Reliability, Cost and Profit Assessment of On-site Generator Installation Capacity for Industrial Plant

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Abstract: - A probabilistic approach for onsite generator installation capacity assessment is proposed from the view point of the reliability, cost and profit during maintenance for industrial plants. The improved reliability, maintenance cost and avoided failure shutdown risk of an industrial plant with onsite generator installation are assessed as probabilistic values by the proposed approach. With the proposed approach, owner of industrial plant can make a decision how much capacity onsite generator to have. The validity of the proposed approach is demonstrated with numerical examples by using an industrial plant model.

Key-Words: - Reliability, Maintenance, Industrial Plant, On-site Generator, Power System

1 Introduction
Onsite generator installation is a conventional and effective option for backup power supply and/or reducing electrical power purchase in an industrial plant. In developing companies where electrical power system is not sufficiently constructed, on-site generator is the unique option in general. On the other hand, the initial cost of the on-site generators has a large impact on the economy of the plant, and plant owners are required to assess the cost performance of the on-site generators installation. Under such situation, reliability evaluation method for plant owners has become far more important and critical.

Probabilistic approaches have been applied to many of reliability assessment researches. Especially Monte-Carlo simulation has been applied in many researches [1]-[3] and is still one of the major schemes for probabilistic approaches as the scheme can deal with complicated failure conditions [3]. However, Monte-Carlo simulation requires a lot of iterations of calculation. That is why the improvement of calculation time is still under studies. The expected value based method is also one of the major schemes for probabilistic approach [4]-[9]. The scheme requires a very simple calculation instead of the difficulty on the complicated failure analysis.
Bulk power system consists of a large number of generators, transformers, cables, and so on. That makes the analysis too complicated.

On the other hand, an industrial plant also has generators, transformers, cables and so on same as bulk power system, however, the number of such equipment is far smaller than that of bulk power system. That is, expected value based scheme can be suitable for the reliability analysis of the industrial plant.

In this paper, a probabilistic risk analysis is proposed for onsite generator installation strategy in an industrial plant. The proposed approach considers the cost relating to the maintenance of industrial plant and the risk of the shutdown/outage of industrial plant caused by failure in onsite generation.

In Section 2, the shutdown cost of the industrial plant is formulated.

In Section 3, the risk of the onsite generator failure in industrial plant is formulated. In this formulation, the reliability of industrial plant is expressed in the form of reliability cost, and the risk is formulated based on the reliability cost. Furthermore, the section gives the contribution analysis of the redundant installation of the on site generators with an example.

Section 4 shows the plant electrical model used in the proposed analysis and the philosophy of the model structure.

Section 5 gives the assumptions of the maintenance cost calculation and risk analysis for the proposed approach.

Section 6 demonstrates the validity of the proposed approach using a simplified industrial plant model. Concluding remarks are summarized in section 7.

2 Plant Shutdown Cost Formulation

When plant is shutdown for planned maintenance or due to a failure of equipment in the plant, an opportunity cost occurs because of no production. In addition, recovery operation cost and product losses will arise during failure shutdown.

Therefore, the cost of plant shutdown due to failure can be formulated as unplanned downtime cost (UDC).

\[ UDC(x, t) = \sum \{ \text{OppCost}(x, t) + \text{RcvOpr}(x, t) \} + \text{Loss} \]  

(1)

where,

- \( x \): Vector of generators in a plant
- \( t \): plant downtime
- \( \text{OppCost} \): Opportunity cost
- \( \text{RcvOpr} \): Cost of recovery operation
- \( \text{Loss} \): Product loss

3 Risk Formulation

The risk of the unplanned shutdown of plant depends on the plant reliability. In this paper, the risk of the unplanned shutdown of plant is given as the expected value of unplanned downtime cost obtained from the plant reliability.

The plant reliability is the probability of the plant operating capability without any failure. In general, the plant reliability is equal to 1.0 when the plant is newly constructed and starts to decrease to 0 according to time passage. Fig. 1 shows the general shape of the plant reliability curve.

\[ \text{ExUDC}(x, t) = UDC(x, t) \times \text{FOR}_{\text{GEN}} \]  

(2)

where,

- \( \text{ExUDC} \): Failure risk of the plant expressed as the expected value of UDC
- \( \text{FOR}_{\text{GEN}} \): Integrated forced outage rate of the generators in the plant

\( \text{FOR}_{\text{GEN}} \) is calculated from the all the forced outage rate of the generators in the plant. That will vary according to the numbers of generators and total capacity of them.

If there are several generators in a plant and the total supply capacity is equal to, or a little larger than the total load capacity, all the generators have to be operated simultaneously. That means a failure of only one generator leads to plant shutdown. In such case,
reliability of the plant will become worse than single generator supply. On the other hand, when the total capacity of the generators is as large as total load capacity and at least one generator capacity, the reliability of the plant will becomes much higher than single generator case. The redundancy of the generators will contribute to the reliability improvement of the plant very efficiently. Figure 2 shows an image of the reliability differences among single generator case, multi generator with redundancy case and multi generator without redundancy case.

Plant owner should consider not only the initial cost of generator installation but also the contribution of the reliability improvement when installation capacity and numbers of the generator are decided or planned. The number of redundant generators is not necessary to be large. Only by one number of generator, the reliability of the plant will be significantly improved. For example, assuming that there are three generators having same forced outage rate in a plant and the required load capacity is equal to the total of two generators, \( FOR_{GEN} \) can be calculated as below.

The plant can be operated when two of generators are available. Therefore, the plant will stopped only in two or three of generators are in fault condition. The probability of such condition is

\[
FOR_{gen} = 3 \times FOR_g \times (1 - FOR_g) + FOR_g
\]

where,
\( FOR_g \): Forced outage rate of a generator

If the \( FOR_g \) is 0.05 (5\%), \( FOR_{GEN} \) will become 0.00725 (0.7\%). 5\% of FOR is higher than the FOR of general public utility generators, however, redundancy of generator installation realizes a high reliability condition.

In this paper, one number of the redundancy is considered for the capacity and the number to be installed of the generator.

### 4 Plant Electrical Model

There are many kinds of electrical equipment in an industrial plant, such as generators, transformers, cables, loads and so on, same as an electrical power system. Generally, outline of the electrical circuit of an industrial plant is like Figure 3. The plant model used in this paper does not connect to public utility power system. That is because the price of the electricity varies widely among countries. Furthermore, the quality of the electricity supplied from public utility also varies and the comparison from the cost viewpoint is very difficult and complicated.

From the above background, public utility supply was excluded from the plant electrical model. Each line (Line X-M) has stand-by system (Line X-S). Stand-by system has the same capacity and ability of main system and runs when switched from main line system.

Since this paper focuses the on site generator installation, the electrical circuit is simplified shown in Figure 4. The simplified electric circuit model consists of generators and an integrated load. This simplified electric circuit model is used for analysis by the proposed approach.
5 Assumptions of Calculation
For calculations in the proposed analysis, several assumptions listed below are applied.

1) In stalled generator FOR (Forced Outage Rate)
   Every generator has the same FOR. The FOR depends on the reliability curve of generators and will vary according to the operated time. The definition of FOR in this paper is the forced outage rate of generator which is warranted by generator manufacturer. That is the forced outage rate at the several time passed.
   The FOR used in the proposed analysis is assumed sufficiently later than the focused timing. Therefore, the actual forced outage rate can be smaller than used FOR for the analysis (Figure 5).
   The result from used FOR is stricter than the actual from reliability viewpoint.

2) Required maintenance period
   Maintenance for one generator requires 7 days. After 7 days have passed, the generator is ready to operate.

3) Electrical Load Operation
   Electrical load is operated constantly for 24 hours. Switching from the running production line to the standby production line can be done instantaneously. From the assumption, power consumption of the load can be regarded as constant.

4) Generator installation capacity
   Installed generators have same capacity in one plant.
   Owner chooses appropriate capacity as per installed numbers of generators.

6 Numerical Examples
Parameters used in numerical examples are shown in Table I through III. By using and based on shown parameters, the proposed probabilistic analysis is demonstrated.
Table I shows the basic parameters of the plant. The result using the values in Table I becomes the base case for the reliability and/or the economy comparisons in numerical examples.
In this section, gas engine generator is applied to the installed generator type.
Table II shows the values.
Turnkey cost is assumed to change according to the installed generator capacity to reflect the scale merit of the generators. Turnkey cost variation is summarized in Table III.

### Table I
<table>
<thead>
<tr>
<th>Parameter</th>
<th>FORG (%)</th>
<th>Integrated Load (kW)</th>
<th>Product ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>5</td>
<td>6000</td>
<td>1,000,000</td>
</tr>
</tbody>
</table>

### Table II
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Turnkey Cost ($/kW)</th>
<th>Maintenance Cost (%/year)</th>
<th>Heat Recovery Cost ($/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>600 - 1,000</td>
<td>20</td>
<td>150</td>
</tr>
</tbody>
</table>

### Table III
<table>
<thead>
<tr>
<th>Capacity (kW)</th>
<th>Cost ($/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~1000</td>
<td>300-500</td>
</tr>
<tr>
<td>1000-3000</td>
<td>800</td>
</tr>
<tr>
<td>3000-6000</td>
<td>600</td>
</tr>
</tbody>
</table>

6.1. Reliability Analysis
As explained in section 3, the redundancy of the installed generators improves the reliability of the plant. However, too many generators installation will have impacts on the reliability. Figure 6 through 8 show the overall forced outage rate (FOR) of the plant with 0.05, 0.03 and 0.01 of each generator FOR.

Fig. 4. Simplified plant electrical circuit model

Fig. 5. Generator reliability of focused point
respectively. Overall FOR corresponds to $\text{FOR}_{\text{GEN}}$ in (2).

The overall FOR is the smallest when two generators are installed in every case. The FOR of generator becomes smaller, more generators can be installed to have the higher reliability than single generator installation.

From the reliability viewpoint, it is clear that one normal generator and one stand-by generator installation is the best selection. However, such selection cause to a large capacity generator stand-by. That has a significant impact on the economy of the plant. Therefore, plant owner have to consider the balance between the reliability and the economy of the plant.

### 6.2 Economy and Reliability Analysis

To consider the balance between the reliability and the economy of the plant, the reliability of the plant is transformed to a cost formulation using (3). By (3), the reliability of the plant is expressed as the expected value of the unplanned downtime cost, which is the expected value of the risk of the plant shutdown in case of failures.

The redundant installation of the generator has an advantage of the reliability. Furthermore, it has an advantage of the economy. When maintenance of the generator is required, the plant without redundant generator has to be shutdown and planned downtime cost is required during the maintenance. On the other hand, the plant with redundant generators can be operated without shutdown during maintenance under the condition that the maintenance of the generator is carried out one by one.

Table IV shows the scheduled maintenance cost and the plant shutdown risk, that is expected value of the unplanned downtime cost. The maintenance cost becomes bigger when the number of installed generator is small, however, plant shutdown risk is lower due to shorter maintenance period. It means that the plant has longer period with redundant generator.

Figure 9 shows the profit of the plant during one by one generator maintenance. As assumed in section 5, maintenance period is 7 days. The profit of the plant is obtained the difference between the total of the product and the sum of the scheduled maintenance cost and the plant shutdown risk.

<table>
<thead>
<tr>
<th>No. of Generators</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance Period (Days)</td>
<td>14</td>
<td>21</td>
<td>28</td>
<td>35</td>
<td>42</td>
</tr>
<tr>
<td>Maintenance Cost (M$)</td>
<td>1.62</td>
<td>0.81</td>
<td>0.72</td>
<td>0.54</td>
<td>0.43</td>
</tr>
<tr>
<td>Shutdown Risk (M$)</td>
<td>0.7</td>
<td>2.05</td>
<td>3.99</td>
<td>6.49</td>
<td>9.50</td>
</tr>
</tbody>
</table>

From figure 9, profit becomes the largest when one generator (6000kW) operated and the other (6000kW) is stand-by. That means one generator and one redundant generator, totally two generators installation, are the best selection for this plant from the reliability and economy viewpoint. Furthermore, more than four generators operation (less than
1500kW generator installation) will have the negative impact on the profit of the plant because of the increase of plant shutdown risk caused by the long maintenance period, which requires the plant operation without generator redundancy.

Fig. 9. Generator installation numbers and profit

7 Conclusion

In this paper the reliability of the plant has been formulated as a cost of failure risk using the proposed probabilistic approach, and optimal installation capacity of the generator was obtained based on the proposed approach.

The proposed approach could consider the balance between the reliability and the economy of the plant. The effectiveness of proposed approach has been verified through the numerical examples using the simplified plant electricity circuit model.

Cost related data of the distributed generators have been enriched with the progress of researches in the world, and reliability related data enrichment is required for more accurate evaluations of the reliability and economy of the industrial plant.

References:


