IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 27 October 2022, accepted 8 November 2022, date of publication 17 November 2022, date of current version 23 November 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3222766

RESEARCH ARTICLE

A Novel Multi-Criteria Decision-Making Framework in Electrical Utilities Based on Gray Number Approach

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This work was supported by the University of Shiraz. The work of Mazaher Karimi was supported by the REDISET Project funded by Business Finland under Grant 27081089141/REDISET.

ABSTRACT Given the current trend of reviving the power system, which is considered by competitive markets, the privatization of the power system is forcing them to develop the necessary decision-making policies from a technical and economic point of view to improve their asset management practices. Reliability-centered maintenance is an efficient process to consider these two important aspects, i.e. technical and economic ones when performing maintenance optimization. This paper proposes a new technique to solve the actual stochastic Multi-Criteria Decision-Making (MCDM) problems with uncertain weight information using a combination of Stochastic Multi-Criteria Acceptability Analysis (SMAA) and Elimination Et Choice Translating Reality (ELECTREIII) methods combined with gray system theory. In maintenance planning, gray system theory is used to determine the specific types of power system components that should receive the most attention. Then, the optimal maintenance strategy of every critical component is determined by recognizing the lowest costs associated with various strategies. The suggested framework demonstrates its relevance and efficacy for actual asset management optimizations in electric power systems, as demonstrated in the IEEE 14-bus test system.

INDEX TERMS Critical component, gray number, multi-criteria decision-making, reliability centered maintenance (RCM), transmission system.

I. INTRODUCTION

Electrical transmission utilities experiencing a major impact due to the increasing pressure to decrease enormous costs incurred as a result of the operation, maintenance actions, and investment [1]. Maintenance costs account for a large share of total costs since they play a vital role in keeping the reliability performance of the system within acceptable limits and hence cannot be ignored. Though, existing experience demonstrates nearly one-third of all maintenance costs are squandered due to inefficient or incorrect maintenance procedures [2], which treat all types of equipment equally without regard to their lifespan, outage statistics, economic values, or in a nutshell, the criticality of their overall performance on the system as a whole [3].

As a result, power transmission utilities should adhere to effective operational policies in order to fulfil the market participants' needs for reliability and market fairness, which

The associate editor coordinating the review of this manuscript and approving it for publication was Zhouyang Ren.

has become more stringent. Maintenance is now viewed as a source of profit for electric utilities, therefore research in this area is gaining traction [1], [2]. As an improvement to the previous maintenance strategy, the operator can give priority attention to some essential components during the long-term capital investment, medium-term planning, and short-term maintenance schedule decision-making phases [3], [4], [5], [6], [7]. The main motivation of this research is that if the maintenance strategy organized and planned properly, it will pass the existing conservative and dangerous approach toward executing maintenance tasks, instead of focusing more time and energy on the components that require the most maintenance. Apart from that, it will be a complete waste of resources, including money and time. In order to satisfy the utility's cost-constrained objectives, reliability centered maintenance (RCM) offers a logical and efficient procedure in order to execute for practical maintenance purposes. The RCM implementation process begins with identifying the system's essential parts that their defects would have the biggest effects on the system reliability performance.

The determination of the most critical components in power distribution systems for maintenance prioritization has recently received a great deal of attention in the research community. In such systems, the proposed technique of [8] was the first to utilize RCM in a systematic manner via sensitivity analysis using major criteria. The system load point indices variation has been examined as a surrogate for component relevance. In the power distribution and transmission network, [9], [10] applied a multi-objective optimization framework to optimize maintenance policies using RCM concepts. There are a few examples where RCM has been used on specific types of components, as follows: RCM was used for transmission lines reported by [11], [12], and [13], on voltage regulators by [14], on underground networks including cable systems by [15], on distribution overhead lines by [16], on gas turbine units by [17], on power transformers by [18] and [19], meanwhile on medium-voltage circuit breakers [20], [21], among other things. Nevertheless, the majority of the references listed above did not optimize the main solutions via a comprehensive study. Additionally [2], [22], [23], [24], and [25] have attempted to put RCM into practice at the power distribution level. Concerning RCM applications at the transmission level, [26] and [27] establish and quantify significance indices for identifying the important elements of transmission systems from a reliability perspective. The optimum maintenance schedule for transmission system components is determined in [11] and [28] using conventional modified semi-Markov models in conjunction with the Genetic Algorithm. For transmission line maintenance, RCM is generally recommended and approached qualitatively in [12]. The time-shift-based Monte Carlo simulations and a linear programming optimization model have applied reliability-based methods to transmission system planning for the BC Hydro North Metro System as proposed in [13]. The optimal maintenance plans for electric power transmission systems are selected using particle swarm optimization (PSO) in [29]. Nonetheless, earlier attempts have used approaches that either ignore the requirements of electricity markets or are essentially reliant on the old vertically integrated market framework. Additionally, the ambiguities and inaccurate judgments inherent in RCM decision making could not be adequately addressed in the majority of previous research. Along with the aforementioned research, there is still a need and opportunity to develop a decision-support tool to assist electricity grid operators in implementing RCM strategies in various sections of power systems, most notably the highly interconnected and nonlinear power transmission level of interest to this paper. Therefore, the main objective of this research is to propose a novel approach to identifying the critical components in power transmission utilities via the gray number technique, which is a powerful tool for expressing uncertainty. The main feature of the proposed method is that it can provide an optimal algorithm for maintenance planning even in case of incompleteness and inadequacy of information. This feature is achieved through using gray system gray system is considered as one of the practical techniques for analyzing the uncertainty, which is superior to the mathematical analysis of systems including the incorrect and uncertain information. Besides, the most critical components of the system are selected using gray numbers and a defined index, which has the potential to give the priority to maintenance analysis. The main contributions of this article are highlighted as follows:

1) This work introduces and evaluates an indicator that can assess the risk intensity of system components and identify the critical components in the wide range to address the inaccurate judgments of various decision-makers for power electrical utilities.

2) In the proposed method, three efficient strategies are considered and several relevant criteria are introduced by experts for the analysis of all critical components of the system, so that these criteria are examined in all three strategies for the assessment of final decision outcomes as well as future investment decisions.

3) ELECTRE (Elimination and Choice in Translating to Reality) method, as well-known multi-criteria decision-making technique is implemented for dealing with inaccurate judgments, recognizes the maintenance strategies and forms the decision matrix by considering different indices for entire critical components of each problem. The integration of ELECTRE with SMAA (Stochastic multi-criteria acceptability analysis) method as another multi-criteria decision-making approach for purposes such as issues related to uncertain information utilized based on weight space in order to weigh the criteria and finally by solving the problem of optimal maintenance strategy the lowest cost is determined as the output of the problem.

II. GRAY NUMBERS

Gray theory is a method used to investigate uncertainty that is superior in the mathematical analysis of systems with ambiguous information. According to grey theory, if all of the system's information is known, the system is referred to as a white system; if all of the system's information is unknown, the system is referred to as a black system. A gray system is one that only has partial information, as shown in figure 1.

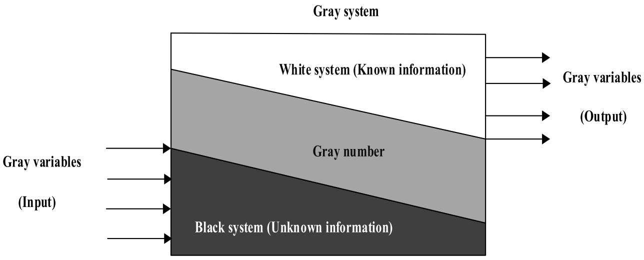

FIGURE 1. **A gray system basic structure.**

Julong [30] proposed the gray theory to deal with scenarios involving unknown and partly unknown information. A gray number (defined by $\otimes$) can be identified as a number with an unknown exact value but a known span.

Typically, a gray number is signified based on a set of numbers or closed interval which is described in the following definition.

Definition 1: Assume $\otimes G = [a, b]$ is a gray number representing a as minimum and b as maximum boundaries $\otimes G$, and a, b ϵ R.

Definition 2: Assume $\otimes G_1 = [a, b]$ and $\otimes G_2 = [c, d]$ are two gray numbers, $\mu \geq 0$, and $\mu \epsilon R$; steps refer as follows:

$$\otimes G_1 + \otimes G_2 = [a + c, b + d] \tag{1}$$

$$\otimes G_1 - \otimes G_2 = [a - c, b - d] \tag{2}$$

$$\otimes G_1 \times \otimes G_2 = \begin{bmatrix} \min(ac, ad, bc, bd), \\ \max(ac, ad, bc, bd) \end{bmatrix} \tag{3}$$

$$\otimes G_1 \div \otimes G_2 = [\min(\mathrm{a/c,\ a/d,\ b/c,\ b/d}), \max(\mathrm{a/c,\ a/d,\ b/c,\ b/d})]; \tag{4}$$

$$\mu \otimes G_1 = [\mu a, \mu b]; \tag{5}$$

Definition 3: Consider $\otimes G_1 = [a, b]$ and $\otimes G_2 = [c, d]$ as two gray numbers; the probability degree of $\otimes G_1$ against $\otimes G_2$ is expressed as bellows:

$$P(\otimes G_1 \geq \otimes G_2) = max\left\{1 - \max\left(\frac{d-a}{L(\otimes_1)+L(\otimes_2)}, 0\right), 0\right\} \tag{6}$$

Here, $L(\otimes G_1) = b - a$ and $L(\otimes G_2) = d - c$ are the lengths.

Definition 4: Consider $\otimes G_1 = [a, b]$ and $\otimes G_2 = [c, d]$ as two gray numbers; the correlation among them is defined as follows:

1. For $P(\otimes G_1 \geq \otimes G_2) < 0.5$, *then* $\otimes G_1 < \otimes G_2$, define as $\otimes G_1$ is lesser than $\otimes G_2$.
2. For $P(\otimes G_1 \geq \otimes G_2) = 0.5$, *then* $\otimes G_1 = \otimes G_2$, define as $\otimes G_1$ is equal than $\otimes G_2$.
3. For $P(\otimes G_1 \geq \otimes G_2) > 0.5$, *then* $\otimes G_1 > \otimes G_2$, define as $\otimes G_1$ is more than $\otimes G_2$.

III. RELIABILITY CENTERED ASSET MANAGEMENT

Nowadays, power system operators with open access markets must achieve the suitable balance to meet the requirements of entire customer for improving the service quality at an appropriate price and demands for sufficient returns on the invested capital. Deregulation of the electricity system market has allowed the RCAM to be implemented in order to optimize these demands. To ensure long-term profitability and the best potential earnings, power system asset management plays a significant role in making and evaluating key decisions. It is proposed in this study that a technical/financial advisor for a utility do an assessment of the value of each equipment type to the reliability of the power system in order to determine maintenance priorities. As a result of this, the advisor can offer appropriate budgetary allocations for those essential tool types that are between all the component kinds, operationally supposed to be addressed in maintenance schedule. These results extracted in a more cost-effective decision by prudent allocation of available financial resources and proper treatment of key physical assets. Given the flaws in current maintenance management systems, it is critical to develop a systematic maintenance programmer that includes the issue. RCM offers a cost-effective plan with the objective of strategically managing maintenance procedures in a more reliable manner. Thus, as illustrated in Figure. 2, a strong correlation exists between RCM and RCAM. As seen in Figure. 2, power system RCAM can be linked to power system asset management via an RCM method, which normally assists the asset manager in finding a solution for power system maintenance scheduling.

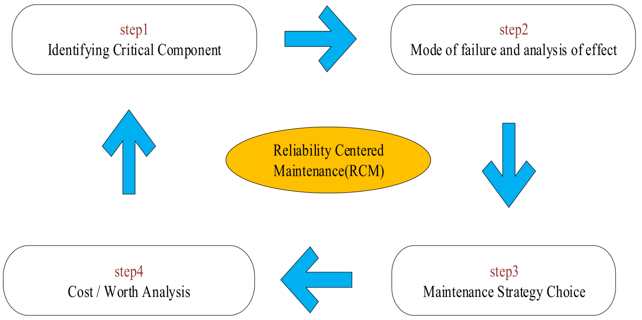

FIGURE 2. **The general structure of asset maintenance, RCAM and RCM.**

The RCM process is divided into four distinct parts. The critical component identification procedure is the first and most critical stage in RCM. After identifying the key components that have a significant impact on system dependability, a failure mode and effect analysis (stage 2) is performed. This assists in directing maintenance efforts toward the required failure modes and avoiding catastrophic failure issues. The next step is to choose the most appropriate maintenance strategy (stage 3), which is followed by a final cost/benefit analysis. These two last stages are aimed at determining the most cost-effective maintenance techniques to implement in response to the first two stages. This technique will assist the asset manager in allocating the available resources by providing useful information. As can be seen, the first stage of the RCM process, which serves as the foundation for later analyses, is the most essential one in this study. There are a variety of components in systems that contribute to varied levels of system reliability. It is clear that power system reliability indices will be affected by a wide range of equipment ageing circumstances and failure impacts. Thus, in power system planning, asset management, and resource allocation, assigning equal weight to all component types is illogical, particularly from a system reliability standpoint. To overcome this, some practical criteria involving the pragmatic aspects of dealing with such a MCDM problem must be proposed.

IV. CRITICAL COMPONENT SELECTION

This section is explained the main stage for doing maintenance optimization to identify the vital components of system utilizing suitable indicators which represent the severity level of various system components. In parallel, the Severity Risk Index (SRI), suggested through the well-known NERC's operating and planning committees in 2010, is used in this article to analyze the criticality of various components and to choose the most critical component with the highest SRI value simultaneously. NERC defined two distinct forms of SRI. SRI_{BPS}, a further modification of SRI, is applied in this research to determine the risk severity level of an event and its system reliability impact. In comparison to the previous version of SRI, SRI_{BPS}, provides a more accurate assessment of the risk severity level associated with incidents that result in load shedding owing to a disruption in supply at the transmission or generating level, rather than a distribution facilities failure. The subscript BPS denotes a bulk power system, which is an interconnected power system that comprises of transmission and generation facilities but excludes distribution facilities. The following defines SRI_{BPS}:

$$SRI_{BPS} = \Big[(LRP) * w_{Load} * \left(N_{BPS_L}\right) + w_{TL} * (N_{TL}) + w_{GL} * (N_{GL})\Big] * 1000 \qquad (7)$$

where,

SRI_{BPS} = Severity Risk Index for specified event (assumed to span one day),

w_{Load} = Weighting of load loss (supposed to be 60%),

N_{BPS_L} = normalized MW of BPS_L in percent,

$$BPS_L = \left(\frac{DPL}{Total_{C/D}}\right) * (CI_{BPS}) \qquad (8)$$

where,

BPS_L = Load loss due to transmission or generation sources outage (MW)for the day,

DPL = Daily peak load (MW),

$Total_{C/D}$ = Total number of customers,

CI_{BPS} = Number of interrupted customers,

w_{TL} = Theamount weight for lines lost in transmission system (supposed to be 30%),

N_{TL} = Theamountofnumberto be normalized for lines lost in transmission system (%),

w_{GL} = The amount weight for generators lost (supposed to be 10%),

N_{GL} = Theamountofnumberto be normalized for generators lost (%),

LRP = Thespecificlevelfor Load restoration promptness, defined as follows:

$LRP = {}^{1}/_{4},\ if\ T_{CAIDI} < 50,$

$LRP = {}^{2}/_{4},\ if\ 50 \leq T_{CAIDI} < 100,$

$LRP = {}^{3}/_{4},\ if\ 100 \leq T_{CAIDI} < 200,$

$LRP = {}^{4}/_{4},\ if\ T_{CAIDI} \geq 200,$

T_{CAIDI} = Customer Average Interruption Duration for the studied event (minutes).

V. MAINTENANCE SCENARIO FOR RCM PROCESS

The process of the maintenance strategies are developed for each of the important components when the selection process is complete. For the most vital generator identified in the preceding sub-section, three degrees of maintenance (Major Maintenance, Minor Maintenance, and No Maintenance) are considered in this study. The maintenance duration time and its impact on the failure rate of the most crucial component distinguish these maintenance procedures. The study period in this work is one year (i.e., 52 weeks), including maintenance implementation. The maintenance is believed to occur during the initial weeks of the research period, with the subsequent weeks regarded to be post-maintenance. For generator, the duration of the maintenance and the time period following the maintenance are estimated to be 4 and 48 weeks, respectively, for major maintenance. These times are assumed to be 2 and 50 weeks for minor maintenance, respectively, while for no maintenance, the entire 52 weeks are considered as the specific time when the maintenance is completed because no maintenance is carried out. Three strategies are defined for the lines, so that the critical line maintenance including electrical and mechanical repairs, the maintenance process on the lines and schedule maintenance operations are implemented once a year, twice a year and three times a year respectively. The following stage involves specialists identifying crucial criteria for critical components and examining them in each plan.

VI. THE PROPOSED MCDM TECHNIQUE VIA COMBINATION OF SMAA AND ELECTRE III METHOD BY CONSIDERING GRAY STOCHASTIC MODEL

This work developed an actual gray stochastic MCDM technique according to combining of SMAA and ELECTRE III in this section.

1) DEVELOPMENT OF THE DECISION-MAKING PROBLEM

Assume a grey MCDM scenario in which the alternative set is equal to $\{a_1, a_2, \ldots, a_m\}$ and the criteria set is equal to $C = \{c_1, c_2, \ldots, c_n\}$. $W_j \in [0, 1]$ and $\sum_{j=1}^{n} W_j = 1$ conditions are used to weight vector criteria $W = \{w_1, w_2, \ldots, w_n\}$.

The alternative evaluation of a_i for criterion c_j is well-defined as $\otimes UF_{ij}$ which represent for the utility function, it is considered gray actual stochastic parameters through the probability distributions functions and density functions $f\left(\otimes UF_{ij}\right)$ in space $X \subseteq R^{m\times n}$ and the gray stochastic decision matrix is stated as $R = \left(\otimes UF_{ij}\right)_{n\times m}.\otimes UF_{ij} = [a_{ij}, b_{ij}]$ and $a_{ij} < b_{ij}$. Decision makers identify the most suitable alternative or offer a hierarchy of alternatives based on the information provided. A method via combining of SMAA and ELECTRE III is presented in solving grey stochastic MCDM problems. The steps are as follows:

Step 1. *Normalize the decision matrix.*

To compare the two types of criteria, the decision matrix must be normalized.

The converting formula is as follows if the criteria consist of the maximizing type:

$$\otimes N_{ij} = \left[\frac{a_{ij}}{b_{ij}^{max}}, \frac{bij}{b_{ij}^{max}}\right]; \quad b_{ij}^{max} = max_{1\leq i\leq m} b_{ij} \tag{9}$$

The converting formula is as follows if the criteria consist of the minimizing type:

$$\otimes N_{ij} = [\frac{a_{ij}^{min}}{b_{ij}}, \frac{a_{ij}^{min}}{a_{ij}}]; \quad a_{ij}^{min} = min_{1\leq i\leq m} a_{ij} \tag{10}$$

Step 2. *Determine the thresholds.*

The decision-makers pick the preference threshold p_j, indifference threshold q_j, and veto threshold v_j considering the criterion C_j, and they fulfill the condition that $0 \leq q_j \leq p_j \leq v_j$. In this paper, three thresholds have been considered as constant value under each criterion due to easy to implement in calculation.

Step 3. *Compute the concordance and the discordance indices.*

The concordance index $C_j\left(\otimes N_{ij}, \otimes N_{kj}\right)$ is calculated using the following formula according to pair of alternatives and every criterion simultaneously:

$$C_j\left(\otimes N_{ij}, \otimes N_{kj}\right) = \begin{cases} 0, & P(\otimes N_{ij} + p_j \geq \otimes N_{kj}) \leq 0.5 \\ 1, & P(\otimes N_{ij} + q_j \geq \otimes N_{kj}) \geq 0.5 \\ \dfrac{p_j + \otimes N_{ij} - \otimes N_{kj}}{p_j - q_j}, & otherwise \end{cases} \tag{11}$$

The discordance index $D_j\left(\otimes N_{ij}, \otimes N_{kj}\right)$ is calculated using the following formula for each criterion and pair of alternatives:

$$D_j\left(\otimes N_{ij}, \otimes N_{kj}\right) = \begin{cases} 0, & P(\otimes N_{ij} + p_j \geq \otimes N_{kj}) \geq 0.5 \\ 1, & P(\otimes N_{ij} + v_j \geq \otimes N_{kj}) \leq 0.5 \\ \dfrac{\otimes N_{ij} - \otimes N_{kj} - p_j}{v_j - p_j}, & otherwise \end{cases} \tag{12}$$

Step 4. *Compute the credibility index, outranking intensity, and overall outranking index.*

The following formulas can be used to calculate the credibility index $CI_j\left(\otimes N_{ij}, \otimes N_{kj}\right)$, outranking intensity $OI_j\left(\otimes N_{ij}, \otimes N_{kj}\right)$, and overall outranking Index $O_j\left(\otimes N_{ij}\right)$ for the criterion C_j:

$$CI_j\left(\otimes N_{ij}, \otimes N_{kj}\right) = \begin{cases} C_j\left(\otimes N_{ij}, \otimes N_{kj}\right), \\ \quad if\ D_j\left(\otimes N_{ij}, \otimes N_{kj}\right) \leq C_j\left(\otimes N_{ij}, \otimes N_{kj}\right) \\ C_j\left(\otimes N_{ij}, \otimes N_{kj}\right) \dfrac{1 - D_j\left(\otimes N_{ij}, \otimes N_{kj}\right)}{1 - C_j\left(\otimes N_{ij}, \otimes N_{kj}\right)}, \\ \quad otherwise \end{cases} \tag{13}$$

Only a partial order of the alternatives can be obtained using the conventional ELECTRE III method. This paper employs outranking intensity and an overall outranking index to determine the whole order of the alternatives.

$$OI_j\left(\otimes N_{ij}, \otimes N_{kj}\right) = CI_j\left(\otimes N_{ij}, \otimes N_{kj}\right) - CI_j\left(\otimes N_{kj}, \otimes N_{ij}\right) \quad i, k = 1, 2, \ldots, m, \quad i \neq k, \tag{14}$$

$$O_j\left(\otimes N_{ij}\right) = \sum_{k=1, k\neq i}^{m} OI_j\left(\otimes N_{ij}, \otimes N_{kj}\right), \quad i = 1, 2, \ldots, m \tag{15}$$

Step 5. *The SMAA-ELECTRE model construction.*

Assuming that information of weight is available; the preceding processes can be carried out in order to generate a ranking of possible solutions. Nevertheless, in actual decision-making situations, information of weight is frequently uncertain, inaccurate, or absent. In this case, the ranking the alternatives process is carried out by the SMAA-ELECTRE model. The alternative with the highest overall ranking index is placed first, followed by the remaining alternatives in order. Firstly, suppose that the information of weight is unknown or just partially known, and that it is shown based on a weight distribution in the weight space W with a joint density function $f_w(w)$. Furthermore, the overall ranking index of the alternative a_i under the criterion c_j is a stochastic variable O_{ij}, and the related density function is $f_X(O)$, as shown in the previous analysis. The ranking function can be expressed as follows, through weight information and the ELECTRE III method:

$$rank\,(i, O, w) = 1 + \sum\nolimits_{k\neq i} \rho\left(w_j O_j\left(\otimes N_{ij}\right) w_j O_j\left(\otimes N_{kj}\right)\right) \tag{16}$$

$W_i^r(\xi) = \{w \epsilon W : rank\,(i, \xi, w) = r\}$ Determines the most beneficial weight sets for each alternative for r ranking. Then compute the rank acceptability index b_i^r, the central weight vector w_i^c, and the confidence factor p_i^c.

$$b_i^r = \int_{O\epsilon X} f_X(O) \int_{w\epsilon W_i^r(O)} f_w(w) dw dO \tag{17}$$

$$w_i^c = \frac{1}{b_i^1} \int_{O \in X} f_X(O) \int_{w \in W_i^1(O)} f_w(w) w dw dO \tag{18}$$

$$p_i^c = \int_{O \in X : rank(i, O, w_i^c) = 1} f_X(O) dO \tag{19}$$

Monte Carlo simulation was used in the aforementioned computation of multidimensional integrations. In this work, Monte Carlo iteration derives uncertain weight and criteria values measures based on the appropriate distributions, and then plugs these values into the overall ranking value function to create a ranking of the alternatives. A central weight vector, acceptability index and confidence factor can be obtained for after a number of iterations.

Step 6. *Evaluate all alternatives*

Each alternative is evaluated using three tools: the rank acceptability index, the central weight vector, and the confidence factor. It's worth noting that the first rank acceptability index, b_i^1, requires greater attention compare to other alternatives. With a great degree of certainty, the option a_i will be the best if the value of b_i^1 is close to one. On the other hand, a_i is unlikely to be the best if the value of b_i^1 is close to zero. The second tool under consideration here is the central weight vector w_i^c, which represents the preferences of a typical decision maker. Once the preference information is accessible, the MCDM problem is simple to solve. The confidence factor jpg is the third tool, which is mostly utilized to determine whether the criteria data is reliable adequately for identifying the most suitable alternatives. With confidence, the alternative with the top ranked acceptance index and confidence factor can be chosen over all others.

2) THE PRACTICAL PROCESS FOR MAINTENANCE OPTIMIZATION OF MCDM

The whole developed MCDM process for the sake of maintenance optimization is explained in detail in this section. It can be observed in Figure. 3, the flowchart of the proposed algorithm is designed via three principal steps consisting of critical component selection, ELECTRE and SMAA phase.

The inherent imprecision and uncertainty in the data, parameters of the systems, and outage statistics is available in the MCDM used to implement maintenance. These uncertainties will effect on daily peak load, the Customer Average Interruption Duration and load restoration rapidity. In addition, gray sets theory is utilized before inserting the analyzed data for using by operator as inputs to the suggested decision-making model. The proposed framework can be connected to gray techniques involving data uncertainties. To calculate the SRI_{BPS} index for the entire practical system, including each generator and transmission line separately, Equation 7 is used.

In the next step, a list of critical components is obtained from the most critical generator and line. For example, the highest SRI_{BPS} value for the generator and the line is calculated from the above analysis. After choosing the critical components, in the second phase, using the experiences of experts, several key criteria were identified for the line and the generator individually. Then, three strategies were defined as alternatives in the decision matrix. Indices such as the concordance and the discordance, the credibility and outranking intensity, and overall outranking are calculated. In the SMAA method, criteria's weights are determined using Monte Carlo stochastic simulation, and finally, based on the combined ELECTRE-SMAA method, the confidence factor, rank acceptability indices and central weight vector are attained for evaluating each alternative. In the last step of the developed model, the most optimal maintenance strategy can be selected for each critical component.

VII. NUMERICAL RESULTS AND DISSCSION

RCM analysis is performed in this paper using an IEEE 14-bus power system obtained from MATPOWER. This is the original IEEE 14-bus system received from MATPOWER (with a nominal load of 466.2 MW and a nominal generation capacity of 564 MW). In some increasingly crowded power systems, RCM becomes more important, By looking at the load (L =259 MW) and total available generation capacity (G =772.4 MW) of the original IEEE 14-bus system, as well as the line capacity limits, it appears that making this system more overcrowded by increasing the load, lessening the generation capacity reasonably, and setting transmission line capacity limits will aid in RCM research. As a result, in this work by implementing gray number due to lack of information and uncertainty after the changing the amount of the nominal load capacity, the nominal generation capacity and all transmission lines under specific limitations, which the numerical values of the load and generation will be less than their nominal values. Figure 4 shows the IEEE 14-bus power system network, and this structure is still the same in the congested version of this system.

The simulation performance of IEEE 14-bus test systems is presented according to table1. For this original system, at the beginning of analyzing, by considering the SRI_{BPS} index, the most critical generator and line are determined based on equation 7 which is including the gray data with uncertain information. Then, after verifying the cost of every existing maintenance strategies, the optimum maintenance strategy is figure out. In this simulation when the SRI_{BPS} index for all generators and transmission lines is obtained, the highest SRI_{BPS} value will be assigned for Generator 1 and Line 13, which links Bus 6 to Bus 13. Therefore, the highest maintenance priority along with the most critical component is conceded in Gen 1 and Line 13. The ranking list of whole component including every generators and the transmission lines are shown in Table 1.

Several benchmarks for critical components are ascertained by power transmission engineers in practical point of view and the criteria's weights are created in the form of interval gray numbers. The criteria defined and criteria's weights to the evaluators are drawn in Table 2.

Based on the corresponding importance of component types at every level, the defined criteria are described in the

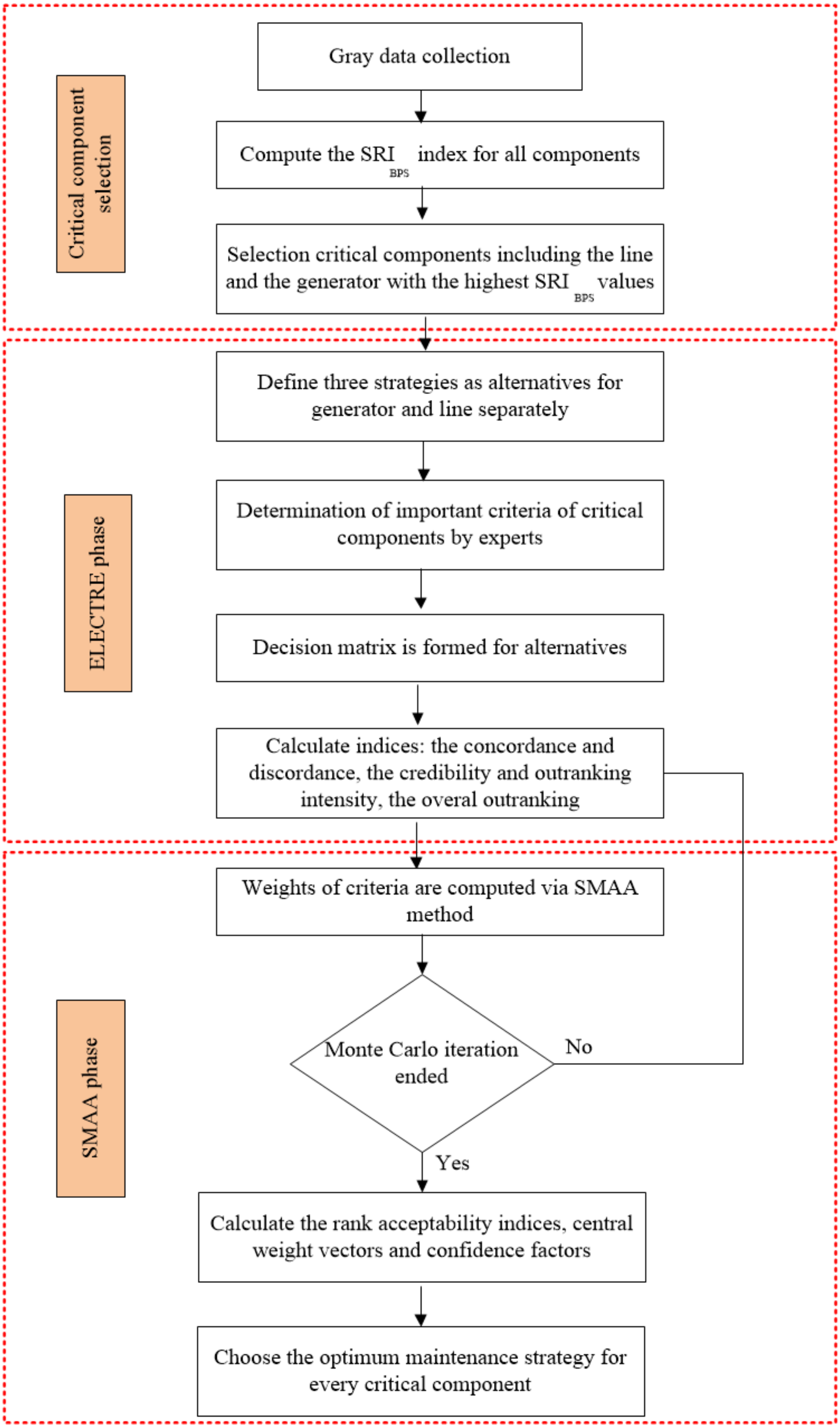

FIGURE 3. The general flowchart for maintenance optimization of MCDM.

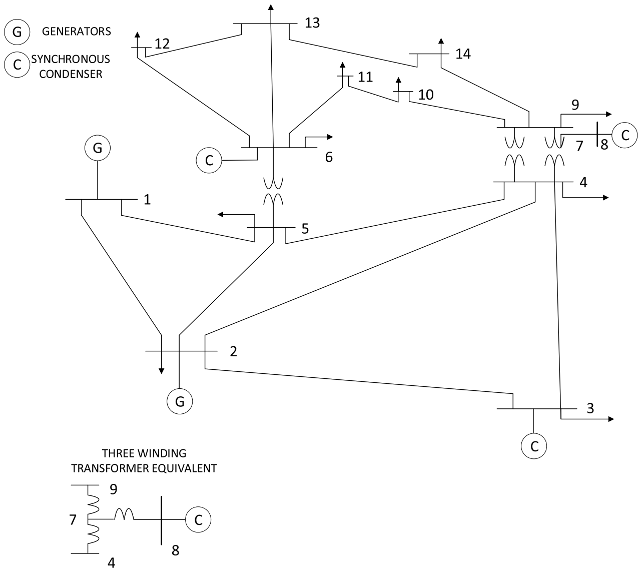

FIGURE 4. The IEEE 14-bus test system.

TABLE 1. List of ranking sri components.

component	SRI Value	component	SRI Value
Gen 1	**[78.627,127.918]**	Line 9	[46.664,77.549]
Gen 2	[23.831,60.965]	Line 10	[48.840,129.794]
Gen 3	[26.311,49.901]	Line 11	[41.668,90.202]
Gen 4	[28.0826,50.716]	Line 12	[154.531,166.463]
Gen 5	[57.5085,90.261]	**Line 13**	**[146.182,208.126]**
Line 1	[29.347,40.154]	Line 14	[22.607,45.158]
Line 2	[62.830,89.224]	Line 15	[15.608,23.572]
Line 3	[79.713,138.620]	Line 16	[52.036,65.919]
Line 4	[30.085,35.93 0]	Line 17	[58.151,90.907]
Line 5	[54.101,137.762]	Line 18	[38.988,68.129]
Line 6	[59.878,112.965]	Line 19	[42.705,55.863]
Line 7	[38.254,95.908]	Line 20	[39.377,79,801]
Line 8	[28.933,47.776]	-	-

following steps, allowing managers to effectively manage assets efficiently. The defined criteria for the generator are given below:

1) Operation Cost: This criterion is one of the most crucial factors in finding the most optimal maintenance strategy for the critical generator proposed by experts and can clearly play a significant role.
2) Energy Not Supplied: It means that the energy is in a specified time period, due to insufficient resources in order to meet the demand that is not expected to be met. There is a significant concern about ENS because of its importance in providing reliable electricity to consumers. Therefore, this factor cannot be ignored for identifying the most optimal maintenance strategy.

TABLE 2. Crteria defined and criteri's weights to prioritize the types of selected component.

	Gen	Weight	Line	Weight
CRI. 1	Operation Cost	[0.4,0.6]	Foundation of tower	[0.4,0.65]
CRI. 2	ENS	[0.15,0.35]	Insulator of tower	[0.15,0.25]
CRI. 3	CO_2emission amount	[0.07,0.15]	Cut down trees	[0.05,0.1]
CRI. 4	Maintenance Cost	[0.1,0.25]	Fittings	[0.3,0.43]

3) CO_2 Emission amount: Theses feature is depending a lot on the amount of the emission comes from the gas or coal generators. As soon as the maintenance is performed on a component, this component is going to start to shut down and is not available during maintenance; therefore, some of the generators will continue to operate and produce more energy for responding to demand.
4) Maintenance Cost: The longer the maintenance time could create the higher the maintenance cost, and this criterion is one of the factors that have been considered by experts. Therefore, ignoring the cost of maintenance of any equipment is inevitable.

The following are the defined criteria for lines:

1) Foundation of tower: The foundation in transmission line towers which transfers the load from the structure to the ground plays an influential role in the suitable performance and safety of the structure. Tower legs in transmission line towers are generally made in concrete which provides adequate protection for the steel. According to experts, the total cost of the foundation is one of the most crucial factors in transmission lines.
2) Tower Insulator: The main function of the insulator in transmission lines is to isolate the conductor from the transmission tower because if the transmission lines are not properly insulated from their masts, current will be transmitted to the ground through the masts, and as a result, the transmission line will not work properly and is dangerous for living organisms.
3) Cut down trees: Another significant factor in this case is required to be considered called the cutting down trees. Trees, shrubs, and other bushes if grown near power lines can lead to power outages and safety dangers. Therefore, in order to maintain the safety purpose, trees grow near or below power lines regularly should be cut down or removed.
4) Fittings: Power cables are essential components of the installation, assembling, and manufacturing process of cable heads. As a result, Transmission Line Accessories are widely used in electrical power transmission

TABLE 3. Critical generator decision matrix.

Gen	Operation Cost ($/MWh)	ENS (MW)	CO_2 *Emission amount* (kg/kwh)	Maintenance Cost ($)
No Maintenance	[9246.2, 9931.5]	[205.5, 295.3]	[100.4, 110.7]	[0,0]
Minor Maintenance	[9020, 9510]	[185, 242.5]	[90, 103]	[400,490]
Major Maintenance	[8853, 9105]	[150, 195]	[80, 91]	[810, 1005]

TABLE 4. Critical line decision matrix.

Line	Foundation of tower ($)	Insulator of tower ($)	Cut down trees ($)	Fittings ($)
Strategy 1	[592, 852]	[200, 240]	[100, 145]	[390, 560]
Strategy 2	[1185, 1740]	[300, 355]	[200,295]	[790, 1150]
Strategy 3	[1814, 2630]	[400, 470]	[304,405]	[1209, 1750]

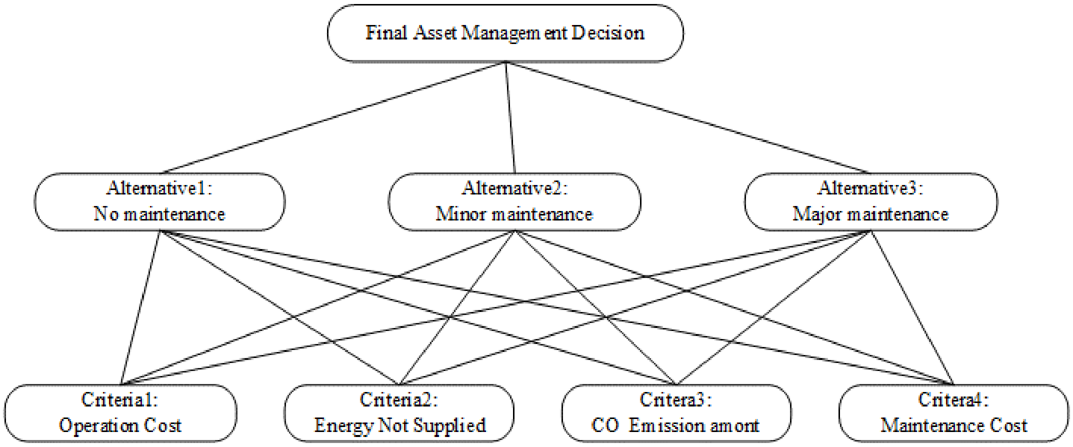

FIGURE 5. The suggested hierarchy process characteristic priority assessment of the MCDM framework.

utilities. The main condition in conductor connection that needs to be evaluated is temperature. If the conductor cable transmits current as the essential modulus for long-term safe operation of the line, this temperature increment does not exceed the allowable limit for holding tension within the tension range of the cable.

In addition, in this paper, more analysis based on hierarchical Structuring of the Problem and Criteria Weighting is accomplished. Finding the appropriate criteria in selecting the most optimal maintenance strategy for the critical component is essential step in this paper. Therefore, the classified structure of the problem here can be shaped as presented in Figure 5. In addition, this structure is applied to the critical line. All mathematics calculations are performed according to the gray number rules introduced in Section II. When, the decision matrix was completed, the strategies which are considered the same alternative must be judge based on the defined criteria. In this stage, the problem is solved using the combined SMAA_ELECTRE method for selecting the most optimal strategy. Here, the final weight is obtained by the SMAA technique which has potentiality to adapt in various situations not only applied for the unknown criteria and weight values but also it can easily manage those values are known or partially known. Besides, the obtained results are analyzed again in order to identify and select the most optimal mode. The last step deals with the final ranking of all alternatives and the final decision for prioritizing the optimal selection achieved.

Hence, the decision matrices related to the critical generator and the critical line are computed in Tables 3 and 4, respectively and show the information of each criterion based on interval gray numbers. According to the structure of the combined model, the overall outranking index and the weights are bound as uniform distributions respective intervals. By performing 10,000 running in simulation model comes from the weight vectors and overall outranking values, the rank acceptability index b_i^r, central weight vector w_i^c, and confidence factor p_i^c attained as shown in Table 5 for the critical generator, where data are stated as percentages.

TABLE 5. The confidence factor, rank acceptiility index, and central weight vector for the generator.

Rank acceptability index						Central weight vector			
Gen	p_i^c	b^1	b^2	b^3		w_1^c	w_2^c	w_3^c	w_4^c
$\boldsymbol{a_1}$	0.00	0.00	0.00	1.00		0.00	0.00	0.00	0.00
$\boldsymbol{a_2}$	0.3	0.00	1.00	0.00		0.00	0.00	0.00	0.00
$\boldsymbol{a_3}$	1.00	1.00	0.00	0.00		0.48	0.24	0.11	0.17

TABLE 6. The confidence factor, rank acceptibilit index, and central weight vector for the line.

Rank acceptability index						Central weight vector			
Line	p_i^c	b^1	b^2	b^3		w_1^c	w_2^c	w_3^c	w_4^c
a_1	1.00	1.00	0.00	0.00		0.42	0.18	0.08	0.32
a_2	0.00	0.00	1.00	0.00		0.00	0.00	0.00	0.00
a_3	0.00	0.00	0.00	1.00		0.00	0.00	0.00	0.00

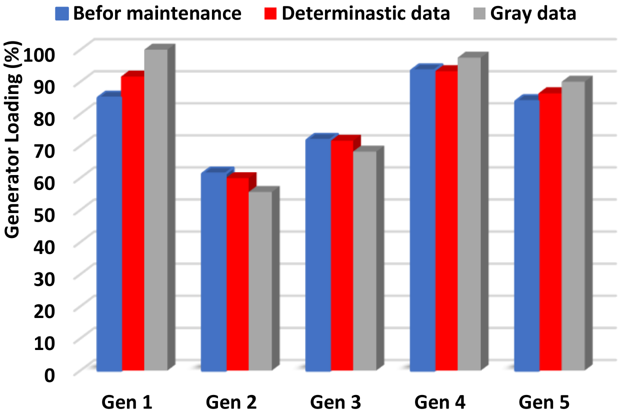

FIGURE 6. Comparison of generator loading on the critical generator.

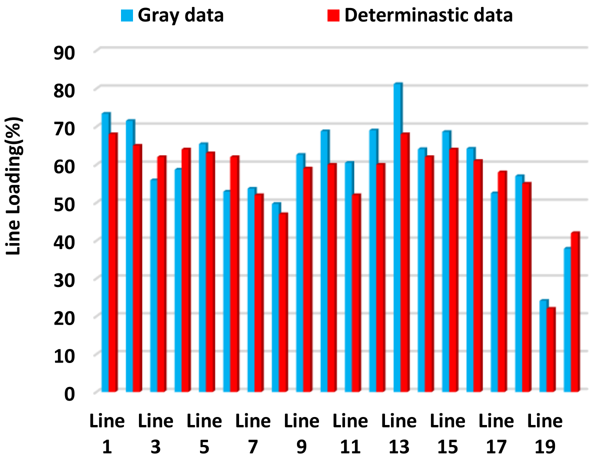

FIGURE 7. Comparison of line loading after maintenance on the critical generator.

When the data is examined based on Tables 5 and 6, results accomplish accordingly for example, the data in Table 5 are managed in such a way that decision-makers prefer a_3, a_2 and a_1 in the first, second and the third rank respectively. The amount of confidence factor of strategy a_3 (100%) displays that the criteria measurements are suitable and precise to identify the effective alternatives and it can be verified that the major maintenance strategy is the most optimal choice for the critical generator. The data in Table 4 for the critical line indicates that decision-makers prefer a_1 as the first rank and the maintenance strategy is selected once a year as the most optimal choice for the line. In addition, as can be observed, every strategy's central weight vector is given in Tables 5 and 6 in order to preferring the most appropriate alternative, in other words, it can be considered as the reference weight vector.

Figure. 6 shows the performance of generators' average loading after the maintenance for the critical generator. It is observed that after the maintenance process, generators 1, 4 and 5 have been more utilized to generate, but loading the rest of the generators has been decreased. In other words, by repairing the critical generator 1, it can be seen that the whole system is depending more on generators 1, 4 and 5. Furthermore, due to the increasing use of some generators, transmission lines will face greater pressures for power transmission as illustrated in Figure. 7. In this figure, the average loading of each line after maintenance is increased except for lines such as 3, 4, 6, 17 and 20. The main reason for increasing in the average loading of the lines due to some generators has capability to generate more power in order to deliver to other buses. In addition, figure 8 demonstrations voltage profile improvement for buses 5, 6, 8, 11 and 14 which is close to 1p.u after maintenance and other buses are relatively far from the ideal case but embedded in their rational range. The results proven, dealing with uncertainty and interval gray numbers which make a difference in critical components and the values of the results to the deterministic state, for example the power produced by generators, the amount of transmission power capacity and total load. Since, the most cases are in non – deterministic range for many power systems applications, therefore, the gray model lead to closer and more realistic results.

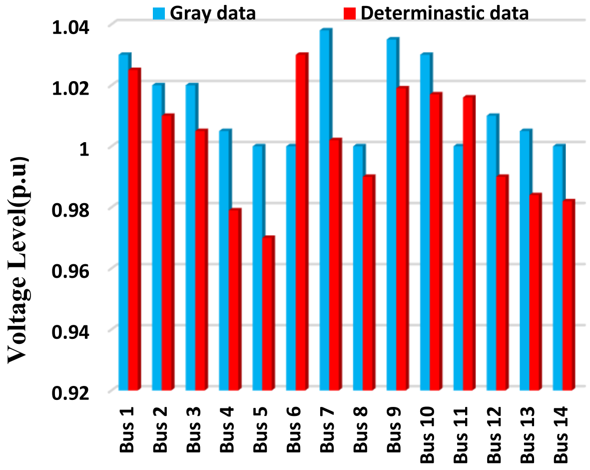

FIGURE 8. Comparison voltage level after maintenance on the critical.

VIII. CONCLUSION

This work describes a method for optimizing power system maintenance. Prioritization of transmission system components is critical for maintenance planning and scheduling, since various components contribute in different ways to the desired performance of any deregulated environment of transmission system. Critical components must be recognized as the first step toward a successful RCM implementation in order to concentrate maintenance priorities on the parts of the system that require it the most. To accomplish this process, the SRI_{BPS} index suggested by NERC is utilized based on the most critical component selection, and SMAA_ ELECTRE III is deployed as a new multi-criteria decision-making support tool for selecting the best maintenance strategy. The proposed algorithm incorporates experts' knowledge and competence by utilizing widely established SMAA_ ELECTRE III techniques and a hybrid qualitative–quantitative assessment. A probabilistic quantitative assessment is undertaken using Monte Carlo simulations to forecast failure outcomes and costs, and the lowest cost strategy is established. To resolve the ambiguity caused by inaccurate and insufficient data, grey numbers were used due to their popularity and simplicity, and the SMAA-ELECTRE method as amended here enables the decision-maker to address a variety of MCDM problems when preference information is dubious, vague, or missing. As proven in a case study of an IEEE 14-bus system and with input from experts at the Regional Electric Company, the suggested method is capable of effectively identifying system-critical components from a variety of viewpoints and selecting the optimal maintenance plan. Within the scope of this paper, the financial assets would be distributed in a fair way as being suggested. However, the interaction restrictions nevertheless constrain the Grey number technique, and grey algorithms frequently fall short of identifying a portion of the possible solution space, especially when faced with unfavorable parameter values. Furthermore, the performance of the grey-number objective function value is frequently worse than the worst-case analysis due to interaction limitations. Every time the interaction restrictions bind, this solution mischaracterization and risk-prone performance that is worse than the worst case occurs. Future developments of this work could include the addition of renewable energy sources, which could alter the optimal maintenance method. The proposed maintenance optimization method will be enhanced by segregating consumers into commercial, industrial and residential loads.

REFERENCES

[1] Y. Gu and L. Xie, "Fast sensitivity analysis approach to assessing congestion induced wind curtailment," *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 101–110, Jan. 2013.

[2] P. Dehghanian, M. Fotuhi-Firuzabad, S. Bagheri-Shouraki, and A. A. R. Kazemi, "Critical component identification in reliability centered asset management of power distribution systems via fuzzy AHP," *IEEE Syst. J.*, vol. 6, no. 4, pp. 593–602, Dec. 2011.

[3] P. Dehghanian, M. Kezunovic, G. Gurrala, and Y. Guan, "Security-based circuit breaker maintenance management," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2013, pp. 1–5.

[4] G. A. Hamoud, "Assessment of component criticality in high voltage transmission stations," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2009, pp. 1–7.

[5] B. Kalinowski and G. Anders, "A new look at component maintenance practices and their effect on customer, station and system reliability," *Int. J. Electr. Power Energy Syst.*, vol. 28, no. 10, pp. 679–695, Dec. 2006.

[6] P. Dehghanian and M. Fotuhi-Firuzabad, "A reliability-oriented outlook on the critical components of power distribution systems," in *Proc. 9th IET Int. Conf. Adv. Power Syst. Control, Oper. Manag. (APSCOM)*, 2012, pp. 1–6, doi: 10.1049/cp.2012.2159.

[7] M. Bulut and E. Özcan, "A new approach to determine maintenance periods of the most critical hydroelectric power plant equipment," *Rel. Eng. Syst. Saf.*, vol. 205, Jan. 2021, Art. no. 107238.

[8] L. Bertling, "Reliability-centred maintenance for electric power distribution systems," Ph.D. dissertation, School Elect. Eng., KTH, Sweden, 2002.

[9] P. Hilber, V. Miranda, M. A. Matos, and L. Bertling, "Multiobjective optimization applied to maintenance policy for electrical networks," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1675–1682, Nov. 2007.

[10] A. R. Misari, J. B. Leite, D. Piasson, and J. R. S. Mantovani, "Reliability-centered maintenance task planning for overhead electric power distribution networks," *J. Control, Autom. Electr. Syst.*, vol. 31, no. 5, pp. 1278–1287, Oct. 2020.

[11] J.-H. Heo, M.-K. Kim, G.-P. Park, Y. T. Yoon, J. K. Park, S.-S. Lee, and D.-H. Kim, "A reliability-centered approach to an optimal maintenance strategy in transmission systems using a genetic algorithm," *IEEE Trans. Power Del.*, vol. 26, no. 4, pp. 2171–2179, Oct. 2011.

[12] M. E. Beehler, "Reliability centered maintenance for transmission systems," in *Proc. Transmiss. Distrib. Conf. Expo.*, 1996, pp. 96–101.

[13] W. Li and J. Korczynski, "A reliability based approach to transmission maintenance planning and its application in BC hydro system," in *Proc. Power Eng. Soc. Summer Meeting. Conf.*, 2001, pp. 510–515.

[14] D. W. Holladay, B. D. Dallman, and C. H. Grigg, "Reliability centered maintenance study on voltage regulators," Tech. Rep., 2006.

[15] W. Reder and D. Flaten, "Reliability centered maintenance for distribution underground systems," in *Proc. Power Eng. Soc. Summer Meeting*, 2000, pp. 551–556.

[16] A. Abiri-Jahromi, M. Fotuhi-Firuzabad, and E. Abbasi, "An efficient mixed-integer linear formulation for long-term overhead lines maintenance scheduling in power distribution systems," *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 2043–2053, Oct. 2009.

[17] F. J. C. Guevara and G. F. M. D. Souza, "RCM application for availability improvement of gas turbines used in combined cycle power stations," *IEEE Latin America Trans.*, vol. 6, no. 5, pp. 401–407, Sep. 2008.

[18] S. Costa and A. F. Brandao, "Optimization of the maintenance of oil filled power transformers based on reliability criteria," in *Proc. IEEE/PES Transmision Distrib. Conf. Expo., Latin Amer.*, Nov. 2004, pp. 297–301.

[19] H. A. Koksal and A. Ozdemir, "RCAM model for Turkish national power transmission system: SF6 circuit breakers, transmission lines, transformer centers and protection relays," in *Proc. Int. Conf. Probabilistic Methods Appl. Power Syst. (PMAPS)*, Jul. 2014, pp. 1–6.

[20] P. Dehghanian and M. Kezunovic, "Cost/benefit analysis for circuit breaker maintenance planning and scheduling," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2013, pp. 1–6.

[21] T. Chan, C.-C. Liu, and J.-W. Choe, "Implementation of reliability-centered maintenance for circuit breakers," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2005, pp. 684–690.

[22] P. Dehghanian, M. Fotuhi-Firuzabad, F. Aminifar, and R. Billinton, "A comprehensive scheme for reliability centered maintenance in power distribution systems—Part I: Methodology," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 761–770, Apr. 2013.

[23] P. Dehghanian, M. Fotuhi-Firuzabad, F. Aminifar, and R. Billinton, "A comprehensive scheme for reliability-centered maintenance in power distribution systems—Part II: Numerical analysis," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 771–778, Apr. 2013.

[24] L. Bertling, R. Allan, and R. Eriksson, "A reliability-centered asset maintenance method for assessing the impact of maintenance in power distribution systems," *IEEE Trans. Power Syst.*, vol. 20, no. 1, pp. 75–82, Feb. 2005.

[25] P. Dehghanian, M. Moeini-Aghtaie, M. Fotuhi-Firuzabad, and R. Billinton, "A practical application of the delphi method in maintenance-targeted resource allocation of distribution utilities," in *Proc. Int. Conf. Probabilistic Methods Appl. Power Syst. (PMAPS)*, Jul. 2014, pp. 1–6.

[26] J. Setreus, P. Hilber, S. Arnborg, and N. Taylor, "Identifying critical components for transmission system reliability," *IEEE Trans. Power Syst.*, vol. 27, no. 4, pp. 2106–2115, Nov. 2012.

[27] R. Ghorani, M. Fotuhi-Firuzabad, P. Dehghanian, and W. Li, "Identifying critical components for reliability centred maintenance management of deregulated power systems," *IET Gener., Transmiss. Distrib.*, vol. 9, no. 9, pp. 828–837, Jun. 2015.

[28] H. A. R. Ardabili, M. Haghifam, and S. M. Abedi, "A probabilistic reliability-centred maintenance approach for electrical distribution networks," *IET Gener., Transmiss. Distrib.*, vol. 15, no. 6, pp. 1070–1080, Mar. 2021.

[29] J. H. Heo, M. K. Kim, and J. K. Lyu, "Implementation of reliability-centered maintenance for transmission components using particle swarm optimization," *Int. J. Electr. Power Energy Syst.*, vol. 55, pp. 238–245, Feb. 2014.

[30] J. L. Deng, "Introduction to grey system theory," *J. Grey Syst.*, vol. 1, no. 1, pp. 1–24, 1989.

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