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A Dynamic Programming Model for Maintenance of Electric Distribution System

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***Abstract*—**The paper presents dynamic programming based model as a planning tool for the maintenance of electric power systems. Every distribution component has an exponential age depending reliability function to model the fault risk. In the moment of time when the fault costs exceed the investment costs of the new component the reinvestment of the component should be made. However, in some cases the overhauling of the old component may be more economical than the reinvestment. The comparison between overhauling and reinvestment is made by optimisation process. The goal of the optimisation process is to find the cost minimising maintenance program for electric power distribution system.

***Keywords*—**Dynamic programming, Electric distribution system, Maintenance.

I. Introduction

ELECTRIC distribution is a monopoly activity in Finland. Traditionally, the maintenance of distribution network is based on visual evaluation of the drift- and maintenance personality who has entered the evaluation data in the maintenance database of the electric company. There are two main approaches to create maintenance strategies, namely, corrective and preventive maintenance [1]. Preventive maintenance can further be divided to time-based maintenance (TBM) and condition-based maintenance (CBM) [2]. TBM is based on the service history of the component using regular and scheduled intervals. CBM is based on the condition and state of the component and, for example, a maintenance activity is determined when the condition of the component falls below acceptable standard.

Reliability-centered maintenance (RCM) is an improvement over TBM and CBM [2]. In reliability based maintenance the maintenance is activated when the theoretical reliability of the component falls below standard. On the other hand the overhaul or reinvestment can be activated when the failure costs rise over the maintenance or investment costs. No doubt, there may be many different approaches to schedule the overhaul and reinvestment operations, for example, optimisation techniques may be applied.

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II. Fault Cost of Components

The reliability of the system may be determined by aggregating the individual failure rates that impact the reliability of the system [1]. Naturally, there may be different approaches to perform this aggregation. The components are categorized according to their type. In most of the studies the components used are a) base case b) busbar c) breaker d) cable e) transformer.

According to [3], the sensitivity studies indicate that cables have a significant impact on system reliability and they are therefore the critical components. The causes of failures which have significant impact on cables are a) damage 16 %; b) personnel 12 %; material and method 59 %. To material and method the main contributions to this failure are a) fabric and material 14 %; b) lack of maintenance 5 %; c) wrong method or instruction 15 % [3]. Those causes of failures can be eliminated by the maintenance activities.

In the example network only three components are used: insulated cables, un-insulated wires and transformers. The fault costs of an individual component are given directly without applying fault risks. Moreover, the reliability of the component or reliability of the total system is not applied. Indeed, each component has its own fault cost function.

Generally speaking the fault cost functions $C_F(t)$, fault costs at the year *t*, may be derived from the probability distribution of the components life-time. Indeed, let $C_F(0)$ be the given fault cost of the component when it is new, that is, $t = 0$. Then, it may be demanded that $C_F(0) = C_F(t) \cdot P(X \geq t)$, where $P(X \geq t)$ denotes the probability that the component will work at least *t* years. If the curve of the probability density function is approximately Gaussian shaped then the curve of C_F would be approximately exponentially shaped.

In the example model, the failure rate is linear for the first 25 years according to

$$X(t) = \frac{1}{30} t \cdot X(0) + X(0), \quad 1 \leq t \leq 25, \tag{1}$$

where $X(0)$ is the failure frequency in the beginning for the component and $X(t)$ in year *t*. After 25 years the failure cost is exponential by:

$$X(t) = \frac{1}{72{,}848} e^{t-25} \cdot X(0) + 1{,}9627 \cdot X(0), \quad t > 25. \qquad (2)$$

The failure cost can be found as follows

$$C_F(t) = X(t) \cdot l \cdot T \cdot P \cdot p \qquad (3)$$

where $X(t)$ is the failure rate [1/km,a], l is the length of the component [km], T is the length of the failure [h], P is the load of the component [kW] and p is the cost effect of the failure for the utility and the customers [€/kWh]

In fact, the explict forms of (1) and (2) are designed to indicate that the probability density function of the component's life-time is not exactly Gaussian shaped. In Fig. 1 is presented the failure cost of the "line 12" in the test network depending on the age of the line (years).

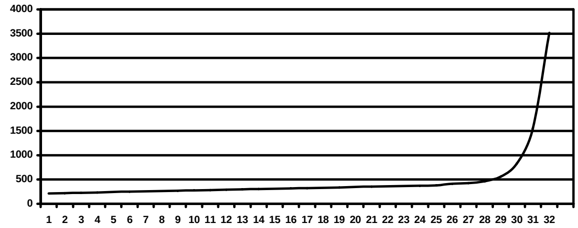

Fig. 1 Failure cost of line 12, euros/year with the age of the component

The approach to give the failure cost functions directly relies on the notion that the probability density functions of the components's life-time seems to be hard to obtain.

The input data to the model is presented in Table I.

TABLE I
INPUT DATA IN THE TEST NETWORK

Component	Failures 1 / km,a	Length km	Energy MWh	Age a	Investment €
12	0.06	4	410	15	100000
23	0.065	5	100	15	125000
tarns 3	0.1		100	15	40000
31	0.06	0.2	15	15	5000
32	0.085	0.3	60	15	7500
33	0.07	0.5	25	15	12500
24	0.06	6.2	310	10	155000
trans 4	0.11		40	10	40000
41	0.05	0.3	40	10	7500
46	0.03	7.3	130	9	182500
trans 6	0.16		130	9	50000
61	0.06	0.15	40	9	3750
62	0.065	0.17	60	9	4250
621	0.08	0.3	30	9	7500
45	0.07	8	140	6	200000
trans 5	0.09		140	6	50000
51	0.04	0.2	50	6	5000
52	0.06	0.4	30	6	10000
53	0.055	0.5	60	6	12500

The cost effect for customers and for energy utility is 5 € / kWh. The write-off period for components is 30 years. Failure time of the components vary from 1h up to 2.8 h.

In the Fig. 2 is presented the 20/0,4 kV test network used; The test network includes lines and transformers. 110kV/20 kV transformer is not included. 20 kV network is in the same protection area. 0,4 kV lines are protected separately.

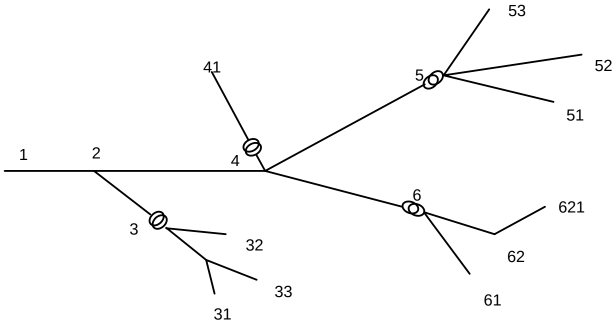

Fig. 2 Test network including lines and transformers

III. ON MAINTENANCE AND INVESTMENT MODELLING

Reinvestment and overhauling schedule is a major priority process for a distribution company. Because there can be several hundreds of components in one distribution area it may be impossible to compute all overhauling and investment alternatives. It is assumed that the different components of the system are independent from each other. It might be then possible to compute optimised maintenance and investment schedule separately for each component. The maintenance priority of the component depends then on its failure costs.

In the model there are three possible strategies in each year during the scheduling period; in the example the scheduling period is 60 years. The first alternative is not to do anything. In this alternative there are no investment and maintenance costs, but the failure costs of the component increase according to (1) and (2). The second alternative is to maintain, overhaul the component. In this alternative there is maintenance cost, in the example 10 % of the reinvestment cost. Overhauling the component decreases the failure cost to the level, which is 5 years before. The third alternative is the reinvestment, that is, to change the component to a new one. The investment costs for the component during the scheduling period are determined, for example, according to Table 1. The problem is to design a maintenance, overhaul and investment program during the scheduling period. This means that optimal path from the current moment of time until the end of the scheduling period should be determined.

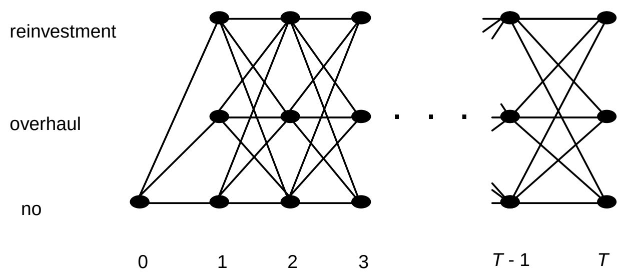

Fig. 3 Chart of all possible strategies for each component

Because there are 3 alternatives, there are then 3^T possible paths from the present moment of time until the end of the scheduling period which is T years. If T is a large number, as it is in the example $T = 60$, then it is reasonable to reduce the number of the paths to be computed or updated.

IV. Dynamic Programming Model in Maintenance

In the current context, see Fig. 3, the idea in dynamic programming is to choose the cost minimizing optimal route for each state (t, n), where $t \in \{1,2,\dots,T\}$ is the current moment of time and $n \in \{0,1,2\}$. If $n = 0$, then nothing is done to the component, if $n = 1$, then the maintenance, overhaul action is performed, and when $n = 2$, then the component is changed to a new one, thus, the reinvestment is performed.

The dynamic programming is considered, because dynamic programming reduces effectively the number of maintain strategies to be compared. Moreover, there are effective algorithms (see [4, 5]) to find the shortest path (Dijkstra's algorithm) or estimated shortest path (A^*-search). At each state (t, n) the total costs are estimated for the whole design period. So, the model is in fact based on the A^*-search method, however, the original idea for the model is from [6].

The task can be presented mathematically as an objective function

$$G = \min \sum_{t=1}^{T} [C_I(t) + C_M(t) + C_F(t)], \qquad (3)$$

where $C_I(t)$ is cost of investment in year t, $C_M(t)$ is maintenance costs in year t and $C_F(t)$ is failure costs in year t.

Maintenance cost $C_M(t)$ is presented with following sum [1]

$$C_M(t) = C_{ins}(t) + C_{clr}(t) + C_{ovh}(t) + C_{uo}(t) \qquad (4)$$

where $C_{ins}(t)$ is costs of inspection and costs of eliminating minor faults, $C_{clr}(t)$ costs of clearing the corridors, $C_{ovh}(t)$ costs of capital overhauls and $C_{uo}(t)$ costs of unplanned outages

Generally speaking in dynamic programming the optimal strategy is found by minimizing the following recursion equation [6]

$$G(t,n) = \min_{m=0,1,2} \{G(t-1,m) + V[(t-1,m),(t,n)]\} \qquad (5)$$

where t is year, (t,n) is state, $G(t,n)$ is minimum costs up to state (t,n) and $V[(t-1,m),(t,n)]$ transfer costs from state (t-1,m) to state (t,n)

In the model the transfer costs can be calculated by

$$V[(t-1,m),(t,n)] = \sum_{t'=t}^{T} INV(m,n)\cdot\varepsilon\cdot\alpha^{-t'} + C_F(t,n)\cdot\alpha^{-t} + C_M(t,n)\cdot\alpha^{-t} \qquad (6)$$

where $V[(t-1,m),(t,n)]$ is transfer cost from state (t-1,m) to state (t,n), $INV(m,n)$ is investment costs when investment is realized as a reinvestment or maintenance investment, ε is annuity factor, α is (1+p/100), p is the applied interest rate, T is length of design period in years, $C_F(t, n)$ is failure cost per year when state alternative n is realized and $C_M(t,n)$ is maintenance cost in year when state alternative n is realized

In transfer cost equation the first term includes all the annuities over the design period of the investment. The investment may be the reinvestment of the component, that is, when $n = 2$, or the cost of the major maintenance operation (n=1), which has effect on the rest failure costs of the component in the design period.

The term $C_F(t, n)$ is the failure cost per year when the alternative n is realized. If the state n represents reinvestment the failure cost decreases to the level, which the component has in the beginning of the life circle of the component. If n is the maintenance operation the failure cost decreases to the level determined for this maintenance activity.

Because the investment costs in equation (6) represent the cost over rest design period and the losses C_F and C_M represent only the cost in year t the additional cost representing losses in the end of the design period is added to the transfer cost (6) when determining the optimal route. This gives us at each state (t, n) the estimated total costs during the whole scheduling period. The equation (7) represents this additional cost

$$A(t-1,m) = \sum_{t'=t+1}^{T} (C_F(t',m)\cdot\alpha^{-t'} + C_M(t',m)\cdot\alpha^{-t'}) \qquad (7)$$

The additional cost includes the approximated failure and maintain costs for maintenance/reinvestment alternative from year t+1 to the end of the design period. Naturally, many different approaches may be applied to give these approximations.

The decisions on optimal routes for each state can now be found minimizing the sum

$$Z(t,n) = \min_{m=0,1,2} \{ MINCOST\ (t-1,m) + V[(t-1,m),(t,n)] + A(t-1,m) \}. \qquad (8)$$

This means that in each state the total cost over the design period is minimized. The minimum cost $MINCOST(t, n)$ stored for state (t, n) includes the $MINCOST(t\text{-}1, m)$ and transfer cost $V[(t\text{-}1, m), (t, n)]$ but not the additional cost. So the additional cost is only used for comparing the optimal route for state (t, n). Notice that this is also the main idea when applying the A^*-search.

In the end of the scheduling period it is possible to find which of the minimum total costs $MINCOST(T, 0)$, $MINCOST(T, 1)$ or $MINCOST(T, 2)$ is minimum. Because the optimal route is stored for every state in every time step, it is possible to find the optimal route for every time stage from the end $t = T$ to beginning $t = 1$.

V. Results for the Test Model

Using dynamic programming the overhaul and reinvestment years are computed for the test network in Fig. 2. The results are presented in Table II. Because the failure cost curve in Fig. 1 is approximately exponential it is obvious that the maintenance and reinvestment years are in most cases sequential. For one component the maintenance seems not to be reasonable (line 32) and reinvestment might be done straight. This result depends on the effectiveness of maintenance.

TABLE II
Overhaul and reinvestment schedule for the test network

Component	Year of the overhaul	Year of the reinvestment
12	18	22
23	18	22
tarns 3	19	24
31	21	26
32		24
33	20	25
24	23	27
trans 4	25	30
41	25	29
46	25	29
trans 6	25	29
61	26	30
62	25	30
621	26	30
45	26	31
trans 5	27	32
51	29	33
52	29	33
53	29	33

VI. Future Development

For electric power companies the maintenance program for each component is not independent on the other components. It may be reasonable to maintain in the same time all components which are near to each other or in the same area. For that purpose there should be the new parameter for the initial values in Table I. This value is the group of each component, which is the parameter which tells the components to be calculated together. In this case there will be the problem to determine the most important component in the group. Another problem is to decide whether the maintenance activity should be performed for all or only some components in the group. The authors think that Fuzzy Set Theory might give some tools to solve am. problems.

VII. Conclusion

Reliability-centered maintenance (RCM) and dynamic programming gives a powerful tool for designing the overhaul and reinvestment strategy for the electric distribution network. The result depends effectively on the initial values and parameters, but the method gives for a network designer a possibility to apply, for example, sensitive analysis. More advanced mathematical models could be used in the future for maintenance problem for distribution companies.

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