CONSIDERATION OF ACQUISITION COST IN LIFE CYCLE COST OF HIGH VOLTAGE SF₆ INSULATED SUBSTATIONS

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Abstract: The paper covers mainly the principle model of the life cycle cost (LCC) which considers the cost of losses during the overall lifetime of high voltage SF₆ insulated substations (GIS). An important task of the life cycle cost calculation is to identify the significant cost contributors including the acquisition cost which have a major impact on the complete life cycle cost. It is decisive for successful applications of life cycle cost method to dispose a suitable database in order to model individual phases of the life cycle cost. The complete process in calculation and analysis of life cycle cost for high voltage substations is presented by using exemplary case studies of different substations. The calculation method is introduced and checked by sensitivity analyses and parameter studies in order to introduce optimization scenarios. The impacts of different service strategies and various design layouts of high voltage SF₆ insulated switchgears are studied.

1 INTRODUCTION

The SF₆ insulated switchgear is generally all optimized components and incorporated into a total system. The integrated encapsulation of gas-insulated switchgears means more complexity in development and production. GIS has a very small design, depending on a voltage level whereby 70% reduction in space compared to air insulated substations is possible. The metal enclosure makes the gas-insulated switchgears impervious to atmospheric influences such as snow, rain, dirt and dust. It also reduces electromagnetic field emissions.

High voltage SF₆ insulated switchgears are an essential equipment in electrical networks. Particularly through the liberalization of the electrical power markets, an increasing economic pressure is imposed on the manufacturer and operator of high voltage SF₆ insulated switchgears. Investment- and operational expenses of high voltage SF₆ insulated switchgears have to align with financial necessities. High voltage SF₆ insulated switchgears are characterized by the large investment cost, the long lifetime and the high reliability. Especially the long lifetime makes it interesting to find a way to reduce the total expense of high voltage SF₆ insulated switchgears.

The failure and the outage of high voltage SF6 insulated switchgears are responsible for a considerable amount of total ownership cost. To reduce operational cost, the manufacturers of high voltage SF₆ insulated switchgears offer a variety of technologies, with which high voltage SF₆ insulated switchgears are optimized for different operational conditions. With a large diversification of switchgear technologies, selecting the best solution becomes a difficult task for the owners of high voltage SF₆ insulated switchgears.

Literatures [1-5] offered many approaches to assess the availability and the reliability of high voltage SF₆ insulated switchgears. However, detailed analysis of life cycle cost of high voltage SF₆ insulated switchgears is not rare only, but also limited by the lack of information about life cycle cost model. A relevant analysis of life cycle cost has not been found, which provided available data intended for the use in life cycle cost calculation. Finding and selecting suitable data, with which the cost structure can be transferred into a calculation model, is extremely difficult. To implement the model, data has to be derived from different sources. In some cases, assumptions have to be made to estimate the individual costs.

Above all, it is necessary to make an economic analysis for high voltage SF₆ insulated switchgears considering the high investment cost and the long lifetime. An important tool for evaluation and selection is life cycle cost. Life cycle cost is a form of capital budgeting, which takes all expenditures over the whole lifetime into account. Therefore, it is possible to assess different variants, redundancy, service, strategy so that the most effective cost solution is found for individual configurations of high voltage SF₆ insulated switchgears. The model must be flexible enough to meet individual applications and to consider alternative data. By means of sensitivity analysis, the influence of various parameters of high voltage SF₆ insulated switchgears on the optimization of life cycle cost can be evaluated.
This work begins with an introduction to life cycle cost. Subsequently, a suitable life cycle cost model is established and described. In case studies, the actual expenses are derived from available data for different typical substations. The life cycle cost is calculated and demonstrated based on this data. As a result, the effect of different monitoring methods on life cycle cost is simulated and discussed.

2 LIFE CYCLE COST STRUCTURE

2.1 Principle of life cycle cost
The life cycle is defined as “time interval between a product’s conception and its disposal” and the life cycle cost as “process of economic analysis to assess the life cycle cost of a product over its life cycle or a portion thereof”. According to the above, the life cycle cost is usually grouped into separate elements:

- acquisition cost;
- ownership cost;
- disposal cost;

The life cycle cost contains all costs to turn an empty field into a functioning substation. According to the chosen cost structure, the individual cost in a life cycle phase is divided into equipment cost and field cost:

\[
LCC = C_{acq\text{ Equ}} + C_{acq\text{ Fie}} + C_{own\text{ Equ}} + C_{own\text{ Fie}} + C_{dis\text{ Equ}} + C_{dis\text{ Fie}} \tag{1}
\]

where:
- \(C_{acq\text{ Equ}}\) = Acquisition cost of equipment
- \(C_{acq\text{ Fie}}\) = Acquisition cost of field
- \(C_{own\text{ Equ}}\) = Ownership cost of equipment
- \(C_{own\text{ Fie}}\) = Ownership cost of field
- \(C_{dis\text{ Equ}}\) = Disposal cost of equipment
- \(C_{dis\text{ Fie}}\) = Disposal cost of field

2.2 Acquisition cost of equipment
The equipment cost contains all payments by the manufacturer until the equipment is ready for delivery. The equipment cost consists of design, manufacturing and monitoring costs. The design costs are divided into the conception and prototype costs as well as experiment and type test costs while the manufacturing costs include the component cost and factory test cost of high voltage SF\(_6\) insulated switchgears.

\[
C_{acq\text{ Equ}} = C_{acq\text{ Des}} + C_{acq\text{ Man}} + C_{acq\text{ Mon}} \tag{2}
\]

where:
- \(C_{acq\text{ Des}}\) = Design cost of equipment
- \(C_{acq\text{ Man}}\) = Equipment manufacturing cost
- \(C_{acq\text{ Mon}}\) = Cost of monitoring equipment

The design cost will not be included in life cycle cost because the procedure of design is not in due course of life cycle phases for high voltage SF\(_6\) insulated switchgears.

During the phase of manufacturing, the equation (2) is replaced by the following equations

\[
C_{acq\text{ Man}} = C_{\text{Man Com}} + C_{\text{Man Tes}} \tag{3}
\]

where: \(C_{\text{Man Com}}\) = Component manufacturing cost
\(C_{\text{Man Tes}}\) = Test manufacturing cost

The monitoring cost is taken and included in life cycle cost calculation as percentage of the initial investment cost (Table 1).

<table>
<thead>
<tr>
<th>Monitoring device</th>
<th>SF(_6)</th>
<th>Function</th>
<th>Partial discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>145 kV</td>
<td>2 %</td>
<td>6 %</td>
<td>12 %</td>
</tr>
<tr>
<td>420 kV</td>
<td>1 %</td>
<td>3 %</td>
<td>6 %</td>
</tr>
</tbody>
</table>

2.3 Acquisition cost of field
The field cost includes all costs, with which the equipment of manufacturers is taken over and a functioning field is built. It includes for example civil engineer, material and labour costs for substation buildings, earthing, steelworks and foundations. If the utility has to buy new land for a substation, the land cost is also part of the field cost.

\[
C_{acq\text{ Fie}} = C_{acq\text{ Ins}} + C_{acq\text{ Lan}} \tag{4}
\]

where:
- \(C_{acq\text{ Ins}}\) = Installation cost of field
- \(C_{acq\text{ Lan}}\) = Land cost of field

Each typical value of the land cost is associated with the land area:

- 0 €/m\(^2\): land area is already owned by operators;
- 100 €/m\(^2\): country area;
- 1.000 €/m\(^2\): city area;

For the case study the installation cost is estimated to be 10% of the initial investment.

2.4 Ownership cost of equipment
The cost of ownership includes all expenses after commissioning of the substation, up to the point of its decommissioning and disposal (Figure 1). The cost of ownership is divided into “planned maintenance cost” and “unplanned maintenance cost”. The planned maintenance cost comprises all costs in connection with routine maintenance activities such as material, labour and travel costs. The unplanned maintenance cost includes the maintenance cost and the subsequent cost resulting from accidents. The subsequent cost
summarizes the outage cost arising from any interruption in power supply.

### 2.4.1 Planned Maintenance Cost

Planned maintenance, also referred to as preventive maintenance, describes all measures to decelerate, reduce or eliminate deterioration of unfailed equipments. Planned maintenance is carried out in regular intervals and the cost is therefore deterministic. The planned maintenance cost comprises labour, material and travel expenses for maintaining high voltage SF$_6$ insulated switchgears.

$$ C_{\text{Own,Equi}} = C_{\text{Eqi,Pl}} = (C_{\text{Lab}} + C_{\text{Mat}} + C_{\text{Tra}}) \cdot \frac{L_0}{\Delta l} $$

(5)

where: $C_{\text{Eqi,Pl}}$ = Planned maintenance cost of equipment  
$C_{\text{Lab}}$ = Cost of labour effort  
$C_{\text{Mat}}$ = Cost of material and spare parts  
$C_{\text{Tra}}$ = Travel cost  
$L_0$ = Lifetime (year)  
$\Delta l$ = Maintenance interval (year)

### 2.4.2 Unplanned Maintenance Cost

The unplanned maintenance cost for eliminating incidents can be deduced similarly from the planned maintenance cost.

$$ C_{\text{Own,Equi}} = C_{\text{Eqi,Unpl}} = (C_{\text{Lab}} + C_{\text{Mat}} + C_{\text{Tra}}) \cdot \lambda L_0 $$

(6)

where: $C_{\text{Eqi,Unpl}}$ = Unplanned maintenance cost of equipment  
$\lambda$ = Failure rate (1/year)

If a failure description of “whole GIS out of service” includes an interruption of energy transport, additional outage cost has to be taken into subsequent cost.

$$ C_{\text{Own,Equi}} = C_{\text{Eqi,Unpl}} = (C_{\text{Lab}} + C_{\text{Mat}} + C_{\text{Tra}}) \cdot \lambda L_0 + C_{\text{out}} $$

(7)

where: $C_{\text{out}}$ = cost of power outage

The outage cost contains all costs that arise from an interruption of power supply.

$$ C_{\text{out}} = (C_{\text{pen}} + C_{\text{los}} \sqrt{3} I U) \cdot t_{\text{down}} $$

(8)

where: $C_{\text{pen}}$ = Loss of supplied energy (€/kWh)  
$C_{\text{los}}$ = Penalty (€/h)  
$U$ = Rated voltage (kV)  
$I$ = Average current (A)  
$t_{\text{down}}$ = Duration of outage (h)

In most industry nations energy transport is based on the (n-1) criteria, so that the failure of a single equipment has no effect on the grid safety without further consequences. Without the (n-1) criteria or if more than one equipment fails, the additional energy transport might overload the functioning electric power grids. This can lead to chain reactions with major consequences.

### 2.5 Ownership field cost

The field cost includes all costs which do not directly belong to switchgears such as:

- maintenance cost for GIS buildings;
- maintenance cost for outside buildings (lawn, cable, visual inspection);

$$ C_{\text{Own,Field}} = C_{\text{Fie,Pl}} = (C_{\text{Lab}} + C_{\text{Mat}} + C_{\text{Tra}}) \cdot \frac{L_0}{\Delta l} $$

(9)

It is expected that all building damages, that might affect the switchgears, can be prevented by regular maintenance.

### Figure 1: Structure of ownership cost of high voltage SF$_6$ insulated switchgears

### 2.6 Disposal cost

The disposal cost has to comprise all cost of salvage and disposal after use, subtracted by earnings which can be received by selling the reusable materials. For the case study the disposal cost is estimated to be 5% of the initial investment.

### 2.7 Capital budgeting

The method of life cycle cost is more suitable for the long-term economic analysis since the payment transaction is affected by the interest or inflation rate in the past or future. With the payment transaction, the pay-out and the cash inflow are used in the model of life cycle cost. The most common method is the net present value (NPV), with which the discounted capital value of all cash inflow and payment-out are associated with $n$ life cycle costs.
\[ NPV = \sum_{j=0}^{n} \frac{LCC_j}{(1 + i)^j} \]  

where: 
- \( LCC \) = Life cycle cost 
- \( i \) = Nominal interest rate 
- \( \pi^e \) = Expected inflation

For the above mentioned all costs in a life cycle phase, a life cycle cost model summarizes different parts of costs (Figure 2).

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3 STUDY CONDITIONS

With the life cycle cost model for substations and available data, the results can be used for its intended purpose. To test and review the strategy how to reduce life cycle cost of GIS substations, the impact of different technologies and configurations on life cycle cost will be investigated. Based on the assumption of life cycle cost model, an optimization of life cycle cost is attempted and discussed. The calculation of the concept optimization use the following steps:

- determine substation layout and calculation conditions;
- determine cost structure and all relevant costs;
- determine all element costs;
- calculate the cash flow;
- discounting the cash flow;
- calculate the life cycle cost;
- find optimum by means of sensitivity analysis;

3.1 Optimization of life cycle cost

Upon completion of design phase, up to 70% of total life cycle cost of SF\(_6\) gas switchgears is determined. Design and manufacturing in the early phase of life cycle cost have a great influence on reliability and availability of high voltage SF\(_6\) insulated substations. Increased expenses in manufacturing will increase quality and reduce cost of ownership. The interaction between initial and subsequent costs plays an important role in life cycle cost. The impact of the changing initial cost on the subsequent cost will be caused by different technical concepts. The possible dependence of the initial cost on the subsequent cost can be derived from the following hypotheses:

- **Hypothesis 1**: increasing initial cost leads to decreasing subsequent cost;
- **Hypothesis 2**: decreasing initial cost leads to decreasing subsequent cost;
- **Hypothesis 3**: decreasing initial cost leads to increasing subsequent cost;
- **Hypothesis 4**: increasing initial cost leads to increasing subsequent cost

The different hypotheses will lead to an investigation of the dependence of subsequent cost on initial cost. It is the hypothesis 1 that the higher initial cost will result in a higher technology and thereby decrease the subsequent cost due to higher reliability and lower maintenance expenses. It shows therefore that the initial cost and the subsequent cost of total life cycle cost are influenced by either utility or supplier. A low maintenance cost can be achieved by increasing reliability so that a reduction in total life cycle cost can be achieved.

The configuration of switchgears and substations has a significant impact on the ownership cost of whole SF\(_6\) gas switchgears. The relationship is shown in Figure 3 that a little redundancy with a small number of equipment causes lower acquisition cost. However, the risk of failures increases as an interruption of power supply brings the ownership cost. An increase in redundancy of an electric power system will reduce the risk of the outage and increase the availability of the system. However, the ownership cost is increasing with more and more numbers of equipment. It is important to find the optimal range in which total life cycle cost is minimized.

![Figure 3: Relationship between the redundancy and cost](image)

3.2 Strategy of monitoring maintenance

The manufacturing and installation costs of monitoring devices lead to high investment cost at...
the beginning of lifetime of an equipment. The investment cost for monitoring devices leads to an increase in life cycle cost, but reduced failure rate lowers life cycle cost. Monitoring devices are economical when the reduction in the failure rate corresponds to its earnings which are the initial and subsequent expenses for operation and maintenance. The economic benefit of the condition monitoring depends heavily on the failure-related cost. The effect of the condition based maintenance is shown in relation to a change of the failure rate (Table 2). The reduction in maintenance cost usually occurs many years later. This makes the economic value of this strategy very much depend on the interest rate.

Table 2: Reduction of failure rate with monitoring device

<table>
<thead>
<tr>
<th>Monitoring device</th>
<th>SF6</th>
<th>Function</th>
<th>PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction of failure rate</td>
<td>6%</td>
<td>21%</td>
<td>27%</td>
</tr>
</tbody>
</table>

Figure 4: Effect of monitoring devices on life cycle cost of double busbar substation

Figure 4 shows the life cycle cost of substations depending on a failure rate. With a decreasing failure rate, the repair and outage costs are reduced and therefore the life cycle costs also decrease. The life cycle cost for substations with monitoring is generally higher because of the acquisition cost of the monitoring equipment. The Figure 4 can be used to determine the necessary reduction in the failure rate for the monitoring equipment to amortize. For example this happens at 80% of the original failure rate (failure reduction by 20%) for the 420 kV substation. For the 145 kV substation the break-even point cannot be reached due to the lower repair and outage costs.

3.3 Optimization of monitoring method

In case of no outage cost from an interruption of energy transport, the unscheduled maintenance cost of 145 kV GIS substation can be reduced by the condition monitoring, but the cost reduction is obviously below the investment cost for monitoring devices (Figure 5).

Figure 5: Influence of different monitoring devices on life cycle cost of 145 kV GIS substation (Double bus bar) without outage cost

With high outage cost, it becomes more obvious that SF6 density monitoring seems to be the most efficient (Figure 6). With slightly higher subsequent cost, the function monitoring would become cost efficient as well. It has considerably higher investment cost than SF6 density monitoring, but offers the best ratio of the investment cost to the reduction of failure.

Figure 6: Influence of different monitoring devices on life cycle cost of a 145 kV GIS substation (Double bus bar) with high outage cost

Similar to 145 kV model substations, the additional investment cost in the condition monitoring for 420 kV substations cannot be compensated by the decrease in repair and replacement costs alone (Figure 7).
Figure 7: Influence of different monitoring devices on life cycle cost of a 420 kV GIS substation (Double bus bar) without outage cost

For 420 kV substations all monitoring devices become cost efficient. Contrary to the 145 kV substations where SF₆ density monitoring leads to the lowest life cycle cost, the combination of function and partial discharge monitoring seems to be most efficient for 420 kV substations (Figure 8). The high investment cost in monitoring devices is more compensated by the reduction in the outage cost.

Figure 8: Influence of different monitoring devices on LCC of 420 kV GIS substation (Double bus bar) with high outage cost

4 CONCLUSION

Life cycle cost analysis of high voltage SF₆ insulated switchgears represents an actual economical and technical solution. The present study complements the existing methods of evaluation and achieves a comprehensive, applied methodology. The life cycle cost model makes it possible to evaluate the effect of different maintenance strategies and to optimize the configuration of substations. Based on the case studies, the optimal proposals are derivable from individual approaches. This simulation is carried out with example maintenance strategies and the results are discussed. As an analytical method, the sensitivity analysis is undertaken to compare different variants. It is demonstrated that the simulation optimizes the maintenance strategy, depending on the layout and operational conditions.

The accomplished life cycle cost analysis of high voltage SF₆ insulated switchgears serves as

- an assessment of the impact and the cost of different components and equipment;
- an early plan of life cycle cost;
- a support of decision making strategies and a description of alternative decision effects;

5 REFERENCES