ABSTRACT

The paper presents the reliability analysis for a combined power generation and distribution system of a petrochemical complex. The production facilities expansion required addition of generation units and extension of the network. The analysis has been performed for both situations – before and after addition of generation units and extension of the network. The results of the analysis have been compared with indicative figures from the international standards. The outcomes show that the availability of the industrial power system is high, both in the existing configuration and also after implementation of the expansion project. The analysis indicates that possible long-term failures of the distribution system may be caused only by transformer failures. Improvements to the supply concept have also been tested and their impact on the overall reliability indices evaluated.

INTRODUCTION

The reliability of the power supply in industrial power systems is a major goal for system design, because of the high cost associated with power outages. This aspect should be carefully respected, starting from the design phase. The paper presents a case study on an existing power system of a petrochemical complex in a fast-growing South-East Asian country where, due to the load increase, the supply network has to be extended.

POWER SYSTEM MODEL

The simplified configuration of the power system of the petrochemical complex is presented in Figure 1. The production complex consists of several independent sites with their networks interconnected electrically at 33 kV for sharing the generation resources. One point of common connection to the local 132/33 kV utility grid is sized for a continuous import of only 10% of the peak load (170 MW before system extension and 200 MW after the planned system extension). The average combined load under normal operation is supplied by on-site simple cycle gas turbine generation units (11 power units before system extension and 13 power units after the planned system extension). Each of the three production plants has its own generation facility. Connection to the local utility is made only in the event of on-site unit outages.

Therefore the increased load will be covered by addition of two new generation units, connected at one of the existing 33 kV switchgear installations.

Figure 1 Simplified configuration of the electrical network

The electrical load configuration corresponds largely to the production modules, as shown schematically in Figure 2. The majority of the drives are direct on-line starting induction motors in the power range of up to 8 MW.

A spinning reserve of N+2 at peak loading is required in order to be able to operate the production plants with no dependency on the utility grid. The operation philosophy is N-1 at distribution level, especially as there are no standby or spare transformers in the power system. Production site maintenance and distribution system maintenance is always performed simultaneously, so planned outages have no significant impact on the security of supply.

RELIABILITY ANALYSIS

Methodology and assumptions

The basic concept of a reliability analysis is the derivation of system performance from component performance, while also considering component interdependency. Components of an electrical supply system are switchgears, cables, transformers and generators, or power units.

Hence the reliability assessment can be divided in terms of its application to the segments of a complete power system.
into Level 1 (generation system only) and Level 2 (generation and distribution facilities) studies. The object of the study performed was to assess the reliability of the industrial power system at Level 2.

One of the major difficulties especially in distribution system reliability calculations may be the large number of system states. Each system component has at least two states - up and down. For the presented distribution system reliability analysis, with more than 360 network elements, this leads to $2^{360}$ system states which is more than $10^{100}$.

There are two major computational methods used in power system reliability analysis: Monte Carlo simulation and the analytical method also called state enumeration method. Monte Carlo simulation is used for simulating one operational period of a system (e.g. one year) some thousand times to achieve the statistical indices. A huge computational effort and often insufficient convergence in probability are the major disadvantages. The analytical method delivers all the possible system states one by one using suitable algorithms which ensure that each possible system state is only analyzed once. The state enumeration method is fast enough even for the analysis of large distribution networks and yet does not compromise accuracy. Exact analytic averages are calculated.

The analytical method is normally based on a quasi-Markov process. For all system components an exponential distribution is assumed for the failure rate. In this situation, the probability of failure in a particular time interval is independent of the position of the time interval and also of the history of that element.

The high number of system states must be limited during calculation. This limitation may be done both by reducing the number of component states and by pre-computational limiting of the number of system states to be analyzed. The first approach is implemented by assessing the generator model (in this study: converting the 6-state model normally used in Level 1 analysis to an adequate 2-state model) as well as by neglecting component maintenance through simultaneous servicing of the electrical power system and the production modules. The second approach is based on two variable constraints: the minimum state probability or the maximum number of system components that have simultaneously failed. Adopted as a constraint is the minimum state probability, which was set at $10^{-8}$.

Reliability analysis of the industrial power system

The assessment of the industrial power system adequacy was conducted using the reliability module of a software package for network analysis [2]. The basic calculation flow chart is depicted in Figure 3.
The sequence of the reliability evaluation was as follows:

- **Network data**
The same network data was used for distribution reliability evaluation and assessment of load-flow and short-circuit system performance for both the present and the future system. Equipment reliability data was extracted from data collection on site or from international standards [5]. For this task, the system equipment was classified as follows:
  - components of varying length (in this study: cables)
  - static components (e.g. transformers)
  - switching components (circuit breakers, disconnectors and their associated protection and control systems).

- **Separation of calculation components**
For the calculation, system elements have to be combined to calculation components (typical example: switchgear bay). The components are separated by a protection zone. This separation of components is easy to apply for modelling the failure process.

- **Modelling failure process**
The following failure modes have been taken into account:
  - independent failures of all system components
  - failure of protection to operate
  - spurious protection trips
  - breaker failures.
Common mode failures have not been taken into account because there are only very small sections of cable routes where common mode failures may occur, so the contribution of this failure to overall unreliability is negligible.

- **Application of restoration, remedial actions after faults**
The following types of restoration or remedial actions have been considered:
  - generation dispatch
  - corrective switching
  - load shedding
  - component restoration time.

- **Power system state analysis**
The outages and their effects on the network (Failure Effect Analysis, FEA) are determined for each state independently of other states performing connection check (very fast) and AC load flow simulation.

- **Evaluation of indices**
For evaluation of the reliability indices for all system states, matching predetermined conditions have been combined, for example all system states with supply interruption to a consumer (busbar).
Results of the calculations [4]:
  - frequency of supply interruption (AIF)
  - duration of supply interruption
  - probability of supply interruption (AID)
  - electrical energy not supplied (EENS).

Besides the above reliability indices, following a special request from the petrochemical plant, an additional two indices have been determined. These indices are used for statistical recording by the customer.

\[
\text{Availability} = 1 - \frac{\text{Down_time}}{\text{Total_time}}
\]

\[
\text{Reliability} = 1 - \frac{\text{Unscheduled_Downtime}}{\text{Total_time} - \text{(Scheduled_Downtime)}}
\]

**STUDY CASES AND RESULTS**
The analysis has been performed for two network configurations – existing situation and after completion of the network expansion project.

**Table 1** presents the results of the calculations for the main busbars in the system – at 33 kV, 11 kV and 6.6 kV voltage levels (peak load). **Table 1** presents the results for the overall availability and reliabilities calculated from equations (1) and (2).

<table>
<thead>
<tr>
<th>Voltage level</th>
<th>Existing configuration</th>
<th>Future configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AIF</td>
<td>AID</td>
</tr>
<tr>
<td></td>
<td>1/year</td>
<td>h/year</td>
</tr>
<tr>
<td>33 kV</td>
<td>1.48</td>
<td>4.89</td>
</tr>
<tr>
<td>11 kV</td>
<td>1.61</td>
<td>10.6</td>
</tr>
<tr>
<td>6.6 kV</td>
<td>1.34</td>
<td>5.25</td>
</tr>
</tbody>
</table>

The analysis shows a reliability improvement for the future configuration regarding all indices except EENS at the 33 kV level due to increased load. Additionally only simultaneous failures of more than 2 power units or transformer outages caused long-term supply interruptions.

**Table 2**

<table>
<thead>
<tr>
<th></th>
<th>Existing configuration</th>
<th>Future configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>Reliability</td>
<td>Availability</td>
</tr>
<tr>
<td>99.944 %</td>
<td>99.933 %</td>
<td>99.977 %</td>
</tr>
</tbody>
</table>

A comparison with reliability indices values for the oil industry from standards [1] and another reference from a German chemical power plant [3] is included in **Table 3**. The values in **Table 3** indicate that the composite system availability (generation and distribution system, normal load) is within or better than international standard values for systems in the oil industry, and is also on a par with other industrial power systems.
### Table 3

<table>
<thead>
<tr>
<th>Source</th>
<th>AIF [1/year]</th>
<th>AID [h/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>International standard [1]</td>
<td>0.33</td>
<td>9.87</td>
</tr>
<tr>
<td>Chemical plant [3]</td>
<td>0.28</td>
<td>3.0</td>
</tr>
<tr>
<td>6.6 kV busbars – Existing configuration</td>
<td>0.69</td>
<td>2.23</td>
</tr>
<tr>
<td>6.6 kV busbars – Future configuration</td>
<td>0.3</td>
<td>1.27</td>
</tr>
</tbody>
</table>

### Distribution system with spare transformers

If there are spare transformers available (at least one per voltage level and rated power), a reduction of the time to replace a failed transformer from 4 months to 5 days may be assumed. Such a reduction may be deemed as essential because transformer failures are the sole cause of long-term supply interruptions. Table 4 shows the results.

### Table 4

<table>
<thead>
<tr>
<th>Voltage level</th>
<th>System without spare transformers</th>
<th>System with spare transformers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AIF 1/year AID h/year</td>
<td>AIF 1/year AID h/year</td>
</tr>
<tr>
<td>33 kV</td>
<td>0.758 1.99</td>
<td>0.861 2.01</td>
</tr>
<tr>
<td>11 kV</td>
<td>1.02 6.52</td>
<td>0.923 2.61</td>
</tr>
<tr>
<td>6.6 kV</td>
<td>0.745 2.37</td>
<td>0.851 2.02</td>
</tr>
</tbody>
</table>

The AID index decreases, especially at the 33 kV level and also at the 6.6 kV level, but doesn’t change at the 11 kV level because power unit failures have only a minor effect on the reliability of the 11 kV busbars.

### New system configuration (two additional connections to the local 132/33 kV utility grid)

Another approach for reliability improvement is the addition of two connections to the local 132/33 kV utility grid at the 33 kV level. This is assumed to reduce the effect of power unit outages, which are the major factors determining system reliability. The connections to the local 132/33 kV utility grid are supposed to be switched on during normal operation. Table 5 shows the results.

### Table 5

<table>
<thead>
<tr>
<th>Voltage level</th>
<th>System with one utility connection</th>
<th>System with three utility connections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AIF 1/year AID h/year</td>
<td>AIF 1/year AID h/year</td>
</tr>
<tr>
<td>33 kV</td>
<td>0.758 1.99</td>
<td>0.974 0.31</td>
</tr>
<tr>
<td>11 kV</td>
<td>1.02 6.52</td>
<td>1.25 5.94</td>
</tr>
<tr>
<td>6.6 kV</td>
<td>0.745 2.37</td>
<td>0.966 0.844</td>
</tr>
</tbody>
</table>

The AID index decreases, especially at the 33 kV level and also at the 6.6 kV level, but doesn’t change at the 11 kV level because power unit failures have only a minor effect on the reliability of the 11 kV busbars.

### CONCLUSIONS AND RECOMMENDATIONS

The investigations have shown that the availability of the generation and distribution systems of the petrochemical complex is high, both in the existing configuration and also after implementation of the expansion project. The operation philosophies based on a spinning reserve of N+2 generators at peak loading and reserve elements at distribution level shows that the individual plants are able to operate reliably and do not depend on the local utility grid.

The analysis shows that possible long-term failures of the distribution system may be caused only by transformer failures, as this is the only equipment item with a lengthy repair time.

The decisive component for the composite system failure rate is given by generation outages, which implies that the distribution system is well maintained and sized.

The expansion project improves the overall reliability of the composite system by raising generation availability.

The following proposals are made for further improving distribution system availability and reliability:

- reduction of breakers’ reclosure times after tripping by protection system (improved system diagnosis after circuit breaker trip at 11 kV and 6.6 kV, remote control)
- availability of spare transformers (at least one per voltage level and rated power)
- two additional connections to the local 132/33 kV utility grid.

### REFERENCES


