Identification of Critical Components in Power Systems: A Game Theory Application

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***Abstract*—As the electricity market undergoes continuous evolutions, along with the outdated nature of the grid, system operators would have to be able to more effectively manage the operation costs since waves of maintenance costs and equipment investments would be anticipated in the years to come. Strategic implementation of cost-effective reliability centered maintenance (RCM) approaches seems to be a key solution. This paper proposes an efficient method to assess the component criticality for the system overall reliability and further maintenance focuses. A solution concept of game theory, called Shapely Value, that is able to fairly identify the contribution of each single equipment to the system reliability performance once a high-order contingency occurs is proposed. The suggested framework would help in realizing where investments to be made in the grid to keep a desirable system performance from the reliability standpoint. Implemented on the IEEE Reliability Test System (IEEE-RTS), the effectiveness of the suggested framework is confirmed.**

***Index Terms*—critical component; failure; game theory; reliability-centered maintenance (RCM).**

I. Nomenclature

B	Set of total bus bars in the system.
G	Set of total generating units in the system.
G_R	Set of total generating units with reserve.
$I_{E_i}^{DN}$, $I_{E_i}^{UP}$	Set of the failed and on-line generating units in outage event E_i
I_L	Set of total lines in the system.
Z_n	Set of generators in zone *n*.
$E_{i,m}^{g}$	The i^{th} outage event of order *m* including the outage of unit *g*.
$Con_t(E_i)$	Consequences associated with the outage event *i* at time *t*.
$EC(E_i)$	Expected cost associated with the outage event E_i .
P_g, P_{g,E_i}^{c}	Real power generation of unit *g* in normal and contingency condition.
PL_d, PL_{d,E_i}^{c}	Real power consumption of load *d* in normal and contingency condition.
Q_g, Q_{g,E_i}^{c}	Reactive power generation of unit *g* in normal and contingency condition.
$TC_{g,t}^{Sh}(Con_t)$	Total contribution of generating unit *g* using Shapley value concept at time *t*.
$TC_{g,t}^{Sh^w}(Con_t)$	Total contribution of generating unit *g* using weighted Shapley value concept at time *t*.
r_g	Reserve quantity of generating unit *g*.
V_b	Voltage magnitude at bus *b*.
$\rho(B_g)$	Energy price at bus B_g which is connected to the unit *g*.
δ_b	Voltage angle at bus *b*.
f_{E_i}	Occurring frequency of outage event E_i
FOR_g	Forced outage rate of unit *g*.
O_d	Offer interruption price of load *d*.
$P_g^{\max}$, $P_g^{\min}$	Upper and lower limit for real power of unit *g*.
P_{E_i}	Occurring probability of outage event E_i
$Q_g^{\max}$, $Q_g^{\min}$	Upper and lower limit for reactive power of unit *g*.
$r_g^{\max}$	Reserve offer quantity of unit *g*.
R_n	Reserve requirement of zone *n*.
$V_b^{\max}$, $V_b^{\min}$	Upper and lower voltage magnitude at bus *b*.
$\xi_{E_i,g}^{G}$	A binary number denoting the status of unit *g* in outage event E_i .
λ_{d,E_i}	Departure rate of outage event E_i .
μ_g, λ_g	Repair and failure rate of unit *g*.
$\delta_b^{\max}$, $\delta_b^{\min}$	Upper and lower voltage angle at bus *b*.
Δ_g	Physical ramp rate of unit *g*.
$C_g(P_g)$, $C_g^R(r_g)$	Energy & reserve cost function of unit *g*.
$f(v)$	Value function of *v*.
$g_P(\theta, V, P) = 0$	Nonlinear equation for nodal real power balance.

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$g_Q(\theta, V, Q) = 0$	Nonlinear equation for nodal reactive power balance.
$h_f(\theta, V) \leq 0$	Nonlinear function of the bus voltage angles and magnitudes for the *from* end of each branch.
$h_t(\theta, V) \leq 0$	Nonlinear function of the bus voltage angles and magnitudes for the *to* end of each branch.
$Sh_h(v)$	Shapley value function of v.
$Sh_h^w(v, w)$	Weighted Shapley value function of v with the weight vector w.
v	Characteristic function.

II. INTRODUCTION

Emergence of the electricity markets has commanded the utilities for further improvements in reliability of power systems and availability of the constituent components for them to keep the pace in this competitive environment. Reliability improvements in power system, although seems contradictory to the current cost reduction policies in utilities, needs to be approached and somehow strictly guaranteed since the customer satisfaction is closely attached to the reliable and high quality electricity. As a result, reliability and risk assessments are always a critical concern for the utilities worldwide [1].

Among the activities utilities are commonly involved with for system reliability improvements, maintenance strategies are regarded as the must do efforts to maintain the components availability and enhance the system overall reliability performance over time. While maintenance costs constitute a large portion of system operational costs, reducing maintenance activities on system components can lead to higher damages caused by increased number of forced outages. Reliability centered maintenance (RCM) is a cost-effective strategy where the cost and reliability requirements are compromised techno-economically [2].

Interesting efforts have recently been dedicated to the application of RCM, some of which are conducted in different industries [3]-[5] and some in the electric domain. Among the latter category, there are some works done in response to RCM implementation in distribution level of power systems. In [6], the authors have employed the conventional sensitivity analysis and investigated the changes in the system load point reliability indices to prioritize the system components based on their types. Traditional reliability indices have been employed in [7]-[10] to calculate malfunction consequences and schedule maintenance of circuit breakers. Switching substations have been studied in [11] and the components are classified based on their importance and condition as a part of RCM adoption. In [12], a new method is introduced to determine the criticality of distribution component types by incorporating the experts' knowledge and expertise into the analysis trough fuzzy analytical hierarchical process (FAHP). References [13]-[17] have introduced an all-inclusive framework to practically implement the RCM in distribution systems. Attempts have been made in [18]-[20] to include the expected outage costs in the process and schedule the most profitable maintenance practices through using optimization techniques. However, the authors are mainly involved in how to mathematically pinpoint the best maintenance strategy, but not addressing critical component identification in the RCM process. References [21]-[23] introduce executable RCM approaches in large-scale transmission systems. The authors have defined the indices representing the importance of each component from different perspectives and prioritized system components accordingly. RCM applications in power plants are studied in [24], [25]. However, to the best of the authors' knowledge, there is no applicable way to fairly identify the critical components of a system regarding the contribution of each component on the imposed consequences when a high-order contingency occurs. Common sensitivity analysis is majorly involved with the effect of one component outage at a time on the system performance. In dealing with the complex, highly non-linear power systems, the consequence associated with simultaneous outages can be extremely different from that estimated by summing individual single-order contingencies and as a result make it a complicated problem to identify the criticality of the involved components for more concentrated maintenance planning.

Generating units are among the important components in power systems with significant influence on the management of probable interruptions and providing the required power of customers and end users in distribution systems. Generator outages may have serious or little consequences depending on their position and network configuration. This paper is focused on proposing an importance index for generating units in power systems and also strives on the fair allocation of outage consequences to the involved units in the case of high-order contingencies. The proposed methodology employs a solution concept of Game Theory, namely Shapely Value, which helps in prioritization of generating units according to their failure impacts on the system reliability performance. Having found the system critical generating units via the proposed approach, the RCM process can be effectively followed upon.

The rest of this paper is organized as follows. The analytical procedure for reliability evaluation of power systems in presence of contingencies is briefly presented in section III. Section IV introduces the concept of Shapely Value Game Theory (SVGT) and the associated mathematical background. Section V provides a detailed description of the proposed approach to determine the criticality and importance of the network components. Numerical case studies are presented in Section VI following by the concluding remarks in Section VII.

III. RELIABILITY EVALUATION OF POWER SYSTEMS

The purpose of power system reliability evaluation is fundamentally to investigate the system capability to handle its desirable performance majorly in the cases of outages. This involves failure impact assessment of various equipment on the system overall performance; as a result, a comprehensive model of the system and the associated components is critical for the process to start. On the other hand, arrival of electricity markets mandates considering the economic aspects of system operation in the associated decision makings. As a result, system modeling for reliability evaluation needs to be accompanied by the electricity market behaviors and related issues. Here in this paper, a reliability model of the system is focused taking into account the system physical constraints, market performance, and the response from operators in different conditions.

Reliability evaluation of large-scale power systems is a complicated task and commonly requires many calculations with considerable computational burden. Two practical methods of Monte Carlo simulations and state enumeration are frequently approached to model the outages in a bulk power system. Either of these methods has both advantages and disadvantages depending on the application conditions. Monte Carlo simulation is divided into sequential and non-sequential categories. The sequential or state duration sampling approach is accomplished by sampling the probability distribution of the component state duration, while the non-sequential approach is done by sampling the probability that the component appears in that state. After each component state is determined, the system state can be obtained by the combination of all component states [26]. State enumeration approach comprises of two independent parts namely statistical analysis and consequence evaluation. In this approach, the possible contingencies are selected first, and probability and frequency of their occurrence is determined in the statistical analysis section. In the consequence evaluation part, impact of each outage event on the system overall performance is evaluated. The reliability indices are calculated then by combining the results of these two steps. In this method, usually a limited number of simultaneous outages is considered as the possible list of contingency. State enumeration technique is more suitable compared to the Monte Carlo approach for a system with low failure probabilities of components since the probability and frequency of contingency decreases very rapidly as the number of component outages increases [26]. Furthermore, this approach provides the advantage of parallel processing applications due to independent behavior of components. Therefore, the proposed method benefits from the state enumeration approach for reliability and risk assessments.

A. Consequence Analysis

Once the system is thoroughly modeled, the overall reliability performance of the system in different operating conditions can be evaluated. For this purpose, the system operational performance in normal conditions and in response to an unplanned outage should be studied first.

In the competitive electricity market, the main task assigned to the independent system operator (ISO) is to achieve the economic efficiency while maintaining the system reliability and security by providing ancillary services that can be either dispatched with energy dispatch simultaneously or dispatched sequentially. In this paper, the simultaneous forms of auctions are considered.

The objective of dispatching the energy and reserves is to optimize the social welfare, which can be maximized by minimizing the total payment or the total cost of energy and reserves while satisfying AC power flow equations, ancillary services, transmission and operating constraints [26], [27]. Mathematically, the objective for ISO is formulated below:

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

s.t.

$$g_P(\theta, V, P) = 0 \tag{2}$$

$$g_Q(\theta, V, Q) = 0 \tag{3}$$

$$h_f(\theta, V) \le 0 \tag{4}$$

$$h_t(\theta, V) \le 0 \tag{5}$$

$$\delta_b^{\min} \le \delta_b \le \delta_b^{\max}, \quad \forall b \in B \tag{6}$$

$$V_b^{\min} \le V_b \le V_b^{\max}, \quad \forall b \in B \tag{7}$$

$$P_g^{\min} \le P_g \le P_g^{\max}, \quad \forall g \in G \tag{8}$$

$$Q_g^{\min} \le Q_g \le Q_g^{\max}, \quad \forall g \in G \tag{9}$$

$$0 \le r_g \le \min(r_g^{\max}, \Delta_g), \quad \forall g \in G_R \tag{10}$$

$$P_g + r_g \le P_g^{\max}, \quad \forall g \in G_R \tag{11}$$

$$\sum_{g\in Z_n} r_g \ge R_n, \quad \forall n \tag{12}$$

Constraints (2)-(3) give two sets of N_b non-linear nodal active and reactive balancing equations. Network constraints (4)-(5) represent two sets of N_l branch flow limits, one for the *from* end and one for the *to* end of each branch, which are non-linear functions of the bus voltage angles and magnitudes. Constraints (6)-(7) represent the bus voltage phase angle and magnitude limits. (8)-(9) are supply constraints and (10)-(12) are capacity reserve constraints. Constraint (10) ensures that the reserve for each generating unit must be positive and is bounded above by a reserve offer while respecting the physical ramping limitation. Constraint (11) enforces that the total amount of energy plus reserve of the unit is limited above by its capacity. Constraint (12) represents the spinning reserve requirements in each region. The locational marginal pricing (LMP) are determined by an AC optimal power flow function in terms of Lagrange multipliers. After this optimization, ISO determines the amount of energy, reserve of each generator and LMP at system each bus bar. In the general case, the occurrence of an unplanned outage or unforeseen event at the operation time influences the system parameters such as bus voltages, branches flow, etc. Meanwhile, according to the ISO's responsibility to maintain system security, by purchasing energy from the specified reserve or load shedding actions, system transits to a new operating point and as a result, safety and economic performance are guaranteed in this condition.

The cost of purchasing energy from the purchased reserve and the cost of total load shedding are added to the operating cost. These costs can be considered as the contingency consequence imposed to the system. Demands in restructured power systems can also offer prices to reduce the load and the interruption cost can be calculated from the accepted offers. The ISO minimizes the total interruption costs.

For each contingency, ISO tries to minimize the following:

$$\begin{aligned} \min \ Con(E_i) = &\sum_{g\in \mathrm{G}} \Big(\rho(B_g)\big(P^c_{g,E_i} - P_g\big)\Big) \\ &+ \sum_{d\in I_L} \Big(O_d\left(PL_d - PL^c_{d,E_i}\right)\Big) \end{aligned} \tag{13}$$

The set of constraints for this optimization formulation are constraints (2)-(7) explained previously, as well as the following constraints:

$$Q_g^{\min}\xi_{E_i,g}^G \le Q_{g,E_i}^c \le Q_g^{\max}\xi_{E_i,g}^G \qquad (14)$$

$$P_g\xi_{E_i,g}^G \le P_{g,E_i}^c \le \left(P_g + r_g\right)\xi_{E_i,g}^G \qquad (15)$$

The outage event i of generating units can be represented by a vector of binary variable ξ_S^G, with 1 denoting the availability of components, and 0 otherwise. Constraints (14)-(15) ensure that the output of generating unit j is zero if it is on outage in i^{th} outage event. If generator j is available, its increased active power output does not exceed the predetermined reserve.

B. Statistical Analysis

Another factor affecting the contingency is probability and frequency of its occurrence such that the contingency with low cost and high probability may be more damaging than the contingency with high cost and low probability. Using Markov model and being independent of equipment failure, the probability, departure rate, and frequency of each contingency are calculated as follows:

$$P_{E_i} = \prod_{g\in I_{E_i}^{DN}} \frac{\lambda_g}{\left(\mu_g+\lambda_g\right)} \times \prod_{g\in I_{E_i}^{UP}} \frac{\mu_g}{\left(\mu_g+\lambda_g\right)} \qquad (16)$$

$$\lambda_{d,E_i} = \sum_{g\in E_i^{DN}} \mu_g + \sum_{g\in E_i^{DN}} \lambda_g \qquad (17)$$

$$f_{E_i} = P_{E_i} \times \lambda_{d,E_i} \qquad (18)$$

Equation (16) calculates the probability of contingency by multiplying the availability of online components and unavailability of failed components. Departure rate of contingency in equation (17) is obtained from summing failure rate of online components and repair rate of failed components. Equation (18) represents the frequency of contingency.

C. Reliability Indices Calculation

Once the consequence analysis of all possible contingencies and statistical analysis of their occurrence probability is done, the reliability index is calculated by combining the results of the aforementioned two parts as follows.

$$EC_t(E_i) = P_{E_i} \times Con_t(E_i) \qquad (19)$$

In which the imposed expected cost to the system due to occurrence of contingency E_i is obtained by multiplying the probability and consequence of its occurrence.

IV. SVGT Algorithm: Theoretical Background

There are numerous approaches for cost allocation among the players of transferable utility (TU) cooperative games, which specify how to share among participants the joint costs resulted from the cooperation. The present work is based on the concepts of Shapley Value providing fair and stable models for embedded cost allocation of power networks to avoid any interest for players to secede the system, that otherwise leads to an overall un-optimal situation [28].

Let $n \ge 2$ denote the number of players in the game, and let $N = \{1, 2, \dots, n\}$ denote the set of players. A coalition, S, is defined to be a subset of N, that coordinate together and v: $2^N \rightarrow R$ is a characteristic function defined on the set, 2^N, of all coalitions (subsets of N) such that $v(\varnothing) = 0$. Characteristic value $v(S)$ gives the maximum cost or payoff incurred by coalition S. Since we take the set of players N to be fixed, the collection of all characteristic functions on N is denoted by g^N. A solution for TU-game is a function f: $g^N \rightarrow R^N$ which assigns an $|N|$-dimensional real vector to every TU-game. This payoff vector $X = (x_1, x_2, \dots, x_n)$ is seen as a distribution of the payoffs with the understanding that player i is to receive x_i. Cost allocation is represented in terms of a payoff vector.

A famous solution for TU-game is the Shapley Value. A value function is assigned to each possible characteristic function, c, an n-tuple, $f(v) = (f_1(v), f_2(v), \dots, f_n(v))$. The Shapley value is the function sh : $g^N \rightarrow R^N$ given by:

$$Sh_h\left(v\right) = \sum_{h\in S} \frac{\Delta_v(S)}{|S|} \qquad \forall h \in N \qquad (20)$$

With dividends of:

$$\Delta_v\left(s\right) = \sum_{T\subset S} (-1)^{|S|-|T|} v(\mathrm{T}) \qquad \forall S \subset N \qquad (21)$$

The most important characteristics of this function are satisfactory fairness property, efficiency, symmetry and the null property. It is notable that there is a theorem that states that a solution for TU-game is equal to Shapley value if and only if it satisfies these axioms [29]-[30]. However, the symmetry axiom can be used only when the parameters of the game are completely symmetric for the players, which make it sometimes unrealistic in practice.

Another value functions that obey the Shapley's axioms except the symmetry axiom are weighted Shapley values. An example of such a weighted Shapley value is the function sh^w : $g^N \times R^N_+ \rightarrow R^N$ given by:

$$Sh_h^w\left(v,w\right) = \sum_{h\in S} \left(\frac{w_i}{\sum_{j\in S} w_j} \right) \Delta_v(S) \qquad \forall h \in N \qquad (22)$$

where $w = (w_1, w_2, \dots, w_n)$ is a weighting vector that assigns different positive weights to the players [28]. Compared to Shapley value function, a share of the joint costs assigned to the player in this function is proportional to its weight additional to its marginal contribution.

V. Critical Component Identification in Power Systems: Proposed Approach

To determine the critical components of a power system for more focused maintenance attention, the imposed cost due to the outage of each component is considered as the index that shows the degree of its importance. For this purpose, each component's contribution from the total consequential costs of an outage contingency should be calculated. Such monetary contribution for each component at each contingency is identified by utilizing the concept of cooperative games. A critical contingency can be better represented as a game with generators being players, and characteristic values associated with coalitions are the consequence of contingencies.

The contributions of each equipment in any contingency could be summed up and the total monetary index for each component can be achieved.

$$TC_{g,t}^{Sh}\left(Con_t\right)=\sum_m\sum_i P(E_{i,m}^g) \times\left[\sum_{S\subset E_{i,m}^g}\sum_{T\subset S}\frac{(-1)^{|S|-|T|}Con_t(T)}{|S|}\right] \tag{23}$$

$$TC_{g,t}^{Sh^w}\left(Con_t\right)=\sum_m\sum_i P(E_{i,m}^g) \times\left[\sum_{S\subset E_{i,m}^g}\frac{FOR_g}{\sum_{k\in S}FOR_k}\sum_{T\subset S}(-1)^{|S|-|T|}Con_t(T)\right] \tag{24}$$

In equations (23)-(24), the contribution of the component j in the total outage cost is calculated by employing the Shapley value and weighted Shapley value concepts, respectively. In equation (24), forced outage rate of components is considered as the weights, which make the probability of component failure effective in determining their contribution in any outage event.

VI. Numerical Case Study and Discussions

The proposed approach for criticality evaluation of generating units on the power system overall reliability performance is applied to the IEEE-RTS [31]. This system is composed of 32 generating units, 20 load points, 24 buses, and 38 transmission lines. The criticality degree of generating units is determined per month according to the system peak load.

System active and reactive power of generating units, load demand, spinning reserve of generating units, and LMPs are initially obtained from the energy and reserve market simulations in the system normal operating condition in such a way that reserve requirement is considered equal to the capacity of the largest unit. Having performed the consequence analysis of all outage events up to the third order, the risk imposed to the system, in each order of outages for each month, is calculated as demonstrated in Table I.

Table I shows that the risk imposed to the system increases with increasing peak load due to growing of load shedding cost and as a result the criticality of generating units varies over time. In addition, it can be seen that the consequence of outages greatly increases in high order outages but due to the low occurrence probability, the expected cost has initially a slight increase, in high order outages declines significantly, and can be neglected in the analysis.

The contribution of each generating unit is determined by utilizing the Shapley value function and weighted Shapley value function. Fig. 1 shows the criticality degree of generating units obtained from the application of the proposed WSVGT method. It can be seen that two nuclear steam units of 400 MW located at buses 18 and 21 are identified as the most critical components of the system. The reason lies in the fact that the generating units U22 and U23 impose more costs to the system due to the high capacity and maximum utilization factor in normal operating condition. Table II gives the contribution of each generating unit in first, second, and third order outages for 100% load condition. From the obtained results in table II, it can be realized that the criticality of generating units majorly depends on the capacity and failure rate of the units in addition to their location in the system. As an instance, the importance of hydro units of 50 MW is less than that of the combustion turbine units of 20 MW, not only due to a low failure rate, but also since they are located on the north side of the system attached to a less important bus-bar. In addition, it can be seen that the units of the same capacity and location have the same total contribution that well reflects the symmetry property of SVGT and WSVGT. Comparisons of the results obtained via these two methods, it can be observed that the WSVGT method allocates a higher share to the units with higher probability of failure in each outage event which makes it more suitable and attractive in cases where the players (here components) may exist in the system down state. As can be seen in tables I and II, the sum of generating unit's contributions in each outage order is equal to the costs imposed to the system, which indicates that the proposed method can efficiently manage a fair allocation of consequential outage costs to the involved components.

VII. Conclusions

An efficient formulation to prioritize the system components, specifically generating units, based on their failure impacts on system reliability is proposed. By the use of the SVGT algorithm, the criticality of each network component was linked to the risk imposed to the system due to its failure and also contribution in high-order contingencies. Example application of the proposed framework was illustrated through simulations on the IEEE RTS case study. According to the results, the proposed approach was well able to fairly map the

TABLE I. Risk Index Imposed to System in the Studied Year

Month	Peak load (%)	1st Order Outages ($/h)		2nd Order Outages ($/h)		3rd Order Outages ($/h)	
		Con_t ($\times10^4$)	EC_t ($\times10^3$)	Con_t ($\times10^6$)	EC_t ($\times10^4$)	Con_t ($\times10^8$)	EC_t ($\times10^4$)
1	90	5.52	3.69	9.70	1.57	3.38	2.27
2	88	5.3	3.54	9.87	1.64	3.39	2.23
3	74	3.05	2.20	6.37	1.30	2.36	1.81
4	80	3.57	2.52	7.89	1.46	2.95	2.12
5	87	5.19	3.48	9.83	1.63	3.39	2.23
6	89	5.47	3.66	9.65	1.56	3.45	2.26
7	81	3.75	2.62	8.04	1.48	3.10	2.14
8	78	3.31	2.35	7.13	1.38	2.68	1.97
9	69	2.78	2.03	6.56	1.23	2.16	1.68
10	80	3.57	2.52	7.89	1.46	2.95	2.12
11	94	13.53	8.83	14.06	1.95	4.24	2.56
12	100	14.86	9.55	14.51	2.07	4.52	2.71

TABLE II. CONTRIBUTION OF SYSTEM GENERATING UNITS FOR 100% LOAD CONDITION

Bus #	FOR	P^{max} (MW)	1st Order Outages ($/h)	2nd Order Outages ($/h)		3rd Order Outages ($/h)	
				SVGT	WSVGT	SVGT	WSVGT
1	0.1	20	81.60	30.14	30.29	123.08	144.39
1	0.1	20	81.60	30.14	30.29	123.08	144.39
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
23	0.04	155	305.22	578.80	358.12	780.27	462.75
23	0.08	350	1348.83	3178.2	2965.92	4095.1	3973.32
Sum of contributions			9552.06	20728	20728	27087	27087

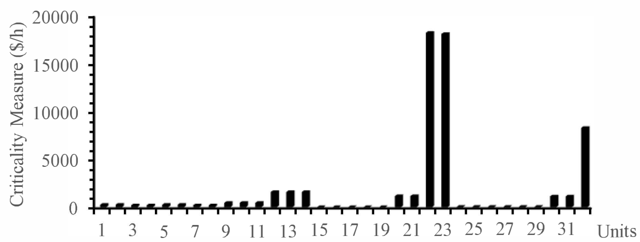

Figure 1. Criticality degree of generating units on system reliability.

outage consequences in case of higher order contingencies to the involved components. The suggested technique could successfully identify the critical components of the system from the reliability viewpoint for further maintenance focuses.

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