EVALUATION OF POWER SYSTEM RELIABILITY:
ADEQUACY AND SECURITY CONSIDERATIONS

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ABSTRACT

Power systems are designed in such a way that many years of reliable service can be expected, even under adverse external and internal circumstances. Therefore, every electrical system has a set of planning criteria that system designers follow and implement to ensure the power system is capable of being operated to meet the required standards of quality of supply.

The application of power system reliability indices and the optimization of the power system operations is evaluated with due consideration to operational criteria, and the available generation and transmission facilities to minimize violation of security criteria and improve power system reliability. The Loss of Load Probability (LOLP) index is the focus in this approach for quality of supply determination for both Generation and Transmission. These indices can be determined by a simple approximation represented by the cumulative area under the normal distribution function up to the actual demand.

Power system reliability for the Bahrain Power System is evaluated with a view of the practical conditions that exist. An approach is presented for determining acceptable levels for reliability indices for different operational conditions. These acceptable levels become the criteria for setting proper reserve margins.

KEYWORDS

1. INTRODUCTION

All over the world, governments, industries, and the general public are always concerned about Electricity Supply Reliability. These concerns stem from the fact that electricity plays an essential role in the modern society life and has a major influence on the economy and development of a nation.

Typically, Power Systems are designed to withstand, without interruption a “single contingency” or in other terms N-1. Therefore, due to economic considerations, system designs would not normally protect all loads for multiple contingencies. However, special considerations are given to special and important parts of the system, where N-2 or even N-3 contingency concept is followed.

After any part of the power system has been designed, constructed, commissioned, and put into service, it is the responsibility of the power system operators to perform their functions to attain the maximum possible reliability that can be realized according to design, as well as to observe design limits. Therefore, all operational possibilities and configuration should be carefully considered during the design stage and verified with system operators.

2. KEY FEATURES OF POWER SYSTEMS

The reason for designing and operating a system in a meshed form is to provide multi paths from every generator to every load, to ensure continuity of supply in the possibility of power system elements outage. In general, bulk-power systems have two unique characteristics:

- The need for continuous and near instantaneous balancing of generation and load, consistent with transmission-network constraints. This requires metering, computing,
telecommunications, and control equipment to monitor loads, generation, and the voltages and flows throughout the transmission system, and to adjust generation output to match load. Generation must follow load in real-time because it is virtually impossible to store Bulk-Power.

- The transmission network is primarily passive. Unlike natural gas or water pipelines, transmission grids have few “control valves” or “booster pumps” to regulate electrical flows; control actions are limited primarily to adjusting generation output, influencing voltage levels and opening and closing switches to add or remove transmission circuits from service.

These two unique characteristics lead to four reliability consequences with practical implications that dominate power system design and operations:

- Every action can affect all other activities on the grid. Specifically, changes in the locations and amounts of power generated and consumed and in the configuration of the transmission grid can affect flows throughout the system. Therefore, the operations of all bulk-power plant must be coordinated.

- Cascading problems that increase in severity are a real problem. Failure of a single element can, if not managed properly, cause the subsequent rapid failure of many additional elements, disrupting increasing parts of the power system, and may lead to total system Blackout.

- The need to be ready for the next contingency, more than current conditions, dominates the design and operation of bulk-power systems. It is usually not the present flow through a line or transformer that limits allowable power transfers, but rather the flow that would occur if another element fails.

- In view of the dynamics of the power system, maintaining reliability often requires actions to be taken instantaneously (within fractions of a second), which requires computing, communication, and automatic control actions. For example, in the case of lightning striking a transmission line, breakers at both ends of the line sense the high current and open automatically. Within a fraction of a second (enough time for the problem to resolve itself), the breakers may re-close and power would continue to flow through the line. Because this process occurs so quickly, it takes place with no human intervention.

3. FACTORS AFFECTING POWER SYSTEM RELIABILITY

Reliability for an electric power system is, most simply, the extent to which consumers can obtain electricity from the system when and in the amount they want. In order to provide electricity to consumers in a reliable manner, electric utilities must be concerned with the adequacy and security of the bulk power electric system.

There are two main issues involved:

**Adequacy** deals with the capacity of the system. Adequacy involves having enough generation and transmission capacity available to meet customer demands for electricity plus reserves for contingencies. Adequacy deals with long-term planning and investment.

**Security** deals with the operation of the bulk power electric system. The security of the system involves the power system’s ability to remain intact even after equipment failures occur. It focuses on short-term operations and operational planning. Operational Planning engineers conduct day-ahead security analysis, analyze current-day operating conditions, and implement transmission loading relief procedures to mitigate transmission overloads. There are however some major factors that affect power system reliability, such as:

1. **Generation Reserve Capacity:** capacity over and above that required for meeting system load.
2. **Adequate Transmission Plant Capacity:** the load carrying capacity of the transmission lines and transformers is sufficient to carry normal load, with sufficient overload capacity to carry additional contingency loads.
3. **Prompt Operation of Protection Equipment and Disconnects.**
4. **Flexibility in changing the arrangements and connectivity of the Transmission System**
5. **Proper Switching Procedures**
6. **Independence of switchgear operations from power system energy:** Depending on batteries, compressed air, and compressed oil for operation without system supplies.
7. **Adequate and reliable interconnections.**
8. **Reliable monitoring and control systems and communications with key generation and transmission stations.**
9. **Proper maintenance practices to ensure proper functioning and high reliability of equipment.**
In our review, we will discuss a selection of these factors and indicate how the reliability considerations are met.

4. GENERATION RESERVE CAPACITY
The amount of generation reserve margin that is required for any one utility to operate reliably depends on factors such as customer demand, equipment characteristics, and what power agreements a utility has with neighboring utilities. There are same major factors or categories of factors that must be considered during design to ensure reliability of power system operations.

For proper operations, every power system should carry a generation capacity that is over and above that required to meet system load. However, there are several categories of generation reserves.

4.1 GENERATION RESERVE CATEGORIES

4.1.1 Spinning Reserve:
Defined as the on-line (synchronized) generation capacity within the system over and above the actual load, which is capable of increasing generation immediately depending on the response characteristics of the machines. Effective Spinning Reserve (ESR) is that part of the spinning reserve that can be provided by the units immediately prior to the intervention of governor controls.

4.1.2 Hot-Standby (Quick Start) Reserve:
These are stand-by units that can be brought on-line in a few minutes, such as gas turbines and hydro turbines.

4.1.3 Cold-Standby Reserve:
These are stand-by units that can be brought on-line after a time period, such as steam turbines and the related boilers. The time period extends from under an hour to a few hours.

4.1.4 Purchased Reserve:
This is reserve capacity that is agreed / purchased from another interconnected system. These reserves can be spinning on that system and made immediately available according to an agreed start-up period.

4.1.5 Interruptible Loads:
Under certain power sale contracts, provisions are made for the automatic/manual interruption of the supply to a certain portion of load during emergency conditions. These may be considered as part of the reserve. Usually such contracts provide power to the customer at reduced rates. An example of such is Under-frequency Load Shedding Schemes (UFLS).

4.2 EXISTING SPINNING RESERVE CRITERIA
Adequate Spinning Reserve is the primary security factor in power system operations. However, the amount of spinning reserve that a system is required to carry is a policy decision, which meets a certain balance between economy and security. Once the spinning reserve policy is set, System Planners should ensure adequate generation capacity exist to cover system load and spinning reserve requirements. It is thereafter the system operators' responsibility to attempt to meet the criterion each day, so that system security is not jeopardized. However, system operators should also have due consideration to economy and ensure no excessive reserve is carried on the system.

According to the existing criteria in Bahrain Power System Operations, and based only on the risk of loss of generation units, the total spinning reserve on the system \( (SR) \) should be more than the load of the most heavily loaded unit on the system \( (L_{\text{max}}) \); i.e.:

\[
SR > L_{\text{max}}
\]

Note that the above does not show how much higher than \( L_{\text{max}} \) should the spinning reserve be.

4.3 PROPOSED SPINNING RESERVE CRITERIA
A more realistic approach of specifying spinning reserve criteria is to base them on Calculated Risks, thus introducing more factors into the equation, such as:

4.3.1 Risk of loss of generation units
As above, Spinning Reserve requirement should basically consider the loss of the most heavily loaded unit on the system \( L_{\text{max}} \).

4.3.2 Allowance for Forecast error
If System load is underestimated, then the required ESR at the peak time will be less than that required. Therefore an allowance is set for forecast errors. Forecast error are calculated in percentage of the total system load, and based on historical data. Values of such errors are typically 2 to 3 % (\( F_{\text{error}} \)).
4.3.3 Allowance for regulation error
For the purpose of regulation, a certain percentage of System load is required to maintain system frequency under changing conditions. Thus a part of the reserve capacity would be utilized. Depending on the size and stiffness of the system, a regulation error is introduced which is in the range 3 to 5 % ($R_{\text{error}}$).

4.3.4 Contingency Factor
Under abnormal system arrangements that result in a higher-than-normal risk, the system operator may introduce an arbitrary contingency factor ($C_{\text{error}}$).

Therefore, the proposed requirement for spinning reserve is:

$$\text{Spinning Reserve} = L_{\text{max}} + F_{\text{error}} + R_{\text{error}} + C_{\text{error}}$$

5. TRANSMISSION PLANT CAPACITY
Transmission Plant Capacities are subject to design factors and are not under the control of system operator. The system operator ensures that normal and abnormal limits of transmission equipment are not exceeded. By constant monitoring of load and voltage conditions, the system operator try to manage the task by adjusting generation outputs and arranging connectivity of the system to prevent overload or fault level violations from occurring.

6. GENERATION & TRANSMISSION ADEQUACY UNDER EVOLVING ELECTRICITY MARKETS
In general, generation reserve margins in Bahrain have been declining in the past two decades. We define the Generation Reserve Coverage Ratio (defined as the multiple of times reserve capacity can cover the largest single generation loss) as an index of generation adequacy. Figure 1 shows that such index has been declining on average at a rate of 1.2 per decade. Currently, generation reserves are very tight, suggesting that additional generation is required to ensure generation Adequacy. The situation on the transmission side is also as grim.

Typically, in a vertically integrated utility, decisions on the amounts, locations, types, and timing of investments in new generation and transmission would be made by a single entity with a common goal of proper coordination and optimization of generation and transmission requirements.

However, as the electricity supply industry is restructured, these decisions become fragmented and dispersed among a variety of entities. This presents a dilemma.

On one side, generation becomes increasingly competitive, and decisions on building new generators and to retire, maintain, or rehabilitate existing units will be made based mainly on assessments of future profitability and only secondarily on System or area reliability.

On the other side, economies of scale imply that Transmission systems design concepts will change to account for carrying significantly higher bulk-power transactions with only limited additions to the grid.

Therefore, coordination of transmission and generation expansions is likely to deteriorate under a competitive and restructured electricity industry because:

♦ For competitive reasons, generation plants investors will not reveal their generation-expansion plans ahead of time, to avoid giving other competitors the chance to reposition their plans to counteract their actions.

♦ Construction and erection of generating units often requires shorter time than building a transmission line.

Therefore, and due to the natural monopoly of transmission grids, electricity markets may play only a modest role in influencing transmission systems expansions. Such conditions will lead to transmission congestion.
6.1 Effect of Low Generation Margin on Generation Marginal Quality of Supply ($\gamma_{QS}(t)$)

Assuming the total generation during hour (t) to be $g(t)$, a critical generation level $g_{crit}(t)$ is defined based on the maximum available generation capacity $g_{max}(t)$ during hour (t). This critical generation level corresponds to a minimum required generation reserve margin $g_{res}(t)$ such that:

$$g_{crit}(t) = g_{max}(t) - g_{res}(t)$$

As $g(t)$ exceeds $g_{crit}(t)$, the reliability of the electricity supply drops and the utility has to take certain measures to restore normal reserve margin and reliability levels. Such measures would be costly and would reflect in the hourly Spot Price to give the right price signal to customers. A high quality of supply component would give incentive to generators to offer more generation and consumers to reduce their consumption levels until $g(t)$ drops below $g_{crit}(t)$.

The Loss of Load Probability due to generation shortage $LOLP_\gamma$ can be used to determine spot price component $\gamma_{QS}$. The $LOLP_\gamma$ can be represented by the cumulative area under the normal distribution curve up to the actual generation $g$ (Figure 2). The specified mean would be $g_{crit}$ and the standard deviation $\sigma$ would be equal to $g_{res}$. The cumulative area under the normal distribution curve would then vary from nearly zero at $-\sigma$ to reach nearly 1 at $+\sigma$ as shown in Figure 2.

$$\gamma_{QS}(t) = LOLP_\gamma(t) C_{QS,\gamma}$$

where $C_{QS,\gamma}$ is the average cost of unserved energy ($/MWh$).

6.2 Effect of Transmission Congestion on Network Quality of Supply ($\eta_{QS,k}$)

The Transmission Network Quality of Supply component ($\eta_{QS,k}(t)$) is determined practically by assuming an aggregated network model based on:

- Loss Of Load Probability due to network limitations during hour (t) $LOLP_\eta(t)$
- Expected Annual Loss Of Load Hours due to network limitations $LOLH_\eta$

The $LOLP_\eta$ would be represented by the cumulative area under a normal distribution curve (Figure 3) up to the actual demand $d$. The specified mean would be $d_{crit}$ (network loading limit) and the standard deviation $\sigma$ would be equal to $d_{res}$ (Network reserve loading margin = $d_{crit} - d$). The cumulative area under the normal distribution curve would then vary from nearly zero at $-\sigma$ to reach nearly 1 at $+\sigma$.

Once the value of $LOLP_\eta$ is determined from the above curve, the value of $\eta_{QS}$ can be calculated as follows:

$$\eta_{QS}(t) = LOLP_\eta(t) C_{QS,\eta}$$

where $C_{QS,\eta}$ is the average cost of unserved energy due to network constraints ($/MWh$).

6.3 Overall Effect of Low Generation and Transmission Adequacy on Reliability

In a responsive electricity market (i.e. highly elastic demands), the above increase in Quality of Supply components would cause increasing price signals that would flatten the peak demand as generation and transmission reserve capacities fall below required levels. However, GCC systems can be characterized with an inelastic demand (i.e. almost non-responsive to price...
changes). Such systems are more susceptible to cascading failures due to the fact that larger duration is spent with lower generation and network reserve margin, raising the probabilities of loss of load (LOLP). These conditions would lead to lower generation and network reliability indices.

7. ALTERNATIVE SYSTEM ARRANGEMENTS
Normal arrangements of the transmission system should account for certain security criteria that are different for a Bulk Supply Point (BSP) than, say, radial feeds to small load point. However, transmission system configuration should allow for the ability to alter the arrangements of transmission circuits in the case of emergencies in order to restore service with the minimum delay time, and without disconnecting additional loads.

In order to optimize the decisions to change the arrangements, various contingency studies are conducted offline, ahead of time, and a set of contingency plan actions are advised for the system operators to follow.

8. PROPER SWITCHING PROCEDURES
Seasonal changes in load present several situational variables that present an opportunity to switch out generation and transmission plant for maintenance or present a requirement to alter the generation mix and transmission system arrangements.

It is quite essential however, to carefully adhere to a pre-set proper sequence of switching for the outage or restoration of circuits. Switching Procedures are required to preclude damage to the equipment, ensure the safety of the power system, and ultimately, ensure the safety of personnel.

In order to ensure such objectives are met on the main system, switching procedures are directed only by the Grid Control Engineer. Proper adherence to procedure will ensure safety of the system and equipment thus improving reliability.

One of the most important issues is that the switching procedure has to be carried out precisely in the pre-determined order and the transition from one phase of switching is only done when the first phase has been completed fully and confirmed from all relevant parties.

Pre-written orders are typically prepared and checked before implementation. With an advanced EMS system and a sophisticated sequence switching system, self contained phases or parts of the sequence switching can be carried out using such facilities which will result in time saving and error minimization.

9. ADEQUATE AND RELIABLE INTERCONNECTIONS
Under emergencies, other interconnected systems can provide significant support and assistance to the power system. One effect is higher System stiffness and thus lower effect of loss of generation on frequency drop, and the possibility of sharing ESR between the systems, thus optimizing the spinning reserve capacity carried by both systems.

10. RELIABLE MONITORING AND CONTROL SYSTEMS
System operators rely on the information they receive through the Supervisory Control and Data Acquisition systems (SCADA) for the decision-making process. Therefore, the reliability of the SCADA and communication systems is a major contributor to the overall system reliability.

In order to optimize the decision-making process, it is required to ensure the reliability of the SCADA and communications by ensuring:

- Independence of SCADA systems from system supplies
- Reliability of Communication Channels
- Providing more than one communication path for each location.
- Maintaining redundancies to account for SCADA plant failures
- Reliability of measurements and indications
- Validity of EMS programs and software

11. EVALUATING RELIABILITY SITUATION IN BAHRAIN POWER SYSTEM

11.1 GENERATION CAPACITY:
Recently, there have been concerns about generation adequacy. Generation reserve margins have been declining (Figure 4).

Currently, reserve margins are tight or even non-existing, suggesting that additional generation is needed (Figure 5).
11.2 TRANSMISSION CAPACITY:

As with generation, expansion of transmission grids has not kept pace with growth in electricity demand, especially between 1988 and 1994. There was no significant transmission expansion while there was an increase of peak loads by more than 40% in the same period. The result is that Transmission Networks are congested, forcing abnormal loadings and peculiar transmission configurations that are not secure. Following are just examples of many such conditions:

### 11.2.1 Loading of Bulk Supply Points

The security criteria for Bulk Supply Points (BSPs) is based on N-1 consideration of loss of transmission is shown for Load Type C in Table 1 below.

According to the above criteria, the loss of a single item during summer or winter load should mean no interruption to supply. In practical terms, following the trip of one item it is to be insured that:

- Remaining items not to exceed overload capacity (e.g. 120%)
- Provisions exist for reducing any overload to normal load limit within a preset time (e.g. 2 hrs)

A review of the bulk supply points loading during the past few years shows that the criteria have not been met for some BSPs.

### Table 1 – Security of Supply Criteria for Transmission System

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Summer</th>
<th>First Item Loss (N-1)</th>
<th>Second Item Loss (N-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Load (MW)</td>
<td></td>
<td>Winter</td>
</tr>
<tr>
<td>A</td>
<td>&lt; 15 MW (Lightly loaded stations)</td>
<td>Load to be met within 2 hours</td>
<td>Load to be met following repairs / restoration of one item</td>
</tr>
<tr>
<td>B</td>
<td>15 to 65 MW (Stations between BSPs)</td>
<td>Load to be met following switching</td>
<td>Load to be met following repairs / restoration of one item</td>
</tr>
<tr>
<td>C</td>
<td>65 to 300 MW (Bulk Supply Points)</td>
<td>No interruption</td>
<td>Load to be met following switching</td>
</tr>
<tr>
<td>D</td>
<td>&gt; 300 MW (Largest Blocks of load)</td>
<td>No interruption</td>
<td>No interruption</td>
</tr>
</tbody>
</table>
11.2.2 Selection of Normal Open Points (NOPs)

Typically, Normally Open Points are selected on the transmission system in such a way to:

- Control fault levels
- Control load flows
- Avoid cascaded tripping
- Ensure proper MVAr flow/Voltage profile

Referring to Table 1 and specifically for Load Type “B” stations, the criteria require that load should be met following switching operation. The typical configuration for such stations is shown in Figure 6, where alternate supply from another BSP exist.

![Figure 6 – Normal Configuration for a Class “B” Substation](image)

With the above configuration, and provided system design is according to criteria, it would be possible to restore supply, say, for substation 1 following loss of the incoming cable from BSP 1 by closing the NOP and transferring its load to BSP 2.

However, lack of system reinforcement will violating the “Planning Criteria”, thus the security criteria cannot be met by the system operator.

For example, assume that due to the uneven distribution of loads between stations 1 & 2, station 1 load may be 56 MVA while station 2 load is 25 MVA. Additionally, cable between BSP 1 and Station 1 has been derated to 52 MVA only. Under such circumstances, and under restrictions of 11 kV load transfer, the system operator would be forced to follow irregular arrangements such as shown in Figure 7, to avoid overloading of cables. By doing so, the criteria stipulated in table 1 cannot be met, as supplies cannot be met due to unswitchable busbar split.

12. CONCLUSION

Power system reliability receives the highest importance for both system designers and operators, who devote a great deal of thought and effort in this subject and invest substantial sums to ensure reliability objectives are met. Reliability of a power system involves the comprehensive consideration of security of system operations and reliability of the individual components of the power system. Modern SCADA systems frequently provide security functions to provide system operators with indications of potential problems affecting the reliability of their system. By considering the appropriate approaches in optimizing the reliability related to the different factors concerned, the overall reliability of the power system can be improved.