconceptions about the modeling of repairable components", *IEEE PES General Meeting,* 2009.
[21] R. Billinton, R. N. Allan, *Reliability Evaluation of Engineering Systems: Concepts and Techniqu*es, Plenum Press, 1992.
[22] J. J. Kumm, M. S. Weber, E. O. Schweitzer, D. Hou, "Philosophies for Testing Protective Relays", *48th Annual Georgia Tech Protective Relaying Conference*, 1994.
[23] J. J. Kumm, E. O. Schweitzer, D. Hou, "Assessing the effectiveness of self-test and other monitoring means in protective relays", *PEA Relay Committee Spring Meeting,*, 1995.
[24] C. J. Zapata, C. M. Arbeláez, C. A. Pulgarín, "Reliability indices of distribution substation equipment", *Mundo Eléctrico*, No. 65, 2006. (In Spanish).
[25] J. F. Valencia, "Reliability of protective systems of power transformers of CHEC", Graduation Project, Universidad de los Andes, Bogota, 2009. (In Spanish).
[26] *IEC "Power law model – Goodness-of-fit test and estimation methods*", Standard 61710, 2000.

XIII. BIOGRAPHIES

Carlos J. Zapata obtained his BScEE from the Universidad Tecnológica de Pereira, Pereira, Colombia, in 1991 and his MScEE from the Universidad de los Andes, Bogotá, Colombia, in 1996. He worked for eleven years for Concol S. A, Bogotá, Colombia and since 2001 he has worked as a professor at the Universidad Tecnológica de Pereira, Pereira, Colombia. Currently, he is working towards his PhD at the Universidad de los Andes, Bogotá, Colombia.

Alejandro Alzate obtained his BScEE from the Universidad Nacional de Colombia, Manizales, Colombia in 2005. Since 2006 he has worked for Central Hidroeléctrica de Caldas S. A. E. S. P. – CHEC as a planning engineer.

Mario A. Ríos obtained his BScEE (1991), MScEE (1992) and PhD (1998) from the Universidad de los Andes, Bogotá, Colombia. He also received in 1998 the PhD from the Institute Nationale Polytechnique du Grenoble, Grenoble, France. He worked for 12 years for Concol S. A, Bogotá, Colombia, and since 2005 he has worked as a professor at the Universidad de los Andes, Bogotá, Colombia.