Evaluation Framework of the Deficit and Reliability Quality Measures of the Transmission System

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Abstract-Power system planning faces various issues related to reliability and quality evaluation. The power system network planning is by nature a complex, huge-scale, and mixed-objective optimization problem, especially when concerning its non-linear behavior and the requirements of future unknown loads. In this regard, the electric power utilities attempt to maintain a balance between the generation energy, the transmission capacity, and the needed demand. The main purpose of the current paper is to utilize modern modeling techniques and computational procedures, including the advanced deficit transmission system evaluation method and sparse-matrix network analysis algorithms, in order to evaluate, with sufficient accuracy, the deficit and reliability levels in practical real-life large-scale power systems. The new evaluation methodology is based on three quantities representing the relationship between the generation push in the grid, the maximum limitation of the transmission capacity, and the needed load. The main contribution of the paper is assessing the deficit transmission system index with novel formulas.

Keywords-reliability evaluation; deficit index; transmission system; quality measures

I. INTRODUCTION

The main objective of electric power utilities is to maintain a continuous and sufficient power supply to customers at a reasonable cost [1]. Cost-effectiveness, security, adequacy, and reliability analyses of a power system have changed over the years to become a vital branch in today's highly competitive business environment of power utility planning and operations. Reliability and quality are considered two vital measures of power system planning and operational procedures. The engineers and utility technicians seek to design and synthesis a large-scale power system, they consider reliability as one of the key design factors [2-4]. Power system development and planning, which include an essential part of reliability and quality assessment, form a complex, large-scale, and multi-objective optimization problem [5, 6], which is related to nonlinear characteristics, future demand uncertainty requirements, and system component availability. The issues of reliability and quality evaluation have seen a growing interest in power system reliability and quality assessment by power utilities and engineers. Several authors were involved in the research aiming at conducting reliability and quality assessment in an efficient and accurate manner and with as much realization of the practical circumstances of the power utility as possible. In this regard, the reliability of an electric supply system is defined as the probability of providing the customers with continuous and satisfactory service.

Generation system reliability indices have been used as a standard for measuring system reliability in [7]. A model was proposed based on a convolutional algorithm that predicts how these indices vary as system annual peak increases. The proposed model was used to calculate and test the same indices of the Benghazi North Power Plant (BNPP) before and after installing additional capacity. A power system by nature is complex, therefore there are multiple random events at different stages of power systems such as uncertainty in customer demand, intermittent outages of power generators and its related units, intermittent electricity production and its impact on the adequacy assessment [8]. Therefore, probabilistic methods have given detailed and more realistic information about random events and their negative impact on power system supply and demand. In this direction, an analytical model of the inverse power system reliability evaluation problem was proposed and formulated to find the Unknown Component Reliability Parameter (UCRP) [9]. In addition, an application to power system planning was tested to examine the way the component reliability parameters can be modified quantitatively in order to achieve the desired system reliability improvement.

The main purpose of this paper is to utilize modern modeling techniques and computational procedures, and focus on the deficit transmission system evaluation method and

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sparse-matrix network analysis algorithms, in order to evaluate, with sufficient accuracy, the deficit and reliability levels in practical real-life large-scale power systems. The new evaluation methodology is based on three quantitative parameters of the power network, which are representing the relationship between generation push in the grid, the maximum limitation of the transmission capacity, and the needed load. The main contribution of the current paper is the assessment of the deficit transmission system index with novel formulas.

II. PROBLEM FORMULATION

A. Power System Network Model

The novel framework applied in this paper is based on the original work of [10], in which 3 dimensions were introduced to represent the relationship between certain system generation capacity and the demand. These dimensions relate to the following demand fulfilment issues:

- The need of capacity for demand fulfillment.
- The existence of capacity (availability for demand fulfillment).
- The ability of capacity to reach the demand.

The first dimension defines whether or not the capacity is needed, the second one defines whether or not the capacity exists, and the last one defines whether or not the capacity can reach (delivered to) the demand. The 8 possible combinations associated with the 0/1 (Yes/No) values of the 3 dimensions, are illustrated in Table I. The generation and transmission 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 index. 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 $\{0, x\}$, i.e. is the maximum of x and zero (= x if $x > 0$, or 0 otherwise). 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).

TABLE I. ILLUSTRATION OF QUALITY ASSESEMENT INDICES

	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

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

B. Linear Program Formulation

In the computational scheme of [10], 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:

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

The 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 a flowchart shown in Figure 1.

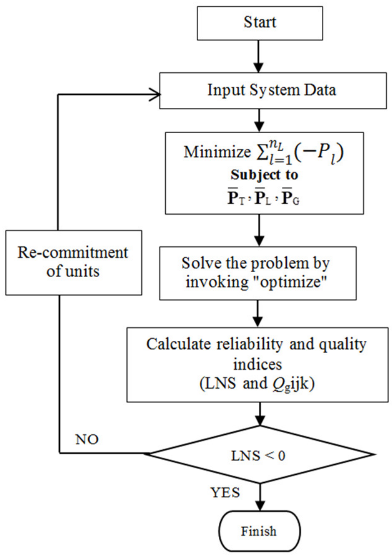

Fig. 1. Flow chart of the proposed methodology.

C. Application of Performance Quality Assessment

Consider the 3-bus sample power system in Figure 2, where a load of 130pu is supplied by two generators that have an available capacity of 170pu. The power system has three transmission lines having an available capacity of 60, 50, and 10pu respectively. For this simple system, the reliability and quality indices can be evaluated as shown in Table II. This paper concerns the indexes related with the deficit of the transmission system.

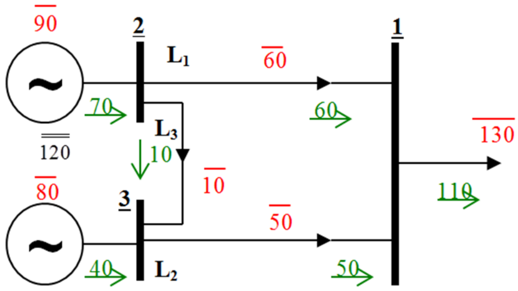

Fig. 2. The 3-bus sample power system.

TABLE II. RELIABILITY AND QUALITY INDICES FOR THE SAMPLE SYSTEM

Index	$Q111$	$Q110$	$Q101$	$Q100$	$Q011$	$Q010$	$Q001$	$Q000$
Value	110	0	0	20	0	0	0	35

D. *Large-Scale Implementation*

On [10], the formulation of 5 reliability and quality performance indices is considered, namely the Load Not-Served (LNS), Utilized Generation Capacity ($Qg111$), Bottled Generation Capacity ($Qg110$), Surplus Generation Capacity ($Qg011$), and Redundant Generation Capacity ($Qg010$) are presented while the current research work is concerned with the Deficit Transmission Capacity ($Qt100$) and new formulas are established as follows:

If: $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] \leq [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g = 0]$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] > [\sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t]$

$$\boldsymbol{Qt100} = [\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] - [\sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t] \quad (2)$$

If: $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] \leq [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g \neq 0]$ and $\sum_{g=1}^{n_G}\overline{P_g} \leq \sum_{t=1}^{n_T}\overline{P_t}$ and $\sum_{l=1}^{n_L}\overline{P_l} \leq \sum_{g=1}^{n_G}\overline{P_g}$

$$\boldsymbol{Qt100} = \sum_{l=1}^{n_L}\overline{P_l} - \sum_{t=1}^{n_T}\overline{P_t} \quad (3)$$

If: $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] \leq [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g \neq 0]$ and $\sum_{g=1}^{n_G}\overline{P_g} \leq \sum_{t=1}^{n_T}\overline{P_t}$ and $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$

$$\boldsymbol{Qt100} = \sum_{g=1}^{n_G}\overline{P_g} - \sum_{t=1}^{n_T}\overline{P_t} \quad (4)$$

If: $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] \leq [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g \neq 0]$ and $\sum_{g=1}^{n_G}\overline{P_g} > \sum_{t=1}^{n_T}\overline{P_t}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] \leq [\sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t]$

$$\boldsymbol{Qt100} = \sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g} \quad (5)$$

If: $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] \leq [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g \neq 0]$ and $\sum_{g=1}^{n_G}\overline{P_g} > \sum_{t=1}^{n_T}\overline{P_t}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] > [\sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t]$

$$\boldsymbol{Qt100} = \sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t \quad (6)$$

If: $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] > [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$ and $\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l] > [\sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t][\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g = 0]$

$$\boldsymbol{Qt100} = [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l] - [\sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t] \quad (7)$$

If: $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] > [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$ and $\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l] > [\sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t][\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g = 0]$ and $\sum_{t=1}^{n_T}\overline{P_t} \leq \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] \leq [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$

$$\boldsymbol{Qt100} = \sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g \quad (8)$$

If: $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] > [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$ and $\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l] > [\sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t][\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g = 0]$ and $\sum_{t=1}^{n_T}\overline{P_t} \leq \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] > [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$

$$\boldsymbol{Qt100} = \sum_{l=1}^{n_L}\overline{P_l} - \sum_{g=1}^{n_G}\overline{P_g} \quad (9)$$

If: $\sum_{l=1}^{n_L}\overline{P_l} > \sum_{g=1}^{n_G}\overline{P_g}$ and $[\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}\overline{P_g}] > [\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l]$ and $\sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l] > [\sum_{t=1}^{n_T}\overline{P_t} - \sum_{t=1}^{n_T}P_t][\sum_{g=1}^{n_G}\overline{P_g} - \sum_{g=1}^{n_G}P_g = 0]$ and $\sum_{t=1}^{n_T}\overline{P_t} > \sum_{g=1}^{n_G}\overline{P_g}$ and $\sum_{t=1}^{n_T}\overline{P_t} \leq \sum_{l=1}^{n_L}\overline{P_l}$

$$\boldsymbol{Qt100} = \sum_{l=1}^{n_L}\overline{P_l} - \sum_{l=1}^{n_L}P_l \quad (10)$$

where $\overline{P_l}$ is the required value of the load, P_l is the actual value of the load, $\overline{\overline{P_g}}$ is the sit capacity of generation, $\overline{P_g}$ is the available capacity of generation, P_g the actual capacity of generation, $\overline{P_t}$ the capacity of the transmission lines, and P_t the actual flow in the transmission lines.

III. APPLICATION ON A REAL-LIFE NETWORK

The main purpose of the presented applications is to illustrate the implementation of the developed methodology on real-life systems and to demonstrate the applicability of the theoretical and computational developments of this work to practical power systems. The Wadi Aldawasir Network represents an isolated zone of the SEC (Saudi Electrical Company) system. Figure 3 shows the single-line diagram of the Wadi Aldawasir network. The system under investigation contains 1 generator, 9 branches (transmission lines and power transformers), and 7 loads. The results (Figure 4) show that the Deficit Transmission Capacity ($Qt100$) stays at zero value for all required load levels up to 198MW, where it starts to increase continuously to reach 80MW at a required load level of 270MW. Since the available generation at Wadi Aldawasir is 263MW, this situation indicates that the unsupplied load (between 180-263MW of load levels) is essentially due to transmission limitations rather than generation availability. $Qg111$ has a similar pattern with the $Qt100$, where it increases to reach 73MW at a required load level of 270MW. On the other hand, the $Qg111$ starts at 90MW and increases continuously to reach 180MW, when the required load level reaches 180MW, after which the $Qg111$ increases at a slower rate and saturates at about 190MW when the required load level is 270MW. At this point, no more available generation capacity can be utilized. Figure 5 shows a 3-dimensional graph depicting the variation of the $Qt100$ with the required load and the available generation capacity levels of the Wadi Aldawasir network. It is noted from Figure 4 that the $Qt100$ stays at zero value for all available generation capacity levels between 50% and 150% of nominal as long as the required load level is below 100% of nominal. This situation, however, changes after a region between 50% and 150% of nominal for the available generation capacity levels and between 100% and 150% of nominal for the required load levels, where more required load levels would increase the amount of the $Qt100$. This situation indicates that the unsupplied load is now caused by the generation unavailability and transmission limitations.

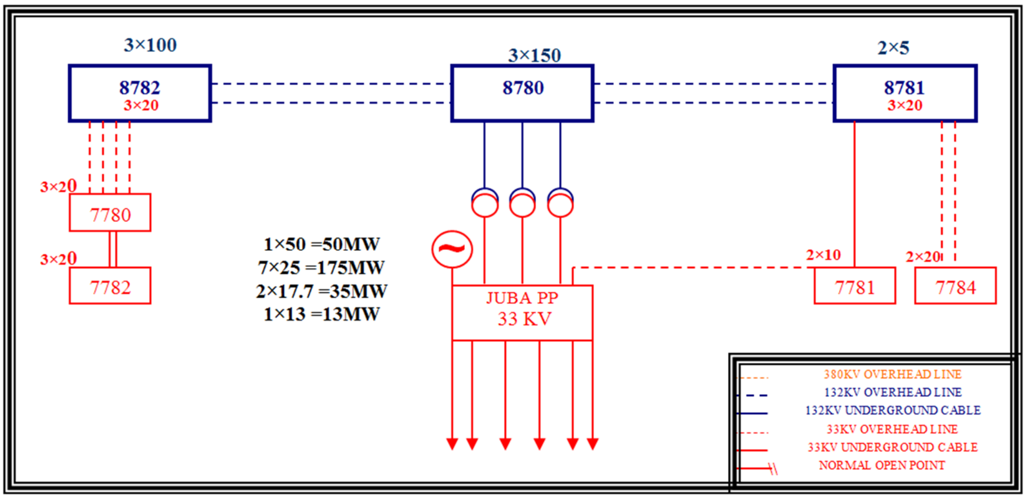

Fig. 3. Single-line diagram of the Wadi Aldawasir network.

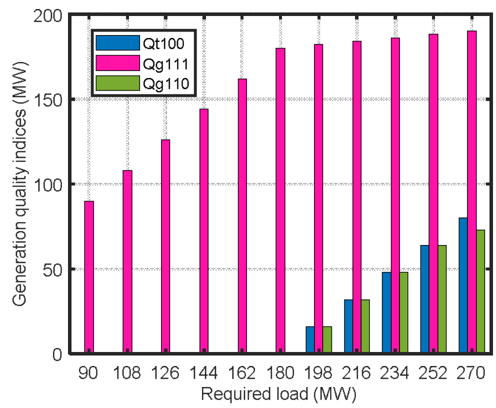

Fig. 4. Variation of generation capacity indices $Qt100$, $Qg111$, and $Qg110$ with the variation of required load levels of the Wadi Aldawasir network.

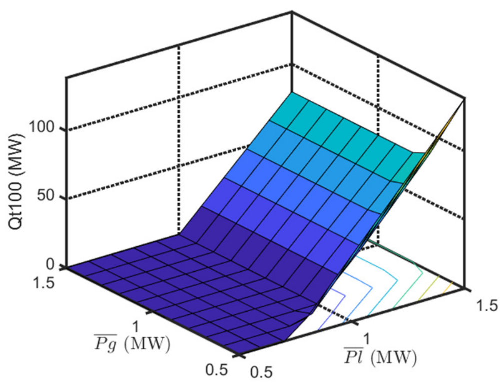

Fig. 5. 3-D graph of the variation of $Qt100$ with the required load levels and the available generation capacity levels of the Wadi Aldawasir network.

IV. Conclusion

In this paper, the evaluation of a new reliability and quality measures methodology is based on 3 quantities of the power network, which are representing the relationship between the generation push in the grid, the maximum limitation of the transmission capacity, and the needed load. At the same time, the maximum future expanded generation capacity that could be available at the same generation site, was discussed. The main purpose of the paper the utilization of modern modeling techniques and computational procedures, including the advanced deficit transmission system evaluation method and sparse-matrix network analysis algorithms, in order to evaluate with sufficient accuracy the deficit and reliability levels in practical real-life large-scale power systems. The main contribution of the paper is the assessment of the deficit transmission system index with novel formulas. The research work also includes a practical application to several operating scenarios in the Saudi electricity system. Most of the deficits on the power system are caused by generation unavailability and transmission limitations (contingency state).

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