RISK-BASED ASSET MAINTENANCE MANAGEMENT IN DISTRIBUTION SYSTEMS

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ABSTRACT

This paper proposes a method for comparing the effect of different maintenance strategies on system reliability and cost. This method examines the potential benefits of treating the comparison of the suitability of different modes of distribution network maintenance as a risk assessment problem. This paper also illustrates the application of optimization tools in resource allocation and maintenance prioritization by using a combined optimal algorithm linear-binary and dynamic programming. The overall approach provides a powerful tool to inform asset managers how alternative resource allocation of maintenance affects the end goal of maximum risk reduction taking into account cost constraint or affects the end goal of minimum cost of maintenance while maintaining the identified level of risk reduction (system reliability). The risk-based optimal strategy is applied in a practical case study in an urban distribution system in Tehran, Iran. The proposed strategy considers resource allocation for distribution equipments categorized into 4 classes of, 1) cable, 2) breakers (such as reclosers, disconnected switch),3) over head line, and 4) transformer.

INTRODUCTION

The goal of an electrical power distribution is to provide a reliable service to the customers. These services must be provided in a cost effective manner. This indicates that utilities must satisfy quantitative reliability requirements while at the same time minimizing their costs [1]. Electrical engineers have strong incentive to maintain distribution network reliability using proper preventive maintenance strategies. Despite of the large equipments in the distribution network, different faults are caused interruptions and subsequently increase system risk. Because of this, many maintenance tasks can be performed to prevent these faults. Due to the limitation in the budget of distribution companies, creating a good balance between the system reliability and investment cost is of utmost important. Reference [2] addresses three hierarchical decision problems: total resource planning for maintenance, resource allocation to maintenance categories, and task selection within each category. There exist some restrictions in techniques proposed in [3]. These concepts are further taken into account by applying an optimization method. This is done using a similar approach presented in [2] where a risk-based approach is utilized. The difference is that the method presented in [2] focused only on the maintenance of sustained failures and a test system has been developed in [3] which consider resource allocation for wood poles, reclosers, and tree trimming. This work presents 3 new approaches, 1) both sustained and momentary failures are considered together, 2) all of equipments and their maintenances can affect to the objective function in 4 categories, a) cable, b) breakers, c) overhead line, d) transformer, 3) two aspect of the dp programming results can use to show either the amount of investment for specific level of risk reduction (benefit) or amount of risk reduction for identified budget. To facilitate this, the paper will first clarify the formal distinction between risk and reliability as applied to quantifying network performance. Afterward, the formulation and related solution approach are given. Then, the proposed approach is applied to a test distribution system to illustrate the impacts of differing maintenance task on apparent network vulnerability and benefits of using risk assessment.

DEFINITION OF RISK

One of the advance and cost effective forms of preventive maintenance strategy is called Reliability Center Maintenance (RCM). RCM can be used to plan a cost-effective maintenance strategy to address dominant causes of equipment failure. Risk assessment techniques can be used to prioritize assets and to align maintenance actions to business targets at any time. By doing so we ensure that maintenance actions are effective and the indirect maintenance costs such as costs associated with safety, environmental risk and customers' dissatisfaction are minimal. The risk-based objective function takes into account reliability and relative cost. Risk is the potential impact to an asset or characteristic of value that may arise from some present processes or from some future events. In every day, "risk" is often used synonymously with "probability" and restricted to negative risk or threat.

Risk (k) =Pr (k). Sev (k)
Where;
K: component number
Pr (k): failure probability of component (k) failure
Sev(k): cost arisen due to failure of component (k)
Reliability can be considered by the following effects of equipment failure:

1) Effect on the customer satisfaction in terms of the expected Number and duration of interruptions (SAIFI, SAIDI, MAIFI factors)
2) Revenue lost by the utility due to energy not served; (ENS factor)
3) Cost of equipment failure in terms of the expenses incurred. (Devrisk factor)
The consequences of equipment failure may thus be expressed as the weighted sum of the quantities provided in the above mentioned (1)–(6) and comprises the "*Risk*" associated with a component's failure. Maintenance reduces the failure rate of equipment and/or increases the time to failure. This paper focuses on the risk reduction through reducing the failure probability. The following expressions can be used to quantify the effect of maintenance performed on a component "k":

$$\Delta\lambda = \lambda_b(k) - \lambda_a(k) \quad (1)$$
$$SAIFI_b(k)\text{-}SAIFIa(K) = \Delta SAIFI(K) \propto \Delta\lambda \quad (2)$$
$$MAIFI(k)_b - MAIFI(k)_a = \Delta MAIFI(k) \propto \Delta\lambda \quad (3)$$
$$SAIDI_b(k) - SAIDIa(K) = \Delta SAIDI(K) \propto \Delta\lambda \quad (4)$$
$$\Delta ENS\ (K) \propto \Delta\lambda.\ load\ (k) \quad (5)$$
$$\Delta Devrisk = \Delta\ \lambda.\ COST\ (K) \quad (6)$$

Where, the subscripts "b" and "a" correspond to the state of the component before and after maintenance, this risk is combined with the financial and human resource requirements to prioritize maintenance projects in order to maximize risk reduction. A detailed composite risk index is given below:

$$\Delta Risk(k) = \alpha_1.\Delta SAIFI(K) + \alpha_2.\Delta SAIDI(K) + \alpha_3.\Delta MAIFI + \alpha_4.\Delta ENS(K) + \alpha_5.\Delta Devrisk \quad (7)$$

The coefficients used in (7) correspond to the weights that an asset manager can assign to different factors based on their relative importance. This paper is in the process of compiling information of cost associated with customer interruption (the expected regulatory penalty). These coefficients are different for industrial, residential, commercial and other customers.

RESOURCE ALLOCATION OPTIMIZATION

Figure 1 shows the procedure in a risk based maintenance approach. Accordingly, it consists of three main stages:
- The functional analysis which enables the function of each item of equipment in the system will be defined(especially modeling of equipment failure rate)
- The Failure Modes, Effects and Criticality Analysis (FMECA) which enables the failures which may occur in any equipment to be analyzed and a list of critical equipment to be deduced. On this basis, by analyzing the impact of the failure on safety and operating costs, a systematic search for the most efficient maintenance tasks is started to remedy the most critical failures (risk and cost of implementation).

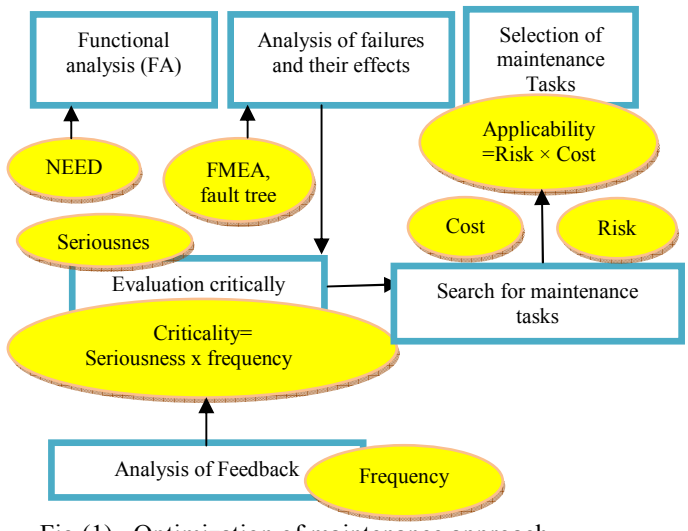

Fig (1). Optimization of maintenance approach

PROBLEM FORMULATION

Once the asset manager has a complete list of maintenance tasks and the corresponding risk reductions for each component proposed to be maintained, tasks are selected to maximize the risk reduction within the resource constraints. This requires the use of optimization techniques to solve the following mathematical program:
To enhance the reliability through the preventive maintenance, it is desired to maximize the summation of the risk reduction introduced by a group of candidate maintenance tasks under a limited allocation of resources, e.g., financial and labor resources, where resources are limited by category.
So for each maintenance category *p* (p is class number of distribution equipments), the problem formulation is:

$$\text{MAX:} \sum_{k=1}^{Np}\sum_{l=1}^{Mk} \Delta Risk(k,l) Iselect(k,l)$$

Subject to: **Problem 1**

$$\sum_{k=1}^{Np}\sum_{l=1}^{Mk} \text{Select}(k,l)\text{cost}(k,l) \le \text{Budget}(p)$$
$$\sum_{k=1}^{Np}\sum_{l=1}^{Mk} \text{Select}(k,l)\text{labor}(k,l) \le \text{labor}(p)$$
$$\sum_{l=1}^{m_k} Iselect(k,l) \le 1$$

Where
N_p: Number of components that need to be maintained in category *p*.
M_k : Number of maintenance levels for component *k*.
ISelect (*k, l*): binary decision variable of maintenance activity to component *k* for level *l*.
Cost (*k, l*): Cost of maintenance activity to the component *k* on level *l*.
Labor (*k, l*): Labor needed to perform the maintenance activity to component *k* on level *l*.
Budget (*p*): Budget assigned to the maintenance category *p*.

Tot Labor (*p*): Available labor hours in category *p*.
Problem 1 is a low-level formulation of the maintenance optimization problem for a specific category p of maintenance tasks. We solve it to create tables of information that are used in a higher level formulation of the maintenance optimization problem. So Problem 1 is solved repeatedly with the increasing the budget in each repetition (e.g., 10%) until all candidate tasks in each category are selected or the available labor resource is exhausted [3].We solve repeatedly Problem 1 for each category *p=1. P*. Task selection is obtained at the same time, by solving the problem, binary strings is resulted, where element *k* of a string indicates whether task *k* is performed (1) or not (0).
Note that a cell of the risk-reduction table as *Cat_Risk* (i,x_i), corresponds to category *i* with budget allocation x_i.
In order to obtain the maximum risk-reduction under constrained total budget, Problem 2 is solved.

$$\text{Max} \sum_{i=1}^{p} cat\_\Delta Risk(i, x_i)$$

$$\sum_{i=1}^{p} xi \leq Totalcost$$

X_i=0, 1, 2…∀i=1,
Where, *Tot_Cost* is the fraction or total cost for all maintenances that asset managers can perform.

SOLUTION METHODS

As mentioned, Problem 1 has to be solved repeatedly, and for distribution systems, the dimensionality can be large. So, a fast algorithm must be used. In this paper, the bintprog function of MATALB software which has capability to solve linearly-binary programming and does not have any constraint to retain the 0-1 integers is used. Solving problem 1, the selection of specific tasks within the different categories will be determined (task selecton). The dynamic programming (DP) method is used to solve problem 2. Solving the DP programs addresses all of the maintenance optimal strategies in several stages. The process of the maintenance tasks selection (using DP algorithm) in order to minimize the cost or maximize the risk reduction of the system is summarized as follows:

- Break the problem into several stages, each stage represents the resource allocated to an object
- Each stage is divided into states, a state encompasses the information required to go from one stage to the next
- Find the best return of N stage, combine the best return with the return of the next stage
- At the final stage, an optimal solution of the problem is derived (100% of total cost)
- Trace back the optimal solution by using backward recursion

TEST SYSTEM RESULT

The AZADI system located in the western part of the Tehran electric distribution network is used as the test system. The system which includes 4 MV feeders from Olympic station 63 KV. There are 156 overhead line segments and 55cable segments and 2 reclosers and 61 transformers. In the network, every component has a specific failure rate and repair rate. In total, this network serves approximately 200000 customers, most of the customers are industrial and some are residential or commercial.
The following procedure is used to apply the risk-based optimal strategy at the AZADI system:
1) System identification, and the listing of critical components and their functions (As a first step in the method, the critical components for the system reliability are identified from a sensitivity analysis or from historical data and old components)
2) Failure mode and effects analysis for each selected component and categorization of failure effects, (for failure rate modeling of recloser and transformers, we use equipment inspection data to assign relative condition ranking. Authors in [4] found that an exponential model best describes the relationship between equipment condition and their failure rates. This paper considers data calibration and data mining approach such as export choice, AHP algorithm to model failure rate of overhead line and cable component.)
3) Maintenance task assignments
4) The coefficients (α_i) used in (7) associated with the weights that an asset manager can assign to the expected regulatory penalty of customers. The regularity penalty for different customers on AZADI system is calculated and shown in Table1.[5]

Table1. Customer Interruption costs $/kw

Customer type	One hour	one minuets
Residential	0.4	0.001
Commercial	4	0.2
Industrial	7	1.25
Other service	0.7	0.04

5) To compute the risk reduction associated with distribution equipment maintenance, reliability module f CYME software is used to determine the effects of equipment failure before and after maintenance, given that the failure rate reduction due to the maintenance is a known parameter (step 2, failure rate function is quantified).
6) Program evaluation, including cost analysis and optimization.
Associated maintenance activities, failure modes, and contingencies are listed in Table 2.
By solving problem 1, for 1) cable, 2) reclosers, 3) over head line, and 4) transformer categories the risk-reduction for various levels of budgetary allocation is obtained as shown in Table 3.(Table 3 illustrates results of overhead line category, others are same as this)

Table2 : Failure modes and maintenance activities

contingency	Failure mode	Maintenance activity
Overhead line	Momentary failure	Relay setting, changing isolator, tree trimming , span setting
Cable	Damage & general aging	Changing cable termination
Transformer	Transformer outage and general aging	Changing oil, bushing, silica gel, buchols relay
Breaker	Mechanical failure and general aging	Minor maintenance

Table 3: Risk-reduction and Decision variable code vs. budget

PM.num	Binary string	Cost (thousand $)	Benefit of risk-reduction($)
1	11010001	10%*35	3328.470
2	10000101	20%*35	13159.670
3	11000111	30%*35	15149.870
4	11001111	40%*35	16309.800
5	11111111	50%*35	16772.350
6	11111111	60%*35	16772.350
7	11111111	70%*35	16772.350
8	11111111	80%*35	16772.350
9	11111111	90%*35	16772.350
10	11111111	100%*35	16772.350

Table 4: output of DP programming

Cost thousand $	Benefit of risk-reduction($)	Selected tasks			
		Num. of PM strategy in			
		line	trans	recloser	cable
3.5	1361.538	0	0	0	1
7.0	1917.466	0	1	0	1
10.5	2026.538	2	0	0	1
14.0	2582.466	2	1	0	1
17.5	2926.658	2	2	0	1
21.0	3224.553	2	3	0	1
24.5	3494.144	2	4	0	1
28.0	3718.214	2	5	0	1
31.5	3973.873	2	4	2	1
35.0	4197.943	2	5	2	1

Table 4 displays risk-reduction with respect to total cost, which is the result of solving problem 2. This table is useful to find the minimum cost for identified level of risk-reduction and the maximum risk-reduction for identified budget. Also it illustrates the necessary budget for each category in each step. For example, in the third strategy of Table 4, necessary budget for overhead line is $7,000 (second strategy in Table 3) and their selected task identified by binary string.

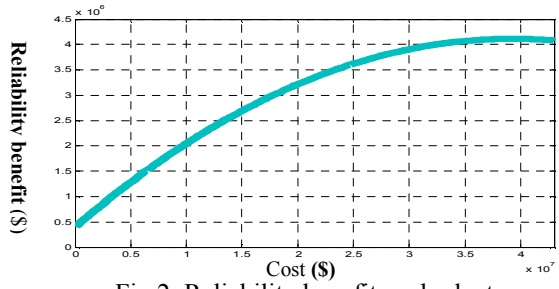

Fig.2. Reliability benefit vs. budget

Figure 2 provides variation in risk-reduction of the system as a function of the resources allocated levels. The maximum desirable investment is usually characterized by the portion of the curve where the marginal benefit per unit resource begins to fall off.

CONCLUSIONS:

This paper studies problem of maintenance management from two aspects, cost and reliability indices level (risk-reduction). In order to simplify the decision-making processes in optimization of maintenance, utilities need a specific strategy such as presented approach to answer 4 questions based on the dp and linear-binary programming results 1) how much should be invest to improve specific level of risk-reduction benefits or system reliability indices? 2) How much can be improve the risk reduction with identified budget? 3) For achieving the goals of prior questions, which maintenance tasks of each categories should be implemented? 4) How much of improving in risk reduction and investment is assigned to each categories?

This tool can be used easily as part of asset management process of each network distribution system.

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