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Reliability Assessment of Protective Schemes Considering Time Varying Rates

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Abstract – *Reliability assessments of protective schemes have been traditionally performed considering constant event rates. As a consequence, situations of improvement and deterioration on protective components reliability and maintenance performance are not considered. As these situations do happen in real life, this paper presents a method which allows considering time varying rates and diverse strategies of maintenance. It combines the modeling of failure and repair processes using stochastic point process theory and a procedure of sequential Monte Carlo to artificially generate the operating sequence of the protective system and for computing its reliability indexes. However, as it is shown in the example, this great improvement in the modeling detail of these kinds of studies has a price; it is the long computational time required by the simulation.*

***Keywords**: Aging, Monte Carlo Simulation, Power System Reliability, Protective Relaying, Stochastic Point Processes*

Nomenclature

β	Shape parameter of a power law process
CTC	Number of calls to close
CTO	Number of calls to open
D	Dependency
$d(.)/dt$	Derivative of
E	Effectiveness
$E[.]$	Expected value of
f	Failure event
FO	Number of false openings
FTC	Number of failures to close
FTO	Number of failures to open
k	A sub-period of T
λ	Scale parameter of a power law process
$\lambda(t)$	Event rate or intensity function
λ_F	Failure rate
m	Maintenance event
n	Number of realizations
N	Number of random events
$P[.]$	Probability of
r	Mean maintenance duration
R	Reliability
S	Security
t	Arrival time of a random event
T	Period of study
u_i	Unavailability of the PZ due to an outage i
U	Uniformly distributed random number
U_o	Operational reliability of a PZ
x	Inter-arrival time
X	Number of protective components

I. Introduction

The mission of a protective system (PS) is to detect abnormal operating conditions in the protection zone (PZ) to which it is assigned and to take actions that guarantee power system safety and security and safeguard investment in power system assets.

Fig. 1. shows the main types of protective system components (PSC). A protective scheme is the optimal combination of PSC which allows the PS to perform its mission with a specified level of reliability. Reliability refers to the degree of certainty that the PS will perform correctly [1]-[2]. It combines the redundancy and diversity aspects of the PSC.

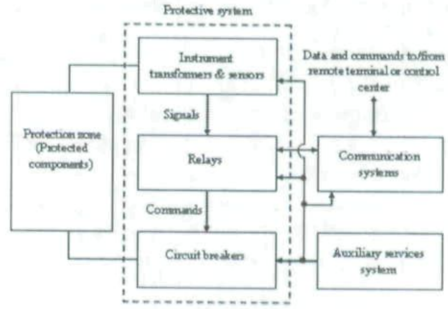

Fig. 1. Components of a protective system

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Due to the critical mission assigned to the PS and the fact that maloperations can spark a sequence of cascading outages that could lead to a catastrophic event such as a blackout [3], [4], PS reliability is a matter of utmost importance.

This fact has long been understood and has been studied from several points of view. Reliability studies of PS can be classified into the following categories:

1. Studies at the component level focus on a given component of the PS, for example, a relay.
2. Studies at the PS level focus on protective schemes at the terminals of the PZ.
3. Studies at the power system level focus on the effects of PS failures on power system reliability.

This paper focuses on studies of the second type. They are helpful for: *i.* Comparing design alternatives. *ii.* Assessing the effect of incorporating PSC with various levels of reliability. *iii.* Evaluating the impact of different preventive maintenance strategies.

II. Problem Statement

Reliability assessments of protective schemes have been traditionally performed under the assumption that PSC failure and repair processes are stationary; this implies constant failure and repair rates, constant probabilities of failure or constant availabilities. Hence, the mathematical methods used for this task are those that work under this assumption; for example, event trees, failure trees, reliability blocks and homogeneous exponential Markov chains [5]-[16].

Although, stationarity has long been a common assumption in power system reliability, its relevance should be carefully re-examined because of the growing importance of factors such as aging [17]-[19], improvement/decrease in preventive maintenance and repair resources, and the recognition that failure and repair rates can be time varying functions. If stationarity is no longer a valid assumption, the application of the mathematical methods mentioned above is no longer valid. This paper thus presents a method on Stochastic Point Process (SPP) theory because this approach can handle time-varying rates.

III. Failure Modes of a Protective System

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

A PS operates correctly and appropriately if it does not fail when it is called to operate and does not operate when this is not required. 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 where the opening or closing takes 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 used because the final effect of a PSC failure on the PS operation depends on the configuration of the protective scheme. Another type of PSC failure is the knocking down (KND) which could lead to a situation where the PS does not operate. All these failure modes do not necessarily apply to every PSC.

IV. Protective System Reliability Indexes

Definitions for PS indexes are taken from [1]-[2] and their formulation is based on [20].

IV.1. Reliability

Reliability refers to the degree of certainty that the PS will perform correctly. It is measured as the ratio of wanted openings and closings which were performed successfully to the number of exposures:

$$R=\frac{(CTO-FTO)+(CTC-FTC)}{CTO+CTC+FO} \tag{1}$$

IV.2. Dependency

Dependency refers to the degree of certainty that the PS will perform correctly when it is called upon to operate. It is measured as the ratio of wanted openings and closings which were performed successfully to the number of calls to operate:

$$D=\frac{(CTO-FTO)+(CTC-FTC)}{CTO+CTC} \tag{2}$$

IV.3. Security

Security refers to the degree of certainty that the PS will not produce false operations. It is measured as the ratio of wanted openings which were performed successfully to the number of wanted and unwanted openings which were performed:

$$S=\frac{(CTO-FTO)}{(CTO-FTO)+FO} \tag{3}$$

V. Protection Zone Reliability Index

PS maloperations affect the PZ service continuity; thus, they are reflected in the PZ operational reliability:

$$U_o = \sum u_i / T \quad (4)$$

VI. Stochastic Point Processes

A SPP is a probabilistic model in which the N random events occurring during T are counted, with the condition that one and only one event can occur at every instant.

Fig. 2 shows a representation of a SPP; As $T = t - 0$, only t appears in the process equations.

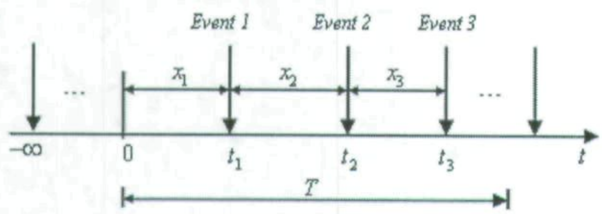

Fig. 2. The concept of stochastic point process

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

$$\lambda(t) = dE\left[N(t)\right] / dt \quad (5)$$

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. 3 shows a classification of SPP models.

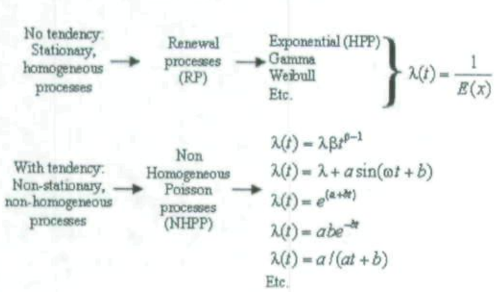

Fig. 3. A basic classification of stochastic point process models

A Renewal Process (RP) is defined by the distribution of the inter arrival times. The most famous RP is the exponential or 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 [21].

When an SPP is used for modeling failure and repair processes, x represents the time interval between failures and repair durations, respectively, and t represents the time at which a failure occurs or a repair is finished.

VII. Proposed Method

VII.1. Modeling

Each failure mode that applies to the PZ is represented by means of a SPP model; these modes are: permanent faults, temporary faults and common mode faults between PZ and PS. Each failure mode that applies to a given PSC is represented by means of a SPP model. To obtain these models, failure data is divided based on the failure mode and the resulting sample data for each failure mode is fitted to a SPP. A SPP is fitted to the repair sample data corresponding to each failure mode of the PSC and the PZ. It is assumed that repair actions are perfect i.e. that they effectively eliminate failures and do not introduce new ones.

Preventive maintenance on the PZ and its PS include the actions performed by maintenance personnel and the auto diagnostic functions (self-check and monitoring) [22]-[23] incorporated in some PSC, such as relays. The time of occurrence of the events of these processes is deterministic because they are programmed to occur at fixed intervals; thus, they are generated using their yearly frequency.

Their duration is random and so it is modeled by means of a SPP. Since 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.

VII.2. Reliability Assessment Procedure

The operation of the PS associated to a PZ is observed artificially for a period T of one or more years of interest by means of a procedure of sequential Monte Carlo Simulation (MCS).

The application of MCS is justified by the fact that it is the only method that can manage all probabilistic models of any type, stationary and non stationary, and also because it easily incorporates all actions which happen during the operating sequence of a PZ and its PS, such as, failures, repairs, maintenance, and self-check.

As depicted in Fig. 4, a simulation consists of n artificial observations of PS performance during T, under a scenario defined by the protective scheme configuration, the failure and repair rates and the strategy for preventive maintenance. The output of a realization is the set of variables which allow computing the indexes of the PS model, i.e. CTO, FTO, CTC, FTC and FO.

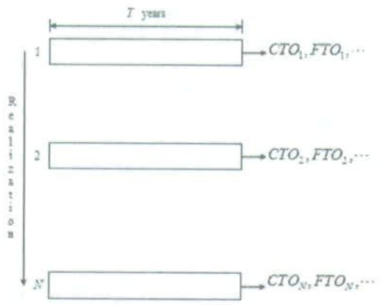

Fig. 4. General procedure of the reliability assessment algorithm

VII.3. Procedure inside a Realization

The procedure inside a realization is depicted in Fig. 5; each downward arrow symbolizes the occurrence of an event of failure, maintenance in a PZ with a PS with X PSC. The steps of this procedure are:

1. Generate the failure process of PZ $\left(f_1 f_2 \cdots f_n\right)$.
2. Generate the failure processes corresponding to each PSC.
3. Generate the process of preventive maintenance that requires the disconnection of PZ $\left(m_1\, m_2 \cdots m_n\right)$.
4. Generate the processes of self-check, monitoring and preventive maintenance on PSC that do not require the disconnection of PZ.
5. For each f_i or m_i analyze if the PS operates correctly for a CTO and a CTC, i.e. observe if PSC failures have occurred before each call to operate and determine if they lead to a PS failure to operate. Tie sets [5] corresponding to the request (CTO, CTC) and its origin (automatic, manual) are used to determine PS success or failure. 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.
6. For each PSC false opening generated whilst the PZ is in the operating state, determine if the PS produces a trip. This requires evaluating the tie sets which guarantee the trip can be performed. Also analyze if the PS operates correctly when CTC.
7. Repeat steps 1 to 6 n times.
8. For each sub period k (week, month, semester, year, etc) of T compute the indexes of the PS failure model. When using time varying rates, reliability indexes should not be computed for a single sub-period equal to T because variation is lost.

VII.4. Detection of Failures by Preventive Maintenance

For each PSC failure present when these processes are performed, a U is generated. If $U \leq E$, it is detected; on the contrary, it remains undetected. Every time a PSC failure is detected by self-check or monitoring, a corrective maintenance action is started immediately; if this implies the PS cannot operate, the PZ is disconnected.

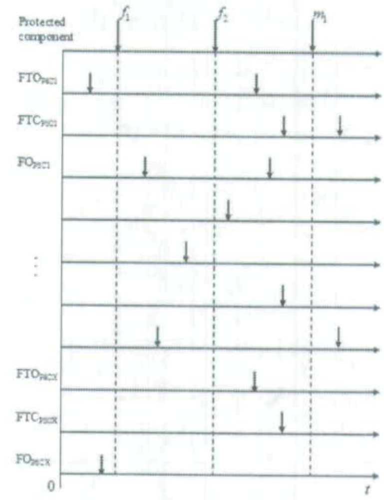

Fig. 5. General procedure inside a realization

VIII. Example

VIII.1. Test System

Let us consider the PS associated with the power transformer (TR) shown in Fig. 6. This PS has three circuit breakers (11, 12, 13), two current transformers (21, 22), an overcurrent relay (31), a differential relay (32), a Buchholz relay (33) and auxiliary services (41).

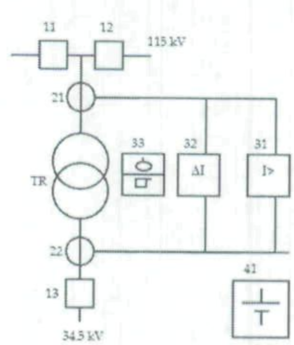

Fig. 6. Protective system of a power transformer

The following PSC are not shown in Fig. 6 but included in the study: a 115 kV closing circuit (51), a 34.5 kV closing circuit (52), a 115 kV opening circuit (61) and a 34.5 opening circuit (62).

Tables I and II show the reliability data for the PZ and the PS, respectively.

TABLE I
POWER TRANSFORMER RELIABILITY DATA

λ_F	r
0.15 [failures/year]	2.00 [hours]

TABLE II
PROTECTIVE SYSTEM RELIABILITY DATA

	KND	FTO	FTC	FO
11, 12	$\lambda_F = 0.0278$	$\lambda_F = 0.0834$	$\lambda_F = 0.0834$	$\lambda_F = 0.0834$
	$r = 2.00$	$r = 2.00$	$r = 2.00$	$r = 2.00$
13	$\lambda_F = 0.0204$	$\lambda_F = 0.0610$	$\lambda_F = 0.0610$	$\lambda_F = 0.0610$
	$r = 3.00$	$r = 3.00$	$r = 3.00$	$r = 3.00$
21	$\lambda_F = 0.0086$	$\lambda_F = 0.0011$	---	$\lambda_F = 0.0086$
	$r = 1.00$	$r = 1.00$	---	$r = 1.00$
22	$\lambda_F = 0.0060$	$\lambda_F = 0.0008$	---	$\lambda_F = 0.0060$
	$r = 1.00$	$r = 1.00$	---	$r = 1.00$
31	$\lambda_F = 0.0022$	$\lambda_F = 0.0033$	---	$\lambda_F = 0.0044$
	$r = 1.00$	$r = 1.00$	---	$r = 1.00$
32	$\lambda_F = 0.0054$	$\lambda_F = 0.0081$	---	$\lambda_F = 0.0108$
	$r = 1.00$	$r = 1.00$	---	$r = 1.00$
33	$\lambda_F = 0.0088$	$\lambda_F = 0.0132$	---	$\lambda_F = 0.0176$
	$r = 1.00$	$r = 1.00$	---	$r = 1.00$
41	$\lambda_F = 0.0183$	---	---	---
	$r = 8.00$	---	---	---
51, 52	---	---	$\lambda_F = 0.0015$	---
	---	---	$r = 8.00$	---
61, 62	---	$\lambda_F = 0.0015$	---	$\lambda_F = 0.0005$
	---	$r = 8.00$	---	$r = 8.00$

Note: Units are [failures/year] for λ_F and [hours] for r.

Data for the opening/closing circuits were estimated from typical values; other data were estimated from indexes obtained in several reliability surveys performed in Colombia [24]-[26].

VIII.2. Cases of Study

1. Failure processes of PZ and PSC are modeled as HPP with $\lambda(t) = \lambda_F$. Repair processes and preventive maintenance durations are modeled as normal RP with $\lambda(t) = 1/r$. There is only a preventive maintenance event per year with a mean duration of 12 hours. E=80% for FTO and FTC and E=10% for FO. This case reflects a situation where failure and maintenance processes are stationary.
2. The failure processes of components 11, 12, 13, 31 and 32 are modeled using a Power Law process with scale parameter λ equal to the values for λ_F shown in Table 2 and shape parameter $\beta = 1.2$. The failure process of these components is thus non stationary with a positive tendency. Other models are the same as in case 1. This case reflects a situation of aging and no strategy for improving preventive maintenance.
3. The same as in case 2, but now preventive maintenance frequency is increased by 100% each year. This case reflects a situation of improving preventive maintenance to reduce the effect of aging.

VIII.3. Results

Tables III, IV and V show the results for $T = 3$ years and $n = 10000$ realizations.

TABLE III
RESULTS FOR CASE 1 [%]

YEAR	R	D	S	U_o
1.0 - 3.0	84.6754	93.7566	78.3917	0.1483

TABLE IV
RESULTS FOR CASE 2 [%]

YEAR	R	D	S	U_o
1.0	85.1367	94.2183	78.7180	0.1483
2.0	76.6338	86.7812	70.4375	0.1510
3.0	75.3358	85.5957	69.0022	0.1522

TABLE V
RESULTS FOR CASE 3 [%]

YEAR	R	D	S	U_o
1.0	85.1268	94.2235	78.6899	0.1483
2.0	84.5231	90.9193	83.3357	0.2882
3.0	90.5142	94.3660	90.9171	0.5632

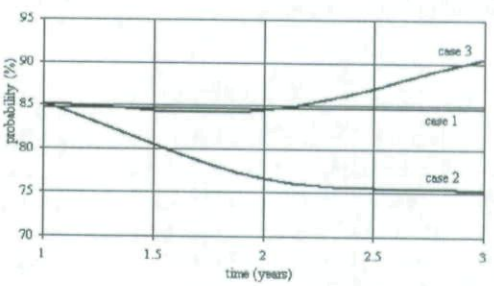

Fig. 7. Reliability of the protective system

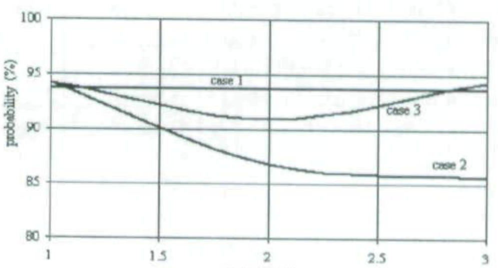

Fig. 8. Dependency of the protective system

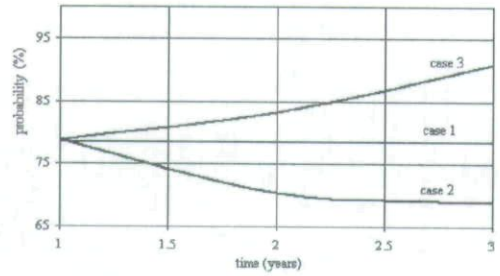

Fig. 9. Security of the protective system

Figs. 7 to 10 show R, D and S for the cases studied. Simulations lasted 0.47 hours, 5.34 hours and 8.81 hours for cases 1, 2 and 3, respectively.

VIII.4. Analysis of Results

In the first case the PS reliability indexes are constant because all PSC failure and repair processes are stationary; thus, it is only necessary to calculate them for one year.

In the second case, the presence of some aged PSC decreases the PS reliability indexes. As can be seen in the results for U_o, the presence of some aged PSC increases the unavailability of the PZ.

Results for case 3 show how the improvement in preventive maintenance increases PS reliability even in the presence of aging; however, as can be seen in the results for U_o, this strategy decreases PZ availability. Thus, the analyst has to assess if the cost of PZ unavailability and additional maintenance pays the replacement of aged PSC.

Simulation times show how as more details a reliability assessment includes, the longest the required simulation time is.

IX. Conclusion

A new method for reliability assessment of protective schemes is presented in this paper. Unlike traditional methods, it supports the consideration of time varying failure and repair rates and diverse maintenance strategies. However, the great improvement in modeling detail offered by this method has a price; it is the long computational time required by the simulation. Thus, its application it is only recommended for those situations of time varying rates because, on the contrary, it is simpler and faster to apply the traditional methods.

This method can also be easily extended to reliability assessment of small portions of a power system such as substations.

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