ASSET SIMULATION AND LIFE CYCLE ASSESSMENT FOR GAS INSULATED SUBSTATION

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SUMMARY

An important task of the asset management process is the evaluation of the long-range investment and resource planning of the assets of the complete power system and the life cycle cost assessment of different type of substations. The calculation of the long-range investment and resource planning can be performed by using dynamic asset simulation tools, which represent the statistical behavior of the complete asset group over a time range of 40 to 60 years. The final result is the evaluation of the total investment and operational expenditures as well as the comparison of different investment and maintenance strategies.
The replacement rate of the different types of asset can be described by statistical data, e.g. Gaussian density functions, which can be gained from experience of the asset manager or from published reports. Depending on the age distribution of the installed assets, the number of the components to be replaced over the simulated time range can be evaluated. Under consideration of the yearly outage and maintenance costs the total costs of ownership can be calculated each year depending on the different group of costs. With consideration of the different expenditures and the knowledge how many components per year have to be maintained and replaced and on the basis of the failure rates ("major" and "minor" failures), in principle it is possible to evaluate the total expenditures for a group of equipment and in consequence for the entire system during the complete simulation period (e. g. 50 years).
The **l**ife **c**ycle **c**ost (LCC) assessment consists of three main cost elements, the cost of acquisition, the cost of ownership and the renewal cost. These three cost elements are evaluated based on experience and on statistical data. According to the present value method all payments in the future, i. e. cost of ownership (costs for scheduled and unplanned maintenance) and renewal costs, have to be represented as present values related to the year 0, at which an interest rate of 10% and an inflation rate of 2.15% per year is taken into account. Finally, for evaluation of the total life cycle costs the different cost shares are accumulated, at which a period of consideration of 40 years and 50 years respectively is regarded.

KEYWORDS

Asset management, asset simulation, life cycle cost calculation, CAPEX, OPEX

1 INTRODUCTION

The Asset Management Process can be divided into different steps, which start with the evaluation of the long term strategy and end with a concrete maintenance activity of certain equipment [1]. In the first part of the following report the initial step is described: The derivation of the capital as well as the operational expenditures of a fleet of GIS bays over the total life time. The goal of this analysis is to develop a long-term plan for the maintenance and investment strategy of a system by suitable equipment models. The main questions which can be answered by usage of the long term resource planning are:

- Evaluation of long term strategies,
- impact on system reliability,
- estimation of capital and operational costs,
- calculation of the yearly budget,
- Identification of investment peaks to allocate the necessary resources.

The second part of the report deals with decision making process for choosing the adequate substation technology. Nowadays different substation technologies are available, i. e. conventional air insulated substation (AIS), gas insulated substation (GIS) and mixed technologies using GIS as well as AIS components. In the past the decision making process for choosing the adequate technology was mainly based on consideration of investment costs and on consideration of spatial requirements and environmental issues. Normally the first option was AIS technology due to the lower investment costs. In case of spatial and environmental restrictions GIS technology was chosen. Today the decision making process is also affected by service costs and further lifetime considerations. Therefore life cycle cost assessment is applied for finding the most economic solution.

2 ASSET SIMULATION

2.1 Equipment model for the operational level

Different models can be used for the presentation of different groups of equipment to develop the long-term plan for the maintenance as well as the investment strategy for the strategic corporate level. The main task of this procedure is to prepare the long-term decision in the asset management process. In general several model reproductions are possible in order to solve the task:

- Age dependent limiting model (chapter 2.3),
- statistic model (e.g. normal distribution, chapter 2.4),
- reproduction under consideration of the survival function (chapter 2.5).

The first two models mentioned are briefly discussed in the following. Thereby the usage of the statistical model is mainly dealt with considering a population of 1676 GIS bays (123 kV). Whereas the last model described in [2] takes into consideration the actual condition of the asset. A lot of data are required to perform the asset simulation and these are described in chapter 2.2 considering the asset group of 123 kV GIS.

2.2 Considered asset group

The data base used to evaluate the principles of the long term resource planning in this report is from the GIS Forum, which was founded in 1997 by the department of “Electrical Power Systems” (TU Darmstadt). The objectives of this GIS User Group consisting momentary of 18 utility members are among others collecting and exchange of service experience.

In total 1676 123 kV bays – 157 coupling bays, 852 line bays and 667 transformer bays – are considered for the dynamic simulation over the time period between 1967 and 2009. The age distribution of the bays under investigation is presented in Fig. 2.1. A high

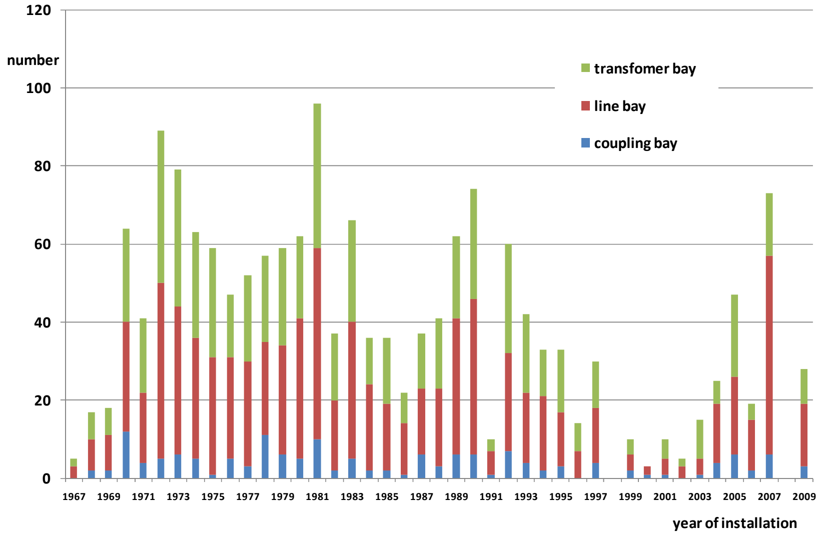


Fig. 2.1: Age distribution of the population under consideration

investment period can be seen between the seventies and eighties with peaks in the years 1972 and 1981 and about 90 bays are erected by the utilities. This period is followed by an area of lower investments and the reason might be the new circumstances in the field of energy supply for example the liberalization of the energy market. If a maximum technical life time of 40 to 45 years is assumed it can be stated that a lot of bays have to be replaced during the next decade.
The various pieces of equipment belong to the different type of bays, e.g. circuit-breakers, disconnectors and instrument transformers. The investment costs for new bays can be estimated between 400 T€ and 560 T€ for the calculation of the capital expenditures (CAPEX) depending on the type.
Different data are important for the calculation of the operational expenditures (OPEX) and in this case only maintenance and repair expenditures are taken into consideration.

These data are summarized in Table 2.1 (maintenance costs) for a general bay, the repair costs for each component are assumed according to practical experience (major/minor fault), which has to be repaired in case of an outage. These data are exemplary used for the calculation and can differ in actual projects.

Table 2.1: Data for the calculation of maintenance costs for a complete GIS bay depending on the type of activity

value	patrol inspection	intensive inspection	overhaul
working hours	4 h	8 h	30 h
material costs	-	100 €	3000 €
cycle	2 years	8 years	16 years

Due to the corrective maintenance strategy of instrument transformers and busbars every fault will lead to a major fault, whereas in the other cases a difference can be made between a major fault with an unplanned interruption of the power supply within 20 minutes and minor fault, which can be solved by a planned maintenance activity. Labor costs of 70 €/per hour are taken into consideration for the calculation of the total repair expenditure.
The failure distribution has to be taken into consideration to calculate the outage costs depending on the type of failure. The distribution of major failures is reported in Fig. 2.2. It can be seen, that roughly 50 % of all outages are caused by a failure of a circuit-breaker. This result is in line with the Cigre survey.

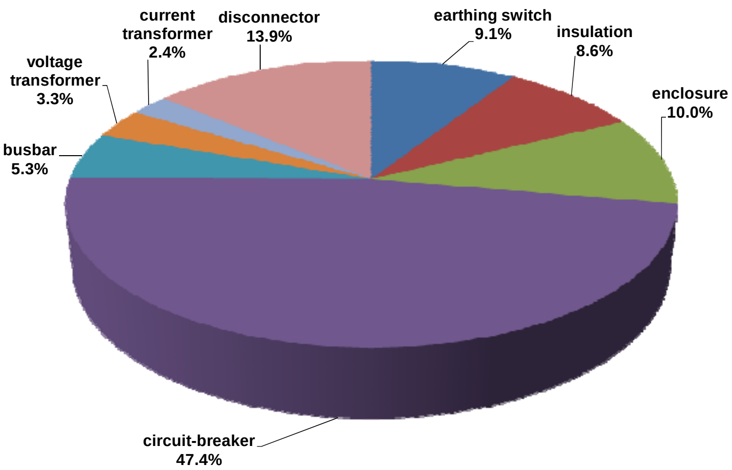


Fig. 2.2: Failure distribution (major failure)

The relationship between minor (mf) and major (MF) failures is derived from [4] and is assumed to mf/MF = 7.0 for circuit-breakers in this voltage range. For simplification the same ratio is applied for disconnectors as well as earthing switches, too. Depending on the number of components per bay, repair costs according to Table 2.2 and the failure distribution (Fig. 2.2), the total costs in case of a major as well as minor fault can be calculated. The final results are listed in Table 2 depending on the type of bay.

Table 2.2: Costs in case of an outage depending on the type of bay

type of bay	repair costs/€	
	major failure	minor failure
coupling	40000	1500
line	45000	2000
Transformer	40000	1500

The failure frequency in case of major faults of the asset group shows Figure 2.3, depending on the age of bays. It can be seen that the failure rate increases in the first period of installation which is followed by a constant area between 5th and 15th year. After this period an increase of the failure rate can be detected but due to the low number of failures and bays the statistical confidence is weak.

The regression curve is used as mentioned in Figure 2.3 for the asset simulation of the outage costs, which is in this case a rough estimation of the age dependent failure rate due to the small number of outage of the GIS bays at every time step.

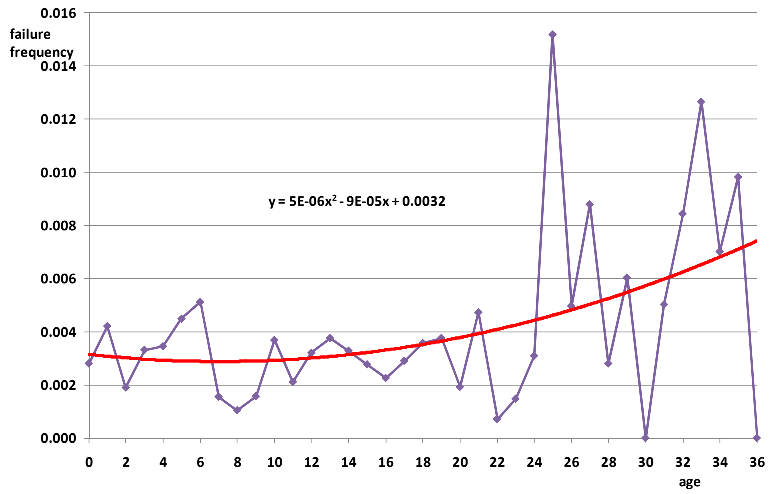


Fig 2.3: Failure frequency of 123 kV GIS

2.3 Age-dependent limiting model

Using this model it is accepted that a type of equipment will be generally removed between a time interval which is defined by t_{min} and t_{max} depending on the operational experience. If for example it has to be determined how many pieces of equipment have to be replaced during the next five years, these components have to be considered which will enter and leave the period (t_{min} and t_{max}). Due to Fig. 1, the following number of components has to be replaced depending on the age distribution within five years, if an operational time range of 30 years up to 50 years is taken into consideration:

- n_{min}: = 0 (minimum number within 5 years)
- n_{max}: = 983 (maximum number within 5 years)

In this example the minimum number is calculated according to the components, which exceed a time of 50 years during the next five years and the minimum value is 0 as the oldest bay is 43 (installation year 1967) year and far from the maximum age of 50 years. In the contrary to this the maximum number is calculated due to the number of components within the time interval (t_{min} and t_{max}) and in addition which will enter this period.
In general this method represents a rough estimation of the number of pieces which have to be replaced during a considered time interval and it makes sense to use the medium value of these two extreme values for the evaluation of the investment budget, in this case 492 bays or 98 bays every year. The operational costs of the asset group have to be calculated, if the yearly costs for maintenance a repair are multiplied by the number of installed bays.

2.4 Statistical method (normal distribution)

In case of the usage of the statistical method to calculate the number of components which have to be replaced it has to be assumed, that a density function of the replacement rate can be applied. The basic principle is that a sufficient population is available, so that for example a normal distribution can be presupposed. In general various types of statistical functions can be used, e. g. Weibull distribution, to achieve the asymmetrical shape of the distribution to simulate the different age behavior of the asset. If for example according to Fig. 2.4 a mean value μ = 42 years of GIS bays is assumed with a standard deviation σ = 8 years, he number of renewed bays can be determined, which should be exchanged in each year within a fixed time range. In addition it should be considered that all components have to be replaced which exceed a maximum technical life time, for example t_{max} = 50 years. The used replacement rate according Fig. 2.4 depends on the information due the Cigre Brochure 176 [5].

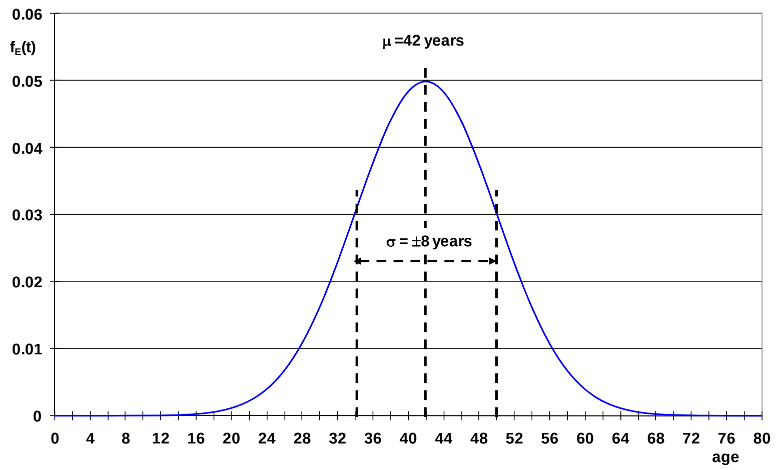


Fig. 2.4: Replacement rate of 123 kV GIS, normal distribution [4]

In general three different equations are available which describe the statistic behavior of statistical functions:

- Density function f(t), Fig. 2.4,
- distribution function F(t),
- hazard or replacement rate $\lambda(t)$.

The other two functions F(t) and $\lambda(t)$ can be derived by the density function, so that with the help of the mean value μ and the standard deviation σ the replacement of an asset population can be calculated depending on the given time interval. If the number of replaced components and assets, which are in service, can be calculated for every year, the related investment and operational expenditure (CAPEX; OPEX) can be derived. Different input data should be used for the complete asset simulation, for example:

- Age distribution of asset groups (number, installation, Fig. 2.1),
- maintenance costs for inspection and overhaul (material costs and working hours, cycle), Table 1,
- time dependent failure rate (major and minor failure), Fig. 2.3,
- repair costs in case of an outage, Table 2.2,
- not delivered energy in case of an outage (not considered),
- replacement rate (statistical behavior of the total asset fleet), e. g. normal distribution, Fig. 2.4,
- investment costs for new equipment, for example 500 T€ per bay,
- costs of power losses (not considered).

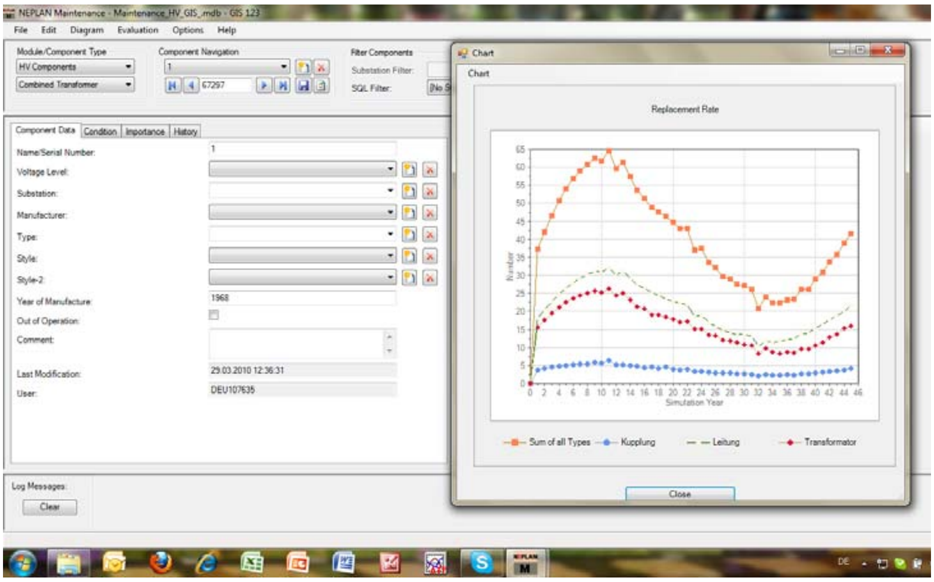


Fig. 2.5: Screen shot of NEPLAN© Maintenance software tool [6]

In general it is possible to evaluate the not delivered energy at certain system nodes in case of an outage. In this case the consequence of an equipment failure has to be calculated at the system nodes which can be performed by reliability calculations. Fig. 2.5 shows the screen shot of a powerful software tool [6] to calculate the investment and operational expenditure over a time range of 45 years (number of replaced bays, right side).

An investment peak has to be expected in about 8 to 13 years with about 60 bays according to the replacement rate. Depending on the number of bays which have to be replaced each year, the total investment costs can be calculated according to Fig. 2.6 for different types of bays (coupling, line and transformer) as the numbers of components belonging to the bays are different.

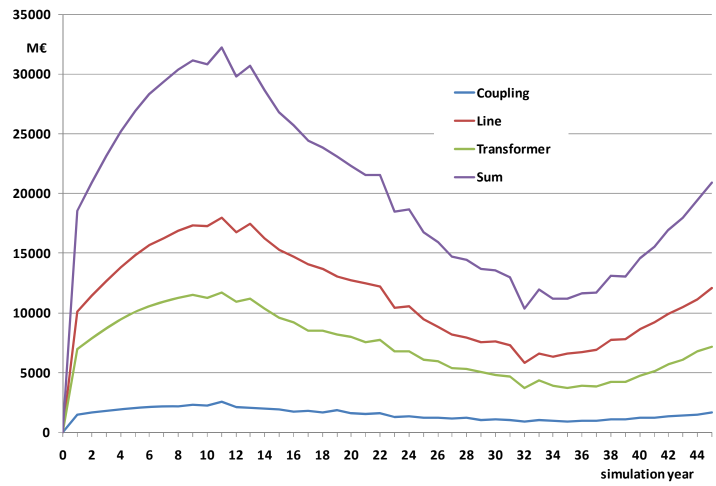


Fig 2.6: Yearly investment costs of the replaced GIS bays (CAPEX)

Table 2.3: Number of replaced components per year

year	number
1	37
2	42
3	47
4	51
5	54
average	46

An investment peak, which amounts to about 30 to 32 M€ per year, will arise in about 8 to 13 years due to the age distribution and it makes sense to smooth the investment peak for an optimal allocation of the resources. The numbers of bays which have to be replaced within five years are listed in Table 2.3 and the average number of replaced bays is about 46 each year. This value can be compared with the number 98 bays according chapter 2.3, if age dependent limiting model is applied and the deviation between the two different models is obvious.

The average replacement value for the next five-year time periods are:

- 6 – 10 years: 60 bays
- 11 – 15 years: 59 bays.

Finally the total operational expenditures (OPEX) are calculated and the overall results are listed in Fig. 2.7, furthermore the repair costs for major and minor failures and the maintenance costs (inspection, overhaul) are reported. Due to the fact that every bay is replaced one by one with the same maintenance and failure behavior, the operational costs are roughly constant and amount to 0.75 M€ each year. In general it is possible to consider the non delivered energy at system nodes which is caused by an outage of a substation. These values depend on the failure rate of the substation and the topology of the system so that reliability calculations have to be performed and finally the energy has to be financially assessed. The repair costs differ slightly according to the medium age of the total asset fleet due to the age dependent failure rate according to Fig. 2.3.

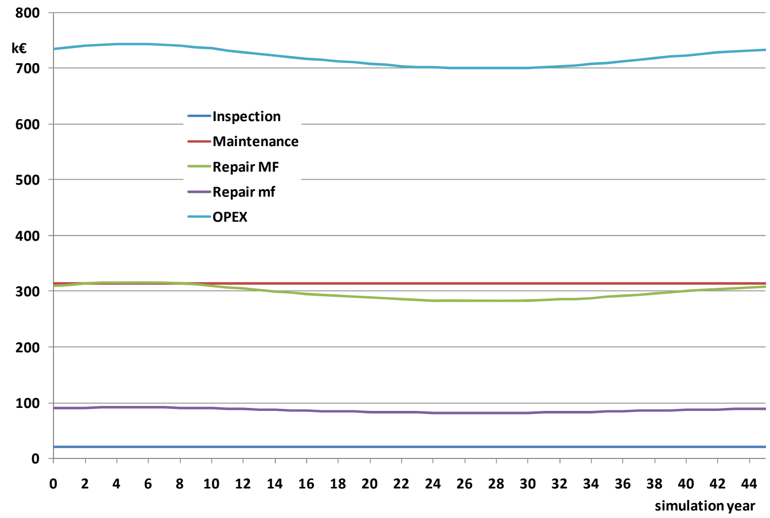


Fig. 2.7: Operational expenditures of the asset group (OPEX)

On the basis of the exact age distribution of the asset fleet the behavior of the entire group of asset is analyzed by the application of the statistic model. Thus an allocation of the exact equipment which has to be changed is in principle not possible.

2.5 Reproduction of the survival function under consideration

Whereas the described method according to chapter 2.4 uses the statistical functions, which for example are published in technical journals, it is the task of the asset simulation to apply the simulation by usage of the actual condition of the asset group. At this time this approach is still in development and the first steps are reported in [2].

3 LIFE CYCLE COSTS ASSESSMENT

3.1 Basic structure of life cycle cost (LCC) calculations

The general procedure of **l**ife **c**ycle **c**ost (LCC) assessment is given in Fig. 3.1. The assessment consists of three main cost elements, the cost of acquisition, the cost of ownership and the renewal cost. The cost of acquisition is subdivided in cost for system and balance of plant. The cost of ownership is differed in a similar way at which the maintenance costs, i. e. costs for scheduled and unplanned maintenance are of interest, mainly. The third main cost element, the renewal costs, also considers equipment and balance of plant.

A first rough LCC estimation is given in Fig. 3.2. This first estimation does not show a distinct difference between AIS and GIS technology. Therefore, in the following the different costs elements are investigated more in details.

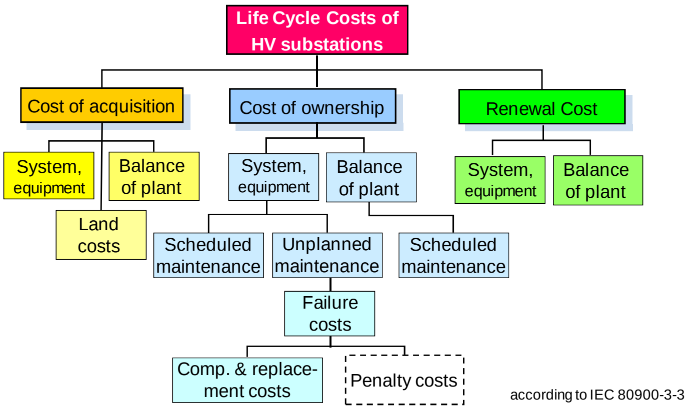


Fig. 3.1: Basic structure of **L**ife **c**ycle **c**ost (LCC) assessment for HV substations

Life cycle costs:

LCC = CI + CP + CR + CO + OC + CD

CI	Acquisition costs
CP	costs for scheduled maintenance
CR	costs for unscheduled maintenance & repair
CO	general service costs
OC	outage costs
CD	costs for decommissioning & disposal

Cost structure	GIS / AIS
CI equipment installation	+ -
CP	-
CR	+
CO	-
OC	0
CD	0
lifetime	+
LCC	0

+ higher 0 neutral - smaller

Fig. 3.2: Rough estimation of **L**ife **c**ycle **c**ost (LCC) for HV substations

The different life cycle cost shares in principal are given in Fig. 3.3. According to the present value method all payments in the future have to be represented as present values related to the year 0, at which an interest rate of 10% and an inflation rate of 2.15% per year is taken into account. According to Fig. 3.1 the different cost shares are analysed in detail.

Costs for system and equipment

The costs for system and equipment refer to

- primary equipment
- secondary equipment
- engineering

Costs for balance of plant

The costs for balance of plant consider

- buildings for secondary & primary equipment respectively
- portals, gantries, supporting structures, foundations
- earthing, secondary cabling
- transport, installation, commissioning

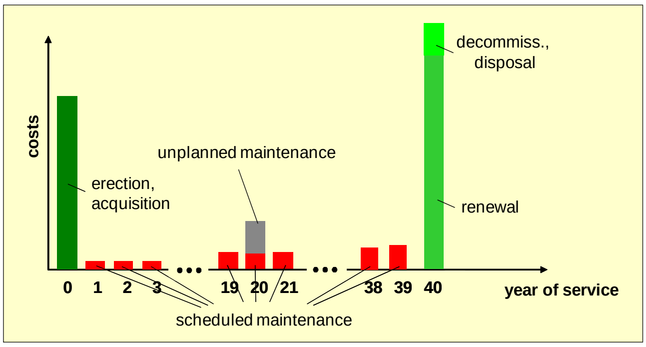


Fig. 3.3: Different shares of LCC over years of service

Fig. 3.4 shows the costs for system and equipment and for balance of plant related to the total investment costs. For the AIS version two different types are assumed. The more costly version is set to 100%. As to be expected in case of the GIS solutions the system and equipment costs are dominant. Regarding the AIS solutions the acquisition cost shares for system and equipment respectively and for balance of plant of 123 kV substations are comparable, whereas at 420 kV substations the equipment costs are prevailing.

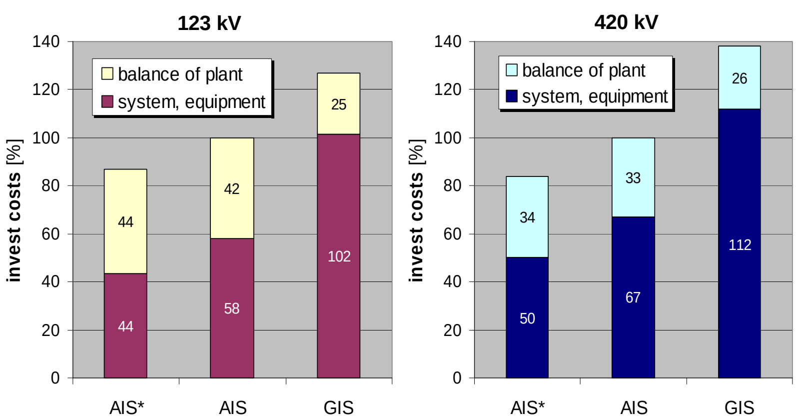


Fig. 3.4: Acquisition costs

Cost shares for scheduled maintenance

The costs shares for scheduled maintenance comprise maintenance of balance of plant and maintenance of system and equipment respectively.

The costs for balance of plant maintenance cover

- General cleaning, special cleaning and general checks of buildings
- Technical maintenance of cranes, fire protection, auxiliaries, lighting, overhauls
- Maintenance expenditure for outdoor installation, e.g. lawn cutting, cleaning of drain, visual checks of foundations, fences & HV equipment, cleaning of cable channels & ducts

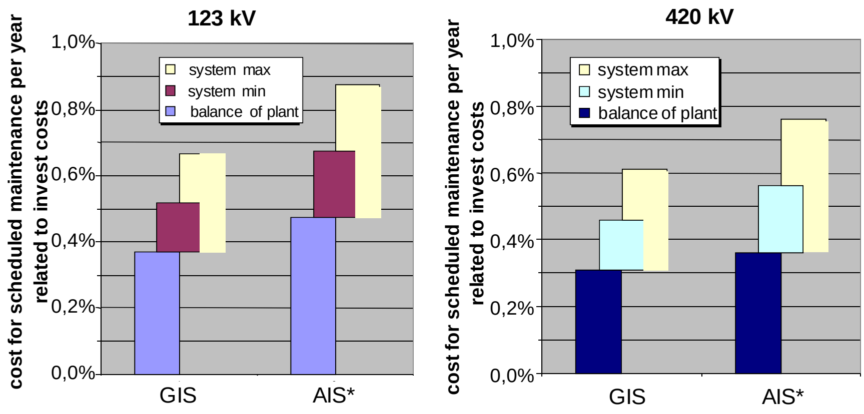


Fig. 3.5: Scheduled maintenance costs per year

The maintenance expenditure for balance of plant is determined in man days per year and multiplied by cost per man day. These cost shares are related to investment costs.

The costs for scheduled maintenance of system and equipment respectively are derived from service experience, at which minimum and maximum costs for scheduled maintenance of AIS & GIS equipment is taken into account. These costs are also related to the investment costs. The costs for scheduled maintenance per year are given in Fig. 3.5. These costs are in the range of 0.6 up to 0.9 % per year related to the investment costs at which GIS are at the lower and the AIS at the upper boundary value.

Cost shares for unplanned maintenance

Unplanned maintenance activities are caused by major failures, mainly dielectric failures and by minor failures. For major failures the failure probability is derived from different national and international failure statistics [3]. The repair costs are taken from service experience at which a minimum and a maximum value is taken into account.

Table 3.1: Cost shares for unplanned maintenance

	Failure probability [% per bay year]		Repair costs [% of invest costs]
	123 kV	420 kV	
GIS	0,1…0,2	0,2…0,4	5…20
AIS	0,1…0,2	0,2…0,4	3…10

Table 3.1 gives an overview of the data presumed. The costs for removal of minor failures are obtained from service experience. In average 10% of the repair costs for major failures can be assumed.

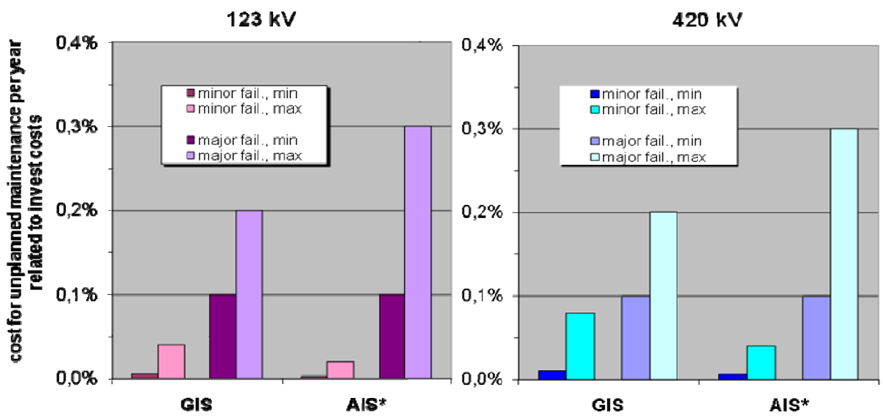


Fig. 3.6: Unplanned maintenance costs per year

In general major and minor failures are stochastic events and the costs for removal would have to be regarded at the time at which the defect appears. For simplification, however, the costs are given as costs per year and related to the investment costs and presented in Fig. 3.6.

LCC shares for maintenance

For LCC assessment the maintenance costs given as costs per year related to the investment costs have to be discounted to the year zero.

Table 3.2: Unplanned maintenance costs

	maintenance costs discounted, related to invest costs [%]							
	123 kV				420 kV			
	GIS		AIS*		GIS		AIS*	
	40 a	50 a	40 a	50 a	40 a	50 a	40 a	50 a
min	7,6	7,8	9,4	9,7	6,9	7,1	8,1	8,3
max	11,0	11,3	14,5	14,9	10,7	11,1	13,4	13,7

Table 3.2 shows the LCC costs shares for scheduled and unplanned maintenance, if a life cycle of 40 or 50 years is considered. Due to the discounting procedure the cost shares amount to about 15% at maximum.

LCC shares for renewal

GIS and AIS exhibit different service lives. Therefore a service life of 50 years for GIS and of 40 years for AIS was adopted.

The renewal process comprises 100 % of the system and equipment respectively and 50 % of the balance of plant.

Table 3.3: Present values of renewal

	renewal costs discounted, related to invest costs [%]					
	123 kV			420 kV		
	GIS	AIS	AIS*	GIS	AIS	AIS*
system, equipment	2,5	3,0	2,3	2,7	3,5	2,6
balance of plant	0,2	1,1	1,1	0,2	0,8	0,9
total	2,7	4,1	3,4	2,9	4,3	3,5

Table 3.3 shows that the discounted renewal costs shares are in the range of 2.7 % up to 4.3 % related to the investment costs. The benefit of the longer GIS service life is 1 % only.

3.3 Life cycle costs of GIS and AIS in total

For evaluation of the total life cycle costs the different cost shares are accumulated, at which a period of consideration of 50 years is regarded. The results are presented in Fig. 3.7.

For GIS the minimum costs for scheduled and unplanned maintenance and for AIS the maximum costs were assumed. In any case the LCC costs of GIS are in the range of 20 up to 30 % higher than those of AIS. This difference is mainly caused by the higher acquisition costs, i.e. investment costs of GIS. The lower costs of ownership cannot compensate the higher investment costs.

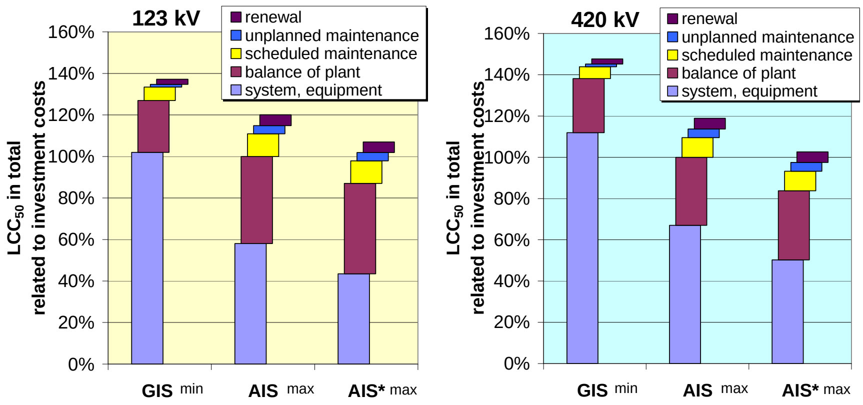


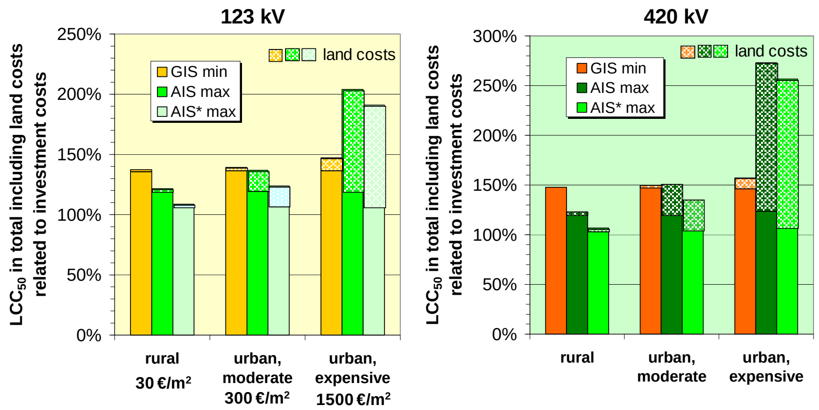
Fig. 3.7: Life cycle costs (LCC) in total

Up to now the space saving features of GIS were disregarded. In practice the space requirements for substation can be reduced 20 up to 10 % by application of GIS technology. Depending on location of the substation the land costs may play an important role.

Table 3.4: Land costs for GIS and AIS

	Land costs, related to invest costs [%]			
	123 kV		420 kV	
	GIS	AIS	GIS	AIS
rural	0.2	2	0.2	3
urban, moderate	2	17	2	31
urban expensive	10	84	10	153

Table 3.4 gives an overview of land costs for 123 kV and 420 kV GIS and AIS. The costs are related to the investment costs and take into account three costs categories. For installation in rural areas land cost of 30 €/m², in moderate urban areas 300 €/m² and in expensive urban areas 1500 €/m² were assumed. As to be seen, in moderate and expensive urban areas the land costs can become dominant.



The life cycle costs including land costs are presented in Fig. 3.8 for a period of consideration of 50 years. For moderate urban areas the LCC costs including land costs are comparable for GIS and AIS. In expensive urban areas the LCC costs are mainly affected by the land costs. In consequence the GIS solution becomes clearly more economic.

Fig. 3.8: Life cycle costs (LCC) in total including land costs

4 CONCLUSION

The investment and maintenance provisions can be evaluated with the help of an asset simulation for different years under the today's boundary conditions (failure rates, expenditure for maintenance etc.). By a change of the boundary conditions, e.g. extension of the maintenance cycle, the influence on the financial requirement and the system reliability can be derived and optimized considering increasing failure rates. It is possible in a second step to identify the equipment, which should be maintained or replaced under knowledge of the annually necessary budget to identify with the help of the RCM procedure according to [5], [7].

The substantial advantage of a dynamic asset simulation is, besides from the knowledge of the financial requirements under consideration of the current maintenance and renewal strategy, to evaluate the influence of different strategies on the final result, e.g. the shift of a renewal measure or extension of a maintenance activity. This will be of special interest in case of the discussion with the appropriate national authorities regarding the investment strategy and the financial expenditures deriving from this.

LCC costs for substation of different technologies, i. e. GIS and AIS, are mainly dominated by acquisition costs, i. e. investment costs, if the land costs are disregarded. The cost of ownership, i. e. the maintenance costs, and renewal costs are less relevant. They amount to 20 % or less compared to the investment costs. Due to the higher investment costs the LCC for AIS are smaller than those for GIS. If land costs are taken into consideration, benefits for LCC of GIS in urban areas can be identified due to the space saving features of GIS technology. The most efficient option for LCC improvements of GIS could be gained, if the investment costs could be reduced.

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