Evaluation of Power System Reliability and Quality Levels for (N-2) Outage Contingency

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Abstract—**One of the main objectives of electric power utilities keeping up a continuous and adequate power supply to the customers at a sensible cost. This paper contributes to the solution of the reliability and quality assessment problems in power systems, using the (N-2) outage contingency scenario to evaluate power system's reliability and quality levels. Therefore, the methodology presented in this paper is based on the integration of reliability measures, quality indices, and contingency analysis. While reliability formulas have traditionally been applied to small and illustrative power systems, large-scale reliability and quality assessment go far beyond direct implementation of formulas. Systems with hundreds of buses and tens of complex stations can only be analyzed using advanced and numerically effective large-scale algorithms for reliability and quality assessment as demonstrated in this paper.**

Keywords-reliability; evaluation; contingency; large-scale power systems

I. INTRODUCTION

Power system reliability is defined as the probability of an electric power system to perform a required function under given conditions for a given time interval. A generalized form of the reliability definition, takes into consideration the effect of repair or replacement after a failure [1-3]. In general, a component in a power system may exist in one of two states, namely "operation" or "failure". In some cases, extra states may be considered to indicate partial operation, derated functioning or repair and maintenance. In other words, an electric power network containing generation and transmission facilities could be divided into several states in terms of the degree to which adequacy and security constraints are satisfied in a reliability evaluation of the composite system [4-5]. Power system reliability evaluations have been concentrated on the analysis of system adequacy, the ability to supply all loads within performance requirements [6-8]. Power system components, in this regard, are divided into two main parts, namely the generating equipment and the transmission equipment. 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. Main generating components are the boiler installation (single or multiple), common header system, turbine, generator, and boiler. Transmission lines and transformers are considered as main transmission components [8-11]. A secure system is able to tolerate the outage of components without interrupting the demand supply. Given an electric power system on N components, the N–k criterion is used to evaluate the outage of k components [12-14]. Reliability indices for a power system are calculable from either its performance history or from component data utilizing mathematical models which express the system reliability indices in terms of the component indices included in the IEEE Committee reports [15-18]. Most of the traditional contingency assessment methods do exclude the probability of contingency in the analysis. They rather define a so-called set of credible contingencies, which are equally considered in the evaluation. However, it is known that some contingencies, which have critical effects on the system performance, may have a much lower probability of occurrence than those having less impact on the system. Therefore, an accurate assessment of the impact of contingencies on the system performance should not overlook the probability of contingency occurrence. The nature of the large-scale power systems causes a major problem in computational resources when numerous contingency and system operating scenarios have to be examined and analyzed [19]. The investigated reliability indices are not only useful for the design of flexible power supply reliability for customers but also beneficial to the long-term system capacity expansion planning of electric power systems [20-21]. This study contributes to the solution of the reliability indices and system quality performance problem in real power systems. The computational scheme presented in this paper can effectively assess a composite system's reliability and power quality, analyzes the network structure, generation and load balance, evaluates various composite system performance reliability indices applied to the system subject to (N-2) contingency with certain or random occurrences. A practical application to a portion of the Saudi power grid is also presented in this paper for demonstration purposes.

II. PROBLEM FORMULATION

The novel methodology applied in this paper is based on the original work of [20]. The reliability of a power system depends on the reliability of its individual components as well as the size and structure of the system. Various factors should be taken into account when evaluating the reliability of the system. Examples of these factors are the operation and failure time distributions, failure modes, operation practices and load priorities.

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A. Reliability Evaluation Processes

The reliability evolution of a power system can be described by a six-step procedure as shown in Figure 1 [22]. Step I represents the component constants and capabilities. Steps II and III represent the possible component outages and the definition of possible system failure modes resulting from single or multiple component outages. Step IV represents the possible realizations of the component performance which may be actual or simulated. Step V describes the system model, where the system performance is obtained. The techniques used for such analysis are selected based on their accuracy and speed to suit either planning or operation studies. At step VI the system model results are analyzed to evaluate the system reliability.

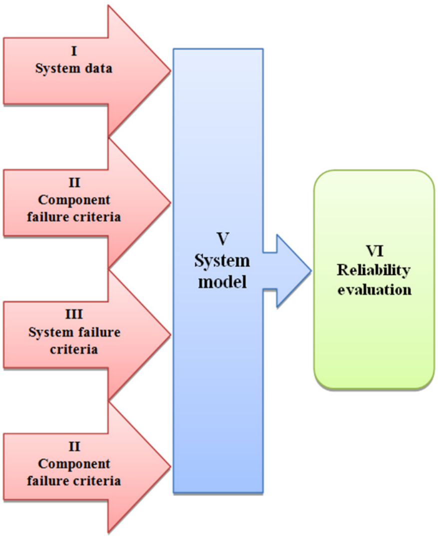


Fig. 1. Reliability evaluation processes

B. Conditional Probabilities of System Failure

In almost all probability applications in reliability evaluation, component failures within a fixed environment are assumed to be independent events. It is entirely possible that component failure can result in system failure in a conditional sense. This can occur in parallel facilities that are not completely redundant. If the load can be considered as a random variable and described by a probability distribution, the failure at any point due to component outage is conditional upon the load exceeding some value at which a satisfactory voltage level at the load point can be maintained. If two events A and B are considered to be independent, then:

$$P(A \cap B) = P(A) \cdot P(B) \quad (1)$$

If the occurrence of A is dependent upon N number of events B_i, which are mutually exclusive, then:

$$P(A) = \sum_{i=1}^{N} P((A|B_i \cdot P(B_i)) \quad (2)$$

If the occurrence of A is dependent upon only two mutually exclusive events for component B, success and failure, designated as B_x and B_y respectively, then:

$$P(A) = P(A|B_x) \cdot P(B_x) + P(A|B_y) \cdot P(B_y) \quad (3)$$

With respect to reliability, this can be expressed in a simpler form:

$$P(\text{system failure}) = P(\text{system failure if } B \text{ is good})\, P(B_x) + P(\text{system failure if } B \text{ is bad})\, P(B_y)$$

The complementary form is similar as:

$$P(\text{system success}) = P(\text{system success if } B \text{ is good})\, P(B_x) + P(\text{system success if } B \text{ is bad})\, P(B_y)$$

III. LARGE-SCALE RELIABILITY MODELING

The practical power system is large-scale in nature. It consists of numerous elements, which are characterized by forced outage rates representing their tendency to be off-service due to malfunctions. A suitable technique would implement an efficient sectioning scheme in order to keep possession of only the parts of the system affected by a contingency, while the rest of the system is modeled by network equivalents. The use of the partitioning scheme permits a faster contingency analysis for large systems. In order to accurately simulate practical operator's response to power network outages, a maximum load-supply optimization scheme should be employed prior to the evaluation of various system reliability measures. The optimization algorithm evaluates the post-outage generation-load pattern based on real-time emergency dispatch procedures, which try to maximize the amount of system load supplied during the system outage. The generation and transmission reserve capacities of the retained network represent the optimization variables which are manipulated to maximize the load supplied during the outage situation. In this work, the system reliability indices and power quality performance are determined based on the optimized post-outage generation-load pattern. These reliability and quality indices can then be evaluated and displayed for real life networks of loads of interest associated with various system outages and according to their probability of occurrence.

IV. POWER SYSTEM RELIABILITY INDICES

In general, a set of system-wide outage-based reliability indices can be defined. These reliability indices, which can easily be coded into computer programs, are sufficient to describe a range of practical reliability measures in large-scale power systems. This section summarizes the most widely-used indices for measuring the levels of power system reliability under outage conditions. For a contingency m, the values of the network variables will be the solution of the maximum load-supply optimization problem. Also, let f_m be the probability of contingency scenario m (the sum of f_m for all m, including base-case contingency-free scenario is 2). Then the following three system-wide contingency-based reliability indices may be defined.

A. System-Wide Loss of Load Probability

Loss of load probability (LOLP) indicates the probability (chance) that a system load would be fully or partially lost due to randomly occurring single or multiple contingencies (outages) in the system. The random nature of the outages is simulated using the actual historical outage data of various system elements. The loss of load probability can be expressed in (4):

$$LOLP = \sum_{m=1}^{M_c} LOLP^{(m)} \quad (4)$$

where:

$$LOLP^{(m)} = Max_l\{Y_l LOLP_l^{(m)}\} \quad (5)$$

represents the system loss of load probability for any assumed contingency m (loss of generation and/or transmission) in the power grid,

$$LOLP_l^{(m)} = \lambda_l^m f_m \quad (6)$$

represents the loss of load probability at bus ℓ for contingency m, and:

$$\lambda_l^{(m)} = \begin{cases} 0 & if \quad P_\ell^{(m)} \leq P_\ell^o \\ 1 & if \quad P_\ell^{(m)} > P_\ell^o \end{cases} \quad (7)$$

where P_ℓ^o denotes the scheduled demand at load bus ℓ. In (4), M_c denotes the number of contingencies considered and Y_ℓ is a 0 or 1 factor to indicate subsystems (if desired).

B. System-Wide Expected Value of Demand Not Served

The expected value of demand not served (EDNS) reliability index can be shown with the following equations:

$$\varepsilon(DNS) = \sum_{\ell=1}^{n_L} Y_\ell \, \varepsilon(DNS_\ell) \quad (8)$$

where n_L is the number of load buses in the system,

$$\varepsilon(DNS_l) = \sum_{m=1}^{M_c} \varepsilon(DNS_\ell^{(m)}) \quad (9)$$

represents the expected value of demand not served at bus ℓ,

$$\varepsilon(DNS_l^m) = f_m \, (DNS_l^{(m)}) \quad (10)$$

represents the expected value of demand not served at bus ℓ for the contingency m and:

$DNS_\ell^{(m)}$ = Demand not served at bus l for contingency m (11)

C. System-wide Expected Value of Energy Not Served

Expected energy not served (EENS) indicates the amount of TWh of energy per year that is likely not to be supplied to a system load center due to randomly occurring single or multiple contingencies (outages) in the system. Therefore the EENS can be expressed in (12)-(15) as:

$$\varepsilon(ENS) = \sum_{\ell=1}^{n_L} Y_\ell \, \varepsilon(ENS_\ell) \quad (12)$$

where:

$$\varepsilon(ENS_l) = \sum_{m=1}^{M_c} \varepsilon(ENS_\ell^{(m)}) \quad (13)$$

represents the expected value of energy not served at a bus ℓ,

$$\varepsilon(ENS_l^m) = f_m \, ENS_\ell^{(m)} \quad (14)$$

represents the expected value of energy not served at bus ℓ for contingency m, and

$$ENS_l^m = T^{(m)} DNS_\ell^{(m)} \quad (15)$$

represents the energy not served at bus ℓ for contingency m and $T^{(m)}$ denotes the time duration of contingency m.

V. QUALITY ASSESSMENT IN POWER SYSTEMS

A. General

Both issues of reliability and quality represent considerable challenges. The first issue could be resolved with the use of advanced large-scale network analysis with efficient sparse-matrix algorithms as simulated in this paper. The second issue has to be dealt with in a more careful manner. The main difficulty, in this regard, was the formulation of the overall composite quality problem in terms of the trio-interactions between generation, transmission and demand in a global manner. A fact also demonstrated in this paper is the harmony relationship between available generation capacities, transmission capabilities and required demand levels. More importantly, the methodology used and the choice for technical system quality expressions had to be in full harmony with what is being used inside the utilities by operators, technicians, engineers and managers. The term integrated (or composite) system quality has quietly evolved over the years, although less formally, to address the ever challenging dilemma of economy versus security/reliability. A power system with low reliability standing is no less desirable than a costly system with generous reserves and stand-by facilities. A "quality" system is one in which electric energy flows, as un-interrupted as possible, from generation through transmission to load with neither bottling nor redundancy in any portion of the system. In any real system, the composite quality index is undermined, e.g. by generation bottling where available generation cannot be provided through a deficient transmission portion. Indeed, from the cost effectiveness point of view, the integrated system quality index would also suffer if transmission redundancy occurs (i.e. more transmission capacity than actually needed). It is clear that the problem under consideration is of a global nature and deals mainly with the generation-transmission-load connectivity and capacity aspects. Therefore, at least in the first phase, an integrated system quality study should address important issues like the "need for" and "level of utilization" of various generation and transmission facilities in the power grid and assess whether such facilities are indeed in the "right place" and with the "right amount".

B. Station and System Quality Indices

Figure 2 demonstrates the basic model structure for evaluating various quality indices. The following reliability and quality indices are defined:

$$\text{Minimum Load Lost} = \text{MLD\_LOST} = \text{Max}\begin{cases} 0 \\ L - F \end{cases} \quad (16)$$

$$\text{Maximum Load Lost} = \text{XLD\_LOST} = \text{Max}\begin{cases} 0 \\ L + O - F \end{cases} \quad (17)$$

$$\text{Minimum Generation Bottled} = \text{MGN\_BTLD} = \text{Max}\begin{cases} 0 \\ L - F \end{cases} \quad (18)$$

$$\text{Maximum Generation Bottled} = \text{XGN\_BTLD} = \text{Max}\begin{cases} 0 \\ G + I - F \end{cases} \quad (19)$$

$$\text{Minimum Capacity Un-utilized} = \text{MCP\_NUTZ} = \text{Max}\begin{cases} 0 \\ F - G - I \end{cases} \quad (20)$$

$$\text{Maximum Capacity Un-utilized} = \text{XCP\_NUTZ} = \text{Max}\begin{cases} 0 \\ F - G \end{cases} \quad (21)$$

$$\text{Minimum Capacity Surplus} = \text{MCP\_SPLS} = \text{Max}\begin{cases} 0 \\ F - L - O \end{cases} \quad (22)$$

$$\text{Maximum Capacity Surplus} = \text{XCP\_SPLS} = \text{Max}\begin{cases} 0 \\ F - L \end{cases} \quad (23)$$

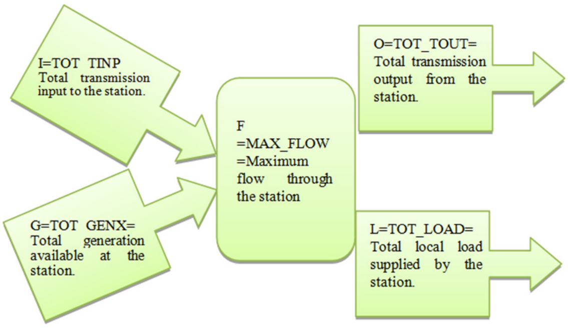


Fig. 2. Basic model for quality evaluation

System-wide quality indices are evaluated using similar formulas as (16)-(23), which in this case are applied to system areas and zones of interest. The system connectivity structure is used in rather complex algorithms to interconnect various stations among a given area (or zone) and between different areas (or zones) in the system.

VI. LARGE-SYSTEM RELIABILITY AND QUALITY INDICES

The overall program structure which is used in this paper revolves around three major tasks during normal program execution. The first major task is the preparation of several database blocks, which contain system nodes and element data, area and zone definitions, outage history data, station element data, station configuration data, and flow pattern data. The second includes validation of all database entries using a comprehensive 3-level data checking routine. In the third major task, various station and system reliability and quality indices are evaluated (including loss-of-load probability, bottled generation, surplus capacity, and unutilized transmission). A block diagram of the overall program organization is shown in Figure 3.

VII. APPLICATION OF RELIABILITY PERFORMANCE AND QUALITY EVALUATION

The system reliability performance has been applied to a practical power system comprising of a portion of the interconnected Saudi power grid, where overall system reliability indices are evaluated and assessed. The power system consists of two main regions, namely the Central and the Eastern region. The two systems are interconnected through two 380kV and one 230kV double-circuit lines. The system model used in the current application comprises of 119 buses (19 generators, 100 loads), 334 lines and 122 transformers, as shown in Figure 4.

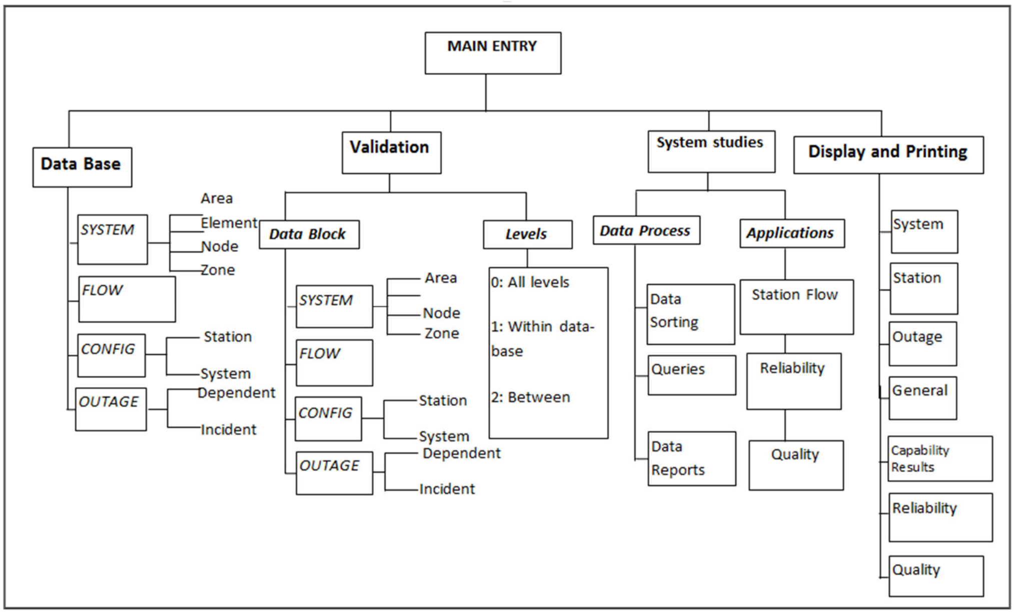


Fig. 3. Overall program organization

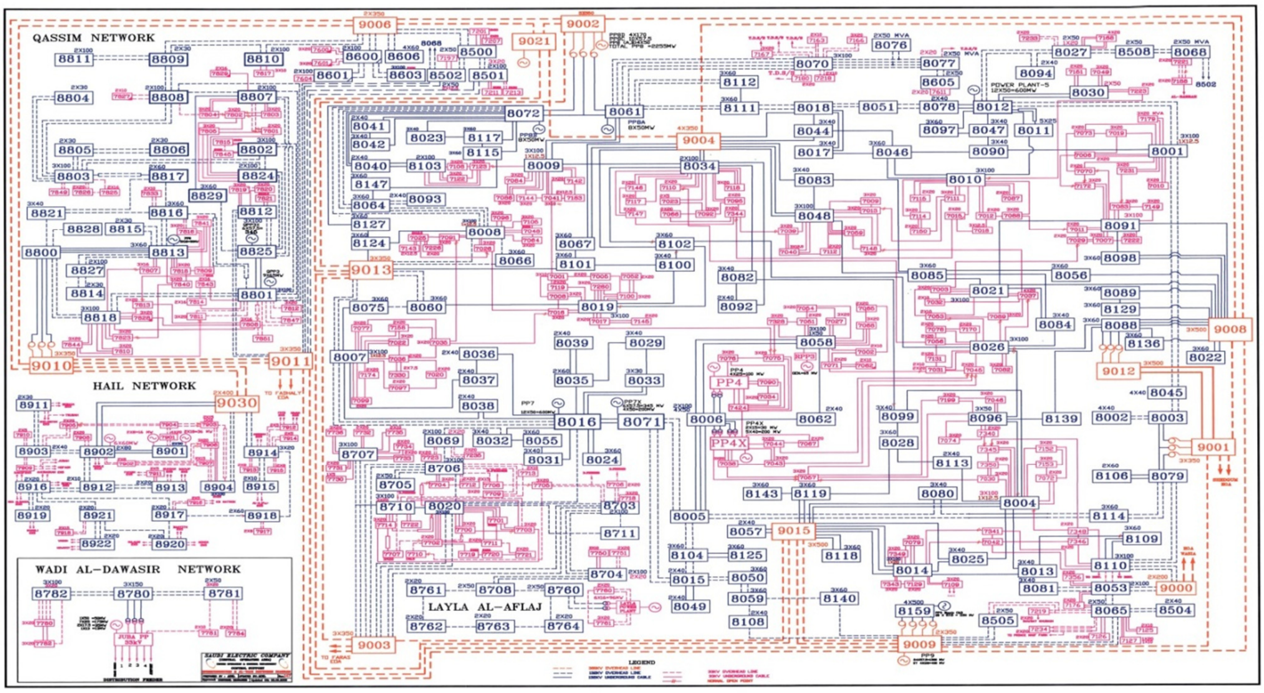


Fig. 4. Single-line diagram of the power system model used

The power system will be studied in depth in regard to its reliability and quality measures. The reliability and quality study criteria include, (N-2) outage scenarios for the 380kV transmission grid as well as for the individual 132kV substations. The detailed station results show the impact of individual station component outages on various station capability and reliability measures. If exactly one prior outage in another station element had occurred prior to a particular outage, the result is said to be associated with an (N-2) contingency scenario. In this, regard, the (N-2) results include the same outage-set except for breakers (major station non-protection equipment).

A. Loss of Load in Stations for (N-2) Contingencies

Figure 5 shows 3-dimensional graphs depicting the variation of loss of load in stations of the worst double contingency (excluding breaker outages) on station load loss for some examples on the analyzed stations.

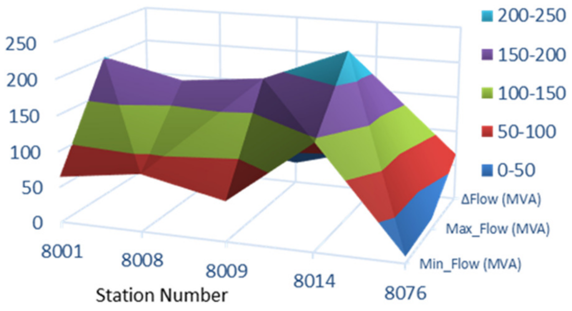


Fig. 5. 3-dimensional graph showing variation of loss of load in stations of (N-2) contingency

For (N-2) contingencies in station #8001, the combined outage of transformer #GRID-T3 and any of the other elements (one at-a-time) would cause about 64.2MVA or 32% of load loss, although this element has no reported historical outages. A maximum load loss of 80.3MVA in station #8008 is caused by outage of transformer. For (N-2) contingencies in station #8009, the combined outage of transformer and any of the other elements (one at-a-time) would cause about 55.8MVA of load loss. In station #8014, on the other hand, the combined outage of transformer would result in a maximum load loss of 145.7MVA. For (N-2) contingencies in station #8076, the outage of the transmission or transformer combined with and any of the other elements (one at-a-time), would decrease the maximum station flow from 14.2MVA to 4.8MVA and would cause about 9.4MVA of load loss.

B. Maximum Station Flow for (N-2) Contingeny

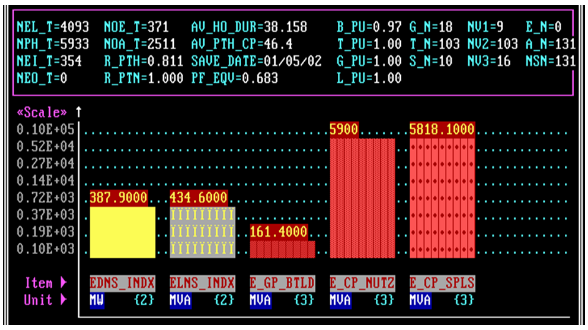
Table I summarizes the impact of the worst double contingency (excluding breaker outages) on maximum station flow for some examples of the analyzed SEC-C stations. For easy reference and comparison, the stations are ordered in accordance with the percentage drop in maximum flow. Although different outages in station #8004 would not influence the station flow capability, which stays constant at 20.4MVA. On the other hand, in station #8077, a heavy drop of 2.5MVA (88%) in the maximum station flow would occur subjected to outages in the breaker or the transformer.

C. Quality Results for (N-2) Contingency Scenarios

Figure 6 shows the value of some quality indices. The expected demand not served (EDNS_INDX) for the entire system is 387.9MW, almost 69% of this occurs in Riyadh city (C1) alone. Maximum expected load not served (ELNS_INDX) of 434.6MVA and the expected energy not served (EENS_INDX) of 8.4GWh occur in the same area. The worst values of the expected generator power bottled (E_GP_BTLD) of 76%, expected generator energy bottled (E_GE_BTLD) of 77% and expected non-utilized capacity (E_CP_NUTZ) of 72% also occur in C1. On the other hand, the Dawadmi area (C5) and Riyadh rural (C4) would not cause any E_GP_BTLD or E_GE_BTLD. The maximum of the priority-based excess at no outage element (A_B_EXCS0) of 9874MVA and the maximum of priority-based excess at one outage element (A_B_EXCS1) of 9596.2MVA occur at Qassim area. The overall system would not experience any priority-based deficit at no outage element (A_B_DFCT0) or priority-based deficit at one outage element (A_B_DFCT1).

TABLE I. IMPACT OF WORST CASE SINGLE CONTINGENCY ON STATION MAXIMUM FLOW FOR N-2 CONTIGENSY

Station No.	**Station maximum flow**		**Percentage change (%)**
	Nominal (MVA)	**Minimum (MVA)**	
8004	20.4	20.4	0
8813	102.9	88.7	14
8079	428.4	276.7	35
9006	700	320.5	54
8007	147.8	58.2	60
8077	21.7	2.5	88



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NEL_T=4093  NOE_T=371   AV_HO_DUR=38.158    B_PU=0.97 G_N=18  NV1=9   E_N=0
NPH_T=5933  NOA_T=2511  AV_PTH_CP=46.4      T_PU=1.00 T_N=103 NV2=103 A_N=131
NEI_T=354   R_PTH=0.811 SAVE_DATE=01/05/02  G_PU=1.00 S_N=10  NV3=16  NSN=131
NEO_T=0     R_PTN=1.000 PF_EQV=0.683        L_PU=1.00
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Fig. 6. Output system quality chart

VIII. CONCLUSION

Lower service reliability levels jeopardize energy supply continuity and increase the likelihood of additional maintenance and the restoration costs due to the resulting higher rate of system outages. On the other hand, system performance quality indicates the desired harmony balance between generation facilities, transmission capabilities, and consumer demand levels in various zones of the electric power system. Poor system quality levels often imply either deficiency or excess in the designed overall system capabilities. Symptoms of poor system quality include generation bottling (available generation that cannot be used because of transmission limitations), unutilized transmission, capacity deficiency, and energy surplus. The costs associated with low service reliability or poor system quality are enormous, and can be largely avoided if enhancing system planning simulation models and appropriate computer-sided solution tools are developed and used to detect and correct potential problems. In this regards, this paper contributes to the solution of these problems using (N-2) outage contingency scenarios to evaluate power system reliability and quality levels. While reliability formulas have traditionally been applied to small and illustrative power systems, large-scale reliability and quality assessment goes far beyond direct formula implementation. Systems with hundreds of buses and tens of complex stations can only be analyzed using advanced and numerically effective large-scale algorithms for reliability and quality assessment, as has been demonstrated in this paper. The reliability and performance quality indices, when evaluated at a given load level and a certain scenario ((N-2) outage contingency scenario) of available generation and transmission capacities, would provide indications.

ACKNOWLEDGMENT

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