51. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

PROCEEDINGS 11-15 September 2006

FACULTY OF ELECTRICAL ENGINEERING AND INFORMATION SCIENCE

INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING - DEVICES AND SYSTEMS, MATERIALS AND TECHNOLOGIES FOR THE FUTURE

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TECHNISCHE UNIVERSITÄT
ILMENAU

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff

Redaktion: Referat Marketing und Studentische Angelegenheiten
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Redaktionsschluss: 07. Juli 2006

Technische Realisierung (CD-Rom-Ausgabe):
Institut für Medientechnik an der TU Ilmenau
Dipl.-Ing. Christian Weigel
Dipl.-Ing. Marco Albrecht
Dipl.-Ing. Helge Drumm

Technische Realisierung (Online-Ausgabe):
Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Verlag:
Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilrnenau

ISBN (Druckausgabe): 3-938843-15-2
ISBN (CD-Rom-Ausgabe): 3-938843-16-0

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=12391

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Modelling of HV Devices Diagnostic Procedures

INTRODUCTION

Consequence of asset restructuring are the increasing needs of cost-effective operation, maintenance and diagnostic processes that means the work's reliability of devices/systems should be on high level and cost of eventual breakdown should be as low as possible. Exploitation of high voltage devices has been based till now on specialized traditional tools, typically using "time-based" cyclic maintenance scheduling as a part of all exploitation processes. Increasing importance of diagnostic for supply quality [4] is a reason that diagnostic procedures determine exploitation processes of high voltage devices.

Supply availability depends on technical state of all power electrical devices which participate in transport and distribution process, e.g.: power distribution stations, power and distribution transformers, power electrical lines, etc.

In many matters which are considering under diagnostic procedure, appear random variables depended on parameter (often interpreted as a time). Mathematical models of these occurrences are stochastic processes, e.g. Markov models.
Mathematical models based on Markov theory are used to study of system state if this state in a given moment is enough to determine probabilistic profiles of future system development

The HV device state can be specified by device insulation condition. Result of diagnostic procedure gives information for the classification of insulation states (Tab. 1.). Additional advantage of diagnostic procedure might be renewal of technical state of devices by corrective maintenance. Preventive maintenance type e.g. CBM include a diagnostic procedure. In general, maintenance is either planned.

Presented models below were used to calculation availability of HV devices depends only on time interval of diagnostic procedure or without diagnostic.

Table 1. The classification of insulation states based on the measuring results

	PI – Polarization Index	DAR – Digital Arc Reflection	TC – Time Constant	DD – Dielectric Discharge
Insulation states	10 minutes 1 minute	60 seconds 15 seconds	resistance x capacity	discharge current (after 60s)/(V x C)
S_3 – weak	< 1	< 1	< 100	> 4
S_2 – indefinite	1 do 2	1 do 1,4	100 do 800	2 do 4
S_1 – good	2 do 4	1,4 do 1,6	800 do 2000	< 2
S_0 – „as new”	> 4	> 1,6	> 2000	

MODELS DESCRIPTION

First model represents degradation process of insulation. The example used stochastic processes theory to build mathematical models of HV device insulation to estimate probability of failure, what is cheaper then after breakdown costs.

Model and appropriate methods for parameter estimation of degradation data have been developed [5, 6]. Model is based on Markov theory of random processes. The Markov processes require to subject matter of exploitation and diagnostics probabilistic approach, based on few assumptions. The following assumptions are here taken into account:

- HV Device might be in six states, where four of them represent degradation state of insulation and two – S_4 and S_5 represent damage.
- Degradation is modeling as the natural one directional transition between the states, S_0, S_1, S_2, S_3 determined by result of diagnostic measurements and tests (Tab. 1).
- The probability of the transition to the following state in the step *(n+1)* does not depend on the probability of the transition from step *(n-1)* to *n.*
- p_{ij} is the probability of transitions between states *i* and *j.*

Graf of model is shown on Fig. 1.

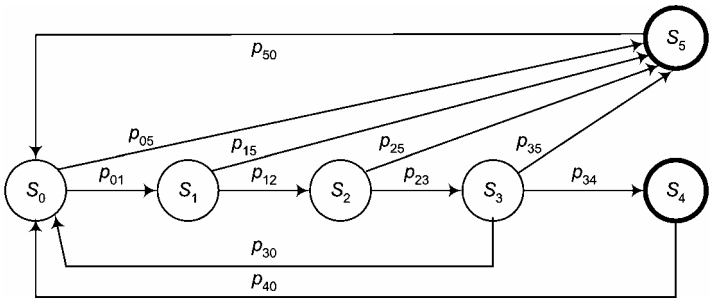

Fig.1. Graph of degradation process

For presented example following simplified probabilities (during single step) are taking into account:

$$p_{01} = p_{12} = p_{23} = p_{34} = 0{,}2 \tag{1}$$

$$p_{05} = p_{15} = p_{25} = p_{35} = 0{,}08 \tag{2}$$

$$p_{30} = p_{40} = 1 \tag{3}$$

One step *n* in simulation is equal 1 year. As the result of calculations are limited state probabilities:

$$p_{S0} = 39{,}5\% \tag{4}$$

$$p_{S1} = 28{,}2\% \tag{5}$$

$$p_{S2} = 20{,}1\% \tag{6}$$

$$p_{S3} = 4\% \tag{7}$$

$$p_{S4} = 0{,}8\% \tag{8}$$

$$p_{S5} = 7{,}3\% \tag{9}$$

Availability is a sum of probability of states S_0, S_1, S_2 and is equal 87,8%.

This mathematical model could support the diagnostics decision process about continuation of devices exploitation or eventually repair.

The next model can be used to simulation and calculation availability of device in exploitation process with diagnostic maintenance. As the practical application, the optimal time of the diagnostic inspection may be calculated on the basis of such model.

The model description has been developed as a continuous time Markov chain [1, 2]. To date, in the power system context, continuous parameter Markov chains have been applied most extensively to model power system and maintenance problems [3]. The following assumptions and approximations have been used for constructing the model:

- The transitions time (times to occurrence of failures, component repair times, preventive maintenance times and times between subsequent preventive maintenance actions) are Weibull distributed random variables. The cumulative distribution function is:

$$F(t) = 1 - \exp(-\beta t^{\alpha}) \tag{10}$$

For α = 1 equation (10) becomes a function of exponential distributions. If α = 1 and $\beta = \lambda$ the expected value of random variable can be expressed as:

$$EX = \frac{1}{\beta} = \left(\frac{1}{\lambda}\right) \tag{11}$$

- Device failures and intermediate state are independent.
- Modeling device cannot become defective during diagnostics and repairs. When device is down the process can only move to up-state at a corresponding repair rate.
- After the occurrence of device failure the process moves to a state in witch the device is in optimal condition (S_0 – state "as new") again.
- The time needed to carry out preventive maintenance is not neglected in favor of a state space reduction.
- When a protection device exhibits a certain defects this defect might be detected and corrected during diagnostic procedure and preventive maintenance.

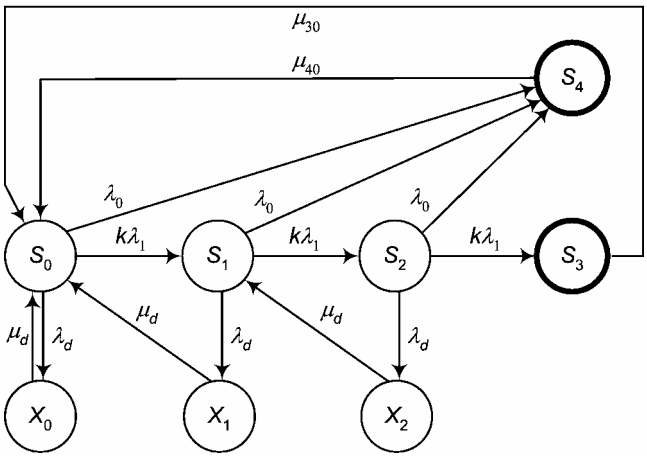

Fig.2. Graph of degradation process with catastrophic damage

Graph of exploitation process in this model (Fig. 2) takes into account the following

states:

- S_0, S_1, S_2 – states of insulating system, defined respectively as new, healthy and degraded,
- S_3, S_4 – damage states,
- X_0, X_1, X_2 – states of diagnostic maintenance.

This model enables the evaluation of optimal interval time between diagnostic procedure and the availability of arrangement as the function of time.

Following quantities are defined in this model:

- rate of occurrence of potential "catastrophic" damage λ_0,
- mean lifetime of insulating system without diagnostic procedure λ_1^{-1},
- rate of repair following "catastrophic" failure μ_{40},
- renewal time of arrangement μ_{30}^{-1},
- time of diagnostic- and repair procedure μ_d^{-1},
- number of intermediate states, in this case k = 3,
- optimal time interval of diagnostic inspection λ_d^{-1}.

The equations describing probability events are in the following matrix forms:

$$\mathbf{P} \cdot \mathbf{\Lambda} = 0 \tag{12}$$

The probability vector **P** is defined as:

$$\mathbf{P} \overset{def}{=} \begin{bmatrix} p_0 & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 & p_7 \end{bmatrix} \tag{13}$$

$$\sum_{i=1}^{n} p_i = 1 \qquad \text{for} \qquad n = 8 \tag{14}$$

whose element p_i denotes the probability that the Markov chain is at state i.

Matrix of transition between states has the form:

$$\mathbf{\Lambda} = \begin{bmatrix} z & k\lambda_1 & 0 & \lambda_d & 0 & 0 & \lambda_0 & 0 \\ 0 & z & k\lambda_1 & 0 & \lambda_d & 0 & \lambda_0 & 0 \\ 0 & 0 & z & 0 & 0 & \lambda_d & \lambda_0 & k\lambda_1 \\ \mu_d & 0 & 0 & -\mu_d & 0 & 0 & 0 & 0 \\ \mu_d & 0 & 0 & 0 & -\mu_d & 0 & 0 & 0 \\ 0 & \mu_d & 0 & 0 & 0 & -\mu_d & 0 & 0 \\ \mu_{40} & 0 & 0 & 0 & 0 & 0 & -\mu_{40} & 0 \\ \mu_{30} & 0 & 0 & 0 & 0 & 0 & 0 & -\mu_{30} \end{bmatrix} \tag{15}$$

where: $z = -k\lambda_1 - \lambda_d - \lambda_0$.

The solution of equations (12) gives the availability of the model, which is

calculated as:

$$A(t) = p_1 + p_2 + p_3 \tag{16}$$

The following example illustrates the implementation of the model. All time and rate are exponentially distributed. In this case: λ_0 = 1/365, λ_1 = 1/365, μ_{40} = ½, μ_d = 2 and k = 3. Thus the equation (16) has a form:

$$A(t) = \frac{1095(37 + 2920 \cdot \lambda_d + 13{,}32 \cdot 10^4 \lambda_d^2)\mu_{30}}{81 + (40{,}73 \cdot 10^3 + 32{,}28 \cdot 10^5 \lambda_d + 14{,}77 \cdot 10^7 \lambda_d^2 + 48{,}62 \cdot 10^6 \lambda_d^3)\mu_{30}} \tag{17}$$

Simulation was taken for renewal time of arrangement μ_{30}^{-1} from 1 day to 7 days. Availability is calculate for constants μ_{30}^{-1} and then depends only on time interval of diagnostic procedure $t = \lambda_d^{-1}$. Plot of whole simulation is shown in Fig. 3.

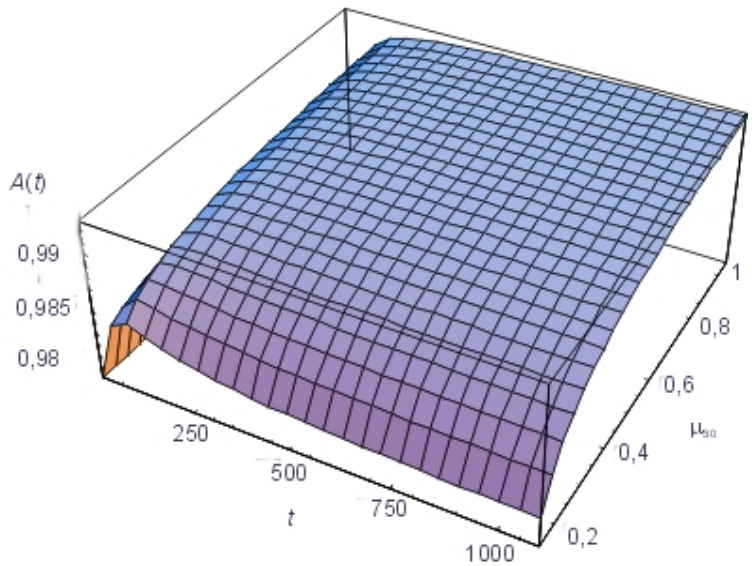

Fig.3. Plot of model availability $A(t)$

For μ_{30} = 1/7 (renewal in 7 days) maximum of function $A(t)$ is equal 0,9851 for t = 74 days. Optimal value of the mean time to diagnostic maintenance (inspection and renewal) is calculated by taking the function $A(t)$ with respect to λ_d and then equating it to zero.

CONCLUSIONS

The mathematical simulation and the knowledge of state changing probability or especially probability of device failure may be applied to increase of preventive effectiveness of diagnostics and HV device work Availability, in other words better supply quality.

Markov theory is very useful to model and analyse the diagnostic processes. Proposed in this paper, mathematical models enable e.g. quick and easy way to equal Availability of HV device. This model makes it possible to simulate any random process with regard to different kind of subject factors.

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