Assessment of Reliability and Quality Performance using the Impact of Shortfall Generation Capacity Index on Power Systems

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Abstract—**This paper presents a novel practical technique developed and applied for assessment of reliability and quality in real-life power systems. System-wide integrated performance indices are capable of addressing and revealing areas of deficiencies and bottlenecks as well as shortfalls in the composite generation-transmission-demand structure of large-scale power grids. The new evaluation methodology offers a general and comprehensive framework to assess the harmony and compatibility of generation capacities, transmission and required demand in a power system. The technique used in this paper is evaluated by the shortfall generation capacity index which is based on three dimensions introduced to represent the relationship between certain system generation capacity and demand. Also, practical applications to the Saudi power grid are presented for demonstration purposes.**

Keywords-shortfall; reliability; quality; assessment; power systems

I. INTRODUCTION

The issues of service reliability and system quality have risen to a high priority on the agenda of electric power companies. In this regard, many power utilities are concerned about the continuous increase in system demand along with the growing limitations on generation and transmission, facility expansion due to financial constraints, environmental concerns, etc. Power system components are divided into two main categories, namely, the generating equipment and the transmission equipment. Definitions for this equipment were prepared and presented in a number of the IEEE Committee Reports [1-4]. In general a component is a piece of equipment or a group of items which is viewed as an entity and is not sub-divided during reliability analysis. The main generating components are the boiler installation (single or multiple), common header system, turbine, generator, and boiler. Transmission lines and transformers are considered as the main transmission components. The other components are either considered as associated with or external to the major components. A number of factors determine when a detailed component model is needed in a reliability analysis. The size and structure of the network are two important factors. Power system cost-effectiveness, security, adequacy, and reliability analyses have evolved over the years from mere theoretical topics of limited interest to a vital branch in utility business during the current competitive market, tight economy and the "do the best with what you have" concept [5-8].

The novel technique utilizes a basic linear programming formulation, which offers a general and comprehensive framework to assess the harmony and compatibility of generation and demand in a power system. Using the developed methodology, integrated system reliability evaluation and quality assessment can be performed globally on the whole system or locally on parts of the power grid. It can be applied to the system under normal operation or subject to contingencies with certain or random occurrences [9-11].The methodology presented in this paper has been implemented in the form of efficient computerized algorithms which analyze the network structure, generation and load balance and evaluate various composite system performance quality indices such as the generation shortfalls capacity index. The investigated reliability and quality measurements are not only useful for the design of flexible power supply reliability for various customers but also beneficial to the long-term system capacity expansion planning of electric power systems [12-17].The current work constitutes a new research in system reliability assessment where the derived system-wide performance quality indices are capable of addressing and revealing areas of shortfall and bottlenecks as well as redundancies in the composite generation-demand structure of large-scale power grids.

II. POWER SYSTEM QUALITY ASSESSMENT

A. Performance Quality Framework

The novel framework applied in this paper is based on [18], in which three metaphors (dimensions) were introduced to represent the relationship between a certain system generation capacity and the demand. These metaphors 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

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The first dimension defines whether or not the capacity is needed, the second defines whether or not it exists, and the last one defines whether or not it can satisfy the demand. The eight possible combinations associated with the 0/1 (Yes/No) values of the three dimensions would, in turn, define a set of powerful system-wide performance quality measures, namely:

- Utilized: A given capacity is said to be utilized if it is needed (for demand fulfillment), if it exists, can if it can reach the demand.

- Bottled: A given capacity is said to be bottled if it is needed (for demand fulfillment) and exists, but cannot reach the demand.

- Shortfall: A given capacity is said to be shortfall if it is needed (for demand fulfillment) and, anyhow, does not exist and can reach the demand.

- Deficit: A given capacity is said to be deficit if it is needed (for demand fulfillment) but, however, does not exist and cannot reach the demand.

- Surplus: A given capacity is said to be surplus if it is not needed (for demand fulfillment) although it exists and can reach the demand.

- Redundant: A given capacity is said to be redundant if it is not needed although it exists but, anyhow, cannot reach the demand.

- Spared: A given capacity is said to be spared if it is not needed and, anyhow, does not exist although it can reach the demand.

- Saved: A given capacity is said to be saved if it is not needed and, anyhow, does not exist and cannot reach the demand.

We note here that the above performance quality measures are associated with different combinations (topples) of the three quality dimensions, namely, "existence", "need" and "ability to reach the demand". The corresponding quality state of a given capacity can be represented by a three-value expression of either a "Yes/No" or "1/0" type indicating the true/false value associated with each quality metaphor. The evaluation of the above quality indices requires the knowledge of the following data types for the demand and various system facilities:

- The value of the demand required to be supplied.

- The value of generation capacity as well as the maximum site capacity (the limit of potential increase in existing generation capacity).

- The value of transmission capacity.

- The linear program formulation.

In the computational scheme of [18], the integrated system quality assessment is performed via solving a master linear programming problem [19] in which a feasible power flow is established which minimizes the total system non-served load subject to capacity limits and flow equations. The master linear program, which utilizes the network bus incidence matrix $\mathbf{A}$, is formulated as:

$$\text{Minimize} \quad f = \sum_{l=1}^{n_L} \left(-P_l \right)$$

$$\text{with respect to} \quad \mathbf{P}_L, \ \mathbf{P}_G \ \text{and} \ \mathbf{P}_T$$

$$\text{such that}$$

$$\mathbf{A} \ \mathbf{P}_T = \begin{bmatrix} -\mathbf{P}_L \\ \mathbf{P}_G \end{bmatrix}$$

$$\mathbf{P}_L \leq \overline{\mathbf{P}}_L, \ -\mathbf{P}_L \leq \mathbf{0}$$

$$\mathbf{P}_G \leq \overline{\mathbf{P}}_G, \ -\mathbf{P}_G \leq \mathbf{0}$$

$$\mathbf{P}_T \leq \overline{\mathbf{P}}_T, \ -\mathbf{P}_T \leq \overline{\mathbf{P}}_T$$

$$(1)$$

In the above master linear program, $\overline{\mathbf{P}}_T$ is the vector of n_T elements representing transmission branch capacities, $\overline{\mathbf{P}}_L$ is the vector of n_L elements of peak bus loads, and $\overline{\mathbf{P}}_G$ is the vector of n_G elements representing generator capacities.

Also, in the above master linear program (1), $\mathbf{P}_L$, $\mathbf{P}_G$, and $\mathbf{P}_T$ are n_L, n_G and n_T column vectors representing the actual load bus powers (measured outward), generator bus powers (measured inwards), and transmission line powers (measured as per the network bus incidence matrix $\mathbf{A}$) respectively. The solution of the above linear program provides a more realistic (less conservative) flow pattern in view of the fact that when the load curtailments are anticipated, all system generation resources would be re-dispatched in a way which minimizes such load cuts. The feasible flow pattern established from the master linear program is then used to evaluate various integrated system quality indices through a set of closely related sub-problems.

B. Implementation Mechanisms

For real life power systems with practical sizes, the quality indices cannot be evaluated by inspection. An appropriate computerized scheme is needed in order to properly evaluate various quality indices according to their stated definitions. The master linear program presented before forms the base for analyzing and evaluating quality indices, for example the Load Supply Reliability can be evaluated as follows:

LNS_l=Load Not-Served at Load Bus (l)= $\overline{P}_l - P_l^{(1)}$

LNS= Total System Load Not-Served= $\sum_{l=1}^{n_L} \overline{P}_l - P_l^{(1)}$

where the bus loads at the solution of the master linear program are termed as $P_l^{(1)}$, and P_l denotes the solution load value at bus (l).

On the other hand, 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 dimension. 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 <*x*> will be used to denote *Max* {0, *x*}, that is the maximum of *x* and zero (= *x* if *x*> 0, or 0 otherwise). For example, the Utilized Generation Capacity index ($Q_g 111 \equiv \{needed, exists, can reach\}$) is given by:

$$Q_g 111 = \sum_{l=1}^{n_L} P_l^{(1)} \qquad (2)$$

The Bottled Generation Capacity index($Q_g 110 \equiv \{needed, exists, cannot reach\}$) is given by:

$$Q_g 110 = min\{[\sum_{l=1}^{n_L} \overline{P}_l - \sum_{g=1}^{n_G} P_g^{(1)}], [\sum_{i=1}^{n_G} Max\{0, (\overline{P}_g - P_g^{(1)})\}]\}(3)$$

The Surplus Generation Capacity ($Q_g 011 \equiv \{not\ needed, exists, can\ reach\}$) is calculated as:

$$Q_g 011 = Min\{[Max\ \{0, (\sum_{g=1}^{n_G} \overline{P}_g - \sum_{l=1}^{n_L} \overline{P}_l)\}], [Max\{0, (\sum_{g=1}^{n_G} P_g - \sum_{l=1}^{n_L} \overline{P}_l)\}]\}(4)$$

where the generation output values P_g are calculated at the solution of the linear program with open limits on the loads.

The above reliability and quality indices (2)-(4)only require knowing the available generation capacity and the value of required demand. On the other hand, to evaluate the energy shortfall index depends on the inspection of the capacity of transmission lines along with knowing the available generation capacity and the required demand. Therefore, the S*hortfall Generation Capacity* index ($Q_g 101 \equiv \{needed, does\ not\ exist, reach\}$) is given by:

$$Q_g 101 = 0 \quad, where \sum_{l=1}^{n_l} \overline{P}_l \le \sum_{g=1}^{n_G} \overline{P}_g \qquad (5)$$

$$Q_g 101 = Min \begin{cases} \sum_{g=1}^{n_G} \overline{P}_g - \sum_{g=1}^{n_G} \overline{\overline{P}}_g \\ \sum_{t=1}^{n_T} \overline{P}_t - \sum_{t=1}^{n_T} P_t \\ \sum_{l=1}^{n_L} \overline{P}_l - \sum_{l=1}^{n_L} P_l \end{cases}, where \begin{cases} \sum_{l=1}^{n_L} \overline{P}_l > \sum_{g=1}^{n_G} \overline{P}_g \\ \sum_{g=1}^{n_g} \overline{P}_g - \sum_{g=1}^{n_G} P_g = 0 \end{cases}(6)$$

$$Q_g 101 = 0 \quad, where \sum_{g=1}^{n_G} \overline{P}_g \le \sum_{t=1}^{n_T} \overline{P}_t \qquad (7)$$

$$Q_g 101 = Min \begin{cases} \sum_{t=1}^{n_T} \overline{P}_t - \sum_{g=1}^{n_G} \overline{P}_g \\ \sum_{l=1}^{n_L} \overline{P}_l - \sum_{g=1}^{n_G} \overline{P}_g \end{cases},$$

$$where \begin{cases} \sum_{l=1}^{n_L} \overline{P}_l > \sum_{g=1}^{n_G} \overline{P}_g \\ \sum_{g=1}^{n_g} \overline{P}_g - \sum_{g=1}^{n_G} P_g \ne 0 \\ [\sum_{l=1}^{n_L} \overline{P}_l - \sum_{g=1}^{n_G} \overline{P}_g] \le [\sum_{g=1}^{n_G} \overline{P}_g - \sum_{g=1}^{n_G} \overline{P}_g] \\ \sum_{g=1}^{n_g} \overline{P}_g \le \sum_{t=1}^{n_T} \overline{P}_t \end{cases} \qquad (8)$$

$$Q_g 101 = 0, where \begin{cases} \sum_{l=1}^{n_L} \overline{P}_l > \sum_{g=1}^{n_G} \overline{P}_g \\ \sum_{g=1}^{n_g} \overline{P}_g - \sum_{g=1}^{n_G} P_g \ne 0 \\ [\sum_{l=1}^{n_L} \overline{P}_l - \sum_{g=1}^{n_G} \overline{P}_g] \le [\sum_{g=1}^{n_G} \overline{\overline{P}}_g - \sum_{g=1}^{n_G} \overline{P}_g] \\ \sum_{g=1}^{n_g} \overline{P}_g > \sum_{t=1}^{n_T} \overline{P}_t \end{cases} \qquad (9)$$

$$Q_g 101 = Min \begin{cases} \sum_{t=1}^{n_T} \overline{P}_t - \sum_{g=1}^{n_G} \overline{P}_g \\ \sum_{g=1}^{n_G} \overline{P}_g - \sum_{g=1}^{n_G} \overline{P}_g \end{cases},$$

$$where \begin{cases} \sum_{l=1}^{n_L} \overline{P}_l > \sum_{g=1}^{n_G} \overline{P}_g \\ \sum_{g=1}^{n_g} \overline{P}_g - \sum_{g=1}^{n_G} P_g \ne 0 \\ [\sum_{l=1}^{n_L} \overline{P}_l - \sum_{g=1}^{n_G} \overline{P}_g] > [\sum_{g=1}^{n_G} \overline{P}_g - \sum_{g=1}^{n_G} \overline{P}_g] \\ \sum_{g=1}^{n_g} \overline{P}_g \le \sum_{t=1}^{n_T} \overline{P}_t \end{cases} \qquad (10)$$

where:

$\overline{P}_l$ = Required value of the load. P_l = Actual value of the load.

$\overline{\overline{P}}_g$ = Sit capacity of generation. $\overline{P}_g$ = Available capacity of generation.
P_g = Actual capacity of generation. $\overline{P}_g$ = Available capacity of generation.
P_g = Actual capacity of generation. $\overline{P}_t$ = Capacity of transmission lines.
P_t = Actual flow in transmission lines.

III. EXAMPLE OF QUALITY ANDRELIABILITYDIMENSIONS

Consider the 4-bus system of Figure 1. All load, flow and capacity values are in MW. Note that the generation and transmission element capacities shown in Figure 1 are for illustration purposes only and may not reflect the actual element values. For this simple system, the quality and reliability indices can be evaluated as shown in Table I.
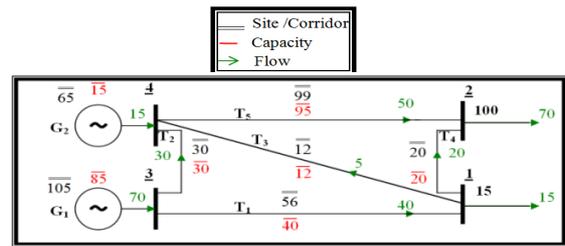
Fig. 1. A 4-bus sample power system

TABLE I. QUALITY AND RELIABILITY INDICESFOR THE SAMPLE SYSTEM

Index	$Q_g 111$	$Q_g 110$	$Q_g 101$	$Q_g 011$	*LNS*
Value	85	15	15	0	30

IV. APPLICATIONS TO SEC POWER SYSTEM

In a recently completed industry supported study, applications were conducted on a practical power system comprising of a portion of the interconnected Saudi power grid. The power system consists of two main regions, namely the Central region and the Eastern region. The two systems are interconnected through two 380kV and one 230kV double-circuit lines. One zone is identified in the present analysis, Hail zone. In this application, four reliability and quality performance indices were considered, namely the system Load Not-Served (*LNS*), Utilized Generation Capacity ($Q_g 111$), the Bottled Generation Capacity ($Q_g 110$), and the Shortfall Generation Capacity ($Q_g 101$).The system model used for Hail network zone is shown in Figure 2. Table II outlines the network data in terms of generation and transmission facilities as well as system loads. Figures 3 and 4 summarize the results of the reliability and performance quality measures applied to the Hail network power system for various system status (isolated or connected) of the Hail zone. In particular, Figures 3-4, depict the variation of the variation of quality indices ($Q_g 111$, $Q_g 110$, and $Q_g 101$) with the required load level of the Hail isolated and interconnected network respectively. The results reveal several important observations. For example, the obtained results for the isolated network scenario of Hail zone (Figure 3) show that the shortfall Generation Capacity ($Q_g 101$) is non-zero even for relatively low generation levels as it decreases continuously from 350MW to reach 0MW when the generation level is 653MW. This problem is clearly mitigated in the interconnected network scenario of Hail zone (Figure 4), where generation support from Qassim zone becomes available.
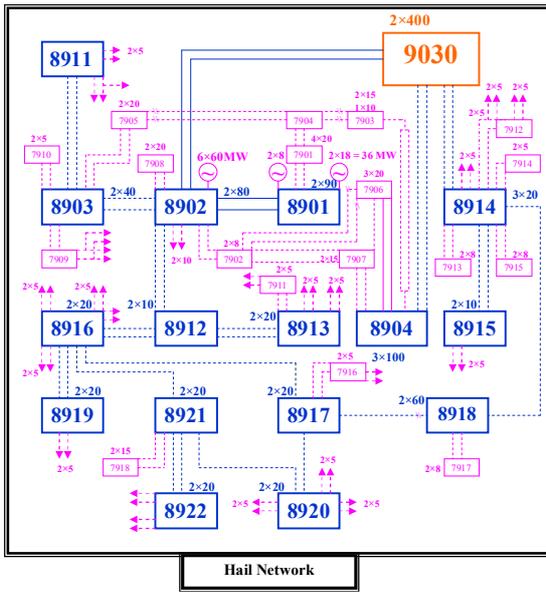
Fig. 2.   Single-line diagram of SEC – Hail zone

TABLE II.   GENERATION, TRANSMISSION AND LOADS OF HAIL NETWORK

state		Isolated	Interconnected
Generators	value	593.63	1393.6
	number	9	10
Transmissions	number	68	69
Loads	value	655.3	655.3
	number	46	46
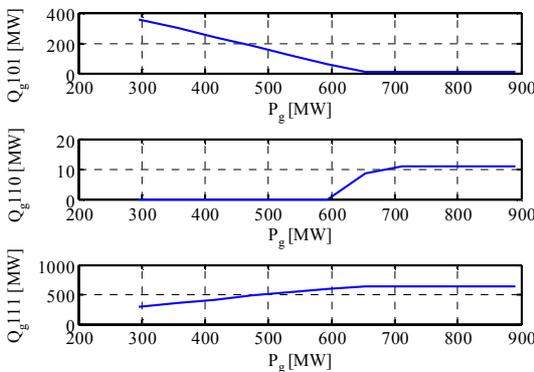
Fig. 3.   Variation of Q_g111, Q_g110 and Q_g101 with the variation of available generator capacity levels of the Hail interconnected network

Bottled Generation Capacity (Q_g110) stays at zero value for all available generation capacity levels up to 594MW where it starts to increase slowly to reach saturation, due to limitations of transmission lines, at about 11MW when the available generation capacity level is 653MW. It is also noted from Figure 3 that the Utilized Generation Capacity (Q_g111) starts at 300MW and increases continuously with the available generation capacity levels until it saturates at 644MW when the available generation capacity is 653MW. For the Hail interconnected network the results of Figure 4 show that the Bottled Generation Capacity (Q_g110) remains at zero value for all available generation capacity levels (supplied fully). On the

same regard, the Utilized Generation Capacity (Q_g111) stays constant (nominal load) for all available generation capacity levels.
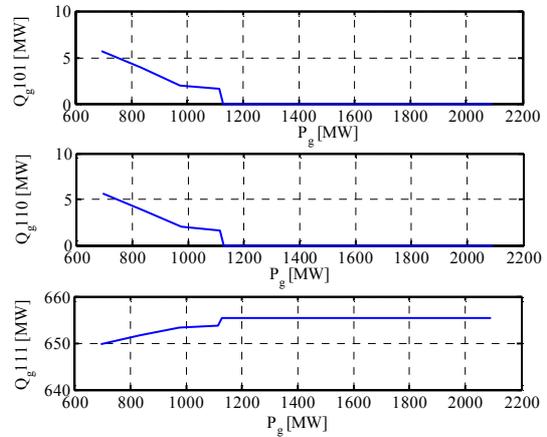
Fig. 4.   Variation of Q_g111, Q_g110 and Q_g101 with the variation of available generator capacity levels of the Hail isolated network

V.   CONCLUSIONS

This paper presents a major extension to a previously published work by developing a theory and formulas for computing the expected values of different system reliability and performance quality indices. The reliability and performance quality indices, when evaluated at a given load level and a certain scenario of available generation and transmission capacities, would provide indications on system performance only for such a particular system condition (snapshot). Based on the solution of the basic linear program described in this paper, a more realistic (less conservative) flow pattern can be established. The more realistic nature of such a flow pattern comes from the fact that when the load curtailments are anticipated, all system generation resources would be re-dispatched in a way which minimizes such load cuts. This work constitutes a new line of research in system reliability assessment where the derived system-wide performance quality indices are capable of addressing and revealing areas of shortfall and bottlenecks as well as redundancies in the composite generation-demand structure of large-scale power grids. Examples of such very important quality measures is the Shortfall Generation Capacity(Q_g101), which is needed(for demand fulfillment) and, anyhow, does not exist and can reach the demand. The practical applications presented in the paper have demonstrated the powerful features of the adopted approach and its suitability for large-scale system implementations. The, under investigation, Hail network contains 10 generators, 69 branches (transmission lines, underground cables, and power transformers), and 46 loads.

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