QUALITY MANAGEMENT OF THE MAINTENANCE WORKS OF THE DISTRIBUTION NETWORKS

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Abstract

The authors propose to the utility manager some specific tools to optimize the maintenance of the network components. Two optimization methods are presented. First of them is based on the maintenance costs minimization with the failure risk limitation as a restriction while the second is on the basis of a complex objective function considering the preventive and corrective maintenance costs as well as the supply interruption costs to consumers. The results related to the usual situations are included: the single and double way supply systems.

1. INTRODUCTION

A good network operation means a regular maintenance. If the maintenance time intervals are short, the failure probability is small but the involved manpower and the 'out of service' total duration are important. When the time between maintenance activities becomes higher the risk of failures becomes also higher.

Consequently, for both cases, some disadvantages exist and this is the reason of the necessity to optimize the time maintenance intervals based on an accurate and direct process observations: frequency and duration of the supply interruptions, interruption costs to customers, preventive and corrective maintenance costs, etc.

The contribution of every component of the supply system to the global network reliability is depending on the network structure, on own reliability and on the location of the component in the network with respect to the consumers.

The main results are the reliability indices and the optimal maintenance time intervals.

Specific indices as 'weight', 'importance' or 'contribution' [2] offer a global information related to the network components from reliability point of view but these indices are not considering the economical aspects.

Other indices [3] like the overvoltage risk factor or overload risk factor allow for ranking the network components taking into account its adequacy and dynamic security to optimize the maintenance time intervals but without detailed quantitative criteria.

The maintenance time intervals are not the same for every component as established by the actual norms and they could be fixed according to the component influence on the network reliability . Similar components can have different maintenance if they have different influence on the global network reliability.

In the following, two methods about how to calculate the optimum preventive maintenance time intervals are presented. The maintenance costs are considered.

2. THE RISK LIMIT METHOD

The operating probability of a component, having the failure rate λ, during [0…..T], the time interval between two consecutive maintenance activities, is

$$p(T) = \frac{1}{T}\cdot\int_0^{T-t_m} e^{-\lambda\cdot t}\cdot dt = \frac{1}{\lambda\cdot T}\cdot\left[1-e^{-\lambda\cdot(T-t_m)}\right] \approx 1-\frac{\lambda\cdot T}{2}-\frac{t_m}{T} \qquad (1)$$

from which the failure probability is

$$q(T) = 1-p(T) = \frac{\lambda\cdot T}{2}+\frac{t_m}{T} \qquad (2)$$

where t_m is the average preventive maintenance duration of the component.

The operating probability of a n-components system or the probability for supplying all consumers, is

$$p_S(T_1,T_2,...,T_n) = \sum_{k\in S}\prod_{i\in F}[1-q_i(T_i)]\prod_{j\in NF} q_j(T_j) \qquad (3)$$

where:

S – success states of the network;

F – the number of the operating components in the success state *k*;

NF – the number of the failed components in the same state, *k*;

T_i - the time interval between two consecutive maintenance activities of the component *i*, to be optimized.

The condition for $q<q_{\lim}$ is

$$q_S(T_1,T_2,...,T_n) = 1-p_S(T_1,T_2,...,T_n) = q_{\lim} \qquad (4)$$

The specific preventive maintenance cost of the component i is derived from the utility statistics and can be calculated with

$$C_i = t_{mi} \cdot c_h \cdot n_{mi} + c_{ci} \quad \text{[\$/maintenance]} \qquad (5)$$

where t_{mi} is the preventive maintenance duration [h] of the component i, c_h is the specific labor cost [$/h], n_{mi} is the number of workers for the maintenance of the component i and c_{ci} is the material costs for the maintenance of the component i, [$].

The number of the maintenance activities/year for the component i is

$$N_{mi}(T_i) = \frac{8760}{T_i} \text{[maintenance/year]} \qquad (6)$$

The maintenance total cost for the distribution network during a year is

$$CT(T_1, T_2, .., T_n) = \sum_{i=1}^{n} N_{mi}(T_i) \cdot C_i = 8760 \cdot \sum_{i=1}^{n} \frac{C_i}{T_i} \quad \text{[\$/an]} \qquad (7)$$

The optimization task is defined by

$$\begin{cases} F(T_1, T_2, .., T_n) = 8760 \cdot \sum_{i=1}^{n} \frac{C_i}{T_i} = \min! \\ 1 - \sum_{k \in S} \prod_{i \in F} [1 - q_i(T_i)] \prod_{j \in NF} q_j(T_j) = q_{\lim} \end{cases} \qquad (8)$$

The eq. (8) defines a usual constrained optimization problem.

3. A METHOD BASED ON THE ESTIMATED INTERRUPTION COSTS TO CONSUMERS

The method considers not only the preventive and corrective maintenance costs but the interruption cost to customers also. The number of maintenance interventions is depending on the number of the network failures. The total maintenance cost, CMC, is given by:

$$CMC(T_1, T_2, .., T_n) = N_d(T_1, T_2, .., T_n) \cdot C_d \quad \text{[\$/an]} \qquad (9)$$

where $N_d(T_1, T_2, \ldots, T_n)$ means the expected average annual number of network failures [interruptions/year] and C_d is the specific average corrective maintenance cost [$/maintenance]. C_d includes only the network failures and not the failures affecting it from the neighboring system. It can be calculated through the network reliability indices.

The dependence of the time between the maintenance activities (TBM) is based on the failure rate variation. This dependence can be derived from statistics. A relation, the authors used also, is given by:

$$\lambda_i(T_i) = \frac{\lambda_i^0 \cdot T_i}{T_i^0} \qquad (10)$$

where λ_i^0 is the failure rate when the TBM is T_i^0.

We must note that in the previous model of §2, the TBM affects directly the operating probability through relations like (1). This time the influence is taken into account through the reliability indices.

The estimated interruption costs to consumers can be evaluated using the corresponding cost-duration characteristics given by:

$$D(t) = d \cdot t + \sum_{k=1}^{ns} 1(t - t_k) \cdot \Delta D_k \quad \text{[\$/interruption]} \qquad (11)$$

where the first term is a time depending one and the second is related to the critical moments t_k, k=1,2,…,ns. In eq.(11), d is the specific interruption cost to customer [$/h], t_k are the critical moments and ΔD_k [$] are the cost variations corresponding to t_k critical moments.

1(t) is the step function:

$$1(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases}$$

For a given time-interruption cost relationship, the interruption cost to a consumer supplied form the network, depending on the duration T_i, i=1,2,..,n is;

$$\begin{aligned} D_{an}(T_1, T_2, .., T_n) &= N_r(T_1, T_2, .., T_n) \cdot \\ &\cdot D[T_r(T_1, T_2, .., T_n)] + N_m(T_1, T_2, .., T_n) \cdot \\ &\cdot D(T_m) + N_a(T_1, T_2, .., T_n) \cdot D(T_a) \end{aligned} \qquad (12)$$

where:

- $N_r(T_1,T_2,\ldots,T_n)$, $N_m(T_1,T_2,\ldots,T_n)$, $N_a(T_1,T_2,\ldots,T_n)$, are the average annual number of the interruptions [interruptions/year] followed by reparations, by manual switching and by automate switching respectively.
- $T_r(T_1,T_2,\ldots,T_n)$, T_m, T_a are the average duration [h] of an interruption followed by reparations, by manual switching and by automate switching respectively.

$N_r(T_1,T_2,\ldots,T_n)$, $N_m(T_1,T_2,\ldots,T_n)$, $N_a(T_1,T_2,\ldots,T_n)$ are depending on the duration T_i, i=1,2,..n like N_d is depending on. Note that the average manual switching duration T_m is depending specially on the utility technical facilities while T_a on the type and the settings of the automation device.

Considering the three components of the objective function given by eq. (7), (9) and (12), the optimization function is:

$$F(T_1,T_2,..,T_n) = 8760 \cdot \sum_{i=1}^{n} \frac{C_i}{T_i} +$$
$$+ N_d(T_1,T_2,..,T_n) \cdot C_d +$$
$$+ N_r(T_1,T_2,..,T_n) \cdot D[T_r(T_1,T_2,..,T_n)] + \quad (13)$$
$$+ N_m(T_1,T_2,..,T_n) \cdot D(T_m) +$$
$$+ N_a(T_1,T_2,..,T_n) \cdot D(T_a) = \min!$$

The Lagrange Multipliers method was used to solve eq. (8) system for the two test supply systems. The

Eq. (13) represents a nonlinear optimization problem, without restrictions. The gradient type or the direct searching method are suitable to solve it.

4. NUMERICAL RESULTS

To check the mathematical model, authors performed some tests using two supply systems as shown in fig.1 and fig.2

Fig. 1 shows a radial supply system while fig.2 shows a double way supply system..

results, for the different $q_{\lim}$ values are given in table 1 and fig. 3, 4 and 5.

For the second method, based on the expected interruption costs to a consumer from the paper industry, a function like that given by eq. (14) was used:

$$D(t) = 562.5 + 590 \cdot t + 1(t-0.3) \cdot 282 + + 1(t-0.5) \cdot 337.5 \quad (14)$$

The first order Markov chain was the method used to calculate the reliability indices, the interruption cost and the corrective maintenance cost.

The eq. system (13) was solved using the conjugate gradient method. Six iterations in the case of the first supply system and seven iterations for the second were necessary for the calculation convergence. The results are presented in the table 2.

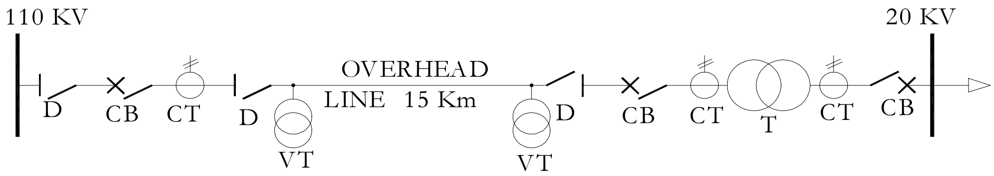

Figure 1
Single line diagram of the 1st test system

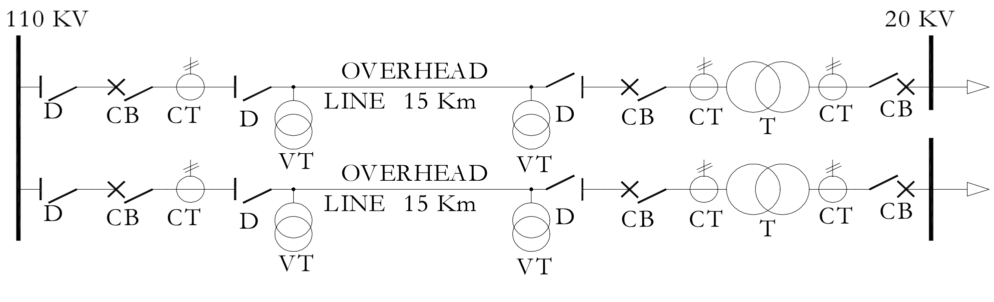

Figure 2
Single line diagram of the 2nd test system

Table 1
The risk limit method results

No.	Test system	Component	The optimal time interval between maintenance activities [years], for an imposed q_{lim} [%]					
			5	10	15	20	30	40
1.	Supply test system no.1	Circuit-breaker	-	-	0.300	0.432	0.703	0.997
2.		Disconnector	-	-	0.611	0.875	1.433	2.060
3.		Current transformer	-	-	0.732	1.063	1.754	2.532
4.		Voltage transformer	-	-	0.335	0.484	0.796	1.144
5.		Line	-	-	0.386	0.570	0.940	1.340
6.		Power transformer	-	-	0.673	0.955	1.549	2.210
7.		20 kV circuit breaker	-	-	0.592	0.825	1.331	1.909
8.		20 kV current transformer	-	-	0.551	0.782	1.277	1.840
9.		20 kV busbar	-	-	0882	1.219	1.955	2.796
10.		F [$/y]	-	-	2849	1973.9	1208	846.7
11.	Supply test system no. 2	Circuit-breaker	0.495	0.750	0.960	1.148	1.499	1.842
12.		Separator	1.005	1.530	1.980	2.394	3.189	4.004
13.		Current transformer	1.201	1.837	2.398	2.946	3.930	4.907
14.		Voltage transformer	0.555	0.850	1.097	1.327	1.763	2.207
15.		Line	0.656	1.004	1.288	1.546	2.024	2.494
16.		Power transformer	1.092	1.654	2.127	2.558	3.376	4.198
17.		20 kV circuit breaker	0.939	1.420	1.833	2.220	2.961	3.729
18.		20 kV current transformer	0.896	1.362	1.755	2.135	2.864	3.606
19.		20 kV busbar	1.385	2.084	2.646	3.162	4.310	5.424
20.		F [$/an]	3446.6	2266.6	1763.7	1466.9	1113.1	898.3

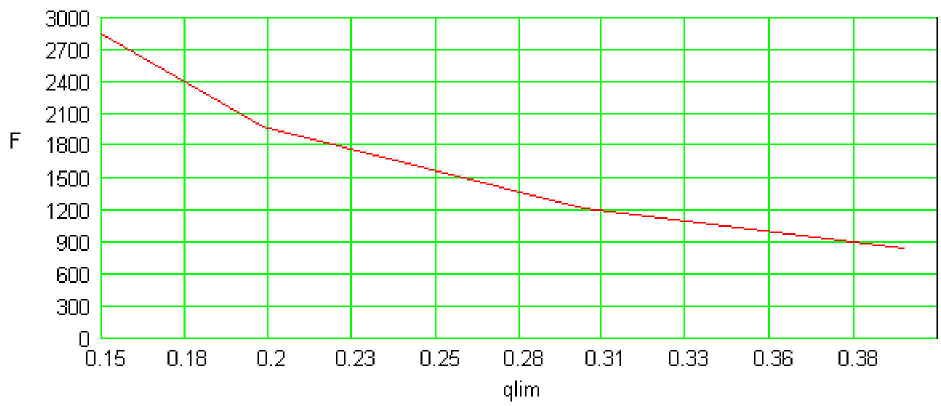

Figure 3
F[$/year] =f($q_{lim}$), relationship for the supply test system no.1

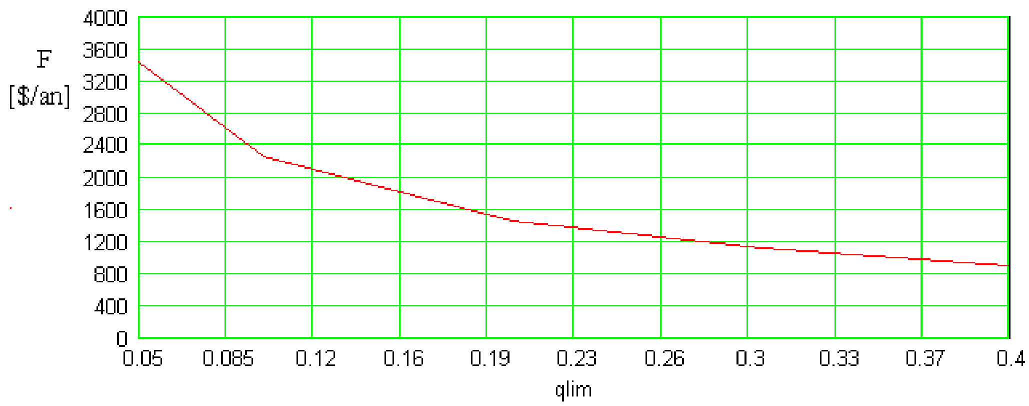

Figure 4
F[$/year] =f($q_{lim}$), relationship for the supply test system no.2

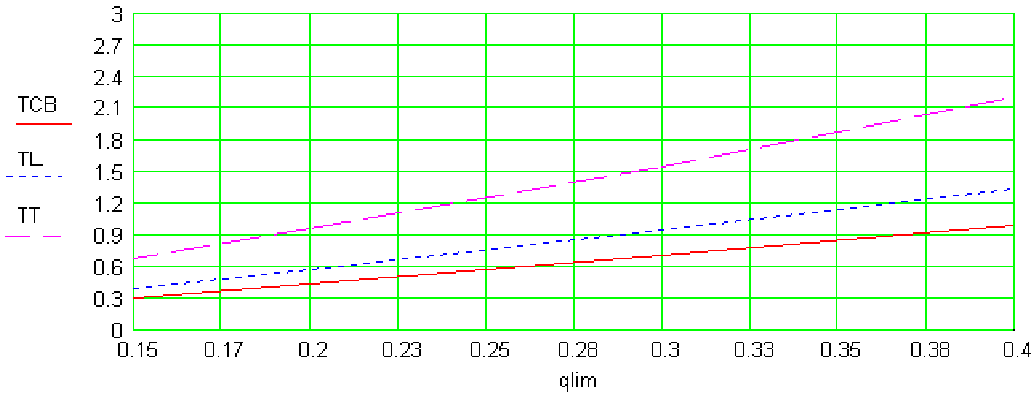

Figure 5
The optimal duration between maintenance activities[years] and the failure probability dependence (supply test system no.1) for different components: CB – circuit breaker, L-line, T – power transformer

5. CONCLUSIONS

The paper offers to the utility managers to useful methods for an efficient maintenance policy starting from the preventive and corrective maintenance costs and the interruption costs to consumers. The total operating cost minimization due to the reduction of the maintenance cost can be in the range 8%-50%.

The practical results are:

a) A supplementary cost is the result of the fixed maintenance time intervals, without considering the network components hierarchy of their influence on the global reliability.

It was demonstrated how the actual maintenance cost of 628$ for thew supply test no.1 can be used in an efficient way to reduce the risk of one failure/year from 78% to 50%.

b) The preventive maintenance cost are increasing for the small values of the failure rates. In the case of a single way supply system this value is q = 0.2 (fig.3) while for the double way supply system, q = 0.1 (fig.4)

c) In the case of a single way supply system, to decrease the value of q under a given value is not possible due to high value of the preventive maintenance interruptions (table 1).

d) In the same case, the expected interruption costs to consumers are high and this is the reason for which in the corresponding method, the maintenance cost is increasing with the iteration order to reduce it. In the case of double, or more, way supply system, the interruption cost are similar to the preventive maintenance cost and they are not decreasing with the iteration order.

Table 2

The optimal results of the second method

Supply test no./ iteration	Optimal time interval between maintenance activities, [years] for the component:									The objective function, F [$/year]	Preventive maintenance cost, [$/year]	Corrective maintenance cost, [$/year]	Expected interruptions cost, [$/year]
	Circuit-breaker	Disconnector	Current transformer	Voltage transformer	Line	Power transformer	20 kV circuit breaker	20 kV current transformer	20 kV busbar				
1/0	2	2	2	2	2	2	3	3	3	12088	628	157	11304
1/1	1.41	1.90	1.83	1.13	2.02	0.67	2.9	3.0	2.8	7820	1014	111	6695
1/2	1.19	1.86	1.76	0.79	2.03	0.28	3.0	3.0	2.8	6957	1687	94.5	5175
1/6	0.50	1.66	1.41	0.25	2.07	0.41	2.9	3.0	2.4	5838	1933	60.3	3844
2/0	2	2	2	2	2	2	3.0	3.0	3.0	2945	1253	158	1533
2/1	1.36	2.15	2.17	1.81	2.78	2.43	3.0	3.0	2.9	2794	1225	139	1429
2/2	1.67	2.40	2.48	1.50	3.66	2.82	3.0	3.0	2.7	2737	1080	152	1504
2/7	1.41	2.61	2.79	1.53	4.44	2.88	3.0	3.0	2.4	2701	1090	145	1466

e) The risk limit method considers only the influence of the preventive maintenance duration on the network reliability but not the corrective maintenance and the expected interruption cost to consumers. The second method these are included but the influence of the planned maintenance on the consumers is neglected.

The authors recommend the risk limit method for the maintenance optimization in the case of the radial, single way, supply systems while the second method is a suitable one for the looped networks.

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