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Modeling of Protective System Failures to Operate for Reliability Studies at the Power System Level Using Stochastic Point Processes

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Abstract – *This paper present a method for representing protective systems in reliability studies of the power system which condenses at the circuit breakers of the protection zone the effect of protective component failures, protective scheme configuration and preventive maintenance strategies. 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 the probabilities of failure to operate seen at the circuit breakers. Its main advantage is that it supports the use of time varying failure rates, a feature not offered by the other methods that have been traditionally applied for this task. On the other hand, its main disadvantage is the long computational time required by the simulation.* ***Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.***

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
E	Effectiveness of maintenance
f	Failure event
FTC	Number of failures to close
FTO	Number of failures to open
I	A circuit breaker
k	A sub-period of T
λ	Scale parameter of a power law process
λ_F	Failure rate
m	Maintenance event
n	Number of realizations
$P[.]$	Probability of
r	Mean maintenance duration
T	Period of study
U	Uniformly distributed random number
X	Number of protective components

I. Introduction

A protective system (PS) can take two kinds of actions: disconnection and connection of its protection zone (PZ). These actions arise due to abnormal operating conditions in the PZ or due to orders given by an operator and are materialized through the opening and closing of the circuit breakers associated to the PZ. Requests to a 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
- It does not operate when it is not required

Thus, the basic failure modes of a PS are:

- Failures to operate, which include failures to open (FTO) and failure to close (FTC)
- False operations, which include false openings (FO), hidden failures (HF) and false closings (FC)

A HF is a false operation defined as [1]: "*A permanent defect that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element(s) as a direct consequence of another switching event*". The difference between FO and HF is [1]: "*A failure that results in an immediate trip without any prior event is not considered a hidden failure*".

This paper focuses on the representation of protective system failures to operate, i.e. FTO and FTC, for reliability studies at the power system level.

II. Protective Component Failure Modes

Failures of protective system components (PSC) can be classified in accordance to their potential effect on PS operation, i.e. as FTO, FTC, FO, HF and FC. Another type of PSC failure is the knocking down one (KND), it leads to a situation where the PS could fail to operate and could not produce false operations. 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. All these failure modes do not necessarily apply to every PSC.

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III. Power System Reliability Assessments Considering PS Failures to Operate

To illustrate how a power system reliability study that considers PS failures to operate works, let us to consider the PS at each terminal of transmission lines in the power system shown in Fig. 1 has the scheme shown in Fig. 2.

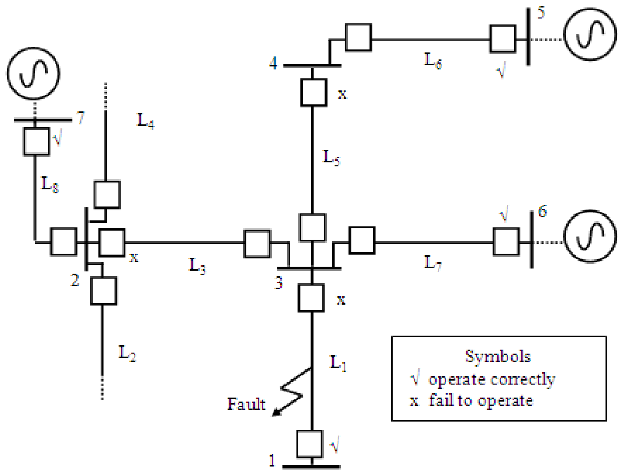

Fig. 1. Analysis on the effect of protective system failures to open

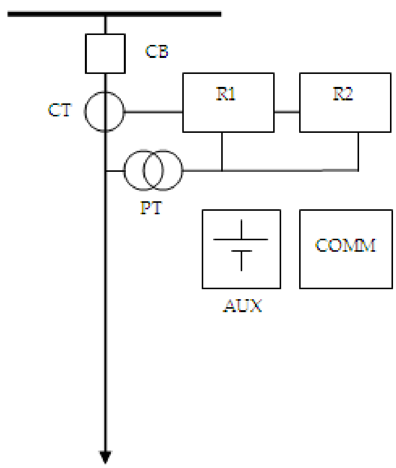

Fig. 2. Protective system at a terminal of a transmission line

For a fault on line L_1, it is necessary to analyze if the PS at terminals 1 and 3 operate correctly, i.e. if they open. If the PS at terminal 3 FTO, it is then necessary to analyze if the PS at terminals 2, 4 and 6 of transmission lines L_3, L_5 and L_7, respectively, operate correctly, and so on. Thus, for this kind of study, it is necessary to represent the PS associated to each PZ; there are two main approaches for this task:

1. To incorporate the reliability models of the PSC associated to each PS.
2. To condense the effect of all PSC associated to a given PS into the reliability models of the circuit breakers associated to the PZ. This can be done because all PS failures are reflected on the PZ circuit breakers no matter the PSC that caused them.

The first approach is the less popular one because it demands more computer processing capacity (RAM) and computing time due to the huge number of reliability models that have to be evaluated. To illustrate this, let us consider a reliability study of the power system shown in Fig. 1; if it only considers failures on the transmission lines, it will require 16 failure models (8 for permanent failures + 8 for temporary failures). If it also considers FTO, it is necessary to incorporate 224 additional failure models in the first approach but only 16 in the second one. These numbers are obtained in the following way:

- 224=8 transmission lines * 2 terminals per transmission line * 7 PSC per PS * 2 failure modes per PSC (FTO+KND)
- 16=8 transmission lines * 2 terminals per transmission line * 1 circuit breaker per terminal

A common practice in the first approach is to restrict the analysis to the PSC considered "most important", i.e. circuit breakers, current transformers and relays; however, this also decreases the level of detail of the reliability study.

Regarding the second approach, the condensed model at each circuit breaker is expressed in the form of a probability for each type of PS failure to operate. These probabilities are computed before and out of the power system reliability study using operating data or by means of a reliability assessment of the protective scheme.

The second method of obtaining the probabilities of the condensed model is applied in those situations where the aim is to evaluate the impact of incorporating PSC with different levels of reliability and of considering diverse protective schemes.

IV. Problem Statement

Several modeling tools have been applied to obtain a condensed model of PS failures to operate: homogeneous Markov chains, event trees, fault trees, cut sets and reliability blocks [2]-[16]. All them work under the assumption that PSC failure and repair processes are stationary; this is expressed by means of constant failure and repair rates, constant probabilities of failure or constant availabilities.

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 and improvement/decrease in maintenance resources. If stationarity is no longer a valid assumption, the application of the mathematical methods mentioned above is no longer valid. By this reason, these authors proposed a method based on stochastic point process (SPP) modeling that can manage constant or time varying rates [17]. It is applied here for obtaining the condensed model of a PS.

A feature of SPP is that it offers a great variety of models for stationary and non stationary random phenomena [18].

V. Proposed Method

A full description of the proposed method is presented in [17]. The main concepts of SPP and the modeling of repairable components are presented in [18].

V.1. Modeling

Each failure mode that applies to the PZ and the PSC and the corresponding repair processes are represented by means of a SPP model with intensity function $\lambda(t)$.

V.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). As depicted in Fig. 3, a simulation consists of n artificial observations of PS performance during T, under a scenario defined by the protective scheme configuration, failure and repair rates and a given strategy for preventive maintenance.

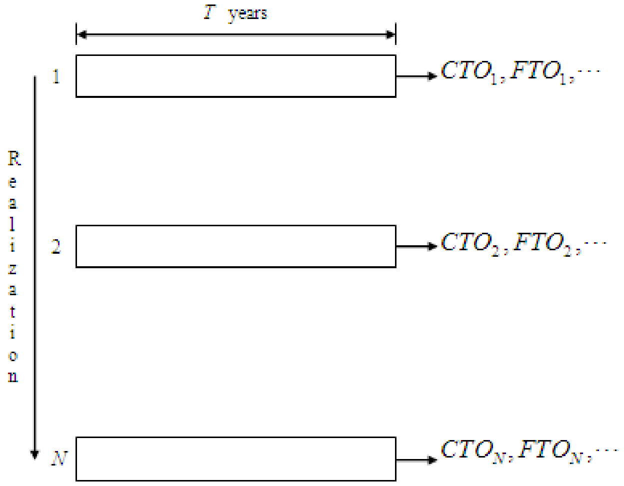

Fig. 3. General procedure of the reliability assessment algorithm

The output of a realization is the set of variables which allow computing the indexes of the PS model, i.e. CTO, FTO, CTC and FTC.

V.3. Procedure inside a Realization

The procedure inside a realization is depicted in Fig. 4; each downward arrow symbolizes the occurrence of an event of failure or maintenance in a PZ with a PS conformed of X PSC.

The steps of this procedure are:

1. Generate the failure process of PZ ($f_1\, f_2 \cdots f_n$).
2. Generate the PSC failure processes.
3. Generate the process of preventive maintenance that requires the disconnection of PZ ($m_1\, m_2 \cdots m_n$).

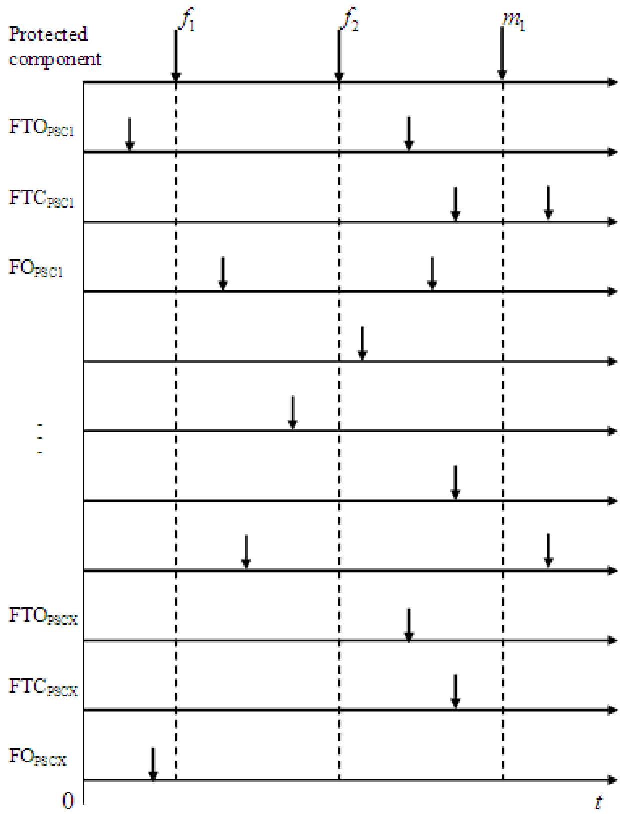

Fig. 4. General procedure inside a realization

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.
6. Repeat steps 1 to 5 n times.
7. The probabilities of the condensed model are computed in the following way:

$$P[FTO]_{Ik} = FTO_k \,/\, CTO_k \qquad (1)$$

$$P[FTC]_{Ik} = FTC_k \,/\, CTC_k \qquad (2)$$

VI. Example

VI.1. Test System

Let us consider the PS associated with the power transformer (TR) shown in Fig. 5. 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). The following PSC are not shown in Fig. 5 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).

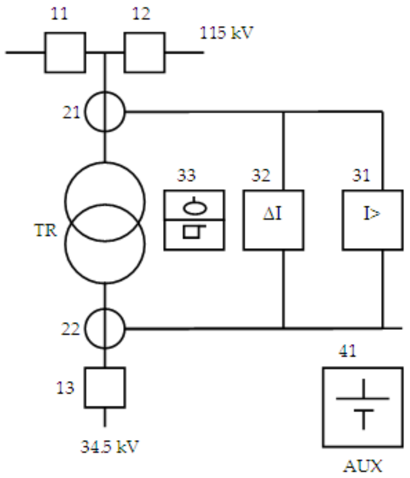

Fig. 5. Protective system of a power transformer

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

TABLE I
PROTECTIVE SYSTEM RELIABILITY DATA [17]

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

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

TABLE II
POWER TRANSFORMER RELIABILITY DATA [17]

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

VI.2. Cases of Study

The proposed method is applied to obtain the condensed model for FTO of the PS at circuit breakers 11, 12 and 13 under the following scenarios:

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.

VI.3. Results

Tables III, IV and V show the results for $T = 3$ years and $n = 10000$ realizations. Fig. 6 shows the probability of FTO at circuit breaker 13 for the three cases of study.

Simulations lasted 0.47 hours, 5.34 hours and 8.81 hours for cases 1, 2 and 3, respectively. The post-processing of the simulation outputs to compute the probabilities of the condensed model lasted less than fifteen minutes in all cases of study.

VI.4. Analysis of Results

In the first case the probabilities of FTO are constant because all failure and repair processes are stationary; thus, it is only necessary to calculate them for one year.

In the second case, the presence of aging in some PSC increases the probabilities of failure as time evolves; this also happens because the repair and preventive maintenance processes are not increased. Results for case 3 show how the improvement on preventive maintenance frequency decreases FTO although the presence of aging in some PSC.

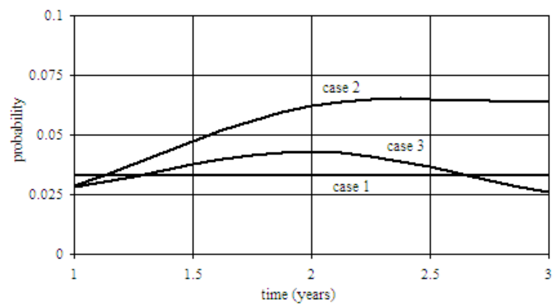

Fig. 6. Probability of failure to open at circuit breaker 13

TABLE III
PROBABILITY OF FAILURE TO OPEN OF THE PROTECTIVE SYSTEM – CASE 1

TIME [YEARS]	$P[FTO]_{I1}$	$P[FTO]_{I2}$	$P[FTO]_{I3}$	$P[FTO]_{I1-I2}$	$P[FTO]_{I1-I3}$	$P[FTO]_{I2-I3}$	$P[FTO]_{I1-I2-I3}$
1.0 – 3.0	0.0484	0.0462	0.0328	0.0000	0.0000	0.0000	0.0080

TABLE IV
PROBABILITY OF FAILURE TO OPEN OF THE PROTECTIVE SYSTEM – CASE 2

TIME [YEARS]	$P[FTO]_{I1}$	$P[FTO]_{I2}$	$P[FTO]_{I3}$	$P[FTO]_{I1-I2}$	$P[FTO]_{I1-I3}$	$P[FTO]_{I2-I3}$	$P[FTO]_{I1-I2-I3}$
1.0	0.0420	0.0414	0.0285	0.0000	0.0000	0.0000	0.0071
2.0	0.1071	0.0937	0.0625	0.0000	0.0000	0.0000	0.0191
3.0	0.1199	0.1070	0.0637	0.0000	0.0000	0.0000	0.0182

TABLE V
PROBABILITY OF FAILURE TO OPEN OF THE PROTECTIVE SYSTEM – CASE 3

TIME [YEARS]	$P[FTO]_{I1}$	$P[FTO]_{I2}$	$P[FTO]_{I3}$	$P[FTO]_{I1-I2}$	$P[FTO]_{I1-I3}$	$P[FTO]_{I2-I3}$	$P[FTO]_{I1-I2-I3}$
1.0	0.0419	0.0413	0.0284	0.0000	0.0000	0.0000	0.0071
2.0	0.0698	0.0620	0.0431	0.0000	0.0000	0.0000	0.0110
3.0	0.0410	0.0402	0.0263	0.0000	0.0000	0.0000	0.0050

VII. How to Use this Model

To illustrate how the PS condensed model is applied, let us consider the sketch shown in Fig. 7.

For a given PS failure mode, for example FTO, the probabilities of occurrence of a FTO at each circuit breaker at a given time are a part of the total probability of the sample space. The sample space also includes the event of not occurrence of FTO.

To sample this model in the reliability assessment at the power system level, a U is generated each time a failure affects the PZ; the value of U defines the event that occurs. For example, using data of Table III, for case 1, if in the first year a failure affects the power transformer and $U = 0.0251$, this means circuit breaker 11 fails to open.

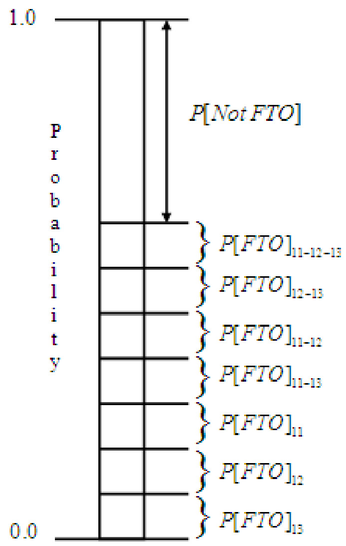

Fig. 7. Sample space for failures to open at circuit breakers

VIII. Conclusion

A new method for representing failures to operate of protective systems in reliability studies at the power system level is presented in this paper. Like other methods that have been applied for this task, it condenses at the circuit breakers of the protection zone the effect of protective component failures, protective scheme configuration and maintenance strategies but unlike them it supports the consideration of time varying failure and repair rates.

The main disadvantage of this method is the long computing time required by the simulation procedure; 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.

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