METHODS FOR MAINTENANCE OPTIMIZATION OF POWER SYSTEM COMPONENTS

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Abstract – **This paper focuses on maintenance optimization techniques for power systems components. The different optimization methods like minimum failure rate, minimum time to repair or minimum total maintenance and repair costs are presented. The second part refers to a time-adaptable maintenance method suitable for complex systems.**

Keywords: *power systems components, time-adaptable maintenance, optimization criteria*

1. INTRODUCTION

The good operation of a power system is strongly related to its components reliability and maintainability. For a repairable system, the reliability is a necessary characteristic but not enough. To be continuously available, a system must be easily to maintain and to repair.

Starting from the consequences on the system after a component failure, there are different criteria for its optimization maintenance.

Another aspect concerns the age-replacement policies of the system components. An optimal age replacement policy is a policy that maximizes the average availability of the equipment over its useful life.

The factors influencing the preventive maintenance management for a power system are presented in fig.1.

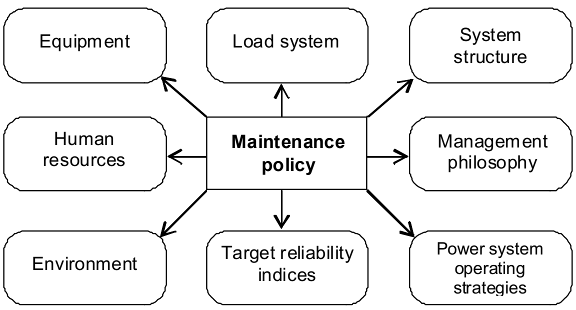

Fig.1 Factors influencing the preventive maintenance policy

The maintenance optimization for power system components is a relative frequent subject in the specific literature [1], [2], [3].

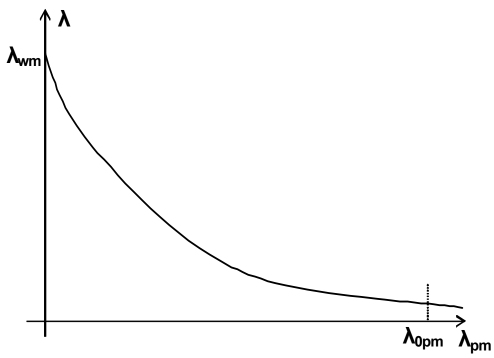

Fig.2 Failure rate-maintenance rate relationship

2. MAINTENANCE OPTIMIZATION CRITERIA FOR POWER SYSTEM COMPONENTS

The initial idea is based on the relationship between the preventive maintenance rate of the component and its failure rate, given by

$$\lambda(\lambda_{pm}) = \lambda_{wm} \cdot e^{-\alpha\lambda_{pm}},\ \lambda_{pm} \le \lambda_{opm} \qquad (1)$$

where:

- λ_{wm}, failure rate without preventive maintenance;
- λ_{pm}, outage rate due to preventive maintenance rate;
- λ, resultant component outage rate
- α, coefficient depending on the component type and the preventive maintenance efficiency;
- λ_{opm}, preventive maintenance rate from which the relationship given by eq. (1) is not valid (fig.2).

2.1. Minimum total failure rate criterion

The total failure rate is given by

$$\lambda_T = \lambda_{pm} + \lambda(\lambda_{pm}) = \lambda_{pm} + \lambda_{wm} \cdot \lambda^{-\alpha\lambda_{pm}} \qquad (2)$$

The minimum λ_T is:

$$\frac{d\lambda_T}{d\lambda_{pm}} = 0 \qquad (3)$$

and

$$\lambda_{pm\ optimal} = \frac{1}{\alpha}\ln(\alpha \cdot \lambda_{wm}) \tag{4}$$

2.2 Minimum total outage duration criterion

The total outage duration of a component is

$$T = \lambda_{pm} \cdot T_m + \lambda_{wm} \cdot e^{-\alpha \cdot \lambda_{pm}} \cdot T_r \tag{5}$$

where:

- T_r is the average repair time of the component;

- T_m is the average preventive maintenance time;

From eq. (5) we can calculate:

$$\lambda_{pm\ optimal} = \frac{1}{\alpha}\ln\frac{\alpha \cdot \lambda_{wm} \cdot T_r}{T_m} \tag{6}$$

2.3 Total minimum cost criterion

The annual repair cost is

$$C_{ar} = (k_{1r} \cdot T_r + k_{2r})\lambda \tag{7}$$

where

- k_{1r} is the repair cost per time unit;
- k_{2r} is the specific repair cost.

The annual preventive maintenance cost is

$$C_{am} = (k_{1m} \cdot T_m + k_{2m})\lambda_{pm} \tag{8}$$

where

- k_{1m} is the maintenance cost per time unit;
- k_{2m} is the specific maintenance cost.

Obviously, the total annual cost is

$$C = (k_{1r} \cdot T_r + k_{2r})\lambda + (k_{1m} \cdot T_m + k_{2m})\lambda_{pm} \tag{9}$$

Considering the eq. (1), the total annual cost is

$$\begin{aligned} C &= (k_{1r} \cdot T_r + k_{2r})\lambda_{fm} e^{-\alpha \cdot \lambda_{pm}} \\ &+ (k_{1m} \cdot T_m + k_{2m})\lambda_{pm} \end{aligned} \tag{10}$$

From

$$\frac{dC}{d\lambda_{pm}} = 0 \tag{11}$$

the optimal preventive maintenance rate is given by

$$\lambda_{mp\ optim} = \frac{1}{\alpha}\ln(\alpha \cdot \lambda_{fm}\frac{(k_{1r} \cdot T_r + k_{2r})}{(k_{1m} \cdot T_m + k_{2m})} \tag{12}$$

$$\lambda_{mp} \leq \lambda_{omp}$$

it is important to bring out that all above calculated optimal values for preventive maintenance are based on the assumption expressed by eq. (1). More systematic research is necessary for a more accurate evaluation of parameter α for different power systems components.

3. TIME-ADAPTABLE MAINTENANCE METHOD FOR COMPLEX SYSTEMS

3.1. Current maintenance practice

An ideal case would be to replace a component just before it is about to fail. This is the opportune preventive maintenance type described in [4]. The necessary, but difficult, condition is to be able to detect, in useful time, that the component has started to fail. Intelligent systems to monitor equipment usage and associated environmental conditions and to predict when preventive maintenance and corrective maintenance will be required are being developed [5], [6].

Traditionally, power system components are inspected at regular intervals. Some times the inspection can be done 'on-site' and, only if damage is found, the component (power transformer, high voltage circuit-breaker, generating unit, etc.) will be removed and recovered in special repairing facility.

The majority of the repair/recovery work done on a power system component takes the form of opportune maintenance. In summary, a component may be removed from installation for the following reasons:

- scheduled revisions;
- failure of an item leading to corrective maintenance; during corrective maintenance some opportune maintenance activities may be carried out;
- components reaching operating life.

A complex component will be removed whenever any of its subcomponents reaches its operating life.

The followings are based on the next assumptions:

- after scheduled inspection and preventive maintenance, the component is assumed to be 'as bad as old';
- the maintenance schedule is determined based on he management policy on he acceptable percentage of failures (or expected life) during the time between maintenance.

3.2 The proposed time-adaptable maintenance method

This method is an age based preventive maintenance one. Its main feature consists in adapting the policy age after each maintenance and inspection activity. The next scheduled maintenance is adjusted so that the risk of failure is not increased.

We can prove that:

- for an aging item it is possible to extend the operating life without increasing the risk;
- for an aging item the time between scheduled preventive maintenance should be decreased to avoid increase the risk of failure.

3.2.1 Increasing the operating time while keeping the initially rated risk of failure

If T_{ol} means operating life of a given component, the failure function, $F(T_{ol})$, gives the probability that this component will fail before T_{ol}. It can be demonstrated that it is possible to increase T_{ol} without increasing the initially accepted risk $F(T_{ol})$ if the power system containing this component is serviced for any other reason (apart from the failure of the component under consideration) before T_{ol}.
For this, let consider T_{sa} be any service activity at the system level. Assume that $T_{sa} < T_{ol}$ then the following relation is valid:

$$R(T_{ol}) \le \frac{R(T_{ol})}{R(T_{sa})} \tag{13}$$

That it is the conditional probability of failure before T_{ol} given that the component survives up to T_{sa} is less than the unconditional probability of failure before T_{ol}. The eq. (13) becomes

$$\begin{aligned} R(T_{ol}) &= [1 - F(T_{sa})] \cdot \frac{R(T_{ol})}{R(T_{sa})} = \\ &= \frac{R(T_{ol})}{R(T_{sa})} - \frac{F(T_{sa}) \cdot R(T_{ol})}{R(T_{sa})} \end{aligned} \tag{14}$$

We can conclude that at T_{sa}, the risk of failure before T_{ol} is reduced by the quantity

$$\frac{F(T_{sa}) \cdot R(T_{ol})}{R(T_{sa})}$$

allowing increasing the operating life of a component after a service event without increasing the initially committed risk.

3.2.2 The relationship between mean time to failure and mean residual life of a component

We can demonstrate that, for any $t_0 \ge 0$,

$$t_o + MRL(t_0) \ge MTTF \tag{15}$$

where MTTF is the mean time to failure of the system, MRL is the mean residual life of a given component and $MRL(t_0)$ is the MRL at age t_0.
The MRL at age t_0 can be calculated with

$$MRL(t_0) = \frac{\int_{t_0}^{\infty} R(t)dt}{R(t_0)} \tag{16}$$

Considering the relations

$$\int_0^{\infty} R(t)dt = \int_0^{t_0} R(t)dt + \int_{t_0}^{\infty} R(t)dt \tag{17}$$

$$\int_{t_0}^{\infty} R(t)dt = \int_0^{\infty} R(t)dt - \int_0^{t_0} R(t)dt \tag{18}$$

But

$$\int_0^{t_0} R(t)dt \le t_0 \quad \text{for any } t_0 \tag{19}$$

and

$$\int_{t_0}^{\infty} R(t)dt \le MTTF - t_0 \tag{20}$$

We can write

$$t_0 + \int_{t_0}^{\infty} R(t)dt \ge MTTF \tag{21}$$

Combining the eq. (16) and (21) we have

$$MRL(t_0) + t_0 \ge MTTF\,, \tag{22}$$

q.e.d.
That means that at age t_0, the expected residual life is greater than the expected life minus the current age. Thus, if the operating life is defined as a fraction of expected life, then we can use the MRL to adjust the operating life.

3.3 How to adapt the time between scheduled maintenance for an aging component

Considering an aging component and assuming that the maintenance policy is to carry out scheduled preventive maintenance at intervals T_{bsm}, the following inequality can be demonstrated:

$$\frac{R(2 \times T_{bsm})}{R(T_{bsm})} \le R(T_{bsm}) \tag{23}$$

or

$$R(2 \times T_{bsm}) \le [R(T_{bsm})]^2$$

$R(2 \times T_{bsm})$ can be written as:

$$R(2 \times T_{bsm}) = \exp(-\int_0^{2T_{bsm}} h(x)dx) \tag{24}$$

where h(x) is the hazard function. Similarly $[R(T_{bsm})]^2$ can be written as:

$$[R(T_{bsm})]^2 = \exp(-2 \times \int_0^{T_{bsm}} h(x)dx \quad (25)$$

To prove inequality (23) means to consider that

$$2 \times \int_0^{T_{bsm}} h(x)dx \leq \int_o^{2T_{bsm}} h(x)dx \quad (26)$$

which is obviously for an aging component.

To implement this time-adaptable preventive maintenance, it is necessary to adjust the scheduling of the service events such as inspections and maintenance after each service event. The next algorithm can be used to carry out the time-adaptable maintenance:

1) Set i=1
2) Carry out i^{th} service event at S_i where S_i = min $\{T_{bsi}, T_{bsm}, T_{ol}\}$ where T_{bsi}, T_{bsm} and T_{ol} are measured from the previous service event and T_{bsi} is time between inspections (revisions)
3) Adjust T_{bsi}, T_{bsm} and T_{ol} using the conditional reliability or mean residual life (MRL)
4) Set i=i+1 and go to step 2.

4. CONCLUSIONS

In the case of complex systems like power systems, according to the effects of failure of their components, we can select different criteria for preventive maintenance with a view to minimize the resultant failure rate, the resultant outage duration or the total maintenance annual cost. All three criteria are simple to put in practice as they were presented in this paper.

The concept of time-adaptable preventive maintenance is especially useful for expensive, complex systems, such as high voltage transmission networks. In time-adaptable maintenance, the inspections (revisions) and maintenance schedule is adjusted after every service activity.

The procedure requires knowledge of the time-to-failure distribution (usual exponential or Weibull) of each important component and the corresponding operating life.

After every maintenance and inspection activity, the operating life and preventive maintenance schedule are revised by adjusting the maintenance interval without increasing the risk of failure (risk initially committed by selecting a maintenance policy).

Future work has to be dedicated to specific study-cases like power transformers, circuit-breakers an generating units as complex components of power systems with a view to demonstrate the real economic advantages (as soon as the primary statistical information will be available) of the time-adaptable maintenance method.

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