An Analytical Method for Optimum Maintenance of Substations

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Background

External reasons:
- Forces of over burdens running
- Different reliability levels requirement
- Severe weather

Internal reasons:
- Aging Infrastructure
- Limited maintenance resources

How to determine the maintenance policies for every equipment in a substation, to meet the reliability requirement of specific load points?

Objectives

For a load point in a substation:

- Evaluating the system level reliability, given detailed modeling of individual equipment, incorporating different maintenances
- Optimum maintenance policies for individual equipment, to maximize the system level availability
- Optimum maintenance policies to minimize the cost

Current reliability evaluation methods

Probabilistic methods for reliability analysis:

Analytical methods

For individual equipment

- Probability methods
- Markov Processes
- Queuing theory

For System

- Fault-tree
- Markov Processes

Simulation

- State sampling
- State duration sampling
- Sequential sampling

Hybrid methods

Limitations of current methods

Limitations of Analytical Method:

- For Markov Processes, limitations of states in individual equipment, for system modeling
- Absence of modeling aging process of equipment (non-exponential distributions)
- Repairing sources are assumed to be unlimited
- Load burdens are not considered

Limitations of current methods

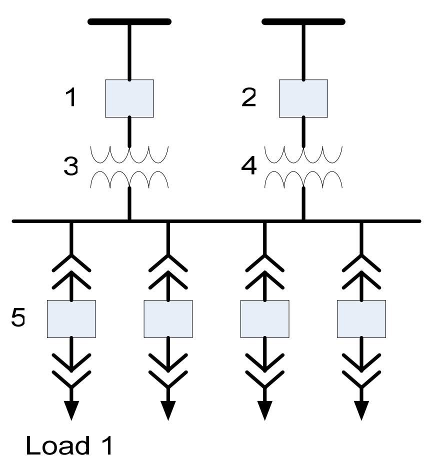
Limitations of Simulation Method:

- High computation burden
- Different results of different running, even for the same system
- Might not capture states that are important but with very low probability

Advantages of proposed method

- An analytical method for system level reliability evaluation
- Quantify the importance of individual equipment in a substation
- Detailed modeling of individual equipment
- Economical analysis for optimum maintenance decision

Quantifying the importance of equipment



Configuration of a typical substation

For Load point 1, which equipment is more important?

The index should reflect:

- Significance of position in a system
- Relevant Unavailability of the system, comparing with other equipment

Importance factors (*IF*)

- Diagnostic Importance Factor

$$IF4 = \Pr\{i \mid S\} = \frac{\Pr\{U_i \cap S\}}{\Pr\{S\}}$$

$\Pr\{i \mid S\}$ The conditional probability that component *i* fails, given that Load Point fails.

$\Pr\{U_i \cap S\}$ The probability that load point fails and component i fails simultaneously;

$\Pr\{S\}$ The probability that load point is unavailable.

- Other Importance factors

Selection of Importance factors

- Capability of reflecting ***importance of position***, ***relevant reliability comparing with others***, ***small varying in value***

No.	Comp. No.	Unavailability	*IF*1	*IF*2	*IF*3	*IF*4
I	1	**0.02**	0.12	3.2258	1.0508	**0.064516**
	2	**0.04**	0.11	2.957	1.0941	**0.11828**
	3	**0.06**	0.12	3.2258	1.1698	**0.19355**
	4	**0.05**	0.11	2.957	1.1205	**0.14785**
	5	**0.03**	1	26.882	5.1667	**0.80645**
II	1	**0.02**	0.11	3.022	1.046	**0.06044**
	2	**0.02**	0.11	3.022	1.046	**0.06044**
	3	**0.06**	0.11	3.022	1.1519	**0.18132**
	4	**0.06**	0.11	3.022	1.1519	**0.18132**
	5	**0.03**	1	27.473	5.6875	**0.82418**
III	1	**0.02**	0.052	4.7785	1.0836	**0.095571**
	2	**0.04**	0.031	2.8487	1.0836	**0.11395**
	3	**0.001**	0.052	4.7785	1.0039	**0.004779**
	4	**0.002**	0.031	2.8487	1.0039	**0.005698**
	5	**0.01**	1	91.895	12.338	**0.91895**
IV	1	**0.009**	0.0218	1.0891	1.0008	**0.009802**
	2	**0.001**	0.0295	1.4737	1.0005	**0.001474**
	3	**0.0005**	0.0218	1.0891	1	**0.000545**
	4	**0.0008**	0.0295	1.4737	1.0004	**0.001179**
	5	**0.02**	1	49.957	1170.6	**0.99915**

Summary of Importance Factors selection

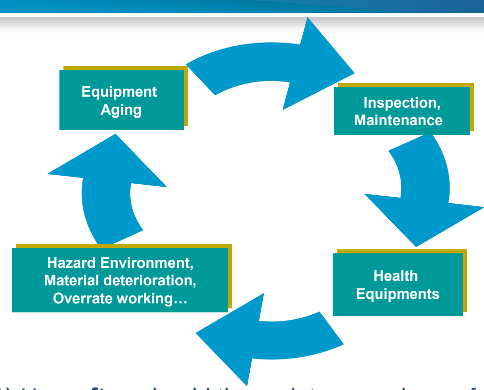
Diagnostic Importance Factor :

- Reflecting the importance of positions
- Relevant availability, which is related to maintenance priority
- High sensitivity

In Practice :

- The availability values for calculating importance factors should be close to real availability values.

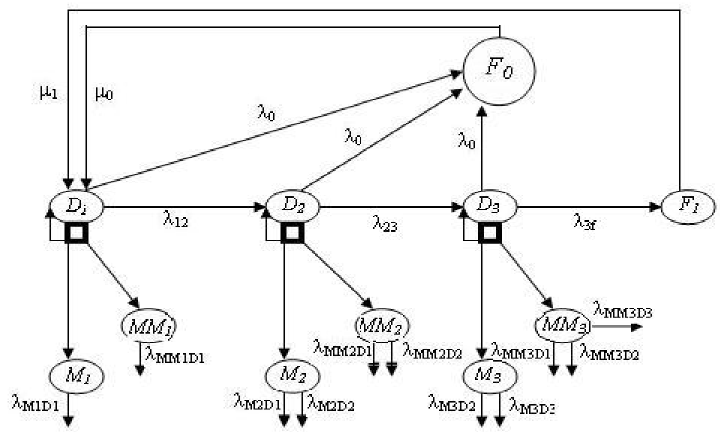
Individual Equipment modeling



1) How **often** should the maintenance be performed?
2) What **type** of maintenance?
3) Under target availability, how to **minimize cost**?
4) How **effective** is the maintenance?

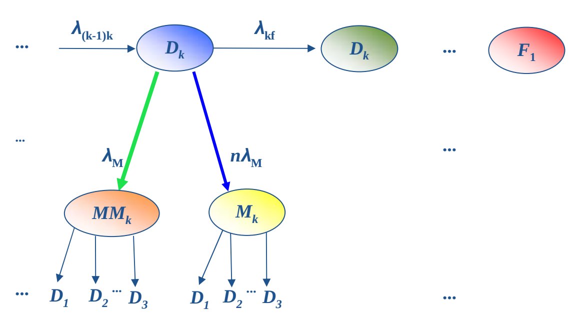
***Quantify* the impact of maintenance on system performance measures**

Individual Equipment modeling- Reliability



State Space Diagram of single equipment of a semi-Markov Process

Optimum policy and expected benefit/cost



What decision to should be made after Inspections?

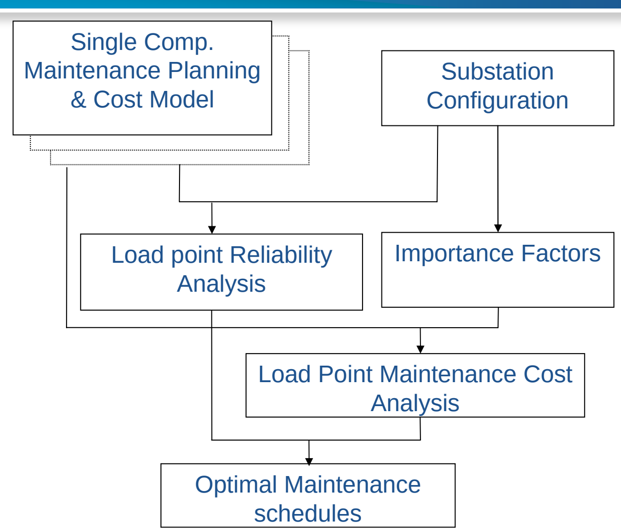
- ***Doing nothing,***
- ***Major maintenance***
- ***Minor maintenance***

Economical modeling

Including following aspects:

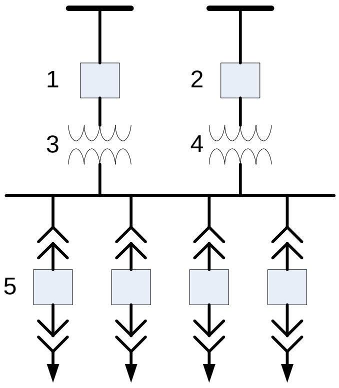
- Utility cost of reliability:
  - Capital investment cost ($)
  - Operation & Maintenance cost ($)
- Customer cost of reliability:
  - Cost of interruption power ($/outage)
  - Cost of interrupted energy ($/kW)
  - Probability consideration of outages (%)

Flow chart of the proposed method



Flowchart for optimal maintenance schedules of a load point

A case study



Configuration of a typical substation

For Load point 1:

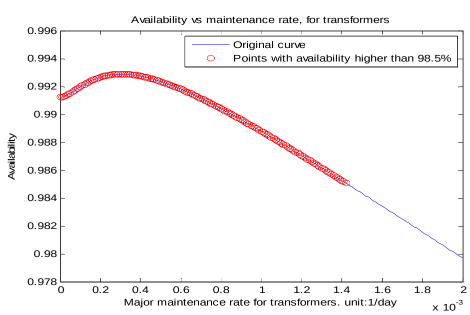
- **How to determine maintenance rates for transformers and breakers, to maximize the availability?**
- **How to determine maintenance policies (minor or major maintenance), to minimize the cost?**

Assumption:

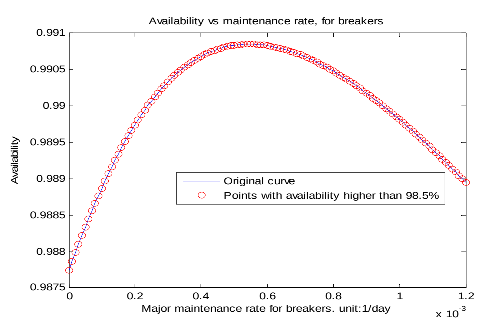
- Same model, same operation and maintenance history for all transformers and breakers
- Future maintenance schedule and policy are also the same

Reliability modeling for single equipment

For transformers



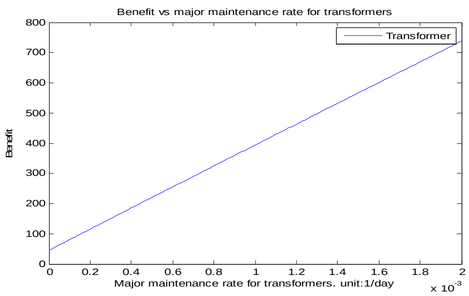
For breakers



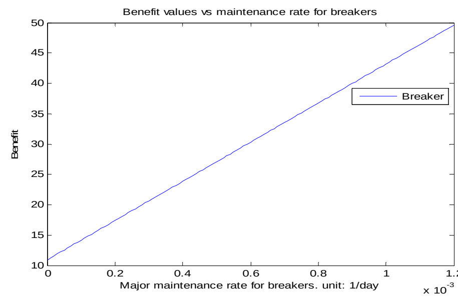
Availability versus major maintenance rates

Expected benefit vs maintenance rate

For transformers

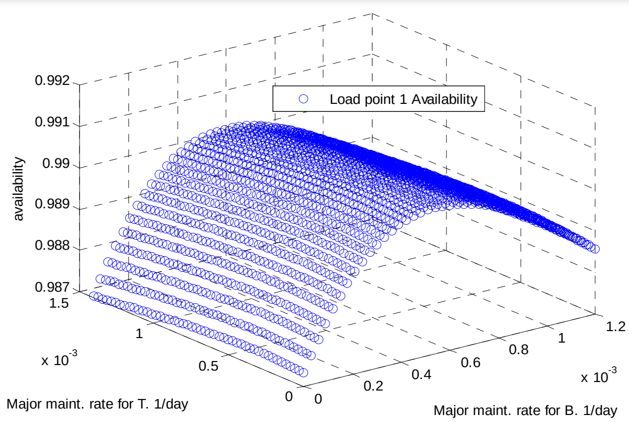


For breakers



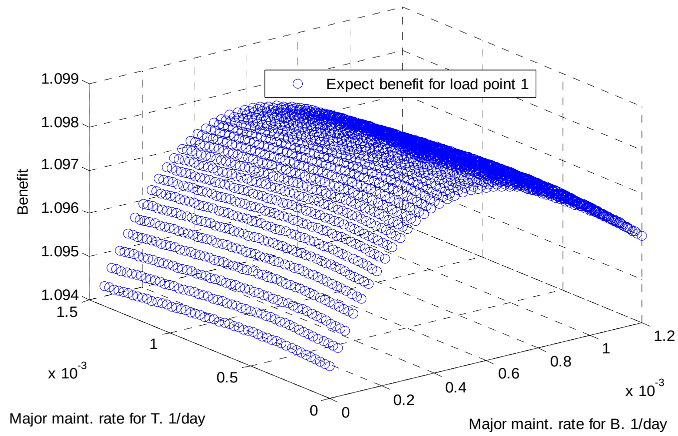
Expected benefit versus major maintenance rate for breakers

Load point reliability



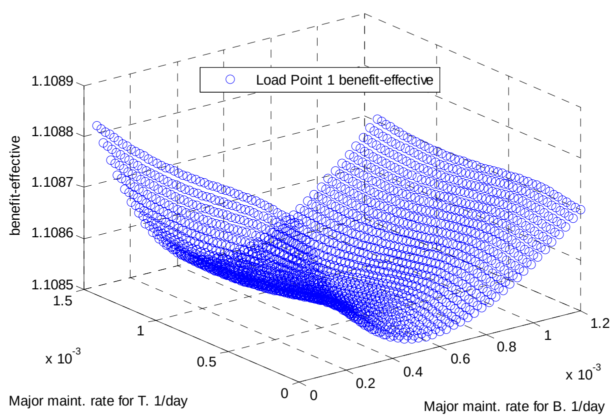
Load point 1 availabilities versus major maintenance rate of breakers and transformers

Expected benefit for load point 1



Load point 1 expect benefits versus major maintenance rates for both breakers and transformers

Benefit-effective analysis



Load point 1 benefit-effective value versus major maintenance rates for both breakers and transformers

Conclusion

Probabilistic substation maintenance planning

- An analytical method for load point reliability modeling, with detailed consideration of maintenance schedules, and policies for individual equipment
- Importance analysis quantifies the contribution of each component toward load point in reliability consideration
- Individual equipment models based on Semi-Markov processes and Semi-Markov Decision processes allow detailed modeling of maintenances and economy

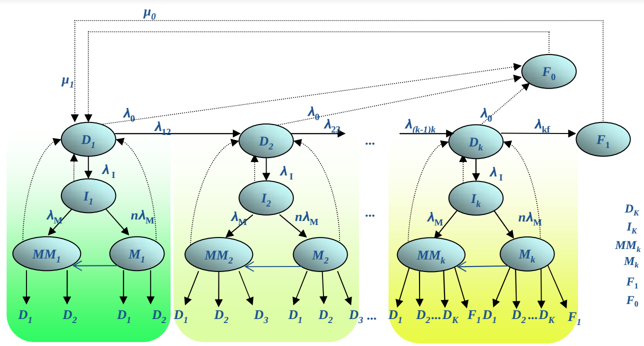
FAQ

- General State-Space Diagram
- How to determine the reward values?
- What type of maintenance is available?
- How to quantify the importance (rank) of load
- What is the difference between this probabilistic method and traditional deterministic method?
- How to get accurate values in Markov model?
- How to determine state and transition rate?

Assumptions

- For individual component modeling with SMP
  1) For a given transition, the time to transit from one state to another follows an exponential distribution;
  2) Assume the equipment can fail due to both deterioration (F_1) or random (F_0);
  3) Assume the maintenance rates are the same in all stages;
  4) Assume there is no transition among maintenance states

General State-Space Diagram



- D_K Kth normal operating state
- I_K Kth Inspection State
- MM_k Kth Major Maintenance State
- M_k Kth Minor Maintenance State
- F_1 Deterioration Failure
- F_0 Random Failure

General state space diagram

More states and transitions, more detailed model;
But requirement of more data for building models.
Needs to balance accuracy and practice.

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How to determine states & transition rates

1. How to determine D_1, D_2, D_3
Perform some diagnosis analysis on equipment, determine the deterioration State based on condition of the equipment.

For Example, IEEE Guide* has a definition of transformer conditions based on oil gas contents. Through condition monitoring, state can be defined from the condition diagnosis result.

2. How to calculate λ_{12}, λ_{23} ,λ_{3f}
From history recording of two consequence states i and j, assuming time to next deterioration state belongs to exponential distribution, the expected value of this time is $1/\lambda_{ij}$.

**Source: IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers, IEEE Std C57.104-1991*

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How to determine the reward values

Rewards are assigned based on transition from a state to another state. The amount of value depend on level of deterioration, maintenance, duration of unavailability of component.
With reward values transition matrix and steady state probability matrix, the expected reward for each state can be calculated.

**Source: IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers, IEEE Std C57.104-1991*

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What type of maintenance is available?

Thermograph testing (magnetic circuit overheating, bushing overheating), ultrasonic testing (oil pump failure), partial discharge testing (magnetic circuit overheating), winding and oil temperature (deterioration of cooling system).

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How to quantify the importance (rank) of load

Quantify the importance of loads is also an importance issues in every substation. But this topic has beyond engineering issues, and Usually related with police and society. We can't just used the standard cost effective or benefit effective to evaluate its importance.

For example, it is apparent that an airport and hospital have higher priority than residences and commercial, even though those load may not give high benefit. Therefore they required more reliable and stable power supplies, and usually power by more than one substations, to ensure the reliability.

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How to get accurate values in Markov model

Markov model is based on probabilistic method, therefore the parameters Used in this models should have probabilistic characteristic. The transition rate value, and transition probability values should be obtained from large number of historical data, in which the type of equipment, the operation environment, and other objective issues that has impact on the life of equipment or reliability are similar.

This requirement needs every utilities to record the reliability data. Now Canadian Electricity Association (CEA) has establish a system to Record reliability data, in which most utilities in Canada have joined.

But usually one can not got enough historical data to reflect the probabilistic character, and the available data often has ambiguity and uncertainty. Another way to building the models with insufficient and ambiguous data is by incorporating fuzzy theory, which is under research now.

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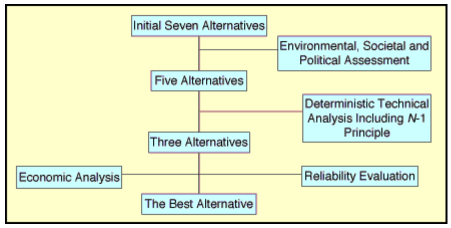
Probabilistic method and deterministic method

Weakness of *N*-1 deterministic method:

1) **The consequences are analyzed but their probabilities of occurrence are usually ignored**
2) **Multiple component failure are excluded from consideration, which exist in reality**
3) **Difficult to deal with all the uncertainty factors, such as load uncertainty and future generation.**



Probabilistic method is not to replace the deterministic method, but to enhance and combine it, to provide more information for planning and operation. Below is a figure of how to combine probabilistic method with deterministic method.

Source: Wenyuan Li and Paul Choudhury,
" Probabilistic Transmission Planning", IEEE Power & Energy magazine, vol.5 No.5, pp: 46-53, Sept. 2007.

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