Probabilistic Evaluation of a Power System's Reliability and Quality Measures

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Abstract—**Reliability and performance quality measures computed so far are deterministic in nature. They represent one operating state (a snapshot of the system conditions) in which the required demand and generation and transmission capacities are known with 100% certainty. In this paper a general and coherent formulation is presented, which can be used to account for the randomness associated with the load level as well as the availability of generation and transmission capacities. The general probability formulation can be used to calculate various reliability indices and quality measures. The paper describes the new approach for computing probabilistic evaluation (expected value) of the reliability indices and performance quality measures and presents illustrative applications. The methodology used in this paper constitutes a new line of research in the probabilistic reliability evaluation of a system where the derived system-wide performance quality indices are capable of classifying and exhibitionistic areas of deficiencies, bottlenecks and redundancies in large-scale power grids.**

Keywords-probabilistic reliability; evaluation; quality; power systems

I. INTRODUCTION

The competitive electricity market is subjected to an increasing amount of uncertainties such as the demand forecast uncertainty, electricity price volatility, reliability of the generation groups, economic growth uncertainties, and changing environmental and social impacts on the energy sector [1-2]. In addition to considerations of these uncertainties, planners also need to balance the technical requirement of the system and the requirements from investors who aim at profit maximization [3-5]. There is a general utilization of reliability models throughout the world as the advantages of probabilistic methods over the deterministic approaches of planning, designing, operating and maintaining electric utility systems have clearly been recognized [6]. As has happened with many power system disciplines, the prime interest in system security, adequacy, and reliability has gradually shifted from completing and refining the theoretical basis, through developing suitable computational tools for demonstrating the capability and practicality of the methodologies, to upgrading the computational tools to handle the large-scale nature of present power systems and, finally, to relate various security, quality and reliability indices to the practical concerns of utility engineers and executives regarding supply and/or transmission deficiencies as well as the risk associated with ignoring such deficiencies [7-10]. Methods for computing probabilistic contingency-based reliability and performance quality indices have previously been published in [11-17]. These methods are based on a combined contingency analysis and reliability evaluation scheme which integrates both the contingency effect and its probability of occurrence into one routine of analysis [18-19]. In the current work, similar analysis will be used to compute the expected values of different system reliability and performance quality indices. In this context, a "contingency scenario" or a system "demand level" are regarded, in a more general sense, as a "state", which occurs with certain probability and represents a given demand value and an availability pattern of various capacities in the system. This paper shares the results of a recent major industry supported research and development study in which a novel framework was developed [2] for evaluating performance quality indices associated with power system generation demand balance. In this paper, the optimization technique based on three metaphors (dimensions) representing the relationship between available generation capacities and required demand levels, is presened. The novel formulation presented in this paper can accommodate the randomness associated with the load level and the availability of generation and transmission capacities.

II. PROBLEM FORMULATION

A. Power System Network Model

Let n_B be the number of buses in the power network, where n_B=n_L+n_G, with n_L and n_G being the number of load and generator buses respectively. Also, in the network model used, n_T is the number of transmission branches (lines and transformers). In order to facilitate the subsequent formulation, it is assumed without loss of generality, that the load buses are numbered as 1, 2, ...,n_L followed by generator buses as n_L+1, .., n_L+n_G, where n_L+n_G=n_B. For example, the sample power system shown in Figure 1 has n_B=4, n_G=2, n_L=2 and n_T=5. Now, let A=(n_B×n_T) be the bus incidence matrix representing the connectivity pattern between buses and lines. The entries of A are 0, 1 or -1. Therefore, an element A_{bt}=1 if bus b is feeding a transmission branch t, A_{bt}=-1 if bus b is fed from a branch t, and A_{bt}=0 otherwise. In the current analysis, the A matrix is partitioned row-wise into A_L and A_G associated respectively with load and generator buses. The rows of A (or columns of

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A^T) represent groups of buses while the columns of A (or rows of A^T) represent groups of transmission links. We also note that for practical large-scale networks, the matrix A is extremely sparse.

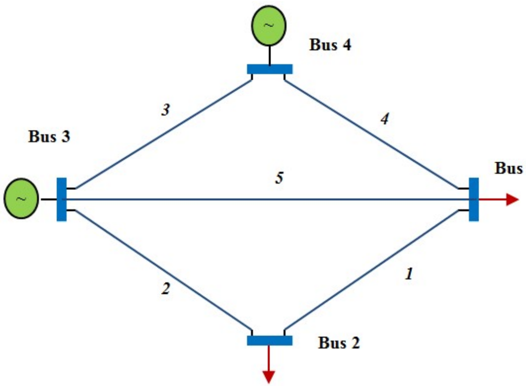

Fig. 1. A sample power system [8]

B. Performance Quality Assessment

Although the basic definitions pertaining to system performance quality are simple to state and often seem intuitive at first glance, care should be exercised in order to recognize some subtle differences in the definition and formulation of the composite performance quality indices. Let $\overline{P}_T$ be a vector of n_T elements representing transmission branch capacities, $\overline{P}_L$ a vector of n_L elements of peak bus loads, and $\overline{P}_G$ a vector of n_G elements representing generator capacities $\overline{P}_g$. For simplicity of notation, we shall use $\overline{P}_T$ to denote a general element t of the vector $\overline{P}_T$ (rather than the more strict notation of $\overline{P}_{TL}$). Similarly, we shall use $\overline{P}_l$ and $\overline{P}_g$ to denote the general elements of $\overline{P}_L$ and $\overline{P}_G$ respectively. However, when confusion may occur, we will use the strict notation of $\overline{P}_{Ti}$, $\overline{P}_{Li}$ and $\overline{P}_{Gi}$. Now, consider the schematic configurations of Figure 2(a) which depicts the transfer connectivity between generations through transmission to load.

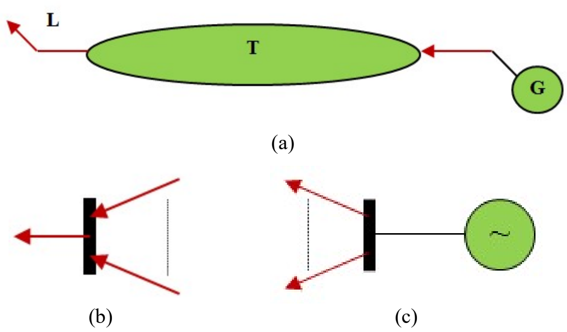

Fig. 2. G-T-L transfer connectivity [8]

If, for example the local generation capacity $\overline{P}_g$ at bus g exceeds the corresponding transmission capability $\sum_{t\in T_g}\overline{P}_t$ in Figure 2(b), where T_g denotes the set of transmission branches connected to generator bus g, then using the terminology introduced in the previous section, we may say that a positive amount of $(\overline{P}_g - \sum_{t\in T_g}\overline{P}_t)$ of generation beyond bus g has been bottled (blocked from usage). We should note that such a definition applies to a specific scenario of system configuration (the A-matrix) and loading conditions. For example, in the above discussion, we assumed that the set T_g does not represent any of pre-defined contingency scenarios. That is, T_g represents the full transmission capacity at bus g. In addition to the above definitions, we also define, using similar notation, the following vector for later use: $\overline{\overline{P}}_G$=vector of generation site capacities, which represents the maximum future expanded generation capacity that could be available at the same generation site. The novel framework applied in this paper is based on the original work in [2], in which three dimensions were introduced to represent the relationship between certain system generation capacity and the demand. These tropes relate to the following demand fulfillment issues:

- Need of capacity for demand fulfillment
- Existence of capacity (availability for demand fulfillment)
- Ability of capacity to reach the demand

The first trope defines whether the capacity is needed, the second defines whether the capacity exists, and the last defines whether the capacity can reach (delivered to) the demand. The eight possible combinations associated with the 0/1 (Yes/No) values of the three tropes, are illustrated in Table I. Generation quality indices are defined in terms of the previously defined "1/0" states indicating the (Needed, Exists, Can-reach) true/false values associated with each quality metaphor. We shall use the symbol $Q_g$ijk to indicate the generation quality index state. Also, in the following expressions, we shall use *Min* $\{x, y, ..., z\}$ to indicate the minimum of x, y, .., z. The notation $\langle x \rangle$ will be used to denote *Max* $\{0, x\}$, which is the maximum of x and zero (=x if x>0, or 0 otherwise).

TABLE I. ILLUSTRATION OF QUALITY ASSESSMENT TROPES

	Needed (L > 0)		**Not needed (L = 0)**	
	Can reach	Cannot reach	Can reach	Cannot reach
Exist *(C>0)*	Utilized Q_g111	Bottled Q_g110	Surplus Q_g011	Redundant Q_g010
Not-Exist *(C=0)*	Short-fall Q_g101	Deficient Q_g100	Spared Q_g001	Saved Q_g000

Table I summarizes the considered quality indices, namely the Utilized Generation Capacity (Q111), Bottled Generation Capacity (Q110), Shortfall Generation Capacity (Q101), Deficit Generation Capacity (Q100), Surplus Generation Capacity (Q011), Redundant Generation Capacity (Q010), Spared Generation Capacity (Q001), and Saved Generation Capacity (Q000).

C. Linear Program Formulation

In the computational scheme of [2], the integrated system quality assessment is performed via solving a master linear programming problem in which a feasible power flow is established which minimizes the total system Load Not Served (LNS) subject to capacity limits and flow equations. The master linear program, which utilizes the network bus incidence matrix ***A***, is formulated as:

$$\left.\begin{array}{l} \text{Objective function= (Minimize } f = \sum_{l=1}^{n_L}(-P_l)\text{)} \\ \text{with respect to } P_L,\ P_G, \text{ and } P_T \\ \text{subject to:} \\ A\cdot P_T = \begin{bmatrix} -\mathbf{P}_L \\ P_G \end{bmatrix} \quad \begin{array}{l} P_L \le \overline{P_L}, -P_L \le 0 \\ P_G \le \overline{P_G}, -P_G \le 0 \\ P_T \le \overline{P_T}, -P_T \le \overline{P_T} \end{array} \end{array}\right\} \quad (1)$$

An optimization software package (CPLEX) has been used to solve the Master Linear Program. The overall process of the evaluation of power systems reliability and quality measures is summarized in the flowchart in Figure 3.

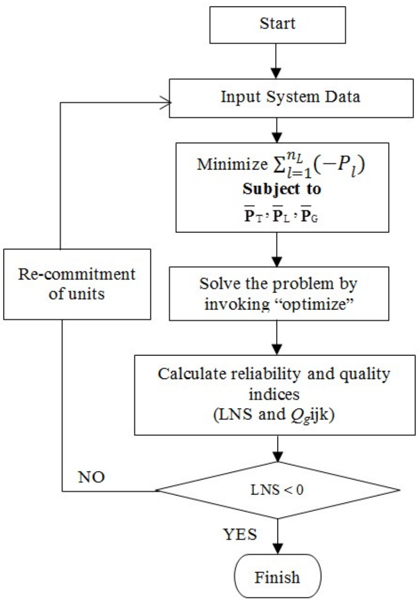

Fig. 3. Flow chart of the proposed methodology

D. Probabilistic Reliability Indices

The power system can be described, for the purpose of composite reliability and performance quality assessment, by the three-component model in which generation, transmission, and load are considered as multi-state elements of the power system. For a given operating state *m*, the values of the network variables will be the solution of the maximum load-supply optimization problem described in the previous section. Also, let f_m be the probability of operating state *m* (the sum of f_m for all *m*, including base-case scenario is 1). Then, the loss of load may be defined as:

$$LOLP = \sum_{m=1}^{M_s} LOLP^{(m)} \quad (2)$$

where:

$$LOLP^{(m)} = Max_l\{Y_l\ LOLP_l^{(m)}\} \quad (3)$$

represents the system loss of load probability for any operating state *m* (load levsrl, loss of generation and/or transmission capacities) in the power grid,

$$LOLP_l^{(m)} = \lambda_l^m\ f_m \quad (4)$$

represents the loss of load probability at bus ℓ for operating state *m*,

$$\lambda_l^{(m)} = \begin{cases} 0 & if \quad P_l^{(m)} \le P_l^o \\ 1 & if \quad P_l^{(m)} > P_l^o \end{cases} \quad (5)$$

and P_ℓ^o denotes the scheduled (required) load at load bus ℓ. Also, in (2), M_s denotes the number of all possible states.

III. PROBABILISTIC EVALUATION

The reliability and performance quality indices computed so far are deterministic in nature, i.e. they represent one operating state in which the required demand and the generation and transmission capacities are known with 100% certainty.

A. Proposed Formulation

In real life, load variations occur randomly and contingencies cause some generation and/or transmission capacities to be lost (become unavailable). In other words, neither the load levels nor the generation or transmission capacities are known with absolute certainty. They are rather subject to random variations and consequently the calculated reliability and performance quality indices are all subject to random variations where only expected values of these indices can be evaluated. For example, the load variations, which are accounted for using the so-called "load-duration curves" can be used to calculate the expected value of the *LNS*, which is widely known as the Expected Load Not-Served (*eLNS*). On the other hand, the randomness in the generation and transmission capacity availability are accounted for using the so-called forced-outage rates (or availability rates) associated with various facilities. Consequently, the expected values of the performance quality indices Q_{g111}, Q_{g110}, Q_{g101}, etc. can be evaluated using the modeled randomness of the system load as well as the generation and transmission capacity availabilities as will be outlined in this section. Methods for computing probabilistic contingency-based reliability and performance quality indices have previously been published [7]. These methods are based on a combined contingency analysis and reliability evaluation scheme which integrates both the contingency effect and its probability of occurrence into one routine of analysis. In the present work, similar analysis will be used to compute the expected values of different system performance quality indices. In this context, a "contingency scenario" or a system "demand level" are regarded, in a more general sense, as a "state" which occurs with certain probability and represents a given demand value and availability pattern of various capacities in the system.

B. Simulation Results

Consider the sample power system in Figure 4. The system consists of two generators, namely G1 and G2, with a total capacity of 100MW and connected to two load buses, with a total required load of 115MW, via five transmission lines. In this illustrative example, the availability of the two generating units are assumed as 0.9 and 0.8, respectively (forced outage rates of G1 and G2, respectively). Also, for simplicity, all transmission lines are assumed to have availability of 0.85. The system load is assumed to have three possible levels, namely 35MW, 75MW, and 115MW with probability of occurrence 0.5, 0.3 and 0.2 respectively.

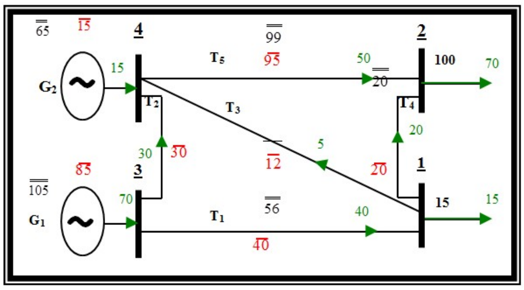

Fig. 4. A 4-bus sample power system

The combined generation/transmission state probability table associated with the generation and transmission capacities of this system, along with the reliability and performance quality indices *LNS*, Q_{g111} and Q_{g110} are shown in Table II for the 35MW load level. The rows of Table II represent various operating states. The first three columns of Table II represent the well-known generation Capacity Outage Probability Table (COPT) [20]. The next five columns (T1 to T5) represent the COPT for the transmission facilities of this system. Column ($\sum \bar{P}_g$) is the total generation available capacities for each operating state shown in the Table. The column ($\sum P_g$) represents the actual total generation as calculated from the solution of the Master Linear Program for various operating states. Similarly, the next three columns represent the associated values of the indices LNS and Q_{g111} and Q_{g110} respectively. When these values are multiplied by the operating state probability shown in the next column, they produce the expected values of these indices as outlined in the last three columns of the Table, namely *eLNS* and *eQg111* and *eQg110*. Using the generation state availabilities shown in Table II, the discrete probability density functions of various capacities and indices can be evaluated and displayed. These discrete density functions show the overall probabilities of occurrence associated with given capacities or indices. For example, the probability density function of the generation capacity (state probabilities) for this system are depicted in Figure 5.

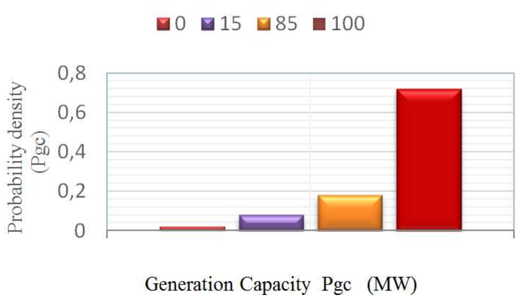

Fig. 5. Probability density of generation capacity for system

Figure 6 shows the probability density of the Utilized Generation Capacity (Q_{g111}) at 75MW load, while Figure 7 shows the probability density of Bottled Generation Capacity (Q_{g110}) at 115MW load and the probability density of Surplus Generation Capacity (Q_{g011}) for this system at 35MW load is shown in Figure 8. Table III summarizes the expected values of various performance quality and reliability indices for this system.

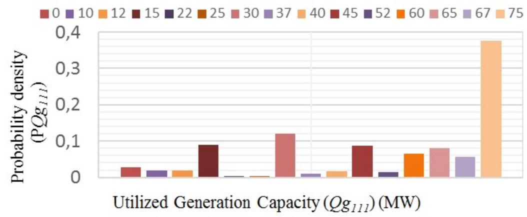

Fig. 6. Probability density of Q_{g111} for a system at 75MW load

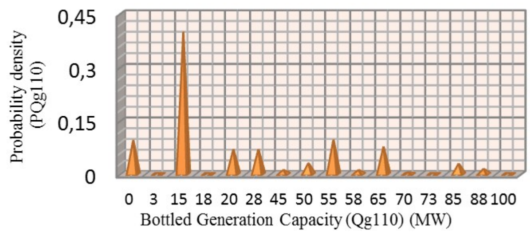

Fig. 7. Probability density of Q_{g110} for a system at 115MW load

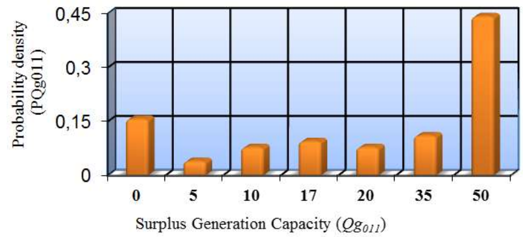

Fig. 8. Probability density of Q_{g011} for a system at 35MW load

The discrete probabilities of Figure 7 for Q_{g110} at 115MW load reveal that the highest probability is associated with generation bottling of 15MW and not with zero as would be expected for well-designed systems. This indicates a general weakness (shortage) in the installed transmission facilities as compared with the existing generation capacities and required load. The discrete probabilities of Figure 8 for Q_{g011} show two distinct high probabilities of occurrence at both 0 and 50MW surplus levels. This is mainly due to the fact that most of the main facilities (generators and transmission lines) are available (outage does not occur) which means that the network could deliver all the available generation (not needed) to the load side. On the other hand, at Q_{g011}=0, most of the main facilities (generators and transmission lines) are not available (outage), especially G1, T1 and T2, meaning that the network either doesn't has the capacity of generation over the required load or it is incapable to deliver the available generation (not needed) through transmission lines to the load side. In this regard, the maximum value of the probability density of the Q_{g111} for the system occurs at 75MW load level as shown in Figure 8.

TABLE II. PERFORMANCE QUALITY INDICES FOR THE TEST SYSTEM AT 35MW LOAD

#	G_1	G_2	T_1	T_2	T_3	T_4	T_5	$\sum \overline{P_g}$	$\sum P_g$	*LNS*	Q_{g111}	Q_{g110}	Probability	*eLNS*	eQ_{g111}	eQ_{g110}
1	1	1	1	1	1	1	1	100	85	0	35	0	0.319468	0	11.18137	0
2	1	1	1	1	1	1	0	100	52	10	25	10	0.056377	0.563767	1.409417	0.563767
3	1	1	1	1	1	0	1	100	85	0	35	0	0.056377	0	1.973184	0
4	1	1	1	1	1	0	0	100	52	30	5	30	0.009949	0.298465	0.049744	0.298465
5	1	1	1	1	0	1	1	100	85	0	35	0	0.056377	0	1.973184	0
6	1	1	1	1	0	1	0	100	40	10	25	10	0.009949	0.099488	0.248721	0.099488
7	1	1	1	1	0	0	1	100	85	0	35	0	0.009949	0	0.348209	0
8	1	1	1	1	0	0	0	100	40	30	5	30	0.001756	0.05267	0.008778	0.05267
9	1	1	1	0	1	1	1	100	55	0	35	0	0.056377	0	1.973184	0
10	1	1	1	0	1	1	0	100	52	10	25	10	0.009949	0.099488	0.248721	0.099488
11	1	1	1	0	1	0	1	100	55	3	32	3	0.009949	0.029846	0.318362	0.029846
12	1	1	1	0	1	0	0	100	52	30	5	30	0.001756	0.05267	0.008778	0.05267
13	1	1	1	0	0	1	1	100	55	0	35	0	0.009949	0	0.348209	0
14	1	1	1	0	0	1	0	100	40	10	25	10	0.001756	0.017557	0.043892	0.017557
15	1	1	1	0	0	0	1	100	55	15	20	15	0.001756	0.026335	0.035114	0.026335
16	1	1	1	0	0	0	0	100	40	30	5	30	0.00031	0.009295	0.001549	0.009295
17	1	1	0	1	1	1	1	100	45	0	35	0	0.056377	0	1.973184	0
18	1	1	0	1	1	1	0	100	12	23	12	23	0.009949	0.228823	0.119386	0.228823
19	1	1	0	1	1	0	1	100	45	0	35	0	0.009949	0	0.348209	0
20	1	1	0	1	1	0	0	100	12	30	5	30	0.001756	0.05267	0.008778	0.05267
21	1	1	0	1	0	1	1	100	45	0	35	0	0.009949	0	0.348209	0
22	1	1	0	1	0	1	0	100	0	35	0	35	0.001756	0.061449	0	0.061449
23	1	1	0	1	0	0	1	100	45	5	30	5	0.001756	0.008778	0.05267	0.008778
24	1	1	0	1	0	0	0	100	0	35	0	35	0.00031	0.010844	0	0.010844
25	1	1	0	0	1	1	1	100	15	20	15	20	0.009949	0.198977	0.149232	0.198977
26	1	1	0	0	1	1	0	100	12	23	12	23	0.001756	0.040381	0.021068	0.040381
27	1	1	0	0	1	0	1	100	15	20	15	20	0.001756	0.035114	0.026335	0.035114
28	1	1	0	0	1	0	0	100	12	30	5	30	0.00031	0.009295	0.001549	0.009295
29	1	1	0	0	0	1	1	100	15	20	15	20	0.001756	0.035114	0.026335	0.035114
30	1	1	0	0	0	1	0	100	0	35	0	35	0.00031	0.010844	0	0.010844
31	1	1	0	0	0	0	1	100	15	20	15	20	0.00031	0.006197	0.004647	0.006197
32	1	1	0	0	0	0	0	100	0	35	0	35	5.47E-05	0.001914	0	0.001914
33	1	0	1	1	1	1	1	85	70	0	35	0	0.079867	0	2.795343	0
34	1	0	1	1	1	1	0	85	52	10	25	10	0.014094	0.140942	0.352354	0.140942
35	1	0	1	1	1	0	1	85	70	0	35	0	0.014094	0	0.493296	0
36	1	0	1	1	1	0	0	85	52	30	5	30	0.002487	0.074616	0.012436	0.074616
37	1	0	1	1	0	1	1	85	70	0	35	0	0.014094	0	0.493296	0
38	1	0	1	1	0	1	0	85	40	10	25	10	0.002487	0.024872	0.06218	0.024872
39	1	0	1	1	0	0	1	85	70	0	35	0	0.002487	0	0.087052	0
40	1	0	1	1	0	0	0	85	40	30	5	30	0.000439	0.013168	0.002195	0.013168
41	1	0	1	0	1	1	1	85	40	0	35	0	0.014094	0	0.493296	0
42	1	0	1	0	1	1	0	85	40	10	25	10	0.002487	0.024872	0.06218	0.024872
43	1	0	1	0	1	0	1	85	40	18	17	18	0.002487	0.04477	0.042283	0.04477
44	1	0	1	0	1	0	0	85	40	30	5	30	0.000439	0.013168	0.002195	0.013168
45	1	0	1	0	0	1	1	85	40	10	25	10	0.002487	0.024872	0.06218	0.024872
46	1	0	1	0	0	1	0	85	40	10	25	10	0.000439	0.004389	0.010973	0.004389
47	1	0	1	0	0	0	1	85	40	30	5	30	0.000439	0.013168	0.002195	0.013168
48	1	0	1	0	0	0	0	85	40	30	5	30	7.75E-05	0.002324	0.000387	0.002324
49	1	0	0	1	1	1	1	85	30	5	30	5	0.014094	0.070471	0.422825	0.070471
50	1	0	0	1	1	1	0	85	12	35	0	35	0.002487	0.087052	0	0.087052
51	1	0	0	1	1	0	1	85	30	5	30	5	0.002487	0.012436	0.074616	0.012436
52	1	0	0	1	1	0	0	85	12	30	5	30	0.000439	0.013168	0.002195	0.013168
53	1	0	0	1	0	1	1	85	30	5	30	5	0.002487	0.012436	0.074616	0.012436
54	1	0	0	1	0	1	0	85	0	35	0	35	0.000439	0.015362	0	0.015362
55	1	0	0	1	0	0	1	85	30	5	30	5	0.000439	0.002195	0.013168	0.002195
56	1	0	0	1	0	0	0	85	0	35	0	35	7.75E-05	0.002711	0	0.002711
57	1	0	0	0	1	1	1	85	0	35	0	35	0.002487	0.087052	0	0.087052

IV. CONCLUSIONS

A general and coherent formulation is presented which can be used to account for the randomness associated with the load level and the availability of generation and transmission capacities. The general probability formulation can be used to calculate various reliability indices and quality measures. The paper describes the new approach for computing the probabilistic evaluation (expected value) of the reliability indices and performance quality measures and presents illustrative applications. The expected values of reliability indices, such as the Expected Load Not-Served (*eLNS*) and the expected values of performance quality indices: Utilized Generation Capacity (eQ_{g111}), Bottled Generation Capacity (eQ_{g110}), Shortfall Generation Capacity (eQ_{g101}), Deficit Generation Capacity (eQ_{g100}), Surplus Generation Capacity (eQ_{g011}), Redundant Generation Capacity (eQ_{g010}), Spared Generation Capacity (eQ_{g001}), and Saved Generation Capacity (eQ_{g000}) are calculated in this paper with the established flow pattern, based on the solution of the basic linear program .

TABLE III. EXPECTED VALUE OF RELIABILITY AND QUALITY PERFOMANCE INDICES

Index	***e*LNS**	eQ_{g111}	eQ_{g110}	eQ_{g101}	eQ_{g100}
Value (MW)	21.44	43.56	12.90	6.85	0.99
Index	eQ_{g011}	eQ_{g010}	eQ_{g001}	eQ_{g000}	
Value (MW)	15.11	17.14	34.03	25.36	

The general framework and formulation introduced in this paper can be applied to practical power systems. Also, it can be applied to a system under normal operation or subject to contingencies with certain or random occurrences. In this paper, the optimization technique based on three metaphors (dimensions) representing the relationship between available generation capacities and required demand levels was utilized. The novel formulation presented in this paper can accommodate the randomness associated with the load level as well as the availability of generation and transmission capacities, in this case, the expected values of reliability indices and the expected values of performance quality measures.

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