Designing A Financially Efficient Risk-Oriented Model for Maintenance Planning of Power Systems: A Practical Perspective

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***Abstract*—This paper is so organized to design an effective financial risk matrix in the planning procedure of maintenance process in power systems. The presented risk matrix contributes in the prioritization of maintenance strategies in power distribution systems and is claimed to be of great assistance in the allocation of available resource to the maintenance plans. Hence, this matrix can be considered as a financial guide for power system planners and operators, and by then, network owners and operators would be able to effectively focus network investments towards the high-risk parts and components. This will avoid wasting the available resources to some low-risk equipments. The proposed within the scope of this paper is placed under experience on a distribution network of Iran's power grid and well demonstrates its applicability and efficacy.**

Keywords- Risk matrix; maintenance plans; risk factor; cost;

I. INTRODUCTION

Maintenance and reinvestment decisions are commonly deemed to be the crucial parts of asset management in power distribution systems which are in charge of improving the reliability of power distribution systems. The former cares for the current condition of the system understudy and maintains its current components within an acceptable level of reliability, while the later results into the reliability enhancement due to the presence of some new components resulted from reinforcement policies. However, due to the nowadays raised economical concerns in distribution companies, maintenance and its vital role in prolonging the components useful lifetime and postponing any further reinforcements has been inevitably perceived. Asset management, as a framework for maintenance implementation, mainly contributes in balancing the maintenance-oriented costs, component performance, and system overall risk level taking into account different consequences such as network performance and safety together with the financial and environmental impacts.

Among the maintenance policies, risk-based inspection (RBI) is a helpful one taking risk analysis as the basis in prioritizing and managing the inspection programs. This issue, although attracted some researchers to work upon [1]-[4], still faces some major challenges in its process. Hence, the need for a more accurate investigation on the risk analysis of the maintenance procedures seems reasonable. This paper highlights major trends in the application of risk matrix analysis in the asset maintenance management of electricity distribution systems.

The paper first provides an introduction to the concept of risk management and RBI in Section II. It also describes different categories of risk analysis (qualitative, quantitative and semi quantitative or semi qualitative methods) there. Then providing a risk matrix (a simple graphical tool) in the next step, it employs "High", "Medium High", "Medium", and "Low" categories of risk, and discusses how the risk matrix can be of assistance in maintenance planning. The proposed approach would be used to answer which component has the acceptable risk level and as a consequence, no further maintenance actions have to be applied. Having presented the pragmatic risk model and its associated cost estimation approach, designed for the inspections, in Section III, the risk estimation versus the associated cost is pursued in Section IV. A practical implementation of the proposed method would be illustrated in Section V. The implementation process would be done through a case study conducted on a part of electrical distribution network in Tehran, Iran. The results well reflects the superiority and robustness of the proposed maintenance decision making based on the risk-oriented strategies. And finally the conclusion comes in Section VI.

II. RISK BASED INSPECTION CONCEPTS AND THE PROPOSED APPROACH

Risk-Based Inspection (RBI) is usually considered as a maintenance approach taking into account risk analysis as its basis and is of considerable importance for prioritizing and managing the maintenance efforts on the equipments' inspection programs. As experienced in different power systems all over the world and due to the recently reported statistics of power system failures, a relatively large percentage of risk is attributed to a small number of system components. This means that there are a few equipments which contributes a great deal in the system overall risk. In response to this common phenomenon, RBI effectively permits the shift of inspection and maintenance resources to provide a higher level of coverage on the high-risk items. This also leads to an appropriate effort on lower risk equipments. As a result, RBI facilitates the lifetime prolonging of the critical equipments while improving or at least maintaining the same level of risk. The RBI approach plays the role of defining the risk attributed to the operating equipments as a combination of both failure consequence and likelihood [1]. The main goals followed by the RBI plans can be summarized in short as follow [5]-[7].

- Screening the system and its components within the system to identify some areas of high risk.
- Estimating and attributing a risk value to the operation of each system component via a consistent methodology.
- Prioritizing system equipments based on the measured risk.
- Designing an appropriate/effective inspection program in response to the components risk levels.
- Managing the risk associated with the equipment failures.

A. Risk Analysis Concept

As it has been previously pointed out, the word “risk” is commonly referred to as a criterion reflecting a combination of both probability of an event and its consequence, where the “event” is the occurrence of a particular set of circumstances, “probability” is the likelihood of the occurrence, and “consequence” is the outcome resulted from that event.

The risk value is commonly calculated through the equations similar to (1).

$$R_i = F_i \times C_i \tag{1}$$

where R_i is the risk associated with the i^{th} event, F_i is a settled number reflecting the probability or frequency related to the occurrence of event i, and C_i is representative of the associated consequences of i^{th} event. Having calculated the risk function for each plan or component, the study is followed by some economical analysis to decide if and how the risk should be treated. This is commonly called risk management.

B. Risk Management

Risk management is deemed to contain all the precautions for the sake of mitigating and controlling the impacts on the risk-arisen components. In this context, management policies and systematic decision making practices are involved to deal with the existent risks. Hence, it aims to mitigate failure or any other high-risk event consequences. It majorly tries the plans to avoid or reduce the cost exposures of the events occurring rather than remedial actions after an event.

To the present time, three main categories of risk assessment methods have been introduced and presented in recent studies. They can be outlined as follows.

- Qualitative approaches
- Quantitative approaches
- Hybrid methods

The applicability of each method can be due to some operational aspects and conditions. Their adaptation is majorly dependent on the purpose of study, the need for the resolution, input data available, etc. Each is going to be briefly explored in the following.

1) Qualitative Approaches

Qualitative risk analysis is often associated with the methods and practices applied in order to evaluate an identified risk in accordance with its possible impacts on the system performance and utility’s objectives. In these approaches, risk probability together with its impacts may be described in a qualitative manner, e.g., via the expressions “very high”, “high”, “moderate”, “low” and “very low”.

2) Quantitative Approaches

Quantitative risk analysis deals with the numerically estimation of the probability a project will meet its objectives and is on the basis of impact evaluation of all identified and quantified risks. Then, it would be possible to discriminate the real risk of hazardous events and can be compared with the pre-determined levels of appropriate risk levels.

3) Hybrid Method (Semi- Quantitative)

Hybrid method is a combination of the previously-introduced risk analysis approaches which can be used in effectively utilizing the available data while minimizing the number of further metrics to be collected or calculated. As a result, this will lead to a less numerically intensive analysis in comparison with the sole quantitative approaches.

C. Risk Matrix

Risk matrix can be employed as a simple tool to help the decision making process discriminate the unacceptable risks from those of allowed. As it is previously discussed, the risk associated with the events or components has to be analyzed through the estimates of consequence and likelihood (frequency or probability). In a risk matrix, the magnitude of a given risk is often established via a two-dimensional matrix, having consequence in one axis and likelihood in the other hand. Risk severity is then evaluated in a scale of 1–50 at the top of the matrix to determine the consequence score [3]. The scores can be interpreted as shown in Table I.

TABLE I. CONSEQUENCE SCORING IN A RISK MATRIX

Scores	Score Explanation
1-10	Negligible Consequence
10-20	Minor Consequence
20-30	Moderate Consequence
30-40	Major Consequence
40-50	Catastrophic Consequence

In addition to the consequence assessments, a number ranging from "1" to "5" is assigned to the occurring likelihood of a risk item. The higher the number is, the more likelihood is attributed to that event. The assigned numbers to the likelihood are as illustrated in Table II.

TABLE II. LIKELIHOOD RATING IN A RISK MATRIX

Scores	Score Explanation
1	Rare Likelihood
2	Unlikely to Happen
3	Possible to Happen
4	Likely to Happen
5	Almost Certain Likelihood

The final step in developing the risk matrix contributes in translating the risk terms into the tolerability criteria. As a result, the risk matrix would be comprised of some blocks reflecting the fact that the risk is tolerable or intolerable. In this respect, risk rating is done through the multiplication of the likelihood against the consequences. Eventually, the risk matrix would be completed in which four zones would be distinguishable. The risk matrix is illustrated in Table III and the described zones are depicted in Fig. 1. As can be traced in Table III, for instance for the highlighted block, the range of risk would be from 30 to 60. In this way, all the blocks can be comparable with each other in the risk analysis of a given event.

Having also a glance at the depicted risk table in Fig. 1, it can be inferred that four different zones are assigned to the risk levels of a given event contrasted in green, yellow, orange, and red. The lower green zone, which represents the "negligible effect" zone, corresponds to some dangerous events of a low enough frequency/consequences. This region will probably have no actual effects on the risk severity of that event. Based on the risk management concepts, in such situations, the risk acceptance seems reasonable and any mitigation policies may lead to waste of money and would not be effective for the system. The intermediate yellow and orange zones represent the "Medium effect" zones. Once facing such zones, it will lead to probably major effects on the risk severity. The states attributed to this region would be selected to be modeled for further severity calculations. Risk management recommends the omission or the reduction of the risk for these zones. The upper red zone, as representative of the "High effect" zone, corresponds to very dangerous events which will imminently have considerable effects on the risk severity, for sure. However, the cost-benefit analysis is too helpful; because most of the time, acceptance of such risks is profitable and cost of the maintenance after the risk acceptance is less than the mitigation costs.

The risk matrix has to have some clear blocks whose associated risk would be tolerable or intolerable. A description of risk prioritization categories is outlined in Table IV. Accordingly, the plan required in response to the risk ranking is provided in Table V. A trust risk management policy has to be then applied to not only identi-

TABLE III. RISK MATRIX FRAMING FOR A GIVEN EVENT.

Risk Matrix		X-axis: consequence classes				
		10	**20**	**30**	**40**	**50**
Y-axis frequencies	**5**	5*10	5*20	5*30	5*40	5*50
	4	4*10	4*20	4*30	4*40	4*50
	3	3*10	3*20	3*30	3*40	3*50
	2	2*10	2*20	2*30	2*40	2*50
	1	1*10	1*20	1*30	1*40	1*50

C: mitigate	**B:** fix now	**B:** fix now	**A:** Avoid	**A:** Avoid
D: lower priority	**C:** mitigate	**B:** fix now	**B:** fix now	**A:** Avoid
D: lower priority	**D:** lower priority	**C:** mitigate	**B:** fix now	**B:** fix now
D: lower priority	**D:** lower priority	**C:** mitigate	**C:** mitigate	**B:** fix now
D: lower priority	**D:** lower priority	**D:** lower priority	**C:** mitigate	**C:** mitigate

Figure 1. Risk zones in a risk matrix.

TABLE IV. RISK MITIGATION GUIDELINES FOR AN EVENT

Risk Level	Category	Description
A: very high risk	Unacceptable	- Has to be mitigated - The mitigation may be too expensive - Do not have any benefit
B: high risk	Undesirable	- Has to be mitigated - Controls are needed to reach the risk category of C
C: moderate risk	Acceptable with Controls	- Needs verifying the fact that the controls are in their right place.
D: low risk	Acceptable	- No mitigation is required - Any mitigation leads to the waste of resources

-fy the level at which the risk would be managed, but also to assign some priorities for remedial actions. The applied management policy has to be capable of determining whether the risks associated with the component are acceptable, based on the color bandings and risk scores, or not. This trust risk management would be independent of any modifications in the risk categorization. In other words, even if the risk categorization boundaries are modified, the trust management model would still work in comparing the scores.

Till now, the above-addressed approach on the development of risk matrices well simplifies the use of this tool, no need to establish some other risk tolerability criteria. The other superiority of this model is that it is able to take different personnel, public, environmental, and business risks into consideration to be identified and mitigated. Moreover, its simplicity makes it rather easy to be implemented with no further expertise in the quantitative risk assessment. Meanwhile, it results in some prioritizations based on the risk level (from A to D). It allows all the investigated scenarios to be mitigated in line with an acceptable risk level (C or D).

Due to all the aforementioned facts in respect with the risk analysis, the key to a systematic and successful risk management is deemed to accurately identifying the intolerable risks. Then the resources could be guided so that either the associated occurrence likelihood or its consequence or both would be reduced. This is the main point becoming increasingly important as the companies have reduced their operating budgets and have limited resources for risk management.

III. The Risk Modeling Approach

Apparently, different risk consequence categories are assigned major differences regarding the extent of their impacts. Network performance, safety, financial and environmental consequences are among the vital concerns in an electrical network. The point of considerable importance is noting that different individual assets could be of different criticality in accordance with each of the introduced categories. To serve as an example, an electrical asset, even though located in a safe and secure environment, may have very high network performance consequences.

In this paper, four types of risk consequence categories are employed [4] as shown in Table V. Many utilities have pursued the policies aiming to identification of the relative importance of the assets or at least those components of great criticality. The proposed approach outlines how the severity of the consequences associated with an event or failure can be assessed. In this process, the factors such as components physical locations, their functions, their accessibility for repair, and replacement costs would be taken into consideration [8]-[11].

As noted before, each individual asset would be able to be assessed based on various factors reflecting the consequences in each category. This can be described as follows.

$$C_i = (OI_i \times OF_i) + MC_i + ISE_i \tag{2}$$

Where C_i, OI_i, and OF_i are respectively the consequences, operational impacts, and operational frequency or redundancy associated with the i^{th} component consequence. MC_i and ISE_i are respectively representatives of maintenance costs of i^{th} consequence and the safety and environment oriented impacts of the i^{th} consequence. It would be interesting to note that the network performance would be evaluated through the following equation, introduced in (3), which is involved in C_i calculation as well, as presented in (2).

$$NP_i = OI_i \times OF_i \tag{3}$$

where NP_i represents the network performance when facing with the i^{th} consequence.

Due to the fact that risk ranking process is quite a semi-quantitative procedure and moreover, the consequences have to be ultimately expressed in units the same as those of introduced in (2) and (3), the consequence categories have to be combined into a single measure by conducting a quantitative risk analysis. The quantitative analysis introduced in Tables VI to X is employed to convert the quantitative analysis to the appropriate number.

TABLE V. CONSEQUENCES CATEGORIES OF AN EVENT

Category	Contents/Units of Measurement
Network Performance Consequences	-Loss of system capacity (MWh.) -System average interruption duration index (SAIDI) (minutes)
Safety Consequences	-Number of fatalities -Number of major injuries -Number of minor injuries
Financial Consequences	-Repair cost -Replacement cost
Environmental Consequences	-Volume of oil spilled -Volume of SF_6 lost -Number of fires with significant smoke/pollution -Volume of waste created -Scale of disturbance (traffic/noise)

TABLE VI. FACTORS CLASSIFICATION AND SCALES

Failure Frequency	Failure per Year	Model Value
Poor	>4	4
Average	2-4	3
Good	1-2	2
Excellent	<1	1

TABLE VII. FACTORS CLASSIFICATION AND SCALES (MC)

Maintenance Cost (MC)	Consequence($)	Model Value
High	≥20000	2
Low	<20000	1

TABLE VIII. FACTORS CLASSIFICATION AND SCALES (OF)

Operational Failure(OF)	Consequence	Model Value
High	No spare nor alternative operation	4
Average	Spare function shared	2
Low	Spare function available	1

IV. Risk Estmiation and the Associated Cost

The concept of risk measurement when is taken into account as a monetary expression is used to specify the reason why some items while ranging from high risk to low risk are not taken into account for preventive maintenance [8]-[10]. In this respect, the following expression can be used to quantify the effect of maintenance performed on the k^{th} component.

$$ERC_k = B_k / C_k \tag{4}$$

where, B_k and C_k respectively correspond to the cost of risk associated with the k^{th} component after and before maintenance for the sake of risk mitigation. Once this index reaches 1, close to 1, or a bit lower than 1, it means that risk mitigation in the given case is not of any assistance neither technically nor economically. Noteworthy is that the cost of mitigation is combined with the network performance penalty, human safety, and environmental tax.

In order to prioritize maintenance plans to have the risk reduction maximized, the consequences associated with each category are expressed in monetary terms. Financial category is expressed as the cost of component maintenance and repairs. Network performance is assigned the cost of energy not supplied together with the customer interruption costs ($/KWh) [5]. And finally in response to the safety consequences, injuries and fatalities, different values have been addressed yet [7, 8].

Environmental consequences are more difficult to be modeled. In Tehran distribution network, huge amount of oil emissions and its consequences are of much considerable importance. Hence, Regulatory operators have recently put great emphasis on the emissions of the network [12], [13].

TABLE IX. CUSTOMER INTERRUPTION COSTS ($/KWH)

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

TABLE X. FACTORS CLASSIFICATION AND SCALES (OI)

Operational Impact(OI)	Consequence	Model Value
Extremely high	Immediate plant shut down	10
Very high	Partial plant shut down	6
High	Impact production levels or quality	4
Average	Operational cost associated to unavailability	2
low	No significative impact on operations	1

TABLE XI. FACTORS CLASSIFICATION AND SCALES (ISE)

(ISE)	Consequence	Model Value
Extremely high	Impact on internal and external human safety requiring notification to public institutions	8
Very high	Irreversible environmental affection	6
High	Impact operation facilities causing severe damage	4
Average	Minor accidents and incidents	2
low	Environmental affection without laws violation	1
Very low	No impact to human, environment nor operation facilities	0

V. PRACTICAL MODEL AND ILLUSTRATIVE STUDY

The risk-matrix based treating of a network can be regarded as a good starting point for an accurate maintenance prioritization. In order to obtain useful results and to investigate the possibility of expanding, the studied network is chosen as a part of the power distribution network in Tehran, Iran. The AZADI system, located in the western part of Tehran electric distribution network, is considered as the paper test system which includes four medium voltage (MV) feeders coming from the 63 kV Olympic substation. The system understudy is also comprised of 156 overhead line segments, 55 cable segments, and 61 transformers. This network serves approximately 200000 customers, most of which are of industrial category while some are residential or commercial.

The proposed method is applied to the system understudy and the results are numerically investigated. Table XII addresses the obtained results associated with a MV feeder oriented from AZADI system. Engineering judgment and expertise would often be used to build on the available raw data to provide an improved estimate of risk factor. In this paper, data calibration and data mining approaches, e.g., expert choice and analytical hierarchical process (AHP) algorithm have been employed to model the possible consequences of a component [14]. The cost/benefit analysis on each component, conducted through the proposed ERC index, is pursued for the sake of risk mitigation. This helps into identification of when to accept or reject the risk.

As it can be followed in Fig. 2, the results to frame the risk matrix for the corresponding decision making are illustrated. It can be inferred that component number 1 and 12 are assigned a very high risk and their associated ERCs are close to 1 or less than 1. As a result, their risk mitigation treatments are not profitable at all. On the other hand, components number 2, 5, 10, 4, 6, and 14 are assigned either high or moderate risk levels. They are also deemed to be the best choices for investment, due to their ERCs. Similarly, the components number 3, 7, 8, 9, 11, 13, 15, and 16 are attributed some far low risk cells and their ERCs show that their risk can be accepted. Further studies prove that the mitigation in components number 13 and 16 are the most effective.

The proposed method within the scope of this paper, not only does provide the possibility of discriminating different components from the risk level point of view, but also it helps in the determination of the effective and required maintenance strategies and inspections. Moreover, this methodology enables network owners and operators to effectively focus the available resources and network investments towards the high-risk parts and components than some of lower risks or trivial effects on the overall system risk.

Frequency \ Consequence	10	20	30	40	50
5				12	
4		5,10			1
3	8	7,17	4,6		
2	9	13,15,16	14		2
1		3,11			

Figure 2. Rrisk-matrix decision making process

VI. CONCLUSION

This paper elaborated a practical approach in response to a long need in maintenance planning of power distribution systems all over the world. The proposed approach in this paper is mainly on the basis of risk matrix and the associated risk analysis. It effectively helps in the determination of when to either accept or reject the risk of an imminent consequence, which can be a failure on a system component, tolerating no waste of the resources. It also enables the network owners and operators to focus the network investments towards some high-risk components, rather than indiscriminately spoiling the available financial resources to the maintenance of all the system components. Employing a qualitative/quantitative approach for that, this paper provides a practical simple framework for the risk analysis of system components. It was applied on a real distribution network located in Tehran, Iran, and proved its effectiveness and applicability through its implementation process.

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TABLE XII. RISK ANALYSIS CONDUCTED ON A MV FEEDER OF THE TEST SYSTEM

Number	Components	F	NP=OF.OI			C		Risk=F×C		Status of Component	ERC
		Failure Frequency	OI	OF	NP	Cost	ISE	F	C		
1	MV Transformers(1)	4	10	4	40	2	3	4	45	Very High Risk	0.98
2	MV Transformers(2)	2	10	4	40	2	3	2	45	High Risk	1.5
3	Substation Building	1	2	4	8	2	2	1	12	Low Risk	1.01
4	Breaker (1)	3	6	4	24	2	2	3	28	Moderate Risk	1.3
5	Breaker (2)	4	4	4	16	2	2	4	20	Moderate Risk	1.4
6	Sectionalizer (1)	3	6	3	15	1	2	3	21	Moderate Risk	1.6
7	Sectionalizer (2)	3	5	2	10	1	2	3	13	Low Risk	1.1
8	Fuse (1)	3	2	1	2	1	2	3	5	Low Risk	0.7
9	Fuse (2)	2	2	1	2	1	2	2	5	Low Risk	0.90
10	Relay (1)	4	6	2	12	1	2	4	13	Moderate Risk	0.5
11	Relay (2)	1	5	2	10	1	2	1	13	Low Risk	1.1
12	Cable	5	10	4	30	2	2	5	34	Very High Risk	1.1
13	Cable termination	2	5	3	15	1	2	2	18	Low Risk	1.2
14	Conductor	2	6	3	18	1	2	2	21	Moderate Risk	1.9
15	Overhead Line Belongings	2	4	3	12	1	2	2	15	Low Risk	1.15
16	Cement Pole	2	4	3	12	2	2	2	16	Moderate Risk	1.5
17	Cutout Fuse	3	4	3	12	1	2	3	15	Moderate Risk	1.2