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Assessment of Performance Measures of Large-Scale Power Systems

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Abstract**—**In a recent major industry-supported research and development study, a novel framework was developed and applied for assessment of reliability and quality performance levels in real-life power systems with practical large-scale sizes. The new assessment methodology is based on three metaphors (dimensions) representing the relationship between available generation capacities and required demand levels. The paper shares the results of the successfully completed stud and describes the implementation of the new methodology on practical zones in the Saudi electricity system.

Keywords**—**Power systems; Large-scale analysis, Reliability; Performance assessment, Linear programming

I. INTRODUCTION

THE electric power utilities have a key mandate to maintain a continuous and sufficient power supply to the customers at a reasonable cost. Power system cost-effectiveness, security, adequacy and reliability analyses have evolved over the years from mere theoretical topics of limited interest, during the era of generous economy and abundant supply and facilities, to a vital branch in today's highly-competitive business environment of power utility planning and operations [1-4]. In response to the growing interest in system security and reliability by power utilities, several schools of thought have evolved with the associated pioneering research aimed at conducting the security and reliability assessment in an efficient, accurate manner and with as much realization of the business nature and practical circumstances of the power utility as possible.

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 [5,6].

This paper summarizes the results of a recent major industry-supported research and development study in which a novel framework was developed and applied.

The new methodology is used for assessment of reliability and quality performance levels in real-life power systems with practical large-scale sizes. The new assessment methodology is based on three metaphors (dimensions) representing the relationship between available generation capacities and required demand levels. 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 portions in the power grid. It can be applied to the system under normal operation or subject to contingencies with certain or random occurrences [7-10]. The methodology presented in this paper has been implemented in an efficient computerized algorithm which analyzes the network structure, generation and load balance and evaluates various composite system performance quality indices. Practical applications to large-scale portions of the Saudi power grid are also presented in the paper for demonstration purposes.

II. BASIC FORMULATION

A. Power System Network Model

Let n_B = number of buses in the power network, where $n_B = n_L + n_G$, n_L and n_G = number of load and generator buses, respectively. Also, in the network model used, n_T = number of transmission branches (lines and transformers). In order to facilitate 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 Fig. 1 has $n_B = 4$, $n_G = 2$, $n_L = 2$ and $n_T = 5$.

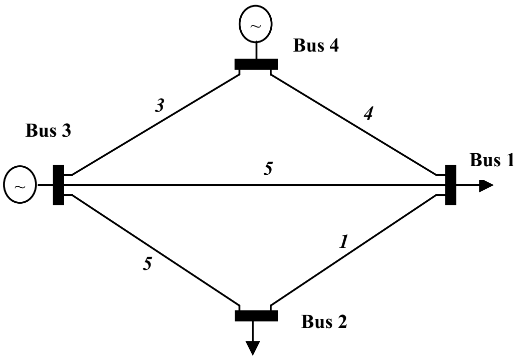

Fig. 1 A sample power system

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Now, let $\mathbf{A} = (n_B \times n_T)$ be the bus incidence matrix representing the connectivity pattern between buses and lines. The entries of **A** are either 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, otherwise $A_{bt} = 0$. In the current analysis, the **A**-Matrix is partitioned row-wise into $\mathbf{A}_L$ and $\mathbf{A}_G$ associated, respectively, with load and generator buses. The rows of **A** (or columns of $\mathbf{A}^T$) represent groups of buses while the columns of **A** (or rows of $\mathbf{A}^T$) represent groups of transmission links. We also note that for practical large-scale networks, the matrix **A** is extremely sparse.

B. Performance Assessment

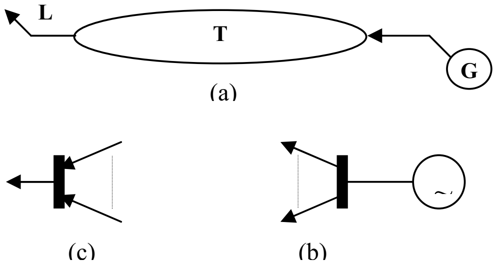
Although the basic definitions pertaining to system performance quality are simple to state and often seem intuitive at first glance, a great deal of care should be exercised in order to recognize some subtle differences in the definition and formulation of the composite performance quality indices. Let,

$\overline{\mathbf{P}}_T$ = vector of n_T elements representing transmission branch capacities

$\overline{\mathbf{P}}_L$ = vector of n_L elements of peak bus loads

$\overline{\mathbf{P}}_G$ = vector of n_G elements representing generator capacities $\overline{P}_g$

For simplicity of notation, we shall use $\overline{\mathbf{P}}_t$ to denote a general element t of the vector $\overline{\mathbf{P}}_T$(rather than the more strict notation of $\overline{\mathbf{P}}_{Tt}$). Similarly, we shall use $\overline{P}_l$ and $\overline{P}_g$ to denote general elements of $\overline{\mathbf{P}}_L$ and $\overline{\mathbf{P}}_G$ respectively. However, when confusion may occur, we will use the strict notation of $\overline{\mathbf{P}}_{Ti}$, $\overline{\mathbf{P}}_{Li}$ and $\overline{\mathbf{P}}_{Gi}$. Now consider the schematic configurations of Fig. 2, which depicts the transfer connectivity between generation through transmission to load.



(a)

(c) (b)

Fig. 2 G-T-L transfer connectivity

If, for example the local generation capacity $\overline{P}_g$ at bus g exceeds the corresponding transmission capability $\sum_{t \varepsilon T_g} \overline{P}_t$ in Fig. 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 $(\overline{P}_g - \sum_{t \varepsilon T_g} \overline{P}_t)$ 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

$\overline{\overline{\mathbf{P}}}_G$ = Vector of generation ***site*** capacities, which represents the maximum future expanded generation capacity that could be available at the same generation site.

C. Linear Programming Formulation

All tables and figures you insert in your document are only to help you gauge the size of your paper, for the convenience of the referees, and to make it easy for you to distribute preprints. In the proposed scheme, the integrated system quality assessment is performed via solving a master linear programming problem [11] 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 **A**, is formulated as

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

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

such that

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

$$\mathbf{P}_L \le \overline{\mathbf{P}}_L,\ -\mathbf{P}_L \le \mathbf{0}$$
$$\mathbf{P}_G \le \overline{\mathbf{P}}_G,\ -\mathbf{P}_G \le \mathbf{0}$$
$$\mathbf{P}_T \le \overline{\mathbf{P}}_T,\ -\mathbf{P}_T \le \overline{\mathbf{P}}_T$$

In the master linear program, $\mathbf{P}_L$, $\mathbf{P}_G$, 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 **A**), respectively. The solution of the above linear program provides a more realistic (less conservative) flow pattern in view of the fact that when load curtailments are anticipated, all system generation resources would be re-dispatched in such 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. For example, a sub-problem may be defined to evaluate the total system loss of load subject to a given contingency scenario. In this case, the sum of all elements of the $\mathbf{P}_L$ vector is subtracted from the total nominal system load. The resulting amount, if positive, would constitute the total system loss of load (Load Not-Served).

III. PERFORMANCE QUALITY METAPHORS

A. Conceptual Framework

As was indicated before, the novel framework presented in this paper is based on three metaphors (dimensions) representing the relationship between certain system generation capacity and the demand. These metaphors are illustrated in Table 1, and relate to the following demand fulfillment issues:

a) ***Need*** of capacity for demand fulfillment
b) ***Existence*** of capacity (availability for demand fulfillment)
c) Ability of capacity to ***reach*** the demand

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

1) *Utilized:* A given capacity is said to be *utilized* if it is *needed* (for demand fulfillment), *exists*, and *can reach* the demand.
2) *Bottled:* A given capacity is said to be *bottled* if it is *needed* (for demand fulfillment) and *exists*, but *cannot reach* the demand.
3) *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.
4) *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.
5) *Surplus:* A given capacity is said to be *surplus* if it is *not needed* (for demand fulfillment) although *exists* and *can reach* the demand.
6) *Redundant:* A given capacity is said to be *redundant* if it is *not needed* (for Demand fulfillment) although *exists* but, anyhow, *cannot reach* the demand.
7) *Spared:* A given capacity is said to be *spared* if it is *not needed* (for demand fulfillment) and, anyhow, *does not exist* although *can reach* the demand.
8) *Saved:* A given capacity is said to be *saved* if it is *no needed* (for demand fulfillment) 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 metaphors, namely, "existence", "need" and "ability to reach the demand". The corresponding quality state of a given capacity can be represented, as demonstrated in Table 1, by a three-value expression of either a "Yes/No" or "1/0" type indicating the true/false value associated with each quality metaphor.

TABLE I
ILLUSTRATION OF QUALITY ASSESSMENT METAPHORS

#	Quality Measure	Quality State			Quality Metaphor of a Capacity		
		N	*E*	*R*	*(N) Needed?*	*(E) Exists?*	*(R) Can Reach?*
1	**Utilized**	1	1	1	Yes	Yes	Yes
2	**Bottled**	1	1	0	Yes	Yes	No
3	**Shortfall**	1	0	1	Yes	No	Yes
4	**Deficit**	1	0	0	Yes	No	No
5	**Surplus**	0	1	1	No	Yes	Yes
6	**Redundant**	0	1	0	No	Yes	No
7	**Spared**	0	0	1	No	No	Yes
8	**Saved**	0	0	0	No	No	No

As will be demonstrated later, the evaluation of the above quality indices requires the knowledge of the following data types for the demand and various system facilities:

a) The value of demand required to be supplied
b) The value of generation capacity as well as the maximum site capacity (the limit of potential increase in existing generation capacity)
c) The value of transmission capacity.

B. Illustrative Example of Quality Metaphors

As a simple illustrative example, consider the sample 2-bus system of Fig. 3, where a demand (load) of 50 (per-unit) is supplied by a generating facility having an available capacity of 70 (per-unit) and a site capacity of 90 (per-unit). The load is supplied through a transmission facility having an available capacity of 40 (per-unit) and a route capacity of 100 (per-unit). For this simple system, the quality indices can be easily evaluated by inspection as shown in Table 2. In order to facilitate understanding of the meaning of the different quality indices and ensure correct interpretation of their definitions, Appendix I contains a complete list of the quality indices for many case scenarios involving different values of required load supply level as well as generation and generation capacities.

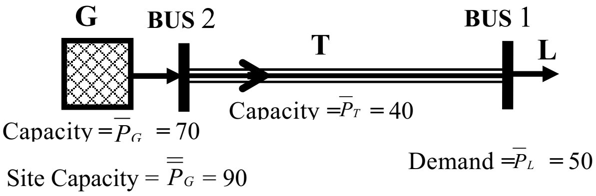


Fig. 3 A 2-Bus sample power system

TABLE II
QUALITY INDICES FOR 2-BUS SAMPLE SYSTEM

$\overline{P}_G$	$\overline{P}_T$	$\overline{P}_L$	$\overline{\overline{P}}_G$	$\overline{\overline{P}}_T$	LNS	***(Needed, Exists, Can-reach)***							
						000	**001**	**010**	**011**	**100**	**101**	**110**	**111**
70	40	50	90	100	10	40	10	0	0	0	20	0	20

C. Implementation on Large-Scale Systems

For real life power systems with practical sizes, the quality indices cannot be evaluated by inspection as was done in the previous illustrative example. 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 bases for analyzing and evaluating the quality indices. For example, the *Load Supply Reliability* can be evaluated as follows:

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

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 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 <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 is given by

Q_g111 = Utilized Capacity ≡ {*needed, exists*, *can reach*}

$$= \sum_{l=1}^{n_L} \left(P_l^{(1)}\right)$$

Similarly, the *Bottled Generation Capacity* index is given by

Qg110 = Bottled Capacity ≡ {needed, exists, cannot reach}

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

Also, the Surplus Generation Capacity (Q_g011) is calculated as

Q_g011 = Surplus Capacity ≡ {*not needed, exists*, *can reach*}

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

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

IV. PRACTICAL APPLICATIONS

A. Saudi Electricity System

The newly developed methodology for power system performance quality assessment has been applied to a practical power system comprising 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 380 kV and one 230 kV double-circuit lines. The system model used in the current application is shown in Fig. 4.

Four zones are identified in the present analysis, three in the Central region (Riyadh, Qassim and Hail zones) and one in the Eastern region. In this application, three reliability and quality performance indices are considered, namely the system Load Not-Served (*LNS*), Utilized Generation Capacity (Q_g111) and the Bottled Generation Capacity (Q_g110).

B. Performance Quality Measures of SEC System

Table 3 outlines the network data in terms of generation and transmission facilities as well as system loads. Fig. 5 to Fig. 8, on the other hand, summarize the results of the performance quality measures applied to the SEC power system for various system status (isolated or connected) of each zone, as well as generation availability and demand levels. In particular, Fig. 5a and Fig. 5b depict the variation of the variation of quality indices (LNS, Qg111 and Qg110) with the required load level of the Qassim isolated and interconnected network, respectively. Also, Fig. 6a and Fig. depict, respectively, the variation of the variation of quality indices (LNS, Qg111 and Qg110) with the required load level of the Riyadh isolated and interconnected network. Fig. 7a and Fig. 7b show.3-dimensional graphs depicting the variation of Utilized Generation Capacity index Qg111 with both load and generation capacity levels of the Hail isolated and interconnected network, respectively.

Similarly, Fig. 8a and Fig. 8b show.3-dimensional graphs depicting the variation of Utilized Generation Capacity index Qg111 with both load and generation capacity levels of the Riyadh isolated and interconnected network, respectively. Finally, Fig. 9a and Fig. 9b show.3-dimensional graphs depicting the variation of the Load Not-Served index LNS with both load and generation capacity levels of the Hail isolated and interconnected network, respectively. Finally,

The results obtained reveal several important observations. For example, the results obtained for the isolated network scenario of Qassim zone (Fig. 5a) show that the Load Not-Served is non-zero even for relatively low demand levels as it increases continuously from 300 MW at a demand level of 1,840 MW to reach 2,400 MW when the demand level is 4,410 MW. This problem is clearly mitigated in the interconnected network scenario of Qassim zone (Fig. 5b), where generation support from Riyadh zone becomes available. In this case, the Load Not-Served stays at zero value for all demand levels up to 2,620 MW where it starts to increase slowly to reach 70 MW at a demand level of 3,370 MW before it starts to increase sharply afterwards to reach about 2,000 MW at a demand level of 5,610 MW.

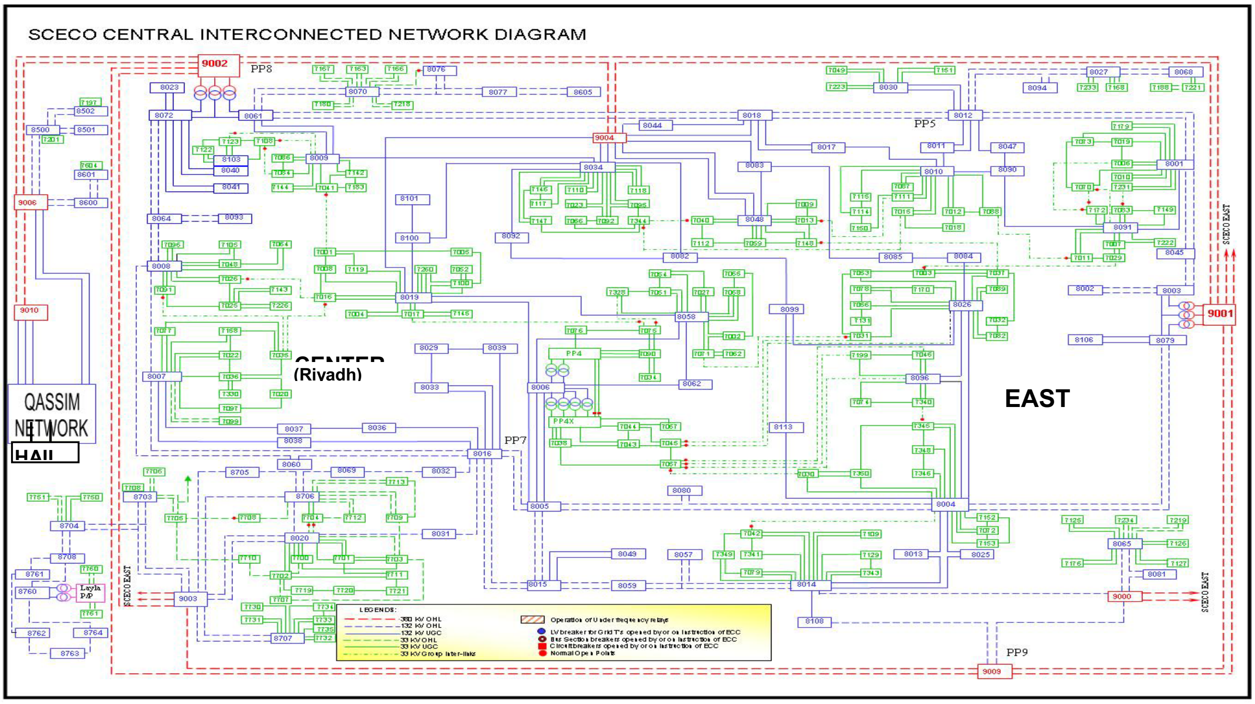


Fig. 4a Single-line diagram of SEC system

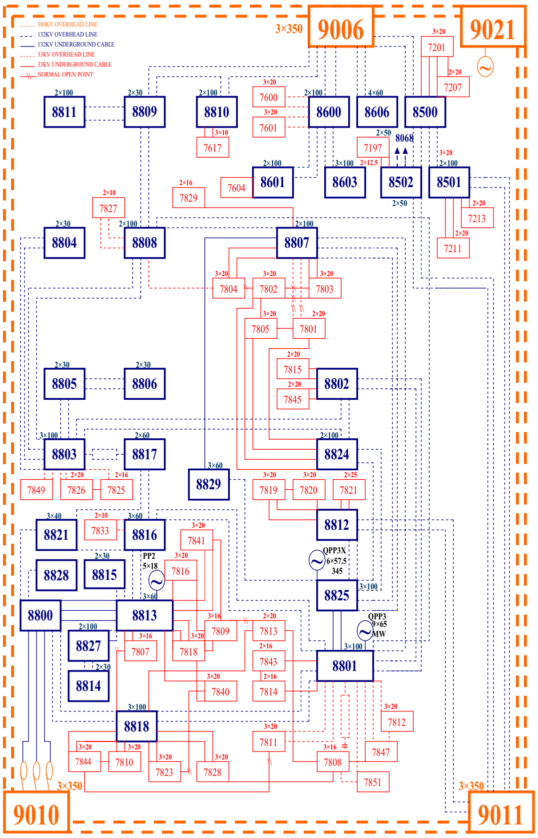


Fig. 4b Single-line diagram of SEC – Qassim

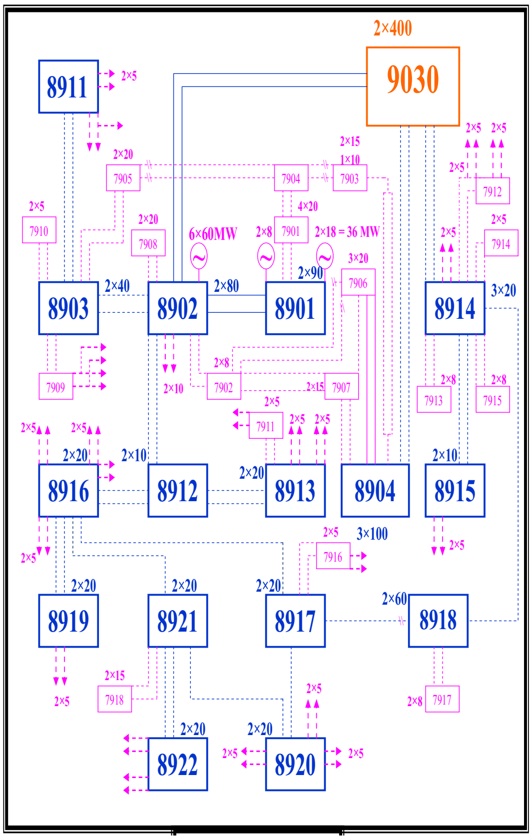


Fig. 4c Single-line diagram of SEC –Hail zone

TABLE III
GENERATION, TRANSMISSION AND LOADS OF SEC POWER SYSTEM

Network	*State*	*Generators*		*Transmissions*	*Loads*	
		Value	*Number*	*Number*	*Value*	*Number*
Hail	*Isolated*	593.6395	9	68	655.3934	46
	Interconnected	1393.6395	10	69	655.3934	46
Qassim	*Isolated*	2008.0355	21	116	3679.4002	76
	Interconnected	4108.0355	24	121	3741.1541	78
Riyadh	*Isolated*	10822.6411	108	577	10351.18	368
	Interconnected	13972.6411	111	577	12036.8322	366

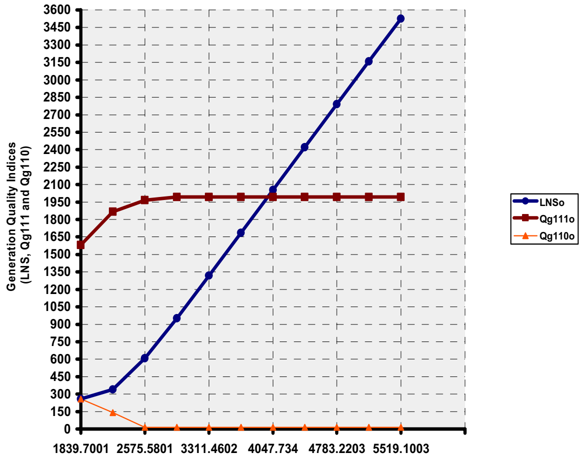


Fig. 5a Variation of Quality Indices (LNS, Qg111 and Qg110) with the required load level of the Qassim isolated network

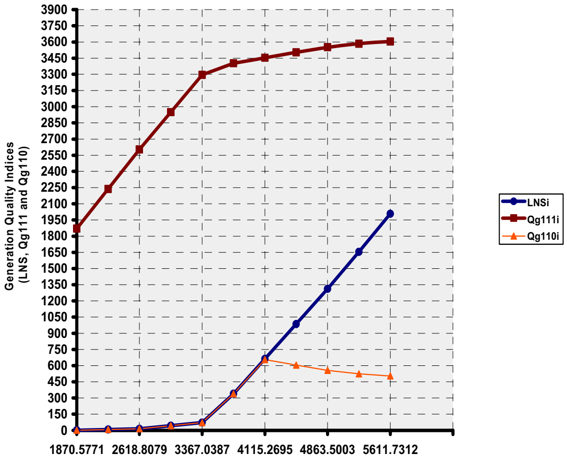


Fig. 5b Variation of Quality Indices (LNS, Qg111 and Qg110) with the required load level of the Qassim interconnected network

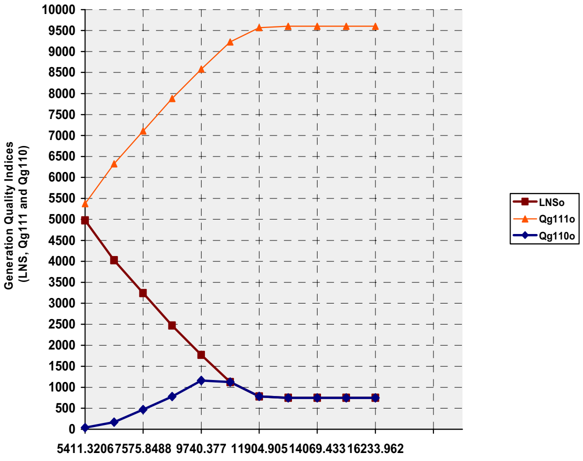


Fig. 6a Variation of Quality Indices (LNS, Qg111 and Qg110) with the available generation capacity level of the Riyadh isolated network

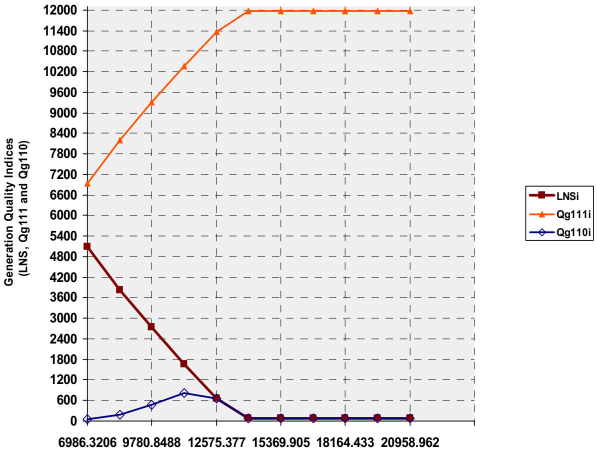


Fig. 6b Variation of Quality Indices (LNS, Qg111 and Qg110) with the available generation capacity level of the Riyadh interconnected network

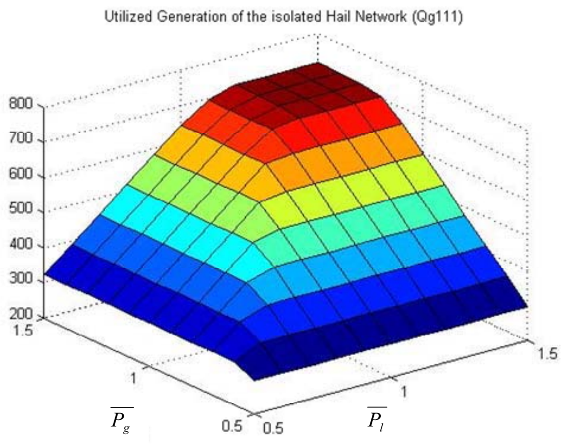


Fig. 7a 3-dimensional graph showing variation of Utilized Generation index Qg111 with both load and generation capacity levels of the Hail isolated network

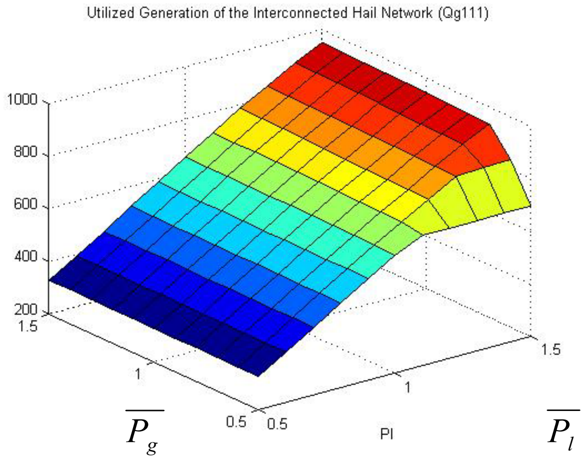


Fig. 7b 3-dimensional graph showing variation of Utilized Generation index Qg111 with both load and generation capacity levels of the Hail interconnected network

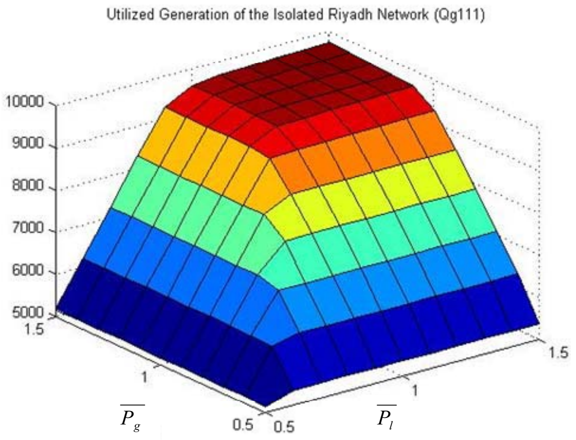


Fig. 8a 3-dimensional graph showing variation of Utilized Generation index Qg111 with both load and generation capacity levels of the Riyadh isolated network

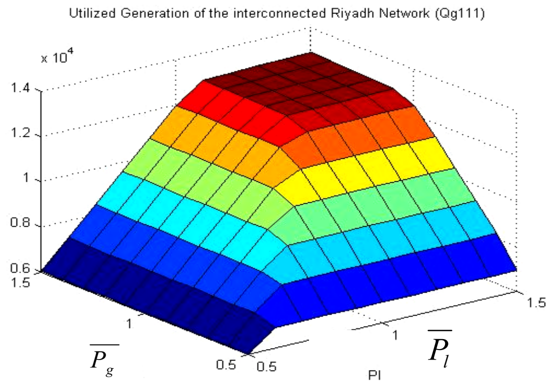


Fig. 8b 3-dimensional graph showing variation of Utilized Generation index Qg111 with both load and generation capacity levels of the Riyadh interconnected network

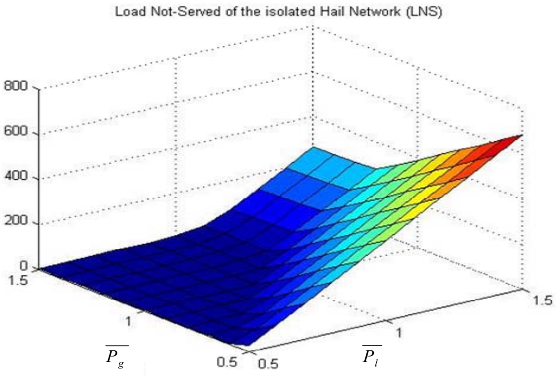


Fig. 9a 3-dimensional graph showing variation of Load Not Served index LNS with both load and generation capacity levels of the Hail isolated network

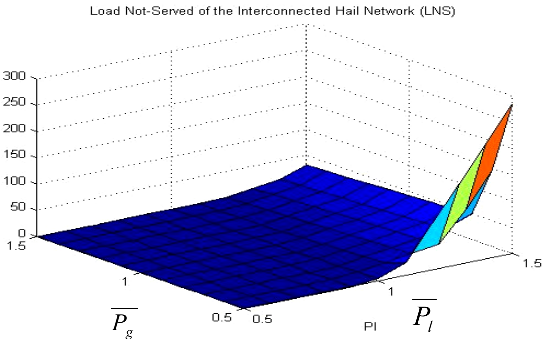


Fig. 9b 3-dimensional graph showing variation of Load Not-Served index LNS with both load and generation capacity levels of the Hail interconnected network

The Utilized Generation Capacity index Q_g111 for the isolated network scenario of Qassim zone (Fig. 5a) increases continuously with the required demand level until it saturates at about 2,000 MW when the required demand reaches 2,943 MW when no more available generation can be utilized. This situation is avoided – as expected – in the interconnected network scenario of Qassim zone (Fig. 5b) where the Utilized Generation Capacity increases continuously to reach, for example, 3,600 MW at demand level of 5,610 MW as more generation support becomes available. The Bottled Generation Capacity index Q_g110, for the isolated network scenario of Qassim zone (Fig. 5a), decreases continuously with the required demand until it disappears at a demand level of 2,575 MW. In the case of the interconnected network scenario of Qassim zone (Fig. 5b), however, the Bottled Generation Capacity coincides with the Load Not-Severed for all required demand levels up to 4,115 MW. After this level, the Bottled Generation Capacity starts to decrease continuously.

The results for the isolated network scenario of Riyadh zone (Fig. 6a) show that the Load Not-Served decreases continuously with the available generation capacity until it saturates at about 700 MW when the available generation capacity reaches 11,900 MW. The same pattern is observed in the case of the interconnected network scenario of Riyadh zone (Fig. 6b), except that the Load Not-Served would actually disappears at available generation capacity of 13,970 MW due to the strong support available to Riyadh from the Eastern zone where abundant generation resources are available. The Utilized Generation Capacity index Q_g111 for the isolated network scenario of Riyadh zone (Fig. 6a) increases continuously with the available generation capacity until it saturates at about 9,600 MW when the available generation capacity is 11,900 MW. Similar pattern is observed in the case of the interconnected network scenario of Riyadh zone (Fig. 6b) except that the Utilized Generation Capacity saturates at a higher level of 12,000 MW when the available generation capacity is 13,970 MW. The Bottled Generation Capacity index Q_g110, for the isolated network scenario of Riyadh zone (Fig. 6a), increases at first to reach about 1,200 MW at an available generation capacity level of 9,740 MW. Beyond this level, the Bottled Generation Capacity follows essentially the Load Not-Served pattern and saturates at 700 MW when the available generation capacity reaches 11,900 MW. The same situation is observed in the case of the interconnected network scenario of Riyadh zone (Fig. 6b) except that the Bottled Generation Capacity (along with the Load Not-Served) diminishes to zero value at an available generation capacity level of 13,970 MW.

V. CONCLUSIONS

This paper has presented the findings and results of a recent industry-supported study to assess the overall performance of power systems in terms of a pertinent set of reliability and quality measures. The new approach is based on three metaphors (need, existence of capacity and ability-to-reach 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 practical applications to large-scale portions of the Saudi power grid presented in the paper have demonstrated to powerful features of the newly developed approach for performance assessment of power systems.

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