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ASSESSMENT OF RESERVE ADEQUACY AND RELIABILITY OF POWER SYSTEMS

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ABSTRACT

This paper presents an innovative approach to reserve adequacy and reliability assessment in bulk electricity systems based on the widely accepted international standards and guidelines. In the presented approach, the electricity reserve associated with a particular operating bulk area is modeled as a random function of three key random operating variables, namely the area generation capacity, the consumer demand, and the area in/out tie-line transfer capacity. The approach followed in this paper allows the evaluation and assessment of the sensitivities of the area reserve and other reliability performance measures with respect to variations in the system planning and operating conditions. The developed approach has been successfully applied to several operating scenarios in a real-life power system consisting of the Hail area in the Saudi Electricity Company.

KEYWORDS: Reserve, power systems, reliability, sensitivity analysis.

INTRODUCTION

Power utilities around the world are concerned about the continual increase in system demand coupled with growing limitations on generation and transmission facility expansion due to financial constraints, environmental concerns, etc. This has inevitably led to a corresponding concern regarding the load demand supply balance and, in particular, the availability of reserve and reliability of electricity supply to major demand centers. In this regard, the electric power grid in the Kingdom of Saudi Arabia has witnessed a very rapid expansion over the past two decades to the extent that any degradation in reserve adequacy of system reliability would often have serious consequences on both the consumer and the electricity company.

A number of publications have appeared in the literature dealing with the general problem of reliability evaluation, reserve management and system performance quality assessment. While most published techniques are theoretical with limited domain of practical applications, they provide adequate background on the subject. Billinton and Allan [1], provide basic background on the problem of reliability evaluation in electric power systems and the associated computation mechanisms of various system reliability indices. Techniques and approaches for evaluating system reliability degradation impacts and assessing system quality levels are discussed by Camac et al. [2]. The use of advanced methodologies for computing system performance quality levels and reduce possibilities of reliability degradation are outlined by El-Kady et al. [3]. Kilk and Valdma [4], deal with the assessment of bulk system reserve and demand-supply balance requirements. The issue of utility-customer interaction and the nature of relationship between supply and demand sides, as well as the associated impacts and costs of reliability degradation on both sides are outlined by El-Kady et al. [5]. Kariuki and Allan [6] deal with the issue of outage costing and reliability worth in electric power systems as well as the monetary impacts of degraded system reliability levels. Other issues on related regulatory aspects, contingency outages and ranking as well as other general related topics are discussed by Mehta, et al. [7].

The existing approaches, as is evident from the published research and development works and power industry business reports to date, have been built almost entirely on the traditional methodologies using conventional numerical methods to deal with reserve management, reliability evaluation and system performance quality assessment. Unfortunately, such traditional approaches would not be adequate in dealing with today's large-scale practical power systems.

The work of this paper summarizes the results of a recent major study in which an innovative approach to reserve adequacy and reliability assessment in bulk electricity systems has been developed based on the widely accepted international standards and guidelines [8]. The developed approach has been successfully applied to several operating scenarios in a real-life power system consisting of the Hail area in the Saudi Electricity Company. As demonstrated in the application, the approach followed in this paper allows the evaluation and assessment of the sensitivities of the area reserve and other reliability performance measures with respect to variations in the system planning and operating conditions.

PROBLEM FORMULATION

Reserve and Reliability Assessment Methodology

The wok of this paper employs the guidelines developed by the North American Electric Reliability Corporation (NERC), which is an international regulatory authority established to evaluate reliability of the bulk power system in North America. NERC develops and enforces reliability standards and assess the adequacy of the bulk power system [9].

Each bulk electricity area is considered as a business entity which is connected to the rest of the interconnected electricity system via a set of tie-lines through which power is imported into the area or exported from it. The bulk area may or may not have it own generation resources. If the generation in the bulk area is greater than its own required demand, then excess (extra) power may be exported to the interconnected system. Alternatively, if the generation in the bulk area is less than its own required demand, then power will have to be imported from the interconnected system into the bulk area.

The power system is never in a stationary operating state. Its demand is changing continuously by the minute. In addition, its generating and transmission facilities are also experiencing partial or total outages in the real time. Therefore, the terms “Area Demand”, “Generation Capacity” and “Transfer Capacity” are all dynamic in nature and assume a range (population) of values depending on their incidental status in the operating time-frame.

For example, if the bulk area has a generation capacity ranging from 500 to 1000 MW, while its demand fluctuates between 800 to 1200 MW and the transfer capacity (Capacity Benefit Margin) is fixed (100% available) at 200 MW, then the un-served demand will be in the range of zero to 100 MW. In general, the “Expected” value of the un-served demand will depend on the probabilities of the transition states of ALL generation units, area ties as well as area demand pattern. The “Expected Demand Not-Served” is an example of applicable reliability indices applied to bulk electricity areas.

In general, the load duration curve – adjusted of demand-side initiatives – is used to determine the load probabilities associated with various demand pattern segments. On the other hand, historical outages are used to determine the availability (or forced-outage) rates of both generation and transmission facilities.

The area reliability assessment is conducted using several key indices such as “System Minutes” (equivalent number of un-supplied peak-demand minutes per year, which equals to the total energy not served per year in terms of an equivalent number of minutes per year for which a demand equal to the peak load would be interrupted), “Loss of Load Expectation” (expected number of days in a year in which a loss of load occurs), “Expected Demand Not Served”, etc. In addition, several area performance criteria such as “Bottled Generation” (existing generation capacity that could not be exported because of limited area transfer capability) and “Excess Transfer Capacity” (Available Transfer Capability) are of interest to area planning tasks.

Reserve Allocation

Reserve is an important issue addressed by power companies around the world. In this regard, specific formulas are used for calculating reserve requirements in order to ensure that sufficient reserve is being allocated. As suggested in, the Reserve Margin calculation formula is:

RM = [(Capacity + CCDR) - (Total Internal Demand)] / (Total Internal Demand) (1)

where CCDR represents the Controllable Capacity Demand Response and the Total Internal Demand is defined as the sum of the metered (net) outputs of all generators within the bulk area and the metered line flows into the area, less the metered line flows out of the area. The demands for station service or auxiliary needs are not included. Internal Demand includes adjustments for demand-side management programs.

Practical Applications

The developed reserve and reliability assessment methodology has been applied to the Hail electricity system in Saudi Arabia in order to demonstrate the theoretical and analytical developments of this paper and to illustrate the applicability and usefulness of the technical approach adopted in the work of the paper.

Hail Bulk Area System Data

The first step in the present application is to conduct bulk area equivalency and outage processing analysis of the base-case (Peak loading condition) for the Hail bulk area under study.

Figure 1 depicts the simulation screen capture of the "extrapolated" hourly demand pattern for the HAIL base-case (PEAK) as well as the associated demand duration curve. As shown, the peak power level is 840.1 MW while the minimum power level is 213.0 MW.

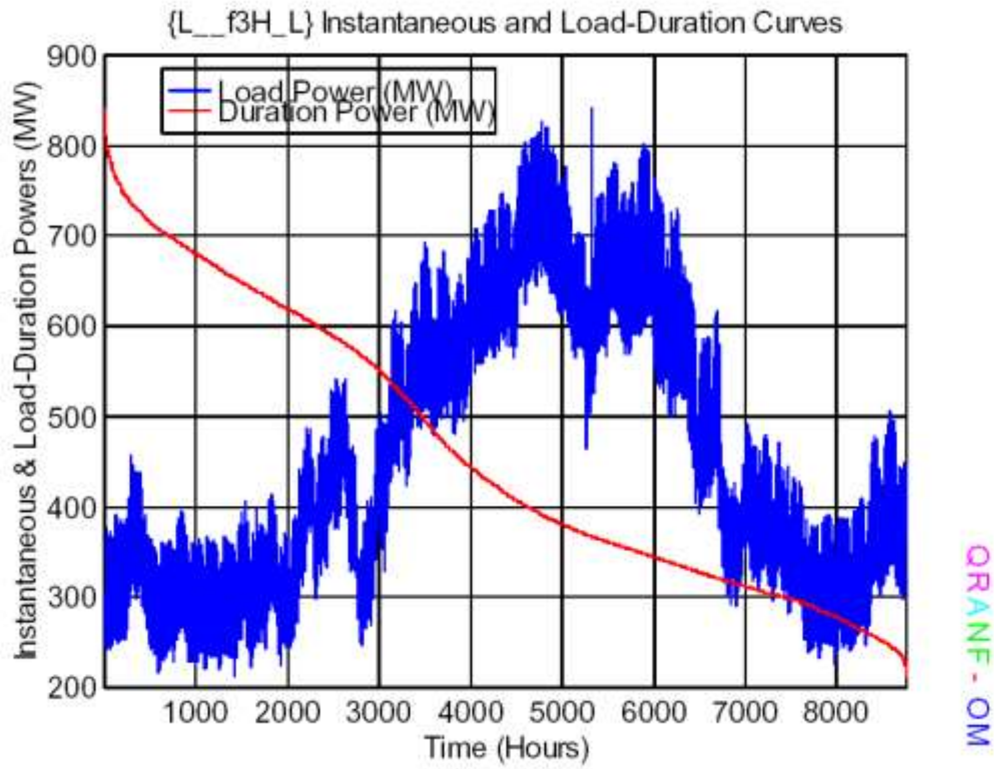

Fig. 1 Load Probability Simulation Results – SEC/HAIL Base-Case (PEAK)

Reserve and Reliability Assessment of Hail Area

The first step of the reserve and reliability assessment in the present application is to conduct bulk area equivalency and outage processing analysis of the base-case (peak loading condition) for the Hail bulk area under study. Such assessment would reveal whether or not the networks and facilities within the selected area are being planned, designed, constructed, and operated according to established criteria.

Tables 1 and 2 show the simulation screen capture (Probabilistic "Expectation" and Deterministic "Base-Case") which depicts the reliability and reserve adequacy indices for the Hail bulk area under study.

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Table 1. Overall Summary Of Area Reserve Adequacy/Reliability Probabilistic Indices – Sec/Hail Peak

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==============================================================================
Assessment of Bulk Electricity System Reserve Adequacy . Module #4 V5.8 /RSV1
[QRANFOM]: [Area Supply Adequacy Assessment] . <............................>
------------------------------------------------------------------------------
Case-#HAL: [HU/RAED Project]  <NERC-Reliability Scenario Simulation Runs>
------------------------------------------------------------------------------
Overall Summary of NERC-Based Area Probabilistic Indices  [COMPARISON REPORT]
------------------------------------------------------------------------------
1  2                   3      4         5      6      7         8         9
## BASE-CASE/AREA-NAME [PCDM] [-EDNS-] [LOLE] [SYSM] [-GBTL-] [-TSPS-] [RSVn]
-- ------------------- ------ --------- ------ ------ --------- --------- ------
 1 2013-Peak/Hail       0.00       0.0    0.1   12.4      0.0     418.6   9.25
------------------------------------------------------------------------------
LEGENDS & DEFINITIONS OF DATA COLUMNS:
 1. Case-Scenario Sequential Number
 2. Scenario-ID [Base-Case Year, Peak/Mini Load-Condition, Bulk-Area Name]
 3 [PCDM]: Percent Capacity-Demand Margin (%)
 4 [EDNS]: Expected Demand Not-Served (MW)
 5 [LOLE]: Loss-of-Load Expectation (Days/Year)
 6 [SYSM]: System Minutes (Minutes/Year)
 7 [GBTL]: Bottled Area Generation Capacity (MW)
 8 [TSPS]: Surplus Area-Tie Capacity (MW)
 9 [RSVn]: Area-Reserve Using NERC NEW-Formula (%)
==============================================================================
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Table 2. Overall Summary Of Area Reserve Adequacy/Reliability Base-Case Deterministic Indices – Sec/Hail Peak

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==============================================================================
Assessment of Bulk Electricity System Reserve Adequacy . Module #4 V5.8 /RSV1
[QRANFOM]: [Area Supply Adequacy Assessment] . <............................>
------------------------------------------------------------------------------
Case-#HAL: [HU/RAED Project]  <NERC-Reliability Scenario Simulation Runs>
------------------------------------------------------------------------------
Summary of NERC-Based Area Base-Case Adequacy/Reliability [COMPARISON REPORT]
------------------------------------------------------------------------------
1  2                   3      4         5      6      7         8         9
## BASE-CASE/AREA-NAME [PCDM] [-BDNS-] [BLOP] [SYSM] [-GBTL-] [-TSPS-] [RSVn]
-- ------------------- ------ --------- ------ ------ --------- --------- ------
 1 2013-Peak/Hail       0.00       0.0    1.0    8.9      0.0       0.0   3.81
------------------------------------------------------------------------------
LEGENDS & DEFINITIONS OF DATA COLUMNS:
 1. Case-Scenario Sequential Number
 2. Scenario-ID [Base-Case Year, Peak/Mini Load-Condition, Bulk-Area Name]
 3 [PCDM]: Base-Case %-Capacity-Demand Margin (%)
 4 [BDNS]: Base-Case Demand Not-Served Value (MW)
 5 [BLOP] Base-Case Loss-of-Load Probability (PU)
 6 [SYSM]: Base-Case System Minutes (Minutes/Year)
 7 [GBTL]: Base-Case Bottled Area Generation (MW)
 8 [TSPS]: Base-Case Surplus Area-Tie Capacity (MW)
 9 [RSVn]: Area-Reserve Using NERC NEW-Formula (%)
==============================================================================
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The definitions of the data columns in the above tables are listed in the “Legends & Definitions of Data Columns” in the bottom portion of the table. The discussion below will pertain in particular to Columns # 6 (SYSM: System Minutes in Minutes/Year) and # 9 (Percentage Area-Reserve). A full analysis and assessment of the results will be carried out as part of the subsequent sensitivity analysis and conformance with international thresholds to identify below-standard performance and develop proper options for mitigation if necessary. Nonetheless, some few observations are made here:

a) It is observed from the results of Table 1 that the peak loading scenarios of the base-case for Hail bulk area experience around 12.4 expected system minutes (taking into account randomness in generation/transmission availability as well as load fluctuations). However, the base-case scenario (one deterministic operating point) from the results of Table 2, experiences system minutes of 8.9.

b) It is also observed from the results that the expected for Hail bulk area is around 9.25 % for the Hail base-case (peak loading conditions). On the other hand, the reserve for the base-case scenarios (one deterministic operating point) is around 3.8 %.

It is important to note here that the reserve values obtained represent a special case for the Hail bulk area, which does not have a local generation and depends entirely on incoming transfers (which are sufficient) to supply its demand.

Sensitivity Analysis of Hail Reserve and Reliability

The sensitivity analysis of reserve and reliability levels for the Hail bulk area represents a powerful tool for identifying potential reserve and/or reliability degradation (if exists) and, therefore, viable options for mitigating such degradation can be explored in light of the applicable standards and guidelines. In this regard, the author has conducted a comprehensive sensitivity analysis of the Hail bulk area reliability results, which reveals the expected changes in the obtained reliability and reserve adequacy indices subject to variations in key planning assumptions. Such sensitivity analysis is particularly important in the current study in which some of the data items, such as historic outage records, may not be very accurate. In this regard, the calculated sensitivities of the reliability and reserve indices to the assumed values of generation and/or transmission facilities would show just by how much these indices would change if the forced outage rates are to change over a specified range. The bulk area reliability and reserve adequacy sensitivity analysis results are considered as an essential part of establishing the technical framework and defining the associated assessment criteria. Such criteria are then used to explore the planning, design, and operating options that exist for Hail area in order to bridge the "below-standard" reserve and/or reliability levels (if any).

The following parameter variations are considered in the sensitivity analysis:

i) Variations in Maximum Required Load [MW]
ii) Variations in Tie-Line Transfer Capacity [MW]
iii) Variations in Area-Tie Per-Unit Availability [PU]

Some key sensitivity results are shown here for two sensitivity parameters, namely the maximum required load and the area-tie per-unit availability. In this regard, the results were assembled and summarized in several key simulation screen captures:

i) The first simulation screen capture shown in Figure 2 is a simulation generated sensitivity chart depicting the impact of variations in the Hail bulk area demand (expressed as a per-unit of the nominal base-case value) on the System Minutes (SYSM) reliability index.

It is clear from the sensitivity chart that the System Minutes index is very sensitive to variations in the Hail bulk load level. The System Minutes index reaches the level of 650 just as the Hail demand increases by 10% from its base-case level.

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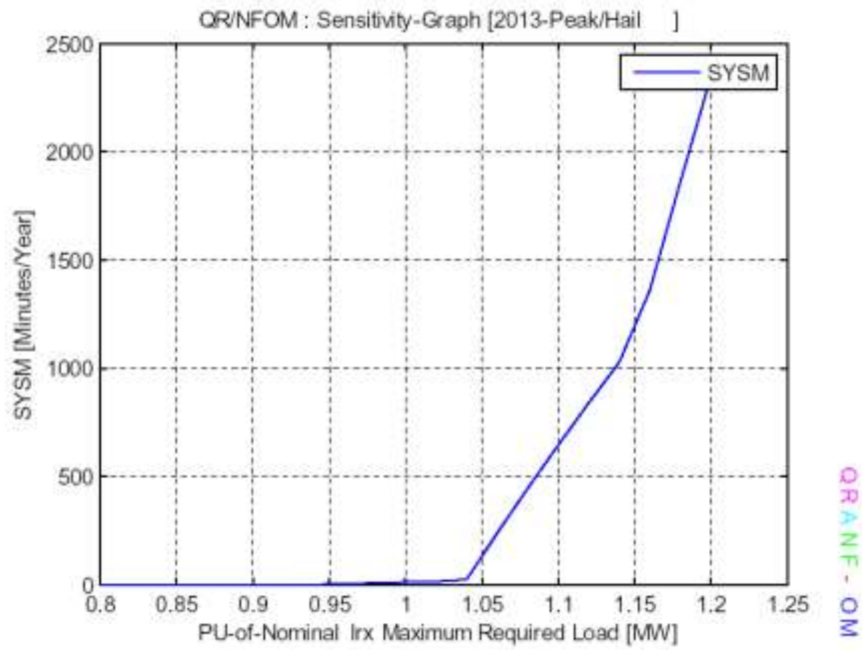

Fig. 2. Impact of Variations in the Hail Bulk Area Demand (Expressed as Per-Unit of the Nominal Base-Case Value) on the System Minutes (SYSM) Reliability Index

ii)The second simulation screen capture shown in Figure 3 is a simulation generated sensitivity chart depicting the impact of variations in the calculated availability rate of transmission facilities in the Hail bulk area (expressed as a per-unit of the nominal base-case value) on the Loss of Load Expectation (LOLE) reliability index. The transmission availability rate is an important planning parameter which is calculated from the collected historical outage records in the transmission facilities. Therefore, the sensitivities of reliability indices to variations in the assumed transmission availability rate are indicative to the extent to which reliability indices results are impacted by inaccuracy and/or insufficiency of the historical records used to generate such availability rates.
It is clear from the sensitivity chart that the Loss of Load Expectation (LOLE) reliability index for the Hail bulk area is also sensitive to variations in the assumed availability rates of transmission facilities (area ties). The Loss of Load Expectation (LOLE) reliability index would increase to 12 days/year if the availability rates of transmission facilities were over estimated by 10% (that is 90% of their respective nominal base-case values).

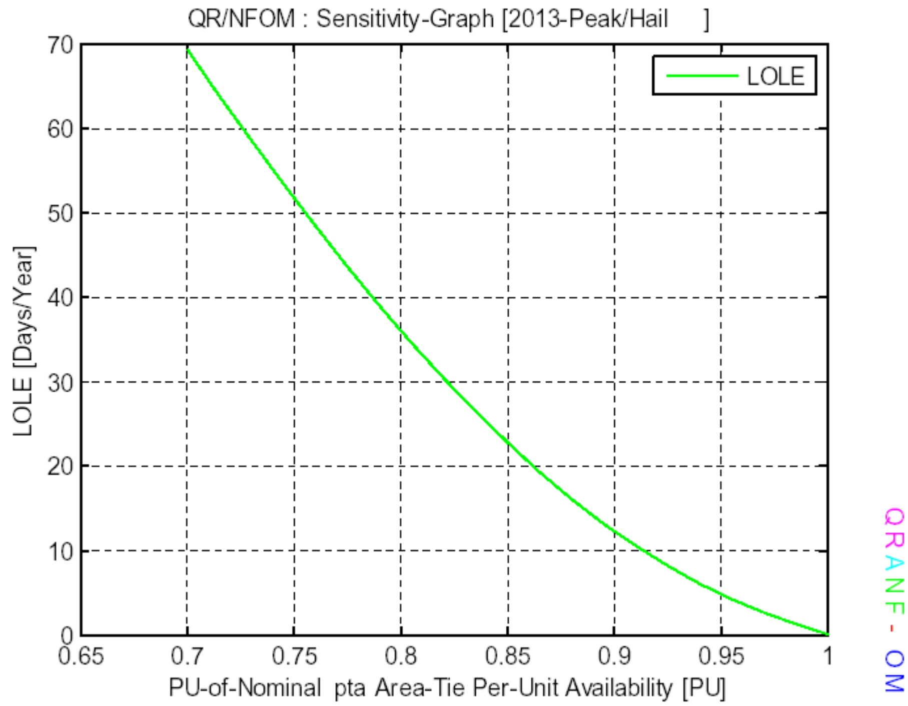

Fig. 3. Impact of Variations in the Hail Bulk Area Tie-Line Availability Rate (Expressed as Per-Unit of the Nominal Base-Case Value) on the Loss of Load Expectation (LOLE) Reliability Index

CONCLUSIONS

Summary of Key Findings

The following key findings are deduced from the simulation based assessment conducted in this paper:

1. It is observed from the obtained simulation results that the peak loading scenarios of the base-case for Hail bulk area experience around 8.9 expected system minutes (taking into account randomness in generation/transmission availability as well as load fluctuations). However, the base-case scenario (one deterministic operating point) experiences system minutes of 12.4.
2. It is also observed from the results obtained that the expected for Hail bulk area is around 9.25 % for the Hail base-case (peak loading conditions). On the other hand, the reserve for the base-case scenarios (one deterministic operating point) is around 3.8 %.
3. The sensitivity analysis of reserve and reliability levels for the Hail bulk area represents a powerful tool for identifying potential reserve and/or reliability degradation (if exists) and, therefore, viable options for mitigating such degradation can be explored in light of the applicable standards and guidelines. In this regard, the simulation generated sensitivity chart depicting the impact of variations in the Hail bulk area demand (expressed as a per-unit of the nominal base-case value) on the System Minutes (SYSM) reliability index has revealed that the System Minutes index is very sensitive to variations in the Hail bulk load level. The System Minutes index reaches the level of 650 just as the Hail demand increases by 10% from its base-case level.
4. The simulation generated sensitivity chart depicting the impact of variations in the available tie-line transfer capacity for the Hail bulk area (expressed as a per-unit of the nominal base-case value) on the Loss of Load Expectation (LOLE) reliability index has revealed that the variations in the Hail area tie-line capacity will have a profound impact on the Loss of Load Expectation value. The LOLE increases to almost 12 days/year as the Hail tie-line transfer capacity decreases by 10%. On the other hand, The LOLE increases rapidly with the deficit in the Hail tie-line transfer capacity, and reaches the level of 70 days/year

as the Hail tie-line transfer capacity drops to 70% of its nominal base-case level.

5. The simulation generated sensitivity chart depicting the impact of variations in the calculated availability rate of transmission facilities in the Hail bulk area (expressed as a per-unit of the nominal base-case value) on the Loss of Load Expectation (LOLE) reliability index has revealed that the transmission availability rate is an important planning parameter which is calculated from the collected historical outage records in the transmission facilities. Therefore, the sensitivities of reliability indices to variations in the assumed transmission availability rate are indicative to the extent to which reliability indices results are impacted by inaccuracy and/or insufficiency of the historical records used to generate such availability rates.

It was clear from the sensitivity chart that the Loss of Load Expectation (LOLE) reliability index for the Hail bulk area is also sensitive to variations in the assumed availability rates of transmission facilities (area ties). The Loss of Load Expectation (LOLE) reliability index would increase to 12 days/year if the availability rates of transmission facilities were over estimated by 10% (that is 90% of their respective nominal base-case values).

Study Conclusions and Recommendations

The following recommendations are made based on the results obtained in this study:

1. It is recommended that Hail electricity authority consider the implementation of the applicable reserve and reliability assessment methodology presented in this paper.
2. It is also recommended that other more up-to-date base-cases for the Hail bulk electricity area be analyzed from the reserve adequacy and reliability point of view as they become available in future.
3. Since the transmission availability rate is an important planning parameter which is calculated from the collected historical outage records in the transmission facilities, it is recommended that a further refined study of historical outage records be conducted in order to increase the accuracy of the reserve adequacy and reliability assessment results. This is particularly important in view of the findings in this paper which revealed that the sensitivities of reserve and reliability indices to variations in the assumed transmission availability rate are significant.
4. Finally, it is recommended that the Hail electricity authority consider developing in-house simulation-based capabilities in order to repeat the reserve adequacy and reliability assessment study – as outlined in this report – for other base-cases as well as other operating planning and operation scenarios.

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