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Life Cycle Cost Analysis of transmission and distribution systems

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Abstract**-- In the last years two topics are often in the discussion about energy supply companies. Special attention has been drawn by the topics of "Life-Cycle-Cost (LCC)" and "Risk Management" since the liberalization of the energy market in the late 90s of the last century.**

In Germany large parts of the 110 kV system were built up in the 60s and 70s, for this reason most of the assets increasingly reach their estimated life time. In this case, life cycle cost analysis offers a helpful methodology to compare different strategies like refurbishment, renewal or redesign.

This paper presents the principle calculation of Life-Cycle-Costs on a complete 110 kV overhead transmission grid with air insulated substations. The results depict the main cost-driving and most important elements of the system. On this basis, different maintenance strategies have been examined with regard to their corresponding Life-Cycle-Costs.

Index Terms**-- High voltage transmission system, life cycle costs, maintenance strategy, substation.**

I. INTRODUCTION

FOR state-of-the-art electrical devices efficient and reliable operation is of particular importance. They must execute their function reliably, preferably lifelong and must be as economical as possible over their complete lifetime. Concerning the assessment of single units like circuit breakers, transformers, overhead lines etc. the Life-Cycle-Cost (LCC) method has been used for quite a long time. The concept of Life-Cycle-Cost means to take into account not only the manufacturing cost, but also to consider the operational and disposal costs. In this case the method supports the cost assessment of equipment, while enabling a comparison of different equipment features.

In principle, this approach related to single devices can also be transferred to a complete system consisting of overhead lines and substations.

II. THE LIFE-CYCLE-COST MODEL

The calculation of Life-Cycle-Costs in this work is performed in accordance to IEC 60300-3-3 "Dependability management Part 3-3: Application guide – Life cycle costing". In this standard, an approach is defined for the calculation of Life-Cycle-Costs in electrical engineering, which can be extended to a complete system, as will be seen in this paper. According to IEC 60300-3-3, the life cycle of an element will be subdivided into the following six cost-causing phases (Figure 1):

a) concept and definition;
b) design and development;
c) manufacturing;
d) installation;
e) operation and maintenance;
f) disposal [1].

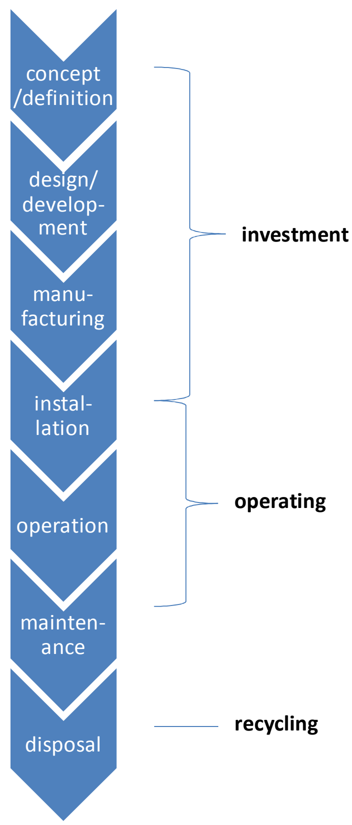

Figure 1: Life cycle phases on the basis of IEC Standard 60300-3-3

On a closer look at figure 1, it often makes sense to combine different cost elements into following groups:

- investment
- operating
- recycling

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The main difference between investment (concept/ definition, design/development, manufacturing, installation) and operating (operation, maintenance) costs is that the former cost group is already known before the investment is made. Installation costs form a special case, as they can be counted to either investment or operating costs [2].

For a more precise cost assessment, a further distinction between operational and maintenance costs has to be made. Such a distinction allows an easier benchmarking of different maintenance strategies, as these turn out to be the main cost drivers for the analysis.

The various cost elements are discussed in the following chapter

III. Definitions

For a better understanding the following terms are used to explain the different expenses:

- Concept/definition: Costs incurring in connection with the concept during the specification or planning phase.
- Design/development: Costs for design, documentation and engineering.
- Manufacturing: These costs contain the expenses for production and sale of the product on the contractor side. Therefore they represent the order value of the whole distribution system. The costs for installation and commissioning of the system are not included in this part.
- Installation: Costs generated on site by installation before the system goes into operation.
- Operation: Costs arising for a sustainable operation of the whole system. Among other things these costs include expenses for power losses of overhead lines or transformers, controlling and staff training.
- Maintenance: Calculation of the complete maintenance expenditures due to different strategies e.g. time based, condition based or corrective.
- Disposal: Costs for work, material and disposal in conjunction with the rebuild of the existing system. For example charges for recultivation of overhead lines are included. Possible profits in the disposal of steel, copper etc. have to be deducted as credit notes of the charges.

Further data has to be used for the calculation of the life-cycle-cost, for example:

- interest rate,
- inflation rate,
- useful lifetime of the equipment.

IV. Data of the 110 kV Network

The studied 110 kV network is fed by a 380 kV system via 380/110 kV transformers and consists of air insulated substations (AIS). The topology of the network represents a mixture of countryside and urban areas. The components which are taken into consideration are listed in Table1.

TABLE 1
NUMBER OF SYSTEM COMPONENTS

Equipment	number
substations	66
circuit-breakers	334
power transformers	83
disconnectors	393
secondary equipment	252
shunt inductors	5
instrument transformers	168
transmission routes (km)	523
steel towers incl. insulators	2.093
overhead lines (km)	1.151

The Life-Cycle-Cost analysis assumes that the network is newly built. That means that all investments of the network are invested at the year zero. The investment costs used for the calculation can be extracting from Table 2.

TABLE 2
INVESTMENT COSTS OF EQUIPMENT (EXEMPLARY)

Equipment	investment costs [€]
substations	558.000
circuit-breakers	34.000
power transformers	675.000
disconnectors	19.000
secondary equipment	26.000
shunt inductors	225.000
instrument transformers	17.000
transmission routes (km)	198.000
steel towers incl. insulators	65.000
overhead lines (km)	26.000

Table 3 represents the hazard rates of the used system components. These rates affect substantially the failure costs of the components and have been used for the calculation of the outage costs per year.

TABLE 3
FAILURE RATES OF DIFFERENT NETWORK COMPONENTS

Equipment	major failure /year	minor failure /year
substations	0,00218	-
circuit-breakers	0,00067	0,00407
power transformers	0,00569	0,01138
disconnectors	0,00035	-
secondary equipment	-	0,00228
shunt inductors	n/a	n/a
instrument transformers	0,00025	-
transmission routes (1/km)	n/a	n/a
steel towers incl. insulators	0,00013	0,00478
overhead lines (1/km)	0,00051	0,01913

The hazard rates of the components were determined on the basis of the “VDN-Störungs- und Verfügbarkeitsstatistik – Berichtsjahr 2006” [2] and [3]. The hazard rate of overhead lines (in this case steel towers and overhead lines) is partitioned with a ratio of 20% on steel towers and 80% on overhead lines (conductors).

The repair costs (major as well as minor faults) depending on the different components are listed in Table 4. These costs present the outage costs. The costs for non delivered energy and sales lost for the company were not taken into account in this table. Costs which arise for the enterprise from failures and non delivered energy are discussed in detail in chapter V.

TABLE 4
REPAIR COSTS FOR MAJOR AND MINOR FAILURES (EXEMPLARY)

Equipment	major failure costs/a [€]	minor failure costs/a [€]
substations	34.800	13.400
circuit-breakers	12.400	9.400
power transformers	77.000	29.300
disconnectors	8.300	4.200
secondary equipment	14.600	3.400
shunt inductors	61.600	86.400
instrument transformers	22.400	5.200
transmission routes (1/km)	n/a	n/a
steel towers incl. insulators	75.000	19.000
overhead lines (1/km)	0	3.000

Beside the repair costs, the expenses for overhauls and inspections are taken into account according to Table 5 and 6. In these tables it is also possible to find the different maintenance intervals.

TABLE 5
OVERHAUL INTERVALS AND COSTS

Equipment	interval in a	costs [€]
substations	1	6.800
circuit-breakers	5	3.400
power transformers	10	10.000
disconnectors	10	2.000
secondary equipment	5	500
shunt inductors	10	2.000
instrument transformers	10	10.000
transmission routes (1/km)	n/a	n/a
steel towers incl. insulators	1	500
overhead lines (1/km)	6	3.000

TABLE 6
INSPECTION INTERVALS AND COSTS

Equipment	interval in a	costs [€]
substations	1	2.300
circuit-breakers	2	200
power transformers	2	200
disconnectors	2	100
secondary equipment	n/a	n/a
shunt inductors	2	200
instrument transformers	2	200
transmission routes (1/km)	n/a	n/a
steel towers incl. insulators	1	100
overhead lines (1/km)	2	200

V. RELIABILITY AND NON DELIVERED ENERGY

Power supply companies have shown during the last years a growing interest for the reliability of their networks and the non delivered energy. After the liberalization of the power grids, the legislator was inducted to create a Federal authority which shall ensure a reliable energy supply and an effective free market. To force the power supply companies towards higher reliability, legislators make use of penalties. Because the German Regulator, the “Bundesnetzagentur” BNetzA has not yet published the height of the penalty, in this paper penalties are applied according to the “Norway Model” (5€/kWh non delivered energy) [4]. For power supply companies the height of penalties is of great importance because this determines the incentive for maintenance and renewal activities. The more expensive one failure is for a power supply company – as a result of penalties – the higher is the effort it has to make in order to sustain a reliable grid. The summation of load interruption frequencies for the examined grid is depicted in Figure 2 divided up into the various equipment groups.

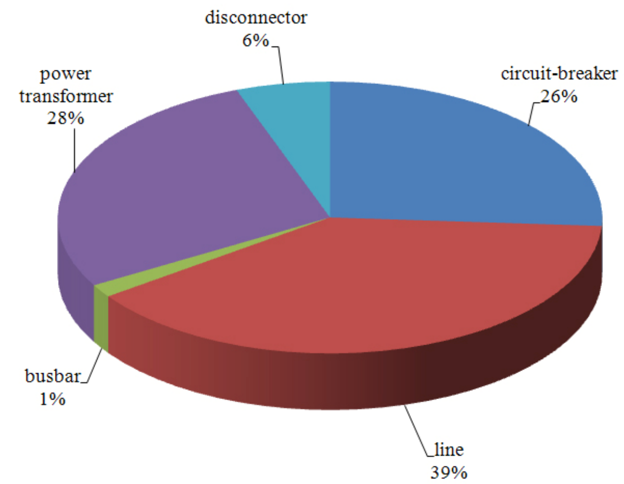

Figure 2: Share of the different pieces of equipment on the interruption frequency

In a similar way, figure 3 shows a segmentation of the accumulated non delivered energy for all loads. A more exact consideration of Figure 2 and Figure 3 makes clear, that the overhead lines are responsible for 39 per cent of the interruptions but only 10 per cent of the non delivered energy. That is due to the fact that most of the loads are supplied by two lines in parallel (in accordance to the n-1 reliability criterion). This is different in the case of power transformers. They are only responsible for 28 per cent of the interruption frequency but because they are not executed in (n-1) they account for 52 per cent of the non delivered energy.

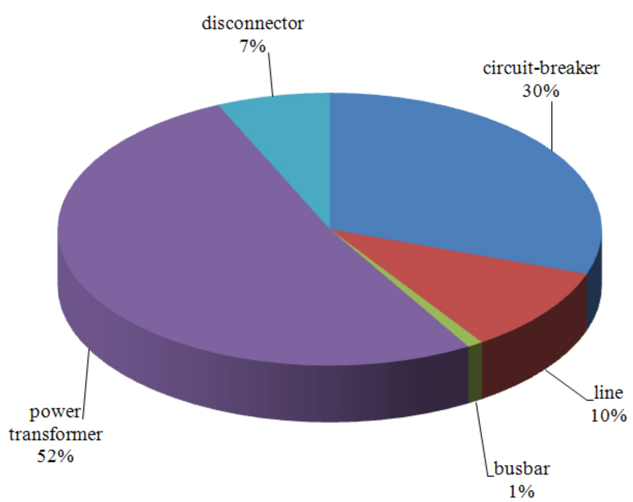

Figure 3: Share of the different equipment groups on non delivered energy

Both the interruption frequency (Figure 2) and the amount of the non delivered energy (Figure 3) are important factors in case penalties are taken into account by the Life-Cycle-Cost method. The main advantage of the "Norwegian model" (which only considers the non delivered energy for penalty calculation) is its simplicity, as only one parameter needs to be determined. An alternative would be to consider also the interruption frequency, because frequent interruptions of only short duration have a negative influence on customer satisfaction.

VI. Calculation of the Present Value

A. Basic economic data of the calculation

The present value is a summary of all payments which arise over a fixed time period discounted e.g. for the year of the installation. The following data are used for the calculation:

- useful life time — 20 to 50 years depending on component types
- outage costs — see tables 3 and 4
- maintenance costs — see tables 5 and 6
- maintenance interval — see tables 5 and 6
- calculation time — 50 years
- penalty — 5 €/kWh

B. Results for reference scenario

For the reference scenario, following financial data have been assumed:

- interest rate — 5,5%
- inflation rate — 1,8%

Figure 4 shows the parts of the total present value of the complete system (740 Mio.€) related to the different components. As can be seen in the detailed view overhead lines have the biggest influence on the present value of the complete network (56 %). It has to be mentioned that the transmission routes have to be considered as existing, so that no planning costs have been taken into account while calculating the present value. Inside the substation, power transformers provide the greatest share, whereas the other components have a minor influence on the result (e. g. instruments transformers, disconnectors and the secondary equipment). Penalties due to unavailability of network components have a significant influence of 7 per cent of the present value.

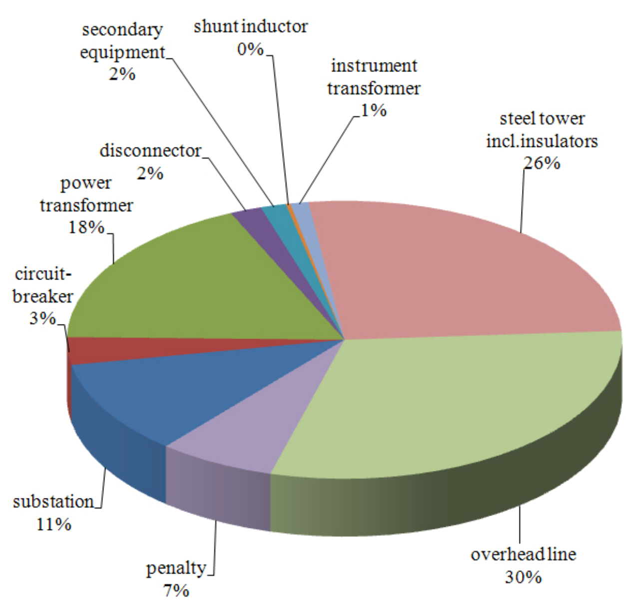

Figure 4: Present value of Life Cycle Costs

The present value of two different components are exemplarily shown in Figure 5 (steel towers incl. insulators and conductors 370 Mio.€) and 6 (power transformers 140 Mio.€). The penalties caused by component unavailability are included in the outage costs. Based on the example of the power transformer it becomes transparent, how much operating costs influence the present value in this case. Figure 6 shows that the overhaul costs for power transformers practically do not influence the present value of their Life-Cycle-Costs. The diagram for the steel tower incl. insulators and overhead lines shows a higher contribution of the overhaul costs (10%) to the present value. If the penalty payments from figure 5 and 6 are not taken into account, the outage costs decrease to 1 per cent. That illustrates the share of the penalties in the outage costs.

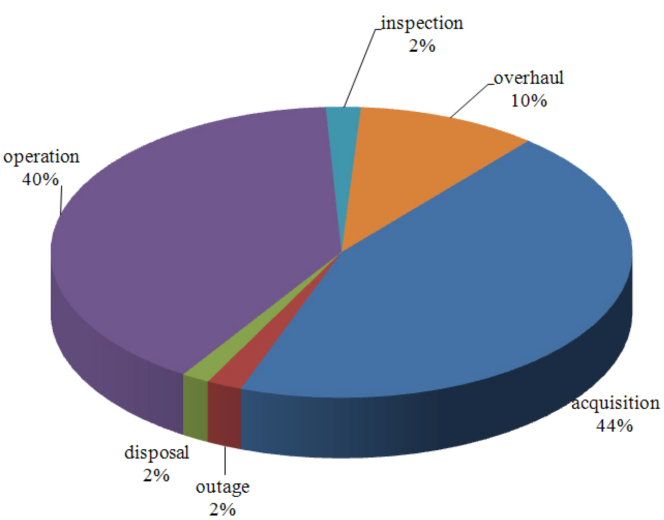

Figure 5: Present value of steel towers incl. insulators and conductors

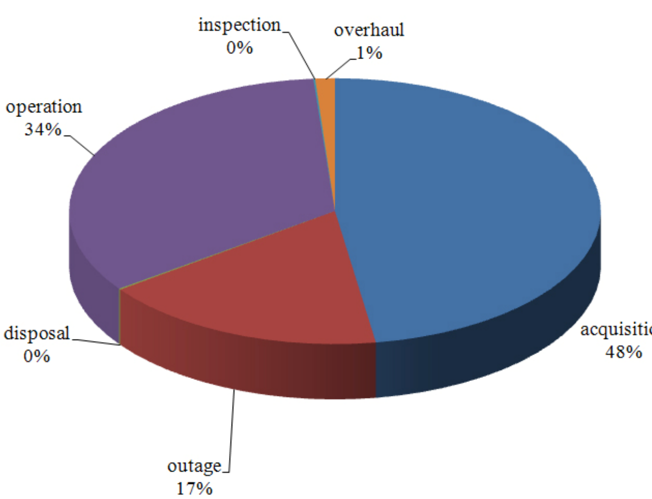

Figure 6: Present value of power transformers

The distribution of the outage costs of the network without penalties (5.3 Mio.€) is shown in Figure 7. The diagram shows that steel towers, overhead lines and power transformers cause together 83% of the outage costs of the complete system. An installation of additional condition monitoring equipment in order to reduce outage costs makes therefore only sense in the case of overhead lines incl. towers and power transformers. But in any case the economic advantage of the installed monitoring systems has to be calculated very carefully, as the additional costs should not exceed the outage costs of the equipment group.

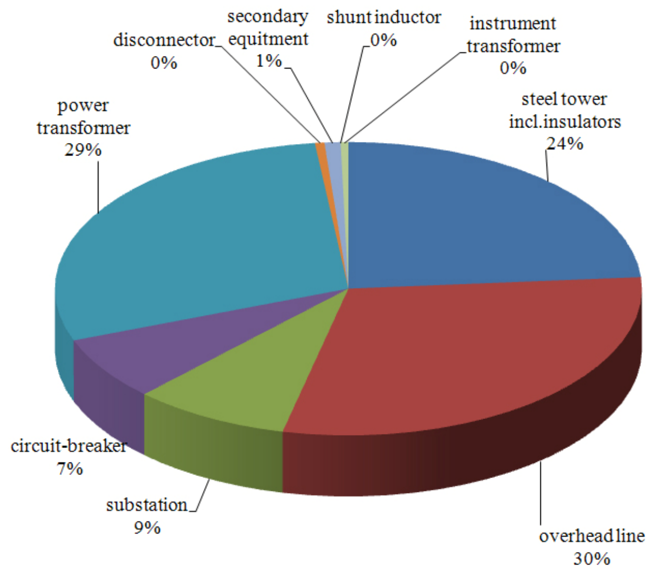

Figure 7: Outage Costs for all components without penalty

In Figure 7 costs for non delivered energy due to an outage has not been taken into consideration. The non delivered energy is further taken into account in Figure 8 in form of penalties with 5€/kWh. This results in additional outage costs of 50 Mio.€, which makes the effect of penalties on outage cots clear. The aforementioned additional outage costs due to penalties has to be now taken into account by power supply companies for their maintenance strategy.

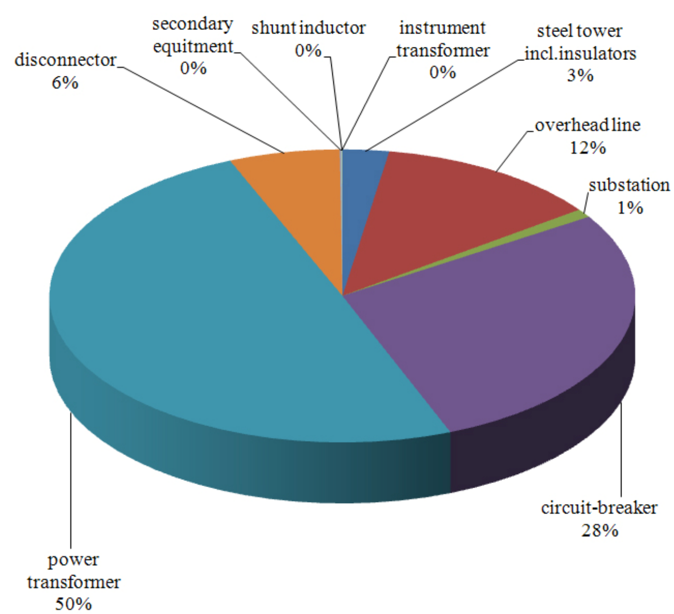

Figure 8: Outage Costs for all components incl. penalties

A comparison of figures 2/3 and 7/8, respectively, may lead to following conclusion: when penalties (accounting for the customer lost energy) are applied, outage costs reflect the shares of equipment groups on non delivered energy (compare Figure 8 and 3). However, when no penalties are applied, outage costs approximately reflect the respective shares on interruption frequency (compare Figure 7 and 2).

C. Results for alternative scenarios

Furthermore, two alternative scenarios have been investigated. The modified financial background is given by:

- interest rate 5,5% or 3%
- inflation rate 1,8% or 0,5%

In order to account for changing economic situations, the influence of different interest and inflation rates on the result of the Life-Cycle-Cost analysis should be examined. An advantage could then be to bet on falling interest rates or to confirm the interest rate for a longer term. The consequences of an interest rate of 9 and 3 per cent and an inflation rate of 3 and 0,5 per cent respectively, can be seen in table 7. Figure 9 also depicts the results for the different scenarios. In particular, penalties have been separated in Figure 9 from the outage costs and are shown as an extra bar.

TABLE 7
VALUES OF THE PRESENT VALUE FOR DIFFERENT INTEREST AND INFLATION RATES

Interest Rate	Inflation Rate	Present Value [Mio.€]
3	0,5	840
5,5	1,8	740
9	3	640

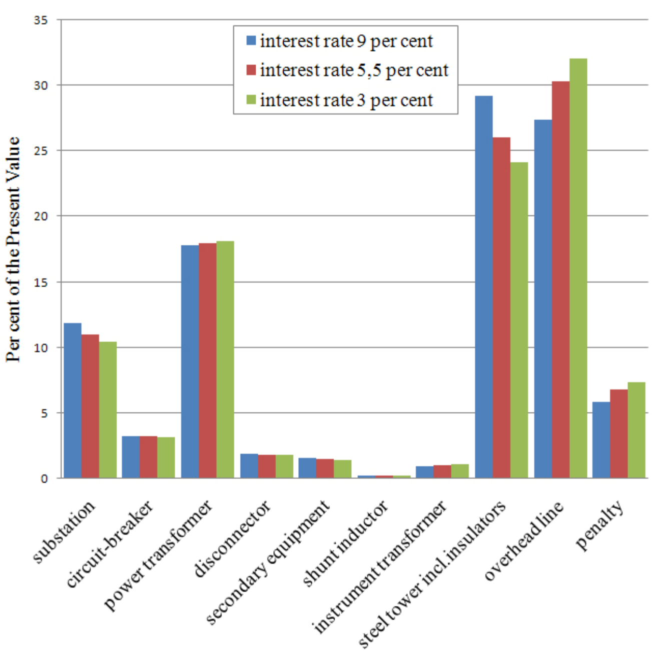

Figure 9: Comparison of different shares on the Present Value by different interest and inflation rates.

VII. CONCLUSION

In summary, Life-Cycle-Cost Analysis is a useful instrument to identify the main cost drivers of a power grid and to take up appropriate actions for cost reduction. Calculation of outage costs plays a crucial part, if the system operator intends to modify the maintenance strategy, for example from time based towards condition based maintenance. Due to the low failure rate of modern system components the benefit for additional condition assessment devices has to be calculated very carefully. In addition, Life-Cycle-cost Analysis is a meaningful instrument to consider changes in the finance sector or induced by regulation. On this way it is possible to customize the maintenance strategies to these new conditions. In particular, the presented study gave an insight by identifying the significant role of penalties on finding the main cost drivers of a power grid.

VIII. REFERENCES

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IX. BIOGRAPHIES

Ingo Jeromin received his Dipl.-Wirtsch.-Ing. degree in Business Administration and Electrical Engineering in 2007 from Darmstadt Univ. of Technology, Germany. He is currently doing his PhD thesis at Darmstadt Univ. of Technology, Institute of Electrical Power & Energy in the area of maintenance strategies for high voltage systems. His research interests are in the area of Life-Cycle-Cost Analysis, maintenance strategies and regulation management.

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