A New Multiattribute Decision Making Support Tool for Identifying Critical Components in Power Transmission Systems

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***Abstract*—The present context of the electric industry, characterized by competitive markets, privatization, and regulatory of technical requirements forces the power utilities to optimize their asset management practices and develop the requisite decision plans techno-economically. Practically approaching, this paper devises a new support tool based on a multiattribute decision making (MADM) framework in combination with analytical hierarchical process (AHP) to determine the most critical components of power transmission systems. Measure of system-wide reliability performance, outage cost, marginal clearing prices demonstrative of market fairness, and network losses are among the attributes considered in this paper for component criticality assessment. With the frequent existence of qualitative and quantitative attributes, the proposed approach can effectively help to deal with the existent uncertainty and conventional judgment vagueness. As verified in a case study on the IEEE Reliability Test System (IEEE-RTS), the proposed framework introduces its applicability and efficiency for the practical asset management optimizations in electric utilities.**

***Index Terms*—Analytical hierarchical process (AHP), asset management, critical component, decision making, reliability-centered maintenance (RCM), transmission system.**

NOMENCLATURE

A. Sets

G	Set of system generators.
G_R	Set of system generators providing reserve.
Ψ	Set of system buses.
Λ	Set of system probable contingencies.

B. Decision Variables

P_g, Q_g	Active and reactive power output of generator g.
$P_{k,ij}$	Power flow through line *k* (connecting bus *i*–*j*).
$Bf_k(P_{d_k})$	Consumer benefit function for load entity *k*.
$C_{g_i}(P_{g_i})$	Energy cost function of generating unit *i*.
$C_{g_i}^R(r_{g_i})$	Reserve cost function of generating unit *i*.
δ_n	Bus angle at bus *n*.
V_n	Bus voltage magnitude at bus *n*.
L_j^i	Interrupted load (MW) at bus *i* due to contingency *j*.
r_g	Reserve quantity of generating unit g.
x_i	Value of an attribute *x* in condition *i*.
$\lambda_{\max}$	Principal or the largest real eigenvalue of the judgment matrix **A.**
$P_{ij}^{k,1}$	Priority of decision element *i* at layer *j* with respect to that of element *k* at layer l.
x_r	Difference between the max. and min. value of attribute *x* in all the considered conditions.
$U\,(x_i)$	Normalized single utility function of decision alternative x_i.
γ_i	Customer interruption cost (k$/year) at bus *i*.
$P_{d_{k,j}}^{\text{supplied}}$	Active power demand at bus *k* in contingency *j*.

C. Parameters

b_k, g_k	Susceptance and conductance of line *k*.
$\Gamma_j(\tau_j)$	Outage cost of contingency *j* with duration τ.
a_i, b_i, c_i	Cost function coefficients of generating unit *i*.
$\alpha_k, \beta_k, \gamma_k$	Benefit function coefficients of load entity *k*.
FOR_g	Forced outage rate (FOR) of generating unit g.
D_j	Duration of outage *j* (h)
m_i	Number of elements at decision layer *i*.
x^*	Value of attribute *x* in the base case condition.
w_i	Weight of each alternative evaluated via AHP.
F_j	Frequency of failure *j* (occ./year).
P_{d_k}	Active power demand (in MW) at bus *k*.

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$r_g^{\max}$	Max. reserve of generating unit *g*.
Δ_g	Physical ramp rate of generating unit *g*.
$P_k^{\max}, P_k^{\min}$	Max. and min. line flow limit for line *k*.
$P_{d_k}^{\max}, P_{d_k}^{\min}$	Max. and min. active power demand at bus *k*.
$P_g^{\max}, P_g^{\min}$	Max. and min. active generation limit of generating unit *g*.
$Q_g^{\max}, Q_g^{\min}$	Max. and min. reactive generation limit of generating unit *g*.
$V^{\max}, V^{\min}$	Max. and min. bus voltage magnitudes.
$\delta^{\max}, \delta^{\min}$	Max. and min. bus angles.
λ	Lagrange multiplier.
$\mathbf{g_P}\left(\boldsymbol{\theta}, \mathbf{V}, \mathbf{P}\right) = 0$	Nonlinear equation of nodal real power balance.
$\mathbf{g_Q}\left(\boldsymbol{\theta}, \mathbf{V}, \mathbf{Q}\right) = 0$	Nonlinear equation of nodal reactive power balance.
$\mathbf{h}\left(\boldsymbol{\theta}, \mathbf{V}\right) \leq 0$	Nonlinear function of the bus voltage angles and magnitudes for each branch.

I. INTRODUCTION

A. Motivation and Problem Description

POWER transmission utilities have been increasingly challenged by a great deal of pressure to reduce the enormous amount of costs, oriented from investment, operation, and maintenance practices [1]. Maintenance costs constitute a significant portion, since it plays a substantial role in maintaining the system reliability within the desirable limits and practically cannot be overlooked. However, current experience witnesses that almost one-third of all the maintenance costs are wasted as a result of unnecessary or improper maintenance activities [2], which indiscriminately takes all types of components into account with no or little consideration to the equipment's lifetime, outage statistics, economical values, and in one word, their criticality on the system overall performance.

In the deregulated environment of power systems, the role of transmission systems is highlighted majorly in the light of market performance and fairness. Therefore, power transmission utilities should follow some efficient operation policies to meet the market players' requirements for reliability as well as market fairness, more strictly than before. Today, research in this area is on the rise as the role of maintenance is regarded as a profit contributor for electric utilities [1], [2]. In order to improve the previous maintenance strategies, one solution for the system operator can be to focus the priorities on some critical components in the long-term capital investments, medium-term planning, and short-term maintenance scheduling decision-making [3]–[6]. If well structured and wisely organized, it will avoid the current conservative and risky attitude in performing maintenance activities, but putting more time and effort on those components needing it the most. Otherwise, it will be a waste of money, time, and resources.

Reliability-centered maintenance (RCM) is essentially found to be one of the most efficient strategies compared to the existing maintenance schemes [7]. RCM is a systematic gateway for the practical maintenance implementation with an entire attempt to meet the utilities' cost-constrained objectives. The first step in the RCM implementation process is to recognize the system critical components, whose failures would have the highest impact on the system reliability performance [7]–[10].

B. Literature Review

Considerable research efforts have been devoted recently to identify the most important components in power distribution systems for maintenance prioritization. Reference [11] was the first that systematically applied RCM in such systems employing sensitivity analysis with major criteria involved. They investigated the change in the system load point indices as an indicator of component importance. Employing a multi-objective optimization framework, the maintenance policies in power distribution systems are optimized in [12] with the RCM principles as the basis. A few references can be traced through which RCM is applied on some specific types of components: [13]–[15] reported RCM application for transmission lines, [16] on voltage regulators, [17] on underground networks including cable systems, [18] on distribution overhead lines, [19] on gas turbine units, [20] and [21] on power transformers, and [22], [23] on medium-voltage circuit breakers. However, most of the aforementioned references did not try to optimize the solutions through a system-wide analysis. There are also some other attempts for practical implementation of RCM in power distribution level [2], [24]–[27]. Regarding the RCM applications in transmission level, importance indices are developed and quantified in [9] and [10] to identify the critical components of transmission systems from the reliability viewpoint. Conventional modified semi-Markov models together with the Genetic Algorithm are used in [13] to find the optimal maintenance schedule of transmission system components. RCM is generally suggested and qualitatively approached in [14] for the maintenance of transmission lines. A reliability-based approach for transmission system planning is proposed in [15] and applied to the BC Hydro North Metro System using the time-shift-based Monte Carlo simulations and a linear programming optimization model. Particle swarm optimization is employed in [28] for the selection of the optimal maintenance plans in electric power transmission systems. However, the methodologies in the previous attempts either neglect the electricity market requirements, or are fundamentally based on the traditional vertically integrated market structures. Moreover, the existing uncertainties and imprecise judgments in the RCM decision making could not be efficiently handled in most of the former studies. In addition to the aforementioned research, there is still both room and necessity for developing a decision-making support tool for the electricity grid operators to employ the RCM strategies in different sections of power systems, specifically the highly interconnected and nonlinear power transmission level, which is the focus of concern in this paper.

C. Paper Highlights and Contributions

For the RCM process to be put in practice smoothly, decision-support tools need to be developed, easy to understand, and user friendly for the operator with the expected benefits highlighted. The contributions of this paper can be pointed as follows.

1) This paper introduces the key factors on criticality assessment of power transmission system components in a deregulated market environment. In the proposed approach, outage cost, network losses, system-wide impacts on reliability, and market clearing prices (MCP, demonstrative of the market fairness) are taken into account as the major criteria.
2) A computationally efficient algorithm based on the analytical hierarchical process (AHP) is suggested to deal with the uncertain and imprecise judgments of the decision-makers as well as various (even contradictory) objectives of different market players.
3) A multiattribute decision making (MADM) support tool is developed through which the most important and critical components of the system would be recognized, useful for further maintenance priority focuses and future investment decisions.
4) Extensive sensitivity analysis is conducted to investigate the impact of existent uncertainties in the experts' knowledge and experiences on the final decision outcome.

D. *Paper Organization*

This paper is organized as follows. Section II introduces the main principle of reliability-centered asset management (RCAM) based on which the proposed framework is developed. Section III briefly hosts the fundamental concept of the MADM frameworks and the AHP method in solving such problems. The proposed method and formulations are presented in Section IV. The applicability of the presented algorithm is demonstrated through a case study on the IEEE Reliability Test System (IEEE-RTS) in Section V, followed by the concluding remarks at the end in Section VI.

II. RELIABILITY-CENTERED ASSET MANAGEMENT

Generally speaking, asset management is defined as the systematic art and science of correct decision-making on exploiting a group of system assets over their life cycle ensuring a desired rate of return and guaranteeing a predefined service standard [2], [29], [30]. In today's electric power industry coupled to various market realizations, transmission system operators have to find a balance between the customer requirements concerning service quality at an affordable price versus the shareholder demands for appropriate returns on the invested capital. Optimized strategies within the realm of asset management in power transmission systems play a key role in determination and evaluation of efficient and mandatory maintenance and investment decisions, and would lead to a long-term economic success with maximum possible earnings. The proposed framework within the context of this paper promulgates the idea that the technical/financial advisor in transmission utilities can conduct a systematic assessment of components' criticality on power system performance considering the requisite decision factors. Consequently, it could be possible for them to benefit from a wise prioritization of components for maintenance concentration. The advisor is then able to recommend appropriate financial allocations to the identified critical equipment. As a result, a more cost-effective decision is expected; the available financial resources would be considerately allocated; and the critical physical assets could be well maintained over time.

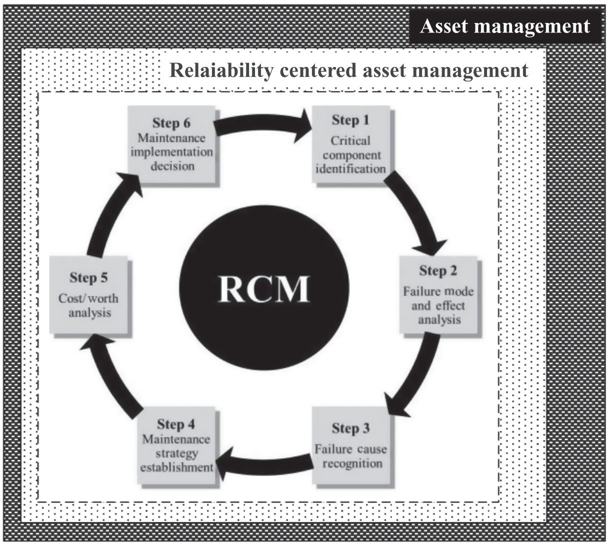


Fig. 1. General interrelation of asset management, RCAM, and RCM.

RCM, as a well-designed derivative of the RCAM practices, as shown in Fig. 1, develops a cost-effective scheme through which the maintenance procedures of system components can be strategically managed more from the reliability viewpoint [2], [24]. The RCM process generally includes six general stages. The first and essential stage, which is actually the backbone of its main analysis, is the identification process of system critical components, those with considerable influence on system performance. The rest of the RCM analyses, which are demonstrated in stages 2–6 in Fig. 1, is concentrated on the identified critical components [10]. Failure mode and effect analysis (FMEA) is performed on such critical components in the second stage and helps to guide the maintenance resources on the failure modes needing it the most and in an attempt to prevent the critical failure causes of the critical components (identified in stage 3). Appropriate maintenance strategies need to be then selected (stage 4) for each system critical component, following by a cost/worth analysis in stage 5 to find the economically attractive strategy and the time interval for maintenance in stage 6. The aforementioned procedure effectively provides the system asset manager with some beneficial information on the system critical components, the weak segments of the system, and an optimized allocation of the available resources when and where necessary. The first stage, identifying critical components from various performance perspectives, is the focus of this paper as to the case of transmission systems.

Transmission systems are equipped with various types of components contributing differently to the system overall reliability performance. The reason lies in the fact that different equipments are of various ages and aging mechanisms and consistently different failure rates. As a result, considering the same importance degree for all the system components in the asset management process and resource-allocation decisions is not a wise and cost-effective decision. Overcoming this, some practical criteria have to be proposed and included, in a well-organized manner, into a MADM framework for maintenance planning and scheduling in transmission systems. In response, AHP approach, which has proven its efficacy and strong applicability for MADM problems in various fields of engineering, is employed in this paper. The principles of the proposed MADM approach are introduced next.

II. DECISION-MAKING FRAMEWORK: AHP

Decision-making in complex environments, consisting of multiple supportive or contradictory with qualitative or quantitative options and criteria, is one of the most complex and critical problems to solve in modern management practices [31]–[34]. In such cases, decision-makers are faced with several options and criteria, all do influence on the final goal and decision with different levels of contribution, and should be investigated focusing on both internal and external aspects of the problem. Such types of decision-making challenges, so called multicriteria decision making (MCDM) methods, may be broadly classified into two categories: multiobjective decision making (MODM) and MADM approaches. These two decision methodologies share common characteristics of MCDM problems, such as conflicting criteria, incommensurable units, and difficulties in selection of alternatives. The difference between these two approaches is found to be in definition of the decision space. In the former, the decision space is continuous and alternatives are not predetermined, whereas in the latter one, which is the basis of the proposed methodology in this paper, the decision space is discrete and each candidate alternative can be evaluated using a combination of analytical tools. This process will associate each planning or design strategy with a set of attributes, thus yielding an attribute database through which various planning or design strategies can be compared [31]–[34].

A strong and well-cited approach in dealing with MADM problems, among the several other applicable ones available, is the AHP method. AHP is employed in this paper as a weighting-selection mechanism for the proposed MADM framework. Generally speaking, the AHP technique may be described as a three-step procedure as follows [35].

1) The judgment matrix needs to be framed by the pairwise comparison of all the factors at a same level of the hierarchy with respect to each factor in the immediately preceding level.
2) The eigenvector of the judgment matrices are computed corresponding to the largest eigenvalue.
3) Finally, the composite priority vector is calculated from the local priorities of each judgment matrix.

Fig. 2 shows a three-layer hierarchy employed for the attribute priority assessment in this paper. At the top of hierarchy is the decision-making goal, which is defined as the "critical component identification in power transmission systems." The second layer comprises five elements involved in the decision process, representative of various market players including the generating companies (GENCOs), the distribution companies (DISCOs), the regulator, the independent system operator (ISO), and transmission owners. There exists, in the third layer of the proposed decision hierarchy, four major attributes of interest, i.e., power system reliability performance [measured in this paper by the expected energy not supplied (EENS) index], market fairness (measured by considering the MCP), outage costs imposed to the system as a consequence of component failure, and network losses. Formulation details and evaluation process of the aforementioned criteria would be discussed later in this paper. In the AHP process, after the decision structure is decided, a group of evaluators would then fill out the comparison matrices designed, as an example, in Table I [2]. The evaluators would be the industry experts who have remarkable experience in dealing with maintenance and operation of power transmission systems and those asset managers involved in such decision-making problems. According to the hierarchy presented in Fig. 2, the assessment of attribute priorities would be proceeded in two evaluation levels by asking the decision maker two sets of rational questions: one set of questions concerning the relative importance of different players in implementing the decision making framework (identifying critical components and prioritization process), while the other set of questions is concerned with the relative influence of different attributes on each individual player. It provides a methodology to adjust a numeric scale for the measurement of quantitative as well as qualitative performance indicators. The linguistic variables, introduced in Table II, are used to complete the comparison matrices [36]. The scale ranges from 1 to 9, i.e., 1 for "equally important," and 9 for "exceedingly more important than" covering the entire spectrum of the comparison. In the comparison matrices, each element is a reciprocal of its transpose element. The final weight for each decision-making player and alternative can be quantified mathematically, as explained later in this paper.

TABLE I
PAIRWISE COMPARISON MATRIX IN THE AHP METHOD [2]

	CRI. 1	CRI. 2	CRI. 3	CRI. 4	CRI. 5
CRI. 1	1	C_{12}	C_{13}	C_{14}	C_{15}
CRI. 2	C_{21}	1	C_{23}	C_{24}	C_{25}
CRI. 3	C_{31}	C_{32}	1	C_{34}	C_{35}
CRI. 4	C_{41}	C_{42}	C_{43}	1	C_{45}
CRI. 5	C_{51}	C_{52}	C_{53}	C_{54}	1
Final weight	C_1	C_2	C_3	C_4	C_5

III. PROBLEM FORMULATION

A. General Formulations of the Decision Criteria

System reliability, outage cost, network losses, and market MCP demonstrative of market fairness are assumed as important attitudes in the decision-making problem. This section introduces the importance of the considered decision criteria as well as their evaluation process and the associated general formulations.

1) System Reliability Performance: EENS index is utilized as a measure of system reliability performance and is

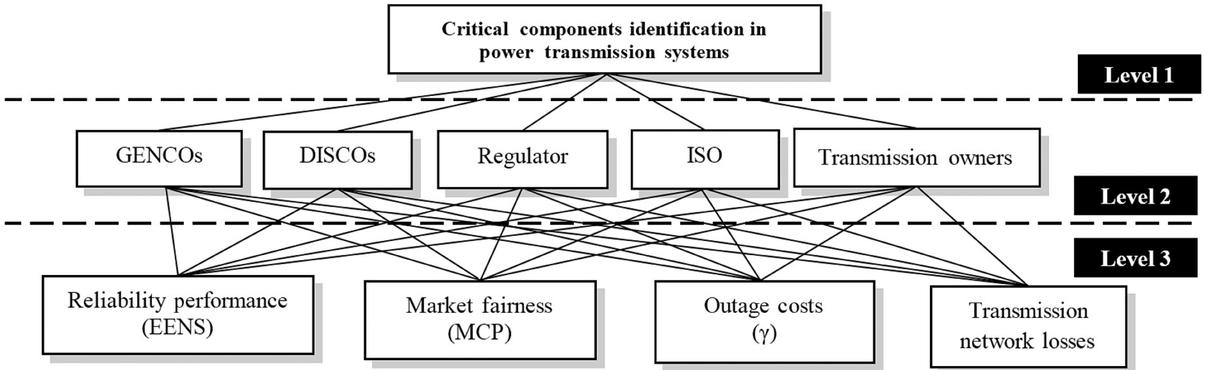


Fig. 2. Proposed hierarchy for attribute priority assessment of the studied decision-making problem.

calculated by solving the following optimization problem at each contingency state:

$$\min_{\theta,V,P,Q} \quad \sum_{g\in \mathrm{G}} C_g(P_g) + \sum_{g\in \mathrm{G_R}} C_g^R(r_g) \tag{1}$$

s.t.

$$\mathbf{g_P}\left(\boldsymbol{\theta},\mathbf{V},\mathbf{P}\right)=0 \tag{2a}$$
$$\mathbf{g_Q}\left(\boldsymbol{\theta},\mathbf{V},\mathbf{Q}\right)=0 \tag{2b}$$
$$\mathbf{h_F}\left(\boldsymbol{\theta},\mathbf{V}\right)\le 0 \tag{2c}$$
$$\mathbf{h_T}\left(\boldsymbol{\theta},\mathbf{V}\right)\le 0 \tag{2d}$$
$$\delta_n^{\min}\le \delta_n \le \delta_n^{\max} \quad \forall n\in\Psi \tag{2e}$$
$$V_n^{\min}\le V_n \le V_n^{\max} \quad \forall n\in\Psi \tag{2f}$$
$$P_g^{\min}\le P_g \le P_g^{\max} \quad \forall g\in \mathrm{G} \tag{2g}$$
$$Q_g^{\min}\le Q_g \le Q_g^{\max} \quad \forall g\in \mathrm{G} \tag{2h}$$
$$0\le r_g \le \min(r_g^{\max},\Delta_g) \quad \forall g\in \mathrm{G_R} \tag{2i}$$
$$P_g + r_g \le P_g^{\max} \quad \forall g\in \mathrm{G_R} \tag{2j}$$
$$P_{d_k}^{\min}\le P_{d_k} \le P_{d_k}^{\max} \quad \forall k\in\Psi \tag{2k}$$
$$\mathrm{L}_j^i = P_{d_k} - P_{d_{k,j}}^{\text{supplied}} \quad \forall k\in\Psi,\ \forall j\in\Lambda \tag{2l}$$
$$\mathrm{EENS}_{TS} = \sum_{i\in\Psi}\mathrm{EENS}_i = \sum_{i\in\Psi}\sum_{j\in\Lambda}\mathrm{L}_j^i.F_j.D_j \tag{2m}$$

The optimization problem in (1) and (2) minimizes the total cost of energy and reserves while satisfying the ac power flow equations, ancillary service requirements, and transmission and operating constraints. Constraints (2a) and (2b) are the nonlinear active and reactive power balance equations at each bus. Network constraints (2c) and (2d) reflect the branch flow limits for both ends of the transmission lines. Constraints (2e) and (2f) represent the upper and lower limits for the voltage phase angles and magnitudes at each bus. Constraints in (2g)–(2h) and (2i)–(2k) are capacity-reserve limits for system-generating units. Constraint (2i) reflects the reserve requirement for each generating unit. Constraint (2j) shows the equality equation enforcing that the total amount of energy plus reserve of the generating unit should not exceed its capacity. Constraint (2k) reflects the demand limits at each load point. Constraint (2l) evaluates the amount of load interruption at each load point. Constraint (2m) finally calculates the EENS index of the transmission system.

TABLE II
FUNDAMENTAL LINGUISTIC VARIABLES USED FOR PAIR WISE RATING THROUGH CONVENTIONAL AHP ANALYSIS [2], [36]

Scale	Definition
1	Equally important
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Exceedingly more important
2, 4, 6, 8	Intermediate preferences

Note that contingencies up to the third order are considered to calculate the total EENS index of the transmission system.

2) Electricity Market Fairness: In a competitive electricity market, the combined participation of all the loads (electricity consumers) on one side and all the suppliers (electricity generators) on the other side would determine the electricity price. The equilibrium price, the so-called market clearing price (MCP), is calculated such that the supply and demand bidding strategies collide. In other words, MCP is the price that the consumers are willing to pay for a certain amount of power and is equal to the price that producers must receive for the same quantity [37]. Electricity market fairness is quantified in this paper employing the MCP values. If the bid function for generator *i* is formulated in (3a) and the consumer benefit function for load entity *j* of the system is as shown in (3b), the objective for the market operator would be to maximize the social welfare function represented in (3c) subject to the power balance constraint (3d) [38]

$$C_{g_i}(P_{g_i}) = a_i P_{g_i}^2 + b_i P_{g_i} + c_i \tag{3a}$$
$$Bf_k(P_{d_k}) = \alpha_k P_{d_k}^2 + \beta_k P_{d_k} + \gamma_k \tag{3b}$$
$$\sum_{k\in\Psi} Bf_k(P_{d_k}) - \sum_{i\in G} C_{g_i}(P_{g_i}) \tag{3c}$$
$$\sum_{k\in\Psi} P_{d_k} = \sum_{i\in G} P_{g_i}. \tag{3d}$$

Hence, the augmented objective function for the at-hand unconstrained optimization would be as in (3e) with the optimality conditions presented in (3f) and (3g) [38]

$$L = \sum_{i\in G} C_{g_i}(P_{g_i}) - \sum_{k\in\Psi} Bf_k(P_{d_k}) - \lambda\left(\sum_{i\in G} P_{g_i} - \sum_{k\in\Psi} P_{d_k}\right) \tag{3e}$$

$$\frac{\partial L}{\partial \lambda} = \frac{\partial C_{g_i}}{\partial P_{g_i}} = 0 \quad \forall i \in G \tag{3f}$$

$$\frac{\partial L}{\partial \lambda} = \frac{\partial Bf_k}{\partial P_{d_k}} = 0 \quad \forall k \in \Psi \tag{3g}$$

Solving the above equations, the incremental cost functions for all the system generating units (λ), equal to the incremental utility functions for all the system loads, would be obtained as the system MCP, formulated as

$$\text{MCP} = \lambda = 2a_i P_{g_i} + b_i \quad \forall i \in G. \tag{3h}$$

3) System Outage Costs: The system outage cost which reflects the financial losses to the electricity customers in the case of outages is also considered as a main criterion in determining the components' criticality for maintenance. The expected outage cost (Υ), which is highly dependent on the type of customers affected by the outage and the outage duration, can be calculated in (4). As can be inferred in (4), the outage cost is actually quantified in terms of the EENS index evaluated in (2) and the value of lost load (VOLL) at each load point [39]

$$\Upsilon = \sum_{i\in\Psi} \gamma_i = \sum_{i\in\Psi} \sum_{j\in\Lambda} \left(L_j^i . F_j . D_j . \Gamma_j(\tau_j) \right). \tag{4}$$

4) Network Losses: Transmission losses play an important role in economic operation of power systems and will affect the decision-making on generation schedules. As a result, network loss is also considered as an important factor for the at-hand decision making problem. The real power flow of the "from" and "to" ends of a transmission line connecting bus *i* to bus *j* can be expressed as follows [40]:

$$\begin{aligned} P_{k,ij} = {} & V_i^2 g_k - V_i V_j \\ & \times \left[g_k \cos(\Delta\delta_{k,ij}) + b_k \sin(\Delta\delta_{k,ij}) \right] \end{aligned} \tag{5a}$$

$$\begin{aligned} P_{k,ji} = {} & V_j^2 g_k - V_j V_i \\ & \times \left[g_k \cos(\Delta\theta_{k,ji}) + b_k \sin(\Delta\theta_{k,ji}) \right]. \end{aligned} \tag{5b}$$

The system total losses would be then calculated as

$$P_{loss,TS} = P_{k,ij} + P_{k,ji} = \sum_{i\in\Psi} V_i \sum_{j\in\psi} V_j G_k \cos(\Delta\delta_{k,ij}). \tag{5c}$$

B. Proposed MADM Problem Formulation

A practical MADM support tool in conjunction with AHP method is proposed on criticality assessment of system components as conceptually shown in Fig. 3. The algorithm starts with the required input data such as historical data on the past failure records, failure causes, outage durations, and component reliability data. It also includes the system technical and economic information. Note that, in practice, there are always some inherent uncertainties and vagueness in the data, system parameters, and outage statistics. For instance, uncertainties would be imposed on the outage frequency and duration originated from the weather forecasts, environmental impacts, and operational conditions. Probabilistic techniques (e.g., the point estimation method) or fuzzy sets theory may be used, and the probabilistically handled data can be then inserted as inputs to the proposed decision-making model for the operator to use. The proposed framework is generic enough to be equipped with such robust probabilistic approaches and fuzzy techniques in dealing with the data uncertainties and vagueness. In the second step, power transmission system is probabilistically analyzed for a determined time interval (e.g., on a yearly basis). Normal probability density functions (pdfs) are employed to model the probabilistic nature and existent uncertainties of the load points and bidding strategies for both GENCOs and DISCOs. A snapshot of the system is taken into account in each iteration, and the random Monte Carlo simulation is used for probabilistic evaluation of the attributes. For reliability analysis, the common approach considering two-states Markov model is considered for all the system components. At each Monte Carlo iteration, the electricity market is run, and the MCP and power flows are measured in a deregulated environment. The EENS index and outage costs are calculated based on (1) and (4), respectively. The MCPs at various buses and the network losses can also be calculated at each Monte Carlo iteration via the market auction

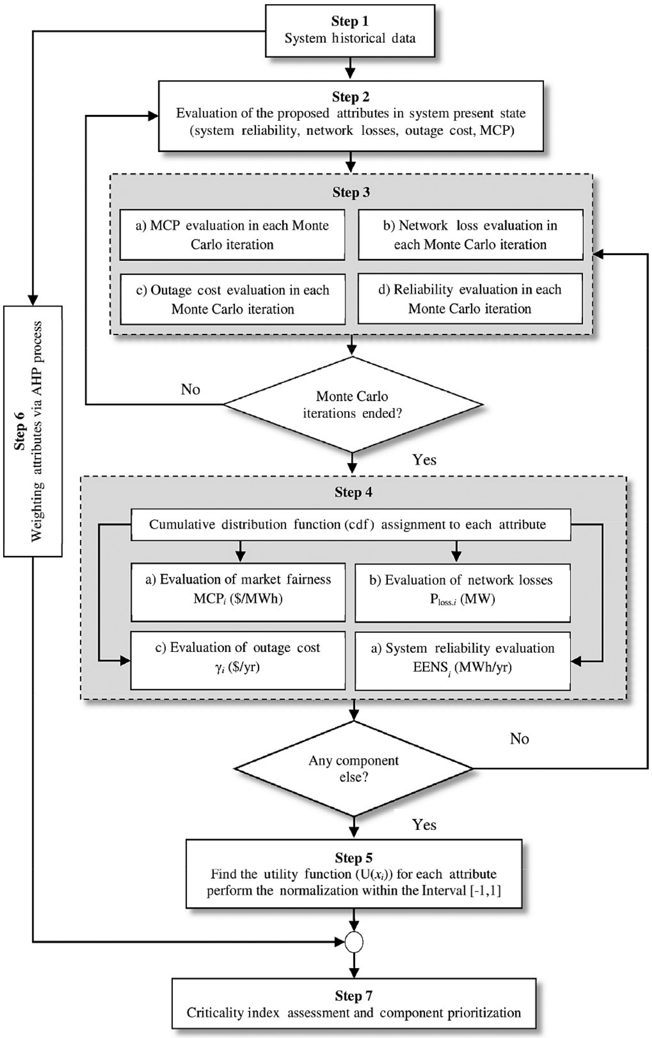


Fig. 3. Flowchart of the proposed algorithm.

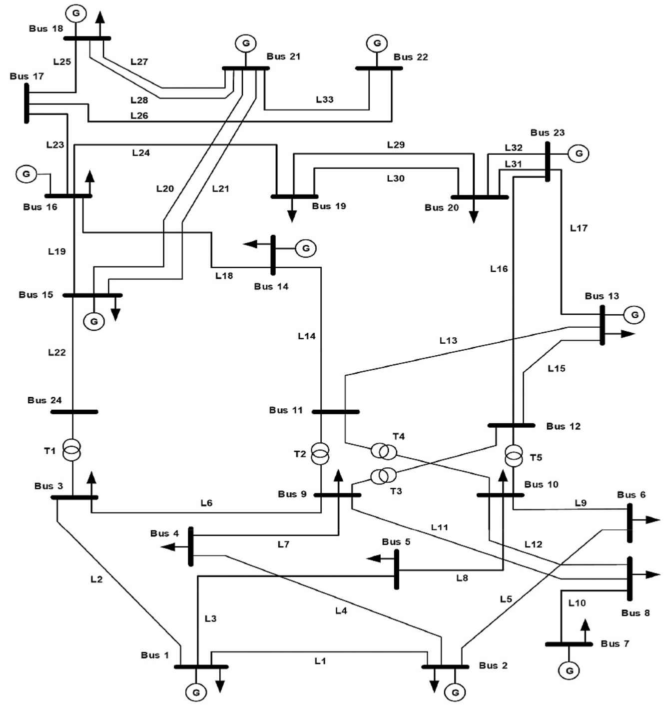


Fig. 4. IEEE reliability test system [41].

optimal power flow and according to (3) and (5), respectively. In the fourth step, when the iterations of Monte Carlo simulations are terminated, a cumulative distribution function (cdf) is fitted for each attribute based on the historical data available. Two scenarios are studied: in the first scenario, it is assumed that all the components are in their healthy and available states with a specific value of FOR. Then, in the second scenario, one component is assumed to be in an outage mode, and the algorithm (Monte Carlo simulations and criteria evaluation process) is repeated at each case until all the system components are considered. In the next step (step 5), and in order to be able to compare the impact of each component outage on the selected attributes, a utility function is proposed and calculated for each component. Utility function normalizes the calculated indices in a simple interval $[-1, 1]$ and is defined by

$$U\left(x_i\right) = \frac{x_i - x^*}{x_r}. \tag{6}$$

In the last step (step 7), a linear additive utility function is utilized for the sake of component prioritization according to the calculated utility functions. One popular approach in dealing with the MADM problems is defining an appropriate formulation that transforms an *n*-dimensional performance vector to a scalar performance measure, usually termed as multiattribute utility function (MUF) [35]. In general, the MUF model is the compromised version of the single-utility functions or preference functions associated with the selected attributes and also the weighting parameters that reflect the relative importance of these attributes toward the overall goal. Equation (7) introduces a general expression of a linear additive utility model

$$U\left(x\right) = \sum_{i=1}^{4} w_i . U\left(x_i\right). \tag{7}$$

TABLE III
EVALUATED ATTRIBUTES CONSIDERING DIFFERENT NUMBERS OF MONTE CARLO ITERATIONS AS THE TERMINATION CRITERION

Monte Carlo iterations	Decision criteria					
	EENS_{TS}	MCP		$P_{loss,TS}$		Υ (×100)
		Mean	SD	Mean	SD	
1	0	19.15	0	35.622	0	0
10	144950	20.44	1.239	27.148	3.033	28898
50	108270	20.75	1.610	29.241	6.019	26045
100	225740	20.61	1.250	28.728	5.899	51291
200	246630	20.24	1.309	28.957	6.540	55943
300	234250	20.56	1.453	28.926	6.431	51834
400	292720	20.57	1.515	29.223	6.367	66494
500	219910	20.45	1.354	28.975	6.576	48553
600	281300	20.62	1.515	29.150	6.435	63204
700	230300	20.57	1.469	29.233	5.868	52004
800	237040	20.54	1.426	28.810	6.267	53491
900	226670	20.54	1.465	29.277	6.093	51509
1000	**252970**	**20.58**	**1.477**	**28.915**	**5.899**	**56710**
1100	230620	20.52	1.459	29.404	6.229	52193
1200	256420	20.50	1.453	28.952	5.848	57557
1300	251000	20.56	1.438	29.110	6.375	56813

It can then be possible to recognize the system critical components: the ones with the highest index of criticality obtained through (7).

C. AHP Method Formulations

AHP methodology, as described earlier in Section III, is utilized for weighting the driving criteria and attributes in the decision-making problem. In so doing, the eigenvalue prioritization method is used to determine the relative ranking of factors associated with each judgment matrix by normalizing the principal eigenvector **P** of the judgment matrix **A,** which is obtained by solving the following eigenvalue problem [35]:

$$\mathbf{A}.\mathbf{P} = \lambda_{\max}.\mathbf{P}. \tag{8}$$

For an *n*-layer hierarchy, the composite priority vector which forms the bottom layer with respect to the top layer can be calculated by the following equation:

$$\begin{bmatrix} P_{1n}^{11} \\ P_{2n}^{11} \\ \vdots \\ P_{nn}^{11} \end{bmatrix} = \begin{bmatrix} P_{1n}^{1,n-1} & \cdots & P_{1,n}^{m_{n-1},n-1} \\ P_{2,n}^{1,n-1} & \cdots & P_{2,n}^{m_{n-1},n-1} \\ \vdots & \vdots & \vdots \\ P_{m_n,n}^{1,n-1} & \cdots & P_{m_n,n}^{m_{n-1},n-1} \end{bmatrix} \cdots$$
$$\times \begin{bmatrix} P_{1,3}^{1,2} & P_{1,3}^{2,2} & \cdots & P_{1,3}^{m_2,2} \\ P_{2,3}^{1,2} & P_{2,3}^{2,2} & \cdots & P_{2,3}^{m_2,2} \\ \vdots & \vdots & \vdots & \vdots \\ P_{m_3,3}^{1,2} & P_{m_3,3}^{2,2} & \cdots & P_{m_3,3}^{m_2,2} \end{bmatrix} \begin{bmatrix} P_{1,2}^{1,1} \\ P_{2,2}^{1,1} \\ \vdots \\ P_{m_2,2}^{1,1} \end{bmatrix}. \tag{9}$$

The same process is performed for all the comparison matrices at any level of the decision hierarchy, and the alternatives can be finally assigned the importance weights accordingly. The obtained weighting factors, which are primarily calculated employing the operators'/asset managers' knowledge and expertise, are then incorporated into step 6 of the proposed algorithm shown in Fig. 3.

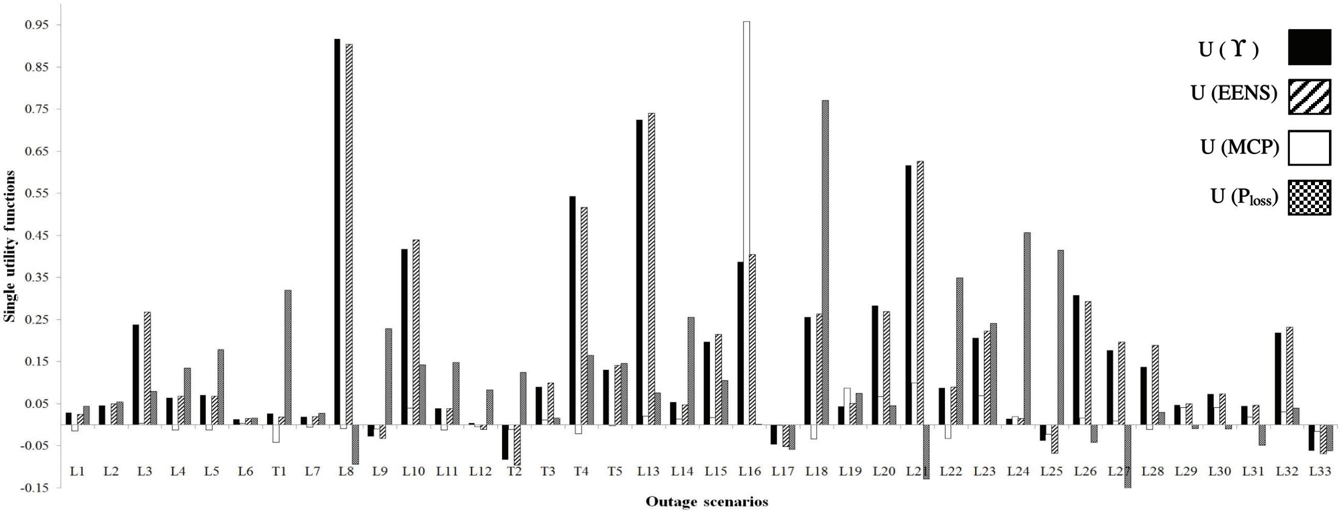


Fig. 5. Results of the single-utility functions for the defined criteria concerning various first-order outage scenarios.

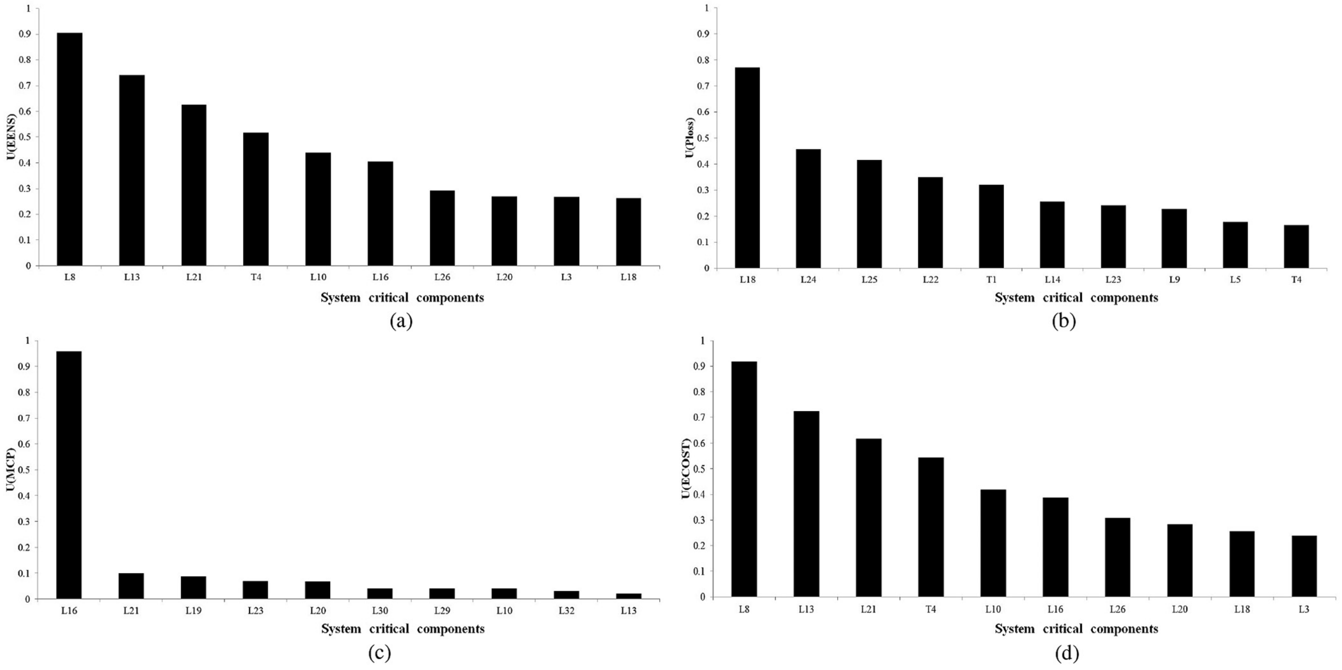


Fig. 6. First 10 critical components of the IEEE-RTS from the viewpoint of various criteria. (a) System critical components from the perspective of system reliability. (b) System critical components from the perspective of network losses. (c) System critical components for market fairness. (d) System critical components from the perspective of imposed outage cost.

IV. NUMERICAL CASE STUDY

A. *Description of the Test Transmission System*

In order to investigate the applicability of the proposed technique, the IEEE 24-bus RTS is employed as the case study, for which the one-line diagram is shown in Fig. 4 [41]. This transmission system contains 24 load points and generation buses connected by 38 transmission lines, and autotransformers at two voltage levels of 230 and 138 kV. The employed data for the analysis are summarized in [42].

B. *Assessment of Single-Utility Functions*

Subsequent to several meetings with power transmission engineers, operators, and asset managers of the Mazandaran Regional Electric Company located in the north of Iran, several major criteria are proposed on the criticality assessment of transmission components for maintenance concentrations (shown earlier in Fig. 2). These criteria are investigated in the IEEE-RTS, and random Monte Carlo simulations are conducted for considering different system conditions and various possible states. The Monte Carlo states are randomly sampled using the sampling technique in [43]. The algorithm implementation and the required simulations are conducted in the MATLAB environment using the Matpower toolset [44]. This test case was run on a desktop machine with 6-GB RAM and two 2.40-GHz Intel Xeon processors. While it took 6.75 h to execute the algorithm on the studied test case, it can be solved significantly faster considering the quick advances in both computing

TABLE IV
JUDGMENT MATRIX FOR THE SECOND LEVEL OF THE DECISION PROBLEM

Goal: critical component identification						
	GENCO	DISCO	Regulator	ISO	Utility	Final weight
GENCO	1	1	1/3	1/3	1/5	0.066
DISCO	1	1	1/3	1/3	1/5	0.066
Regulator	3	3	1	1/5	1/5	0.124
ISO	3	3	5	1	1/3	0.268
Utility	5	5	5	3	1	0.475

hardware and computational capability of modern optimization solvers. This anticipated progress in solving speed can also further be expedited by the use of parallelized computations of the current program. Monte Carlo simulations are conducted in 39 different subproblems: one subproblem is actually the system base case condition, where all the components are considered in service, each of which assigned a certain FOR value and normal distribution functions are used for generation and load-bidding strategies; the rest of 38 subproblems is actually demonstrating the outage scenarios for the system components (33 transmission lines and 5 transformers), each of which contains one component in the outage state while all the other components are in service. Table III demonstrates how the evaluated attributes in the first scenario change considering different numbers of Monte Carlo iterations as the termination criterion. One thousand Monte Carlo iterations are approached for the analysis of this paper. The evaluation results are shown in Fig. 5, where the single-utility functions (criticality measures) at each scenario are calculated for each criterion. As one can see in this figure, the single-utility functions for some criteria in several outage scenarios (e.g., in the case of T1, T2, L17, and L21) are negative values, which demonstrate that such outage scenarios will have positive impact on some criteria and, interestingly enough, will improve the associated indicators. For the sake of clarification, we first take only one criterion into account and identify the system critical components, the ones whose failure will create major impacts on one specific criterion. The first ten critical components from the perspective of system reliability performance, network losses, market fairness, and imposed outage costs are recognized and demonstrated in Fig. 6(a)–(d), respectively. It can be seen from the obtained results that outage scenarios for different system components contribute differently to the value and importance of different criteria. It can be understood from Fig. 6(a) that transmission lines 8, 13, and 21 are the ones whose outage would last into the highest deterioration of system reliability performance compared to the others.

Fig. 6(b) demonstrates that transmission lines 18, 24, and 25 are the most critical ones from the network losses point of view; if failed, the network losses would be impacted the most. In Fig. 6(c), components are prioritized regarding their outage impact on the market fairness and those critical ones, i.e., the transmission lines 16, 21, and 19 are recognized. It is also demonstrated in Fig. 6(d) that when the impact on the system-imposed outage cost is considered as the driving attribute for identifying system critical components, transmission lines 8, 13, and 21 are identified to play the most steering roles.

TABLE V
JUDGMENT MATRIX FOR THE THIRD LEVEL OF THE DECISION PROBLEM

	Outage cost	MCP	EENS	Loss	Final weight
GENCOs					
Outage cost	1	1/3	3	3	0.276
MCP	3	1	3	3	0.483
EENS	1/3	1/3	1	1/2	0.101
Loss	1/3	1/3	2	1	0141
DISCOs					
Outage cost	1	3	1/5	3	0.247
MCP	1/3	1	1/3	3	0.169
EENS	5	3	1	1/2	0.390
Loss	1/3	1/3	2	1	0.194
Regulator					
Outage cost	1	1/5	1/5	2	0.109
MCP	5	1	2	3	0.462
EENS	5	1/2	1	3	0.330
Loss	1/2	1/3	1/3	1	0.098
ISO					
Outage cost	1	1/5	1/5	2	0.109
MCP	5	1	2	3	0.462
EENS	5	1/2	1	3	0.330
Loss	1/2	1/3	1/3	1	0.098
Utility					
Outage cost	1	5	3	3	0.523
MCP	1/5	1	1/2	1/3	0.085
EENS	1/3	2	1	1/2	0.152
Loss	1/3	3	2	1	0.240

TABLE VI
FINAL RESULT ON THE WEIGHTING OF THE STUDIED ATTRIBUTES

Criteria	Final weight	
Outage cost	W_1	0.226
Market fairness	W_2	0.266
Reliability performance	W_3	0.234
Loss	W_4	0.275

C. AHP Analysis and Criteria Weighting Process

Following the concept of the AHP method introduced in Sections III and IV, the judgment matrices for the at-hand hierarchical decision-making problem and the final weight for each decision variable are tabulated in Tables IV and V. Such analyses are conducted by several operators and asset managers, who have a wide understanding of the problem and the system components. Accordingly, the values presented in these tables are the aggregated results of the selected participants in the field. Eventually, the priority vectors for each criterion are obtained according to (8) and (9) as shown in Table VI. Such weighting vectors are then incorporated in the algorithm for final decision-making.

D. Component Criticality Assessment via Linear Additive Utility Function

The results from the AHP analysis (i.e., the final weights of criteria) and single-utility functions (i.e., the criticality of each component based on the impact on various criteria) are integrated by means of a linear additive utility function as described in (6). The criticality index of each system component would then be calculated, helping the asset manager

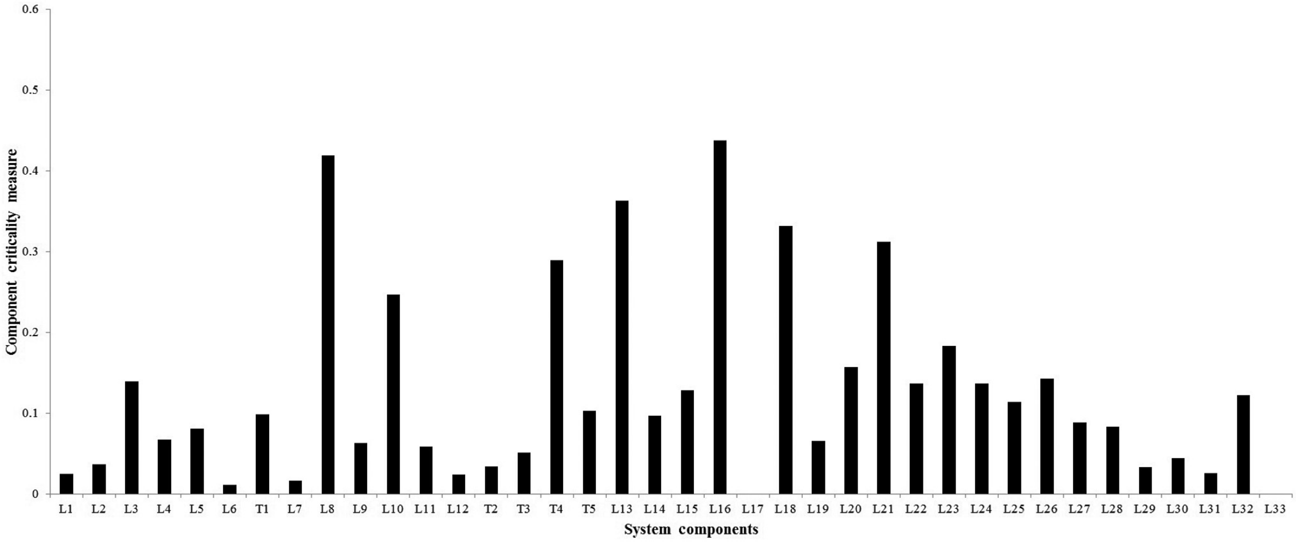
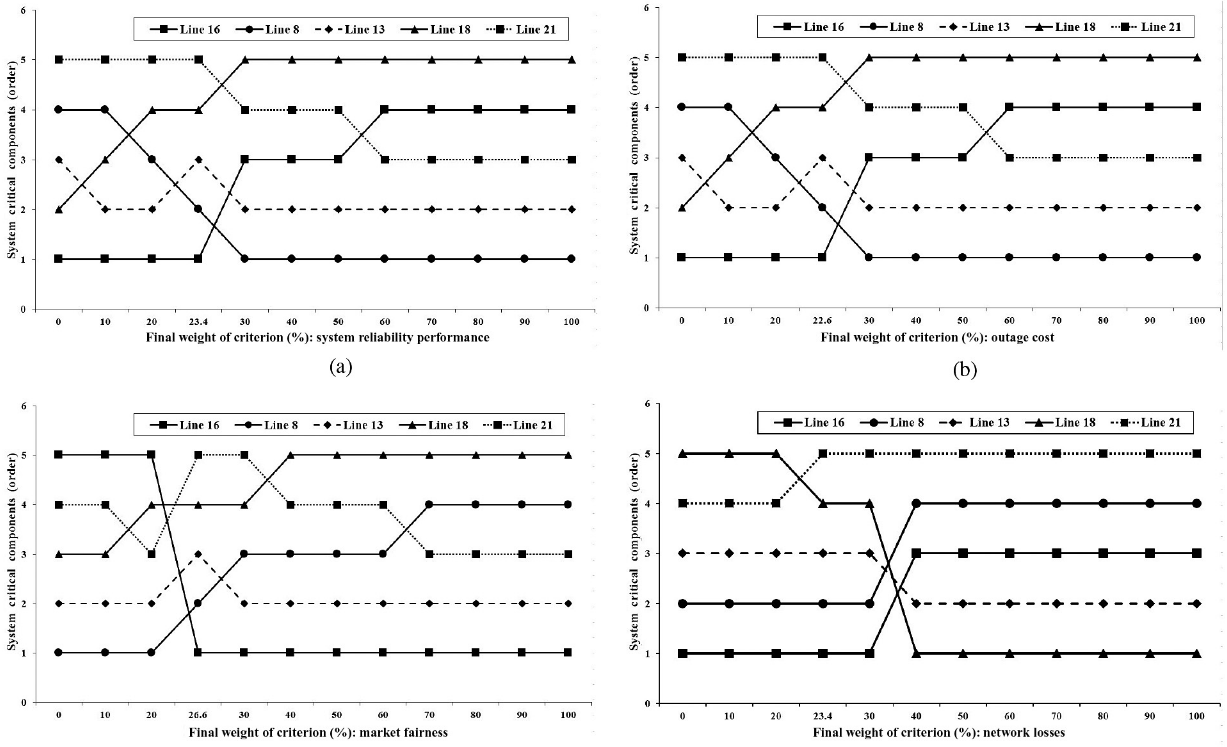


Fig. 7. Final criticality measure for the components of the IEEE-RTS considering all the major criteria.



(a)

(b)

(c)

(d)

Fig. 8. Sensitivity analysis: variations in the criticality order of system components with different weights of criteria. (a) Sensitivity analysis of the final results to the weight of criterion 1: EENS. (b) Sensitivity analysis of the final results to the weight of criterion 2: Υ. (c) Sensitivity analysis of the final results to the weight of criterion 3: MCP. (d) Sensitivity analysis of the final results to the weight of criterion 4: P_{loss}.

prioritize the components for maintenance and reinforcement decision-makings. The total criticality measures for the components in the IEEE-RTS system are calculated and demonstrated in Fig. 7. As can be seen in this figure, transmission lines 8, 16, 13, 18, 21 and transformer 4 are ranked the highest in terms of the role they are playing for the system successful performance. It is interesting to note that:

1) Component prioritization is accurately accomplished in this paper based on a combination of both qualitative and quantitative analyses taking into account the experts' knowledge and specialists' technical experiences.
2) Consideration of outage cost, as one of the major criteria for identification of system critical components, would help in a wise discrimination of different load points and the associated VOLLs.
3) As shown in Fig. 7, the criticality measures for some system components are calculated as zero or very small values close to zero. One can take L17 and L33 as

examples. This observation demonstrates that the outage scenario of such components does not have any negative impact (or very minor impacts) on the selected criteria and as a result are not critical for prompt/more frequent maintenance and reinforcement considerations.

4) The identified critical components through the proposed qualitative–quantitative analysis can then take part in the next steps of the RCM process for transmission systems if planned to be implemented in practice.
5) The proposed approach will provide the operator/asset manager with informative signals on the weak points of the system, so that the cost-effective asset management strategies can be planned accordingly.

E. Sensitivity Analysis

In this part, a sensitivity analysis is conducted to investigate the impact of uncertainties in the experts' knowledge and experiences on the final decision outcome. In so doing, the final weight of each criterion, calculated using the qualitative–quantitative analysis of the AHP technique, is varied to reflect various possibilities for different participants' thinking in the decision-making problem, and the trend of changes in the criticality measure and the order of critical components is studied. The results of the sensitivity analysis are shown in Fig. 8. As can be seen in this figure, variations in the final weight of each criterion will impact the criticality of system components differently. For instance, as one can see in Fig. 8(a), the criticality measure of system components is highly sensitive to the importance of reliability criterion (indicated by EENS) especially when the final weight of this criterion varies over 10%–30%. To put a figure on this, one can see that if the weight of this criterion is changed from 23.4% to 30%, the criticality measure of some components (e.g., L16, L8, and L13) would change, and the order of system critical components will accordingly change from L16-L18-L13-L8-L21 to L21-L13-L16-L21-L18. Also, in another note, if the final weight of this criterion overweighs 0.6, no change will be observed in the criticality measure and neither the prioritized order of system components. Similar analysis can be performed for the rest of criteria for which the results are demonstrated in Fig. 8(b)–(d). From such analyses, one can conclude that, due to the significant sensitivity of the final decision to the inputs from the experts and operators, the selection of such participants in the decision-making problem and the accuracy of their inputs should be wisely taken into account and well managed for a reliable decision-making.

V. CONCLUSION

Component prioritization for maintenance planning and scheduling of transmission system components is indispensable as scarce resources of utilities are frequently reported, the deregulated environment of transmission systems dictates, and different components contribute differently to the system-desirable performance. As the first step toward a successful RCM implementation in practice, critical components need to be identified to focus the maintenance priorities on the parts of the system needing it the most. A new multiattribute decision-making support tool for identifying such system critical components in transmission systems is developed in this paper. The proposed algorithm takes into account the experts' knowledge and expertise through the widely accepted AHP technique and benefiting from a hybrid qualitative–quantitative assessment. Employing the Monte Carlo simulations, a probabilistic quantitative assessment of component contribution to the system reliability, market fairness, network losses, and imposed outage costs is conducted to foresee the failure consequences. Mathematically integrating the aforementioned analysis, the criticality measure of system components would be computed for maintenance priorities and reinforcement decision-making.

As demonstrated in a case study (IEEE-RTS) and using the experts' inputs from the Mazandaran Regional Electric Company in the north of Iran, the proposed method could effectively recognize the system critical components from various aspects of interest. The conducted sensitivity analysis on the results also illustrated that the experts' knowledge and experiences play an undeniable role in the final outcome, and also, major changes in their inputs would drastically change the components criticality order and final decision plans.

This paper was focused on the first step of the RCM process: critical component identification. Future extensions of this work may be on the development of new formulations for the next steps of RCM implementation in power transmission systems (e.g., selection of an optimal maintenance strategy) compatible with the proposed approach in this paper. RCM implementation in the integrated power generation and transmission systems is also suggested for future studies. Application of the fuzzy sets theory and other robust probabilistic techniques in dealing with the uncertainties involved in the RCM implementation process can also be focused in the future works.

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