Model of improvement of maintenance policies for electrical substations

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Abstract: We observe that in electrical substations, issues often arise that directly influence the requirements for maintenance actions to be adequate. Maintenance policies are sometimes inappropriate because the aging of assets has been incorrectly evaluated, because technological upgrades are not properly reflected in maintenance plans, or because the operational regime is not taken into account. Thus, once the need for adjustments because of the presence of one or more of the issues mentioned above has been identified, it is essential that a different systematic be implemented to achieve the expected performance of the affected substation. Accordingly, this article proposes a model for establishing adequate maintenance policies to produce more effective results, taking into account not only the possible consequences of failure to which the system under study is subject but also the various specific concerns associated with the performance indices of the electricity system. A real electrical substation is used as a pilot system.

Keywords: Maintenance effectiveness, multi-criteria decision-making, additive veto model, maintenance of electrical substations

1. INTRODUCTION

According to [1], electrical systems suffer from wear and tear, causing them to deteriorate over time. This often leads to failures that can interrupt the power supply. As a result, the absence of appropriate maintenance planning inevitably leads to economic losses and unnecessary downtime.

High costs are incurred by such failures of planning in two different aspects: First, there may be failures caused by the insufficient implementation of preventive actions, which may have serious consequences in the form of prolonged interruptions or damage of another nature as a result of equipment failure. On the other hand, it is possible to perform excessive maintenance, which generates high maintenance costs and may lead to damage or malfunction caused by errors made at the time of maintenance. Thus, in either extreme, serious consequences may result from inadequate maintenance planning.

Therefore, effective maintenance planning should be conducted to ensure that the maintenance actions to be performed are truly the most effective and that the available resources are used rationally. For this purpose, the development of a maintenance plan should be guided by reliable methods of identifying effective and ineffective maintenance actions to achieve continuous improvement through the identification of ineffective maintenance actions and the replacement of such actions with new, effective ones [2].

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2. THE MULTI-CRITERIA MODEL FOR THE SET OF ACTIONS TO BE IMPROVED

Multiple-Criteria Decision Making (MCDM) is a set of methods and techniques that has been developed to support individuals and organizations in resolving decision-making problems [3]. According to [4], multi-criteria decision-making analysis structures and analyzes complex decisions in which several criteria must be considered, some of which conflict with each other. In this context, [5] argues that MCDM offers a broad variety of tools that support the decision maker in solving problems while considering different points of view, often ones that are contradictory and heterogeneous.

Multi-criteria decision models have found diverse applications in fields such as water resources ([6]), multi-criteria risk analysis ([7], [8]) and maintenance. As an illustration a brief description of various maintenance problems from a multi-criteria perspective is presented. [9], [10], and [11] use multi-criteria models to address repair and outsourcing contracts. [12] presents a preventive-maintenance decision model for addressing conflicting criteria that takes into account the decision maker's preferences. [13] proposes a multi-criteria decision model concerning inspection intervals for condition monitoring and the decision maker's preferences regarding downtime and cost.

In this context, this paper proposes a multi-criteria decision model to support maintenance planning by allowing actions that are not contributing to adequate equipment performance to be identified by a prioritization model based on a multi-criteria decision method.

In fact, it is plausible to incorporate the desires of the maintenance manager into the organizational culture to create an ongoing process of reviewing proposed maintenance plans to correct actions that are not effectively contributing to good system performance, thus ensuring the best possible use of maintenance resources.

An ineffective action is one that is problematic in at least one of the following aspects: (1) it may be not feasible, (2) it may be too difficult to perform, (3) it may be likely to cause damage or malfunction, (4) it may not be procedurally appropriate, (5) the time investment required for the action may not be commensurate with the degradation of the equipment, and so on.

It is evident that an ineffective action could be identified as ineffective for any of a number of different reasons, as elucidated above, so it is possible for such a set of actions to have very different characteristics. Therefore, to identify a critical set of actions, it is necessary to define an appropriate approach to address this diversity of potential problems.

It is not a trivial task to distinguish effective maintenance actions from those that are not effective, and such an evaluation involves analysis from multiple perspectives. Thus, a multi-criteria decision model is developed here to support the selection of the critical set of actions that should be revised for the next iteration of a maintenance plan.

The construction of a multi-criteria model relies on certain steps related to the specific multi-criteria method that was chosen. In this article, we propose a model based on the compensatory method with veto, which was proposed in [14]. According to [14], the multi-attribute or multi-criteria decision methods that are most commonly found in the literature are additive methods. The reason for this preference is related to the very intuitive approach that is taken in the aggregation step of these methods. As was suitably noted by this author, despite the popularity of these methods, there are some situations in which the DM is not willing to select a particular alternative to compensate for a criterion whose performance is below a certain level. In such a case, a veto function should be invoked to avoid the selection of such alternatives.

Thus, the construction of the model proposed here consists of 3 distinct phases:

The first step consists of the definition of the set of alternatives. The alternatives are actions associated with a piece of equipment that fulfill at least one of the following conditions: (1) the action is specific to a piece of very critical equipment, (2) factors can be clearly identified that indicate the inefficiency of the action, or (3) there were changes in the system such that adjustments of the maintenance plans associated with this action are required.

The second step consists of the definition of the criteria set. Because this problem is intrinsically related to the measurement of the effectiveness of maintenance actions, the criteria set defined by the decision-maker should reflect his own philosophy regarding the efficiency of maintenance actions. As noted in several different papers (see [15]), the evaluation of the efficiency of maintenance action is not a trivial task. Thus, some criteria will inevitably be subjective. In this case, we invoke the concept of constructed attributes, as defined in [16]. According to [16], unlike natural attributes, which are simultaneously appropriate to a variety of contexts, a constructed attribute is developed for a given decision context. We discuss attributes in the next section, where all details regarding the aspects involved in the decision-making process are described.

In the third and final phase, the preferences of the decision-maker, the actions and the attributes are organized to produce a decision through the aggregation process. Here, as mentioned above, the third phase consists of following all steps that constitute the additive veto method [14].
In the additive model, we consider that the overall evaluation of alternatives $v(a)$ is the result of the additive aggregation of each criterion $v_i(a)$. Thus, the global value of alternative a is expressed by equation (1). The additive sum is a common approach to aggregating various aspects in the process of multi-criteria evaluation [17]. However, the inconvenience of unlimited compensation sometimes must be addressed, as stated by [14]. Equation 3 provides an alternative to handling this type of situation.

$$v(a) = \sum_{i=1}^{n} v_i(a) k_i \qquad (1)$$

According to [14], for the ranking problem, the decision-maker is not interested in rejecting any alternative outright, but he is willing to reject the positions of certain alternatives in the ranking process. For this purpose, the method presented in [14] uses the following expression for the weighted veto function:

$$r_i(a) = z_i(a) k_i \qquad (2)$$

where

$z_i(a)$ corresponds to the veto function for criterion i
and the k_i is the weight of criterion i.
The veto function for each criterion i ($z_i(a)$) is as follows:

$$z_i(a) = \begin{cases} 0, & \text{if } v_i(a) \le l_i \\ 1, & \text{if } v_i(a) \ge u_i \\ \frac{v_i(a) - l_i}{u_i - l_i} & \text{if } l_i < v_i(a) < u_i \end{cases} \qquad (3)$$

Finally, for the veto be taken into account in a general manner, the function $r_i(a)$ should be summed for all criteria. Thus, let us consider a specific alternative a; the overall role of the veto (the veto index of the alternative a) in a ranking problem is represented by the following expression:

$$r(a) = \sum_{i=1}^{n} r_i(a) \qquad (4)$$

This veto index is introduced into equation 1 in such way that the analysis will account for the effect of the veto.

$$v(a) = r(a) \sum_{i=1}^{n} v_i(a) k_i \qquad (5)$$

In the next section, we define all parameters of the model. We also describe the application of the model.

3. A CASE STUDY IN A REAL ELETRICAL SUBSTATION

Substations may be associated with transmission or distribution depending on the level of their operating voltages. Transmission substations operate at voltage levels of 230 kV and above. Substations with operating voltages below 230 kV are designated as distribution substations, which is the case for the particular substation under study.

Substations may also be classified based on the installation of their equipment in relation to the environment. Thus, there are the following categories: (1) external or outdoor substations and (2) internal or sheltered substations.

External or outdoor substations are those whose equipment is installed without any protection against the weather and is subject to unfavorable atmospheric conditions of temperature, rain, pollution, wind, etc. These conditions affect the wear of component materials and reduce the effectiveness of insulation, and the equipment at such facilities therefore requires more frequent maintenance. The substation under study falls into this category.

3.1. Defining the set of actions

Alencar et al. [18] have argued that the decision-making process frequently addresses the necessity of making choices among alternatives. In this case study, it is important to emphasize that each alternative is a combination of a piece of equipment and an action. An alternative may be invoked by three different procedures. It is worth noting that the number of possible combinations could be very large, as each piece of equipment may be associated with an extensive action list. Therefore, the set of alternatives is a set of ordered pairs (ac_i, q_j), which must be ranked.
The ranking could be performed according to the overall value of the alternative in such a way that the best alternative is one that has the largest value of *v( )*. In this case, a larger value of *v( )* indicates a lesser necessity for improvement associated with the alternative. Thus, the alternatives that should be selected for consideration should be those at the bottom of the list, with the smallest values of *v( )*.

For the electrical substation under study, the set of alternatives is summarized in table 1.

Table 1: Set of actions

Alternatives	Actions	Equipment
A1	Collection of Insulating Oil	Main tank and of the transformer
A2	visual inspection	transformer
A3	thermographic inspection	transformer
A4	Measurement of contact resistance	Breaker Mechanism and contacts
A5	Disturbance	Breaker Mechanism and contacts
A6	visual inspection	switch
A7	Measurement of Resistance and Insulation FP	Insulation-System Breaker
A8	Thermographic inspection	Buses, switching and connections
A9	Thorough visual inspection (c / maneuver)	Buses, switching and connections
A10	Measurement of insulation resistance	Insulation-System Recloser
A11	Measurement of contact resistance	Recloser Mechanism and contacts
A12	overhaul	recloser
A13	visual inspection	recloser
A14	thermographic inspection	recloser
A15	visual inspection	Capacitor bank
A16	thermographic inspection	Capacitor bank

A17	Monitoring of neutral current	Capacitor bank
A18	overhaul	Capacitor bank
A19	Collection of Insulating Oil	main tank and voltage-regulator switch
A20	overhaul	Voltage regulator
A21	Measurement of resistance	Ground grid
A22	Measurement of Potential	Ground grid
A23	general revision	Keyswitch under load - OLTC
A24	Overhaul	Key oil capacitor bank

3.2. The objectives and attributes of the decision-making problem

The maintenance manager's objective when preparing the maintenance plan is to ensure that the planned maintenance actions are effective. In other words, the manager desires the resources that were allocated to the maintenance department to be put to their best possible use.

To achieve this objective, there are several aspects to be considered. For example, it is important to evaluate whether the time required for an activity is commensurate with the degradation of the equipment. In fact, it is very important to know whether the time elapsed since maintenance was last performed is indeed a good indicator of degradation. It could be argued that instead of time, the amount of use since the last maintenance activity may be a more precise indicator of degradation. Therefore, an evaluation of this issue should be performed to assess the effectiveness of maintenance.

A constructed attribute related to this issue is proposed for the decision maker. According to [16], a constructed attribute is typically meant to measure more than one facet of a complex problem, and the descriptions of the levels are very important to the correct understanding of the attribute.

Table 2 below offers descriptions of the different levels for the attribute related to age appropriateness.

Table 2: The constructed attribute related to age appropriateness

Value	Description of the attribute level
1	The variable used to measure the time elapsed since the last maintenance action has no correlation with the time to degradation and must not be used to describe the age of the equipment.
2	The variable used to measure the time elapsed since the last maintenance action has a very weak correlation with the time to degradation and should not be used to describe the age of the equipment.
3	The variable used to measure the time elapsed since the last maintenance action has a weak correlation with the time to degradation, and it is preferable that it not be used to describe the age of the equipment.
4	The variable used to measure the time elapsed since the last maintenance action has a non-negligible correlation with the time to degradation and could be used to describe the age of the equipment.
5	The variable used to measure the time elapsed since the last maintenance action has a strong correlation with the time to degradation, and it is preferable that it be used to describe the age of the equipment.
6	The variable used to measure the time elapsed since the last maintenance action has a very strong correlation with the time to degradation and should be used, in addition to other indicators, to describe the age of the equipment.
7	The variable used to measure the time elapsed since the last maintenance action is directly associated with the time to degradation and is the best variable to describe the age of the equipment.

Another aspect that should be considered is whether performing the procedures necessary to execute a maintenance action could cause damage or malfunction. Thus, in some sense, the possibility of causing damage or malfunction should be considered in the effectiveness analysis of a maintenance action.

Table 3 below offers descriptions of the different levels for the constructed attribute related to the likelihood of causing damage or malfunction.

Table 3: Constructed attribute: Possibility of causing damage or malfunction

Value	Description of the attribute level
1	Damage or malfunction is very unlikely to be caused when performing the specific maintenance action
2	Damage or malfunction is unlikely to be caused when performing the specific maintenance action
3	Damage or malfunction is somewhat likely to be caused when performing the specific maintenance action
4	Damage or malfunction is likely to be caused when performing the specific maintenance action
5	Damage or malfunction is more than likely to be caused when performing the specific maintenance action
6	Damage or malfunction is fairly certain to be caused when performing the specific maintenance action
7	Damage or malfunction is almost guaranteed to be caused when performing the specific maintenance action

Another aspect that might be important in the assessment of the effectiveness of maintenance actions is the probability of a false negative. Because a substation is a complex system, a maintenance plan for this type of system typically includes a large number of inspections. When an inspection is performed, the team may overlook some failure or defect present in the equipment.

Table 4 below offers descriptions of the different levels for the constructed attribute related to the likelihood of a false negative at inspection.

Table 4: The constructed attribute: The possibility of a false negative at inspection

Value	Description of the attribute level
1	It is very unlikely that a false negative will be encountered when performing the specific maintenance action
2	It is unlikely that a false negative will be encountered when performing the specific maintenance action
3	It is somewhat likely that a false negative will be encountered when performing the specific maintenance action
4	It is likely that a false negative will be encountered when performing the specific maintenance action
5	It is more than likely that a false negative will be encountered when performing the specific maintenance action
6	It is fairly certain that a false negative will be encountered when performing the specific maintenance action
7	It is almost guaranteed that a false negative will be encountered when performing the specific maintenance action

Once each of the attributes has been described, it is important to consult with the decision-maker to ensure that there is no doubt or ambiguity regarding the understanding of each level of every criterion. Additionally, the decision-maker must evaluate each alternative with respect to each attribute.
Table 6 presents the decision matrix, which contains the evaluation of each alternative with respect to each criterion.

Table 5: Decision Matrix

Alternatives	age appropriateness	likelihood of causing damage or malfunction	likelihood of a false negative at inspection
A1	6	6	5

A2	4	6	3
A3	6	6	3
A4	6	5	1
A5	5	6	1
A6	4	6	3
A7	6	5	1
A8	6	7	5
A9	5	5	5
A10	6	4	1
A11	6	5	1
A12	6	2	3
A13	4	3	3
A14	3	5	3
A15	4	6	3
A16	6	5	3
A17	6	7	3
A18	6	3	3
A19	6	6	1
A20	6	5	1
A21	5	2	4
A22	5	5	5
A23	6	3	5
A24	6	2	5

3.3. Defining the preference functions

Once the decision-maker has confirmed that he has a good understanding of the attributes, the next step involves the quantification of his or her preferences. This process consists of the assessment of the utility function for each attribute. For constructed indices, these functions are assessed directly for the defined points.

Let us define x as a value chosen by the decision-maker to represent the performance of an alternative with respect to a specific attribute based on the consideration of all descriptions associated with all levels.

In our specific case, x may be ordered as follows: $x^0, x^1, .., x^5, x^*$, where x^0 is the least preferred value and x^* is the most preferred value. Thus, for the assessment of the utility values $u(x^j), j=1, \ldots, 5$. The decision-maker must identify for each x^j the correspondent probability p^j such that the decision-maker's preference for this situation is equivalent to his preference for a lottery that yields either x^* with probability p_j or x^0 with probability $(1\text{-}p_j)$. Then, by equating the utilities, we find

$$u(x^j) = p_j u(x^*) + (1 - p_j)u(x^0) = p_j, j=1,\ldots,5 \quad (6)$$

Here, it is important to emphasize that this direct assessment could yield multiple different functions for the association of x^j with $u(x^j)$ because the different levels related to a specific attribute might not be equally spaced.

In our case, for this first application, the decision-maker responded to the lotteries in such a way that the results were nearly linear functions of $u(x^j)$. Thus, for all criteria, for the sake of simplification, linear utility functions were used. Because the number of levels was the same for all attributes, the values of the utility function that were used to maximize the attributes were the same for each attribute; these values are presented in table 6.

Table 6: Values of the utility function for the maximization of attributes

j	x^j	$u(x^j)$

	1 (x^0)	*0.00*
1	*2*	*0.17*
2	*3*	*0.33*
3	*4*	*0.50*
4	*5*	*0.67*
5	*6*	*0.83*
	7 (x^*)	*1.00*

Similar to the case of the attributes to be maximized, the relation between the level of the attribute and the utility function for each attribute to be minimized was also a linear relation. The values of the utility function used for this purpose are presented in table 7.

Table 7: Values of the utility function for the minimization of attributes

J	x^j	$u(x^j)$
	1 (x)*	*1*
1	*2*	*0.83*
2	*3*	*0.67*
3	*4*	*0.5*
4	*5*	*0.33*
5	*6*	*0.17*
	7 (x^0)	*0*

Once the utility functions have been defined, the overall evaluation of the effectiveness of the maintenance actions should be performed; however, before this can be done, it is necessary to define the scale constant for each decision axis. The values obtained by following the process for the assessment of the scale constant for each attribute presented in [19] are presented in table 8.

Table 8: Scale constants

Attribute	***Value of the scale constant***
age appropriateness (k_1)	*0.2*
likelihood of causing damage or malfunction (k_2)	*0.4*
likelihood of a false negative at inspection (k_3)	*0.4*

Once the scale constants have been defined, it is possible to calculate the global values using equation (1).. The interesting aspect is that the decision maker said to be annoyed with low level for some attributes. For each attribute, he defines the values of l_i and u_i that correspond to the lower and upper thresholds for the veto function, as summarized in table 9. To reiterate, the upper threshold corresponds to the minimum value of performance $v_i(a)$ with respect to criterion i that is acceptable to the decision maker, whereas l_i corresponds to the maximum value of performance $v_i(a)$ with respect to criterion i that the decision maker is certain to reject.

For the criteria to be minimized, these interpretations of the veto thresholds are reversed. The upper threshold becomes the maximum value of performance $v_i(a)$ with respect to criterion i that is acceptable to the decision maker, whereas l_i becomes the minimum value of performance $v_i(a)$ with respect to criterion i that the decision maker is certain to reject.

Table 9: Lower and upper thresholds for the veto function for each criterion

Attribute	***l_i***	***u_i***
age appropriateness	*1*	*2*
likelihood of causing damage or malfunction	*7*	*5*
likelihood of a false negative at inspection	*7*	*6*

3.4. Overall evaluation

Once all parameters have been defined, it is possible to determine the final global value for each alternative. It is worth emphasizing that the final global value is a measure of the effectiveness of the maintenance actions, so the worse the action is placed in the ranking, the greater is the necessity for improvement that is associated with it. Thus, our ultimate objective is to address the worst alternatives. This ultimate objective is out of the scope of this work, but the model presented here defines the very first step toward implementing the desired improvement. Therefore, we propose that this multi-attribute model should be run every year to ensure sufficient time for new maintenance actions, far superior to those identified by the model, to be incorporated into the next annual maintenance plan.

Table 9 below summarizes the overall evaluation and the final ranking.

Table 9: Overall values

Alternatives	**age appropriateness**	**u(x)**	**likelihood of causing damage or malfunction**	**u(x)**	**likelihood of a false negative at inspection**	**u(x)**	**v(a)**	**r(a)**	**v´(x)**	**Ranking**
A1	6	0.83	1	1.00	5	0.33	0.70	1.00	0.70	5
A2	4	0.50	2	0.83	5	0.33	0.57	1.00	0.57	15
A3	6	0.83	2	0.83	5	0.33	0.63	1.00	0.63	10
A4	6	0.83	6	0.17	5	0.33	0.37	0.80	0.29	20
A5	5	0.67	6	0.17	5	0.33	0.33	0.80	0.27	22
A6	4	0.50	1	1.00	5	0.33	0.63	1.00	0.63	10
A7	6	0.83	6	0.17	5	0.33	0.37	0.80	0.29	20
A8	6	0.83	2	0.83	3	0.67	0.77	1.00	0.77	2
A9	5	0.67	2	0.83	3	0.67	0.73	1.00	0.73	4
A10	6	0.83	2	0.83	4	0.50	0.70	1.00	0.70	5
A11	6	0.83	2	0.83	4	0.50	0.70	1.00	0.70	5
A12	6	0.83	2	0.83	4	0.50	0.70	1.00	0.70	5
A13	4	0.50	2	0.83	4	0.50	0.63	1.00	0.63	10
A14	3	0.33	2	0.83	4	0.50	0.60	1.00	0.60	13
A15	4	0.50	2	0.83	3	0.67	0.70	1.00	0.70	5

A16	6	0.83	2	0.83	3	0.67	0.77	1.00	0.77	2
A17	6	0.83	1	1.00	3	0.67	0.83	1.00	0.83	1
A18	6	0.83	7	0.00	6	0.17	0.23	0.60	0.14	23
A19	6	0.83	7	0.00	6	0.17	0.23	0.60	0.14	23
A20	6	0.83	5	0.33	6	0.17	0.37	1.00	0.37	18
A21	5	0.67	1	1.00	6	0.17	0.60	1.00	0.60	14
A22	5	0.67	2	0.83	6	0.17	0.53	1.00	0.53	16
A23	6	0.83	5	0.33	6	0.17	0.37	1.00	0.37	18
A24	6	0.83	5	0.33	4	0.50	0.50	1.00	0.50	17

3.5. Some discussion of the results

It is interesting to note that among the 5 worst alternatives (A18, A19, A5, A4, A7), at least 2 actions were recognized by the decision-maker as actions with serious problems to be corrected, and the decision-maker also stated that these actions required deeper study before improvement would be possible. In the case of alternative A18, the decision-maker realized while reviewing the results that this alternative was no longer under consideration for inclusion in the maintenance plan because serious potential problems with this alternative had been identified. By contrast, the decision-maker confirmed that no problems at all had been identified regarding the highest-ranked alternatives. In fact, the best alternative (A17) was designed to replace the worst alternative (A18); however, when the case study was performed, the decision-maker accidentally neglected to delete the alternative A18 from the set of alternatives.

4. CONCLUSION

An electrical substation is a complex system that demands effective maintenance procedures because of the serious consequences associated with its failure. The effectiveness of such maintenance actions depends on various factors; therefore, the discrimination of effective maintenance actions from ineffective ones is non-trivial.

For such a complex system, mistakes that are introduced in standard maintenance procedures are very dangerous because these procedures may be propagated to other electrical substations, potentially leading to countless problems caused by the spread of an incorrect procedure.

Here, the compensatory veto model was applied to the assessment of the maintenance plan of an electrical substation. It is worth emphasizing that in fact, the decision-maker in this case was not comfortable with the idea of unlimited compensation. Thus, the veto function offered an excellent method of ensuring that the results of the analysis satisfied practical expectations.

Finally, based on the results of the model, the decision-maker can select the alternatives to be improved for the next year. Therefore, the proposed model should permit the initiation of a continuous process of improvement that should benefit any segment of any industry that is concerned about improving its results.

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