Life Cycle Cost of High Voltage SF₆ Insulated Substations

X. Zhang*, E. Gockenbach and M. Kuhnke
Institute of Electric Power Systems (Schering-Institut), Leibniz Universität Hannover, Germany
*Email: zhang@si.uni-hannover.de

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 which have a major impact on the complete life cycle cost. Sensitive analyses are performed by modifying different input data. The calculation of the life cycle cost is helpful to compare different variants of substations for a new investment. Moreover, the user can work out and select the optimal configuration of GIS with evaluating and minimized the life cycle cost.

I. INTRODUCTION

A SF₆ insulated substation uses a superior dielectric gas, SF₆, at moderate pressure for phase to phase and phase to ground insulation. The high voltage conductors, circuit breaker interrupters, switches, current transformers, and voltage transformers are in SF₆ gas inside grounded metal enclosures. The atmospheric air insulation used in a conventional, air-insulated substation (AIS) requires meters of air insulation to do what SF₆ can do in centimetres. GIS can therefore be smaller than AIS by up to a factor of 10. A GIS is mostly used where space is expensive or not available. In a GIS the active parts are protected from the deterioration from exposure to atmospheric air, moisture, contamination, etc.

While in the past most evaluations on economic benefits quite often end up with the capital cost of the investment, today the overall life cycle cost is concerned with service and end of life are under consideration [1], [2]. The liberalized electrical market demands efficient methods for evaluating the investment cost as well as the costs of ownership and decommissioning until the end of the service life for realizing the most efficient asset management. The user aims at selecting the best product and the optimal configuration according to his individual requirement. Criteria for evaluation and optimization of the assets are needed to choose the optimum solution for the individual substation. The high variety of high voltage switchgear technologies lead to many approaches for evaluation of the customer’s benefit. The life cycle cost is often discussed in the area of electrical power supply due to the economic circumstances which can decide criteria of investment as well as strategy of replacement.

The goal of any user to minimize the life cycle cost can only be achieved by a detailed knowledge about the specific parameters and their influence on the life cycle cost. The relevant parameters are selected for the life cycle cost which is subjected to sensitivity analyses. By means of this, it shows how different variables of investment and operation costs influence the overall life cycle cost. The risk analysis should be performed if different maintenance strategies have to be compared and optimized.

II. LIFE CYCLE COST STRUCTURE

A. Capital value

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 succeed in the model of life cycle cost from outflow to recycling. The most common method is the net present value, with which the discounted capital value (CV) of all cash inflow and payment-out are associated with the investment costs. The net present value (NPV) of the life cycle cost will result from the calculation of i interest rates up to the end of the service life for n investments.

\[
CV = \sum_{i=0}^{n} \frac{LCC_i}{(1+\text{rate})^i}
\]  

For the above mentioned n investments, a life cycle cost model summarizes different parts of costs:
- acquisition cost;
- ownership cost;
- decommissioning cost;

Due to the long-time attribute, these costs are capitalized.

B. Acquisition cost

The acquisition cost contains all payments to the manufacturer until the device is ready for delivery. The two main issues are the costs of equipment and installation. The equipment cost represents the expenditure for concept / definition design / development, manufacturing and engineering [3]. The engineering cost is the expense for planning and designing the substation:
- equipment cost
- switchgear, control & protection systems;
- engineering of equipment supplier;

The installation cost includes all expenses necessary to turn the switchgear system into a functioning substation. Most
manufacturers offer complete installation service included in the acquisition cost which can be influenced by the supplier or can be shared out totally on local cost basis.

- installation cost
- land acquisition;
- transportation;
- civil works;
- gantries, fences, earthing etc.;
- installation/commissioning;

C. Ownership cost

The cost of ownership consists of two major cost elements:
- operating cost;
- maintenance cost;

The operating cost is all expenses which occur during the normal operation of the substation [4]. This analysis will only respect the cost which is required for the regular maintenance of the investment except the switchgear equipment, e.g. GIS building.

The maintenance cost can be divided into two groups:
- scheduled maintenance;
- unscheduled maintenance;

In order to ensure the fully functional operation, the planned cost is used for monitoring, inspection and overhaul of equipment while the unplanned costs are used to repair and rehabilitate the functional efficiency. The maintenance cost comprises labour, material and travel expenses to maintain the switchgear equipment.

- labour cost;
- material cost;
- travel cost;

For unscheduled maintenance, additional outage cost, which is financially assessed, has to be taken into consideration:
- further damage to other devices;
- loss of supplied energy;
- contractual penalty;
- liability cost;
- cost of short-run energy;

The following equation is introduced in the calculation of interruption cost:

$$ C_{int} = T_d \cdot (C_{pen} + \sqrt{3} \cdot C_{los} \cdot I \cdot U) $$

where $U$, $I$, $C_{los}$, $C_{pen}$ and $T_d$ are the rated voltage, the average current, the loss of supplied energy, the penalty and the duration of interruption, respectively.

In order to determine the life cycle cost of GIS, it is necessary to identify the lifetime of components. The lifetime can be investigated by the failure rate as a function of age [5].

D. Decommissioning cost

The cost has to comprise all cost of salvage and disposal after use, subtracted by earnings which can be received by selling the reusable materials.

III. CALCULATION AND ANALYSIS

Many utility or regional specific structures may have a different impact on the life cycle cost. To make it useful for each utility a sensitivity analysis will show how regional changes of the different parameters will have an impact on the different cost portions of the overall life cycle cost. Thus, the life cycle cost must now be optimized by comparing the life cycle cost for different structures. As an example the influence of the different parameters on the calculation of the life cycle cost is discussed on the basis of a 145 kV substations considering different maintenance strategies. The following parameters will be evaluated:

- installation cost;
- equipment cost;
- land acquisition cost;
- labour cost;
- interruptions of energy;
- disposal cost;
- interest rate;
- inflation rate;

The first sensitivity analysis is to predict the change of the overall life cycle cost when the so-called parameter will be changed by 10%. In this way the different influences of the parameters on the life cycle cost can be evaluated and the results of the sensitivity analysis can be interpreted as follows:

- The installation cost has a relative small influence so that it cannot be too crucial and too cost-effective. A high qualified installation can save money later by reducing the number of failures. The influence of energy interruption on the life cycle cost will be reduced to twice or five times according to switchgear type. 10% savings of installation cost have the same effect on life cycle cost as 2% increase in the energy interruption due to the major failure.

- The land acquisition cost is negligible for the encapsulated technology. The labour cost for maintenance has the similar influence as the cost of energy interruption for the conventional AIS technology.

- The energy of interruption has the strongest influence due to the major failure, even stronger than the cost of scheduled maintenance. Thus, a decrease in energy of interruption can reduce the overall life cycle cost by means of a qualified scheduled maintenance.

- The influence of disposal cost can be neglected due to the long lifetime of high voltage SF$_6$ insulated substations and the effect of discounting on the life cycle cost.

- The influence of interest and inflation rates on GIS is smaller than AIS because the components of GIS, independent of the discounting rate is more dominant.

A second way for sensitivity analysis is to show the effect of a changing parameter on the life cycle cost by setting the
defined parameter to zero. If the following parameters have been neglected in the life cycle cost analysis, it can be concluded as a result of this second sensitivity analysis.

- The land acquisition cost is only relevant for AIS substations. The required surface for GIS is too small under the chosen conditions.
- The cost of maintenance has a significant influence on the life cycle cost. However, no maintenance may lead to an increase in failures.
- No failures will lead to a significant reduction of cost. Beside the reliability of product, the proper maintenance measures can optimize the life cycle cost.
- No interruption of energy in case of failures can save approximately 5-6% of the life cycle cost by additional redundancy within the substation.
- The inflation rate has a similar influence on the life cycle cost as the cost of inspection. The life cycle cost without inflation would be 82% to 88% of that with inflation, mainly due to the long lifetime period of high voltage switchgear equipment.

The life cycle cost depends heavily on the interest rate. An example of the net present value (NPV) over time with three different interest rates is given in Fig. 1. With a moderate interest rate of 6.5%, the net present value (NPV) of the life cycle cost is reduced to 8.1% of the original value for 40 years. For 50 years, the net present value is only 4.3% of the original value.

These additional costs would further decrease the attractiveness of monitoring.

Figure 1: Effect of the interest rate on the decommissioning cost

In the case study of a 145 kV substation, the evaluation of the monitoring system shows that the additional investment in monitoring equipment could not be paid off (Fig. 2). In case of no interruption of energy, it becomes more obvious. The cost for repairs can be reduced by monitoring, but the cost reduction is obviously below the investment cost for the monitoring equipment. Due to the lack of data, the monitoring cost does not contain the cost of unplanned maintenance for monitoring equipment, or other costs caused by monitoring.

Figure 2: Influence of different monitoring systems on LCC of a 145 kV GIS substation without outage cost

With high cost for an interruption of energy, it becomes more obvious that SF6 monitoring seems to be the most efficient (Fig. 3). With slightly higher resulting cost, the function monitoring would become cost efficient as well. It has considerably higher monitoring cost than the SF6 monitoring, but offers the obvious reduction in different costs with reference to the investment cost.

Figure 3: Influence of different monitoring systems on LCC of a 145 kV GIS substation with outage cost

The benefit of monitoring system depends on many different factors such as the interruption of energy. A solution of the optimal monitoring is to calculate the life cycle cost for different financial losses in case of interruption of energy. A penalty is not included in the life cycle cost calculation.

In Fig. 4, the break-even-point of the different monitoring technologies can be observed well. SF6 and function monitoring pay off quickly. High-priced function and partial discharge monitoring have the utmost influence on the failure rate with the steepest slope.
IV. CONCLUSIONS

The life cycle cost is an efficient method to select a proper configuration for high voltage SF6 insulated substations. Additional evaluation techniques such as the sensitivity analyse show the influence of the different parameters on the life cycle cost. The method of life cycle cost is applied for high voltage switchgear technologies to achieve minimal life cycle cost and optimized substation layout.

The investment cost dominates the life cycle cost of GIS which is the larger portion at the high voltage level. The ownership cost is not proportional to the investment cost since it is low with high reliability and low maintenance. For economic reason, the monitoring is used for the high voltage GIS whereas the amount of energy is transferred, so that the incidental damages are avoided. In principle, GIS can compensate the higher investment cost as the new technology may bring the low incidental cost and low acquisition cost.

REFERENCES