Incorporating Probabilistic Cost/Worth Analysis in Maintenance Prioritization of Power Distribution Components-A Practical Approach

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Abstract—**Reliability Centered Maintenance (RCM) seems to be an effective cure to the past vague maintenance challenges in power systems. Hence, it has been placed under experiences in power distribution systems in many countries all over the world. This paper, as a complementary to the past works, devises a probabilistic framework in this area. A probabilistic cost/worth analysis for maintenance plans is introduced to be adopted on the system critical components. The proposed scheme organizes the most effective factors on the economical performance of maintenance strategies. The costs are attributed to the preventive maintenance (PM) strategies and the worth is considered as the suspended cost of corrective maintenance (CM) due to the PM applied. Subsequently, maintenance strategies would be prioritized in such a way that the most cost-effective maintenance plans can be applied. The proposed method employs the point estimation method (PEM) as a robust known stochastic approach to get through the probabilistic nature of the electricity price as well as outage duration in the cost/benefit analysis of maintenance plans. The introduced scheme is finally applied on a real distribution system of Stockholm City, Sweden, and the results are numerically investigated.**

Keywords-Reliability centered maintenance (RCM); preventive maintenance (PM); corrective maintenacne (CM); cost/worth analysis; probabilistic modeling; point estimation method (PEM).

NOMENCLATURE

Variables

$\mu_{BCR_{i,k}}$	Expected value of benefit to cost ratio for i^{th} maintenance strategy on k^{th} critical component.
$\bar{C}^{I,k}_{pm,i}, \bar{C}^{I,k}_{cm,i}$	Expected value of interruption cost of i^{th} PM/CM strategy on k^{th} critical component.
$\bar{C}^{L,k}_{pm,i}, \bar{C}^{L,k}_{cm,i}$	Expected value of lost revenue due to i^{th} PM/CM strategy on k^{th} critical component.
$C^{M,k}_{pm,i}, C^{M,k}_{cm,i}$	Maintenance process cost of i^{th} PM/CM strategy on k^{th} critical component.
$C^{M_l,k}_{pm,i}, C^{M_l,k}_{cm,i}$	Labor cost of i^{th} PM/CM strategy on k^{th} critical component.
$C^{M_m,k}_{pm,i}, C^{M_m,k}_{cm,i}$	Material cost of i^{th} PM/CM strategy on k^{th} critical component.
$C^{M_p,k}_{pm,i}, C^{M_p,k}_{cm,i}$	Tools cost of i^{th} PM/CM strategy on k^{th} critical component.
$Cost^{k}_{pm,i}, Cost^{k}_{cm,i}$	Total cost of i^{th} PM/CM strategy on k^{th} critical component.
n	Number of input random variables of probabilistic analysis.
$\boldsymbol{X}$	Vector of input random variables.
$\boldsymbol{Y}$	Vector of random output variables.
$\mu_{EENS^k_i}$	Expected value of EENS due to i^{th} maintenance strategy on the k^{th} critical component.
μ_{U_j}	Expected value of energy not served index of reliability for the j^{th} load point.
$\mu_{X,k}$	Expected value of X.
$\sigma_{X,k}$	Standard deviation of X.

Parameters

$IEAR_j$	Interrupted energy assessment rate of the j^{th} load point.
$P_{k,i}$	Probability of the i^{th} concentration of random variable k.
r_j	The outage time index of reliability for the j^{th} load point.
$L_{a,j}$	The average load of j^{th} load point.
$Wh^{k}_{pm,i}, Wh^{k}_{cm,i}$	Working hours of i^{th} PM/CM plan on k^{th} critical component.
μ_{χ}	The expected value of undelivered energy price.
$\lambda_{k,3}$	Skewness of random variable k.
$\xi_{k,i}$	Location of the i^{th} concentration of random variable k.

Sets

I^C	Set of all possible CM strategies.
I^P	Set of all possible PM strategies.

I. INTRODUCTION

Reliability has been so far well come to the point of undeniable concern in power system operation and management. The reason is due to the drivers such as globalization and increased deregulation together with the technological changes which have forced many distribution utilities world-wide to provide the customers with high quality electricity as cost-effective as possible [1]. This has made the distribution utilities to reconsider how they conduct their business and specifically their maintenance plans [2].

It falls within the realm of reliability centered maintenance (RCM) to effectively cope with the requisite balance between the reliability requirements and maintenance strategies. RCM places a strong emphasis rather on the system function continuation vs. the traditional maintenance approaches that were on the basis of equipment and subcomponents preservation. In this respect, the maintenance personnel are instructed to concentrate on some critical components of significant contribution to the operation of distribution system [3]. As a result, the financial resources are not getting distracted by maintenance activities of neither only marginal benefit to the organization nor negligible effects on some non-critical components. RCM also guides the resources in preventing critical failure modes and causes. At the ultimate steps of RCM process, it becomes necessary for the distribution utility to strike a balance between reliability levels and maintenance cost to the extent of enough comfortableness for both utility and customers. Consequently, RCM results in a tight association between the components functions, failure behaviors, customer expectations, maintenance costs, and the consequence worth [3], [4]. The number of researches on power system components regarding this reliability-based approach on maintenance has seen a tremendous growth since the maintenance participation in the total operation costs and benefits in power systems has been tangibly approved [5]-[8]. Nevertheless, none has put considerable effort to promote a probabilistic RCM framework.

This paper aims to find a solution for maintenance plan prioritization to be applied on the system critical components. Due to the fact that some probabilistic factors, namely the electricity price variation and the uncertainty in the maintenance-required outage duration are faced in the cost/worth analysis, a robust probabilistic method has to be employed in handling the uncertain nature of these variables. As a result, the point estimation method (PEM) would be utilized and the most cost-effective maintenance strategies would be found by then through a benefit to cost ratio (BCR). This ratio is capable of well investigating the imposed costs and the achieved benefits associated with the PM and CM maintenance plans. This would finally lead to a practical and optimal maintenance strategy to be applied in the RCM process.

The rest of the paper is organized as follows. RCM and its crucial steps are briefly introduced in Section II, where the main steps of RCM in power distribution systems are generally presented. The proposed method within the scope of this paper is mainly concentrated in Section III. Section IV is devoted to the paper case study which numerically investigates the proposed approach. The conclusion is finally summarized in Section V.

II. Reliability Centered Maintenance (RCM)

RCM is referred to as a comprehensive maintenance scheme which strives to find the optimal maintenance plan on the system most critical component and at the most appropriate interval of the component life time [9], [10]. It is an efficient strategy which systematically and comprehensively organizes network components considering available resources such that utilization of the physical assets is satisfactorily optimized. Since the talks have been started for nearly a half century concerning the RCM merits in different industries, it also has been recently adopted in power distribution systems.

Among the three main hierarchical levels of the electric power industry, i.e. generation, transmission, and distribution, the latter is the one which has recently been under concentrations [4]. As long as the door to the power system restructuring has been opened, and regarding the fact that the most failure statistics are reported to be dealt with distribution sector, RCM is applied in power distribution systems.

RCM is fundamentally comprised of three main stages which are presented in Fig. 1. As it can be seen, the first stage deals with the prerequisites to perform the analysis which includes the required data and the desired goals and targets hope to be satisfied. The second stage starts with the system critical component identification. This effectively helps the utility's available financial resources be concentrated where necessary and effective. This stage then incorporates the failure mode and effect analysis on the system critical components to find the most appropriate maintenance plans and strategies. Having modeled the component's failure rate, and due to the found failure modes and causes, the maintenance strategies have to be selected in order to prevent the associated failure causes. Applying the cost/worth analysis on the defined maintenance strategies of the component and adopting the most cost-effective strategy on that component discloses its effectiveness on the component failure rate and as a consequence on the system reliability indices. The process will be continued till the desired reliability indices would be satisfied. And finally, as can be seen in stage 3, some technical and economic analyses have to be conducted on the achieved information about the reliability-based performance of the system understudy.

III. Probabilistic Cost/Worth Analysis of the Maintenacne Strategies

It is more latterly that power system operators have come to see maintenance cost as an issue of great importance in their operational managements, total imposed costs, and annual yielded benefits [11]. As long as utilities have so far sensed a sharp increase in their operation costs in one hand, and with the recent advent of power system restructuring trend on the other hand, the pressure to reduce or control their total costs embracing the investment cost, operation cost, and interruption cost has been under much coercion.

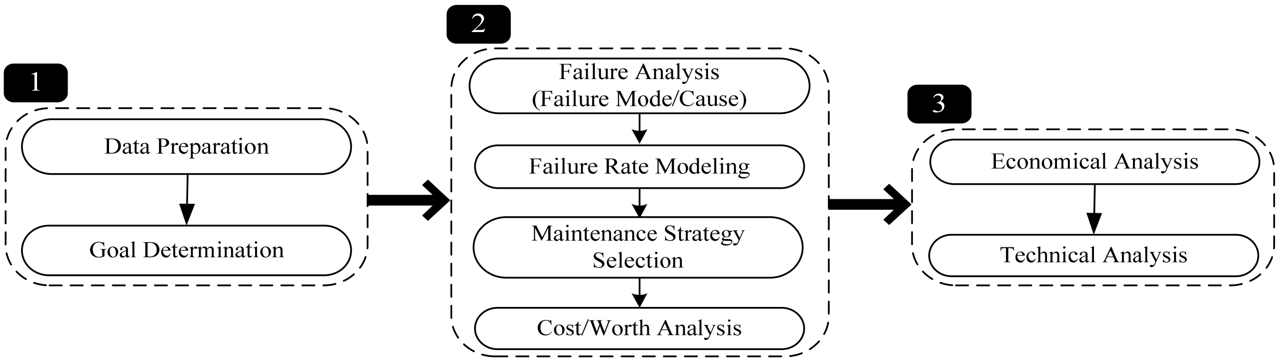

Figure 1. RCM general procedure in power distribution systems.

In this regard, this step takes a long pace in the economical studies of the maintenance strategies due to its vital role in the RCM perspective. Considering only technical parameters, without any deserving attention to the economical aspects of maintenance plans would eventuate into some non-optimal solutions. Having reached the technically and pragmatically suitable maintenance strategies in response to the critical failure modes/causes of the critical component, it seems reasonable to assess the maintenance plans cost-effectiveness. To prioritize the recorded strategies, a benefit to cost ratio is proposed as shown in (1).

$$\mu_{\text{BCR}_{i,k}} = \frac{\text{Expected Value of Total Achieved Benefits}}{\text{Expected Value of Total Imposed Costs}} \tag{1}$$

As can be seen in (2), the total imposed costs (associated with PM plans) are comprised of maintenance costs, interruption costs, and that of lost revenue.

$$\sum_{I^P} Cost^{k}_{pm,i} = C^{M,k}_{pm,i} + \bar{C}^{I,k}_{pm,i} + \bar{C}^{L,k}_{pm,i} \tag{2}$$

The costs of maintenance are considered to be composed of all the PM expenses, including PM equipments, materials and labors. This is introduced in (3).

$$C^{M,k}_{pm,i} = C^{M_p,k}_{pm,i} + C^{M_l,k}_{pm,i} + C^{M_m,k}_{pm,i} \tag{3}$$

The cost associated with the labors involved in each maintenance strategy would be calculated through (4). This follows a practical trend which is common for the asset resource allocation in distribution utilities.

$$C^{M_l,k}_{pm,i} = (\sum_{i=1}^{k_p} C^{m_l,k}_{pm,i}) \times (\sum_{i=1}^{k_p} Wh^{k}_{pm,i})^{-1} \times Wh^{k}_{pm,i} \tag{4}$$

Interruption cost is in fact the cost of failure imposed to the customers when a component is withdrawn from the system for the corresponding PM strategy. This cost would be evaluated through customer surveys and is calculated via (5).

$$\bar{C}^{I,k}_{pm,i} = IEAR_j \times \mu_{EENS^k_i} \tag{5}$$

$$\mu_{EENS_j} = L_{a,j} \times \mu_{U_j} \tag{6}$$

Noteworthy is that the U_j is a function of the component's maintenance outage duration (r). This duration time follows a probabilistic nature which can be modeled using a probability distribution function (PDF). In other words, the required outage time for the maintenance plan on a given critical component might take a range of values due to different weather conditions or maintenance crew performances. So, by utilizing historical records of the components, an appropriate PDF type can be adopted (as an assumption, normal PDF is here considered) and as a consequence, U_j would be obtained as a random variable. Consequently, the associated cost components ($C^{I,k}_{pm,i}$ and $C^{L,k}_{pm,i}$) should be modeled as probabilistic variables. In this study, expected values of these variables are considered.

The third item of the cost function is called the lost revenue cost, which is associated with the imposed costs to the distribution utilities in accordance with the unsold electricity. This lost revenue would be reached via (7).

$$C^{L,k}_{pm,i} = \chi \times EENS^{k}_{i} \tag{7}$$

The survived point of worth mentioning is that the cost function has to be calculated for each maintenance strategy selected in response to the failure modes/causes.

The benefits achieved through the PM tasks are also involved in the proposed economical analysis. The cost of CM can be addressed as the total achieved benefits due to the PM's effective role in CM's postponement. In other words, effectively tolerating the costs associated with some PMs accomplishes the goal of adjourning the imminent CM tasks and so leads to achieving the benefits of their deferments. This is presented in (8). The calculation procedures are almost the same as the above-mentioned expressions (2-7) bearing in mind replacing the PM-related values with those of CM plans for the understudied critical component.

$$\sum_{I^C} Cost^{k}_{cm,i} = C^{M,k}_{cm,i} + \bar{C}^{I,k}_{cm,i} + \bar{C}^{L,k}_{cm,i} \tag{8}$$

Apparently, the electricity energy price varies rapidly over different hours of a day which imposes a great uncertainty in its forecasting in power system studies [12]. As a result, this uncertainty has to be inevitably involved in the price forecasting and revenue lost calculations of the proposed analysis both when PM and CM are applied. Different methods have been introduced in this respect in the literature, e.g. Game Theory, Time Series, and so on. In this paper, the electricity price variation in the studies horizon is simulated via the commonest one, i.e., Time Series [13]. Due to the recent discussions, the uncertain nature of annual outage time and electricity price calls for an efficient probabilistic approach in valuating both PM and CM cost functions.

In this paper, Point Estimation Method (PEM) is applied as a promising approach in dealing with the moments of random quantity that are interrelated to one or some random variables [14]. Its major robustness is expressed as its easy implementation and low computationally demanding in comparison with the other approaches. The maintenance outage time and electricity price are considered as random input variables, expressed in (9).

$$X = [r_j, \chi] \tag{9}$$

Consequently, the lost revenue and interruption cost variables can be expressed as functions of the input random variables as shown in (10), where its output random variables are addressed in (11).

$$Y = h(X) \tag{10}$$

$$Y = [C^{i,k}_{pm,i}, C^{l,k}_{pm,i}, C^{i,k}_{cm,i}, C^{l,k}_{cm,i}] \tag{11}$$

A matter of worth mentioning is that although the PDF of the random input variables are hidden to us, the possibility of calculating the moments of output variables is still approved. However, if the PDF of the input variables is known, the PDF of output variables is expected to be inclined to the same distribution [14]. The presented probabilistic approach in this analysis, the lost revenue and interruption cost evaluation on the basis of PEM, is scrutinized as instructed in the following.

$$E(Y)^{(1)} = 0; E(Y^2)^{(1)} = 0 \tag{12}$$

For k from 1 to n, respectively, the following steps should be taken place [14].

- Calculate the concentration locations and probabilities as follows:

$$\xi_{k,1} = \frac{\lambda_{k,3}}{2} + \sqrt{n + (\frac{\lambda_{k,3}}{2})^2} \tag{13-a}$$

$$\xi_{k,2} = \frac{\lambda_{k,3}}{2} - \sqrt{n + (\frac{\lambda_{k,3}}{2})^2} \tag{13-b}$$

$$P_{k,1} = \frac{-\xi_{k,2}}{2n \cdot \sqrt{n + (\frac{\lambda_{k,3}}{2})^2}} \tag{13-c}$$

$$P_{k,2} = \frac{\xi_{k,1}}{2n \cdot \sqrt{n + (\frac{\lambda_{k,3}}{2})^2}} \tag{13-d}$$

- Determine the two concentrations $x_{k,1}$ and $x_{k,2}$ using the following equations:

$$x_{k,1} = \mu_{X,k} + \xi_{k,1} \cdot \sigma_{X,k} \tag{14-a}$$

$$x_{k,2} = \mu_{X,k} + \xi_{k,2} \cdot \sigma_{X,k} \tag{14-b}$$

- Run the deterministic process using CM and PM cost valuation with respect to the vector X that can be determined as below:

$$X = [\mu_{k,1}, \mu_{k,2}, ..., x_{k,i}, ..., \mu_{k,n}] \qquad i = 1,2 \tag{15}$$

- Update the following equations:

$$E(Y)^{(k+1)} \cong E(Y)^{(k)} + \sum_{i=1}^{2} P_{k,i} \cdot h(X) \tag{16-a}$$

$$E(Y^2)^{(k+1)} \cong E(Y^2)^{(k)} + \sum_{i=1}^{2} P_{k,i} \cdot h^2(X) \tag{16-b}$$

- Calculate the expected value and standard deviation of Y using (17.a) and (17.b):

$$\mu_Y = E(Y) \tag{17-a}$$

$$\sigma_Y = \sqrt{E(Y^2) - {\mu_Y}^2} \tag{17-b}$$

Calculating (17-a) and (17-b), the mean value and standard deviation of output random variables would be reached. Consequently, the expected value and standard deviation of each maintenance strategy costs and benefits would be calculated. From an economic point of view, the ultimate goal of the proposed maintenance strategy optimization has to be maximizing the BCR index in the studies horizon. Using the BCR technique, all the maintenance strategies associated with the critical component can be evaluated and the optimal maintenance strategies in accordance with their expected value of BCR ratios could be by then prioritized.

The flowchart depicted in Fig. 2 well illustrates the overall procedure of the proposed method.

IV. Numerical Analysis

A. System Understudy

The system understudy is taken from the urban distribution system of Stockholm City, Sweden, called Birka distribution system. This system is comprised of some main component types, i.e., transformer, circuit breaker, fuse, underground cable, and bus bars, and holds the electricity from the 220kV generation level to the 400V household customers. Any information associated with the system is available in [4] in detail. The studies are conducted on its most important load point, i.e., LH11.

B. Technical Assumptions

The critical components of a distribution power system are found regarding their significant roles in the system reliability performance. In this paper, and due to the past experiences, it is assumed that a transformer is a critical component. Hence, the proposed methodology in this paper is going to be applied on this transformer. For the sake of guiding the appropriate amount of resources into the critical component maintenance management, critical failure causes had to be found. All the possible failure modes and the related causes are presented in Table I.

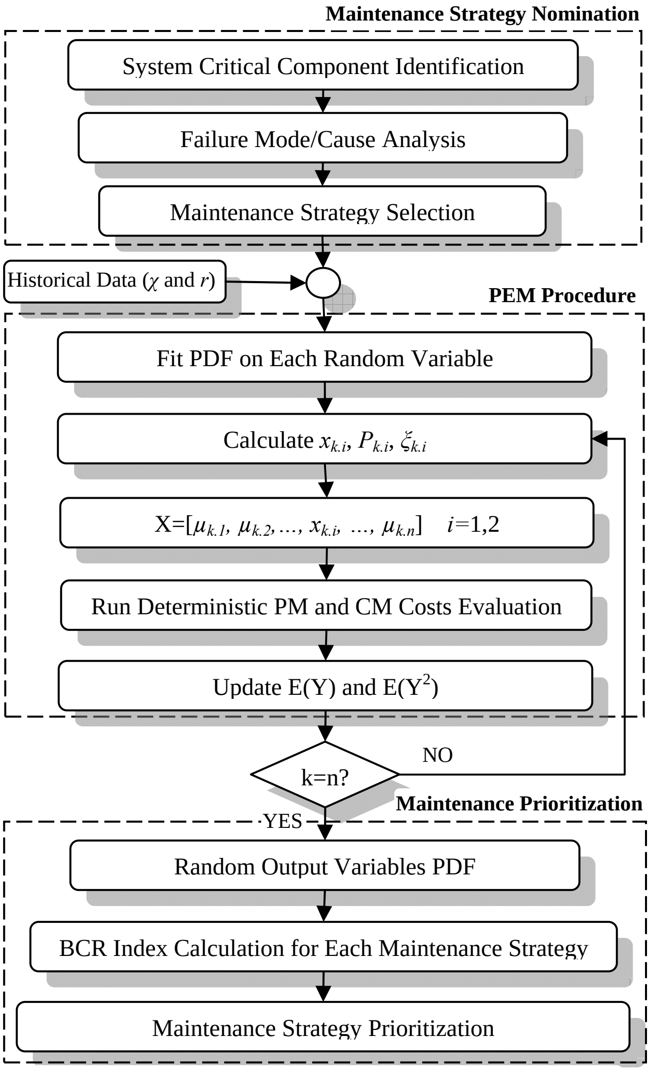

Figure 2. The proposed algorithm flowchart.

Due to the inaccessibility of the authors to the maintenance data of the network understudy, the maintenance-related data were borrowed from Kerman North Distribution Company in Iran. The point to be emphasized is that the maintenance polices had to be put under some feasibility/applicability analysis. In other words, when a component is going to be put under maintenance, it is rather economically justifiable to conduct some maintenance tasks together. It not only does save the human and financial resources, but even imposes lower energy not supplied. The resulted maintenance plans are presented as shown in Table II.

C. Probabilistic Cost/Worth Analysis of the Nominated Maintenance Plans

For the sake of cost/worth analysis of the selected maintenance strategies, the cost and worth functions had to be evaluated. As explained before, PEM is employed to deal with the existent uncertainties in maintenance outage duration and electricity price. In this case study, the electricity price variation rates were taken from the Nordic Market over the past 5 years [15]. As soon as reaching the time series model of the electricity price, the Monte-Carlo Simulation (MCS) is employed for a one-year time horizon. In so doing, the most appropriate normal PDF is then fitted to the simulated electricity price variable. Afterward, its mean value and variance were fed to the PEM method as the inputs. The other PEM inputs are the mean value and variance of the maintenance outage time which is calculated by the historical data. After running the proposed probabilistic method, the results are obtained and illustrated in Table III.

TABLE I. FAILURE MODES AND CAUSES OF CRITICAL TRANSFORMER

Failure Modes	Failure Causes
External leakage	1- Corrosion 2- Gasket failure 3- Loose bolts, connections, fatigue failure of piping 4- Over pressurization 5- Porcelain failure 6- Seal failure 7- Valve leak 8- Weld failure
Fail to provide insulation level	1- Bushing failure 2- Insulation failure 3- Oil contamination / oil degradation 4- Low oil 5- Solid insulation failure 6- Winding insulation failure 7- Oil dielectric failure 8- Tap changer failure
Incorrect/no output	1- High resistance load path 2- Open circuit 3- Out of calibration 4- Shorted turns

TABLE II. PRACTICAL MAINTENANCE STRATEGIES FOR THE CRITICAL TRANSFORMER

Maintenance Plans	Practical Maintenance Strategies
Plan 1	Solid insulation inspection; valve leak and weld failure checking; seal failure, tank external condition, gaskets and oil sampling valves, and paper sample inspection.
Plan 2	Corrosion checking up; out of calibration inspection; inspection of the loose bolts and connections;
Plan 3	Inspection of oil conservator, oil level, low oil examination; oil contamination and dielectric failure analysis; gas in oil analysis, measurement of oil quality.
Plan 4	Inspection of dehydrating breather, assessment of radiators / coolers, gaskets, fans and pumps.
Plan 5	Evaluation of motor drive condition and number of operations; internal inspection of tap changer, pre-selector, contacts and leads, insulation of tap changer connections and leads,
Plan 6	Inspection of bushings external condition, oil levels and gaskets, surge arresters and bushings connections.
Plan 7	Over pressurization analysis; high resistance load path examination; analysis of short circuit, voltage and losses; no-load current and losses.
Plan 8	Protection and secondary system analysis; assessment of Buchholz relays, pressure relief devices, indicators, control cubicle and wirings, winding resistance and associated analysis.

TABLE III. COST/WORTH ANALYSIS OF MAINTENANCE PLANS OF TRANSFORMER (T)

Maintenance Plans	Maintenance Costs				Maintenance Benefits				$\mu_{BCR_{i,T}}$
	$C^{M,T}_{pm,i}$ ($)	$\bar{C}^{I,T}_{pm,i}$ ($)	$\bar{C}^{L,T}_{pm,i}$ ($)	$\overline{\sum Cost^{T}_{pm,i}}$ ($)	$C^{M,T}_{cm,i}$ ($)	$\bar{C}^{I,T}_{cm,i}$ ($)	$\bar{C}^{L,T}_{cm,i}$ ($)	$\overline{\sum Cost^{T}_{cm,i}}$ ($)	
Plan 1	8805.2	4432.38	432.56	13670.14	14495.5	8054.01	802.36	23351.87	1.70824
Plan 2	10152.3	3765.60	365.96	14283.86	15812.53	8635.25	856.75	25304.53	1.77155
Plan 3	13812.4	2014.89	198.75	16026.04	10863.23	9652.97	959.61	21475.81	1.34006
Plan 4	6995.14	2971.352	291.67	10258.16	12135.27	7000.04	659.57	19794.88	1.92967
Plan 5	8890.23	3033.99	300.02	12224.24	15176.02	8429.10	821.98	24427.1	1.99825
Plan 6	4123.13	1872.10	179.83	6175.06	8512.87	4596.10	458.75	13567.72	2.19718
Plan 7	15102.18	4818.1	469.25	20389.53	10339.45	5596.854	549.75	16486.05	0.80855
Plan 8	10026.39	1102.31	100.97	11229.67	17253.39	9249.88	910.39	27413.66	2.44118

The cost variables associated with each PM and CM strategy are calculated whose mean values, obtained via PEM, are used as the decisive criterion in the cost/worth analysis of the maintenance strategies. Then, the expected value of BCR index related to each strategy has been calculated and by then, maintenance strategies could be sorted to be applied on the system critical transformer. As it can be seen, maintenance strategies number 8 and 6 are attributed the most BCR index and hence are deemed to be the most cost-effective maintenance plans on this transformer. The next involves in applying the first optimal strategy to the critical transformer (#8). Not surprisingly, it is expected to meet the desirable reliability indices. The maintenance process terminates if the desirable reliability indices are reached and postponed till the next maintenance interval. Otherwise, the next optimal maintenance strategy of that component (#6) has to be employed and the process continues till the reliability constraints are satisfied. The same process would be done on the other critical components.

V. CONCLUSION

This paper has provided a probabilistic framework for the cost/worth analysis of maintenance strategies. A benefit to cost ratio was proposed which included all the cost functions associated with the maintenance plans both when PM and CM was performed. These functions were composed of maintenance, interruption, and lost revenue costs. Probabilistic natures of the maintenance outage duration as well as the electricity price were handled through a robust stochastic approach namely PEM. Finally, the most cost-effective maintenance strategies were recognized to be accordingly applied on the system critical component. The proposed scheme was applied to the most critical component of the Birka power distribution system in Stockholm City, Sweden, i.e. an 11/0.4kV transformer. The paper claims that adopting the proposed scheme, due to not only its capability in managing the maintenance plans according to the failures criticality and strategies applicability, but also in dealing with the existent uncertainties and the cost/benefit features, would lead to the optimal maintenance resource allocation plans on the system critical components.

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